_ NONFERROUS ALLOYS _

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	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

1. GENERAL

This is a super-alpha titanium alloy having an alpha-stabilized Ti-Al matrix solid solution strengthened by the additions of tin and zirconium. The beta-stabilizing addition, molybdenum, increases room and elevated temperature tensile strength and stability. The alloy is used primarily in jet engine compressor parts and airframe skin components.

The alloy possesses good strength properties up to 1000F, exceeding Ti-8Al-1Mo-1V and, for the annealed condition, Ti-6Al-4V. On a strength-to-weight basis, it is also superior to Ti-679. Its creep properties are better than Ti-8Al-1Mo-1V, Ti-6Al-4V and, above 900F, Ti-679. The alloy is more susceptible to solid salt stress corrosion than Ti-679 but less susceptible then Ti-6Al-4V, Ti-8Al-1Mo-1V and Ti-5Al-2.5Sn in the range of commercial mill products and heat treatments. At elevated temperatures, the alloy is more fatigue resistant than Ti-8Al-1Mo-1V and Ti-679. The alloy appears metallurgically stable up to 800F. Forgeability of the alloy is judged similar to Ti-8Al-1Mo-1V and Ti-6Al-4V. Weld properties of the alloy are variable.

1.01 Commercial Designation
6Al-2Sn-4Zr-2Mo Titanium Alloy

1.02 Alternate Designation
Ti-6242

1.03 Specifications
Table 1.03.

1.04 Composition

1.041 AMS specified composition, Table 1.041.

1.042 Silicon in the range 0.08 to 0.1 weight percent is sometimes added to improve the creep resistance of this alloy. Figures 1.0421 and 1.0422 indicate this may be the optimum addition (although the data is enormously scattered). Thermal stability is unaffected by the addition, as shown in Figure 1.0423 where exposure effects for the alloy with added silicon are not different from those for the base alloy (residual 0.03 weight percent silicon). The silicon produces only a slight increase in room temperature and 900F strength, but a significant drop in the reduction of area at these temperatures (Figure 1.0424) and in the -40F Charpy-V impact values (Figure 1.0425).

Producers (78) (79) give assurances that silicon segregation in the modified alloy is no problem with modern melting practice, and that the high solubility of silicon in the alloy (due principally to the alloy's molybdenum content) precludes precipitation of a silicide compound during heat treatment or thermal exposure. It is considered essential (79) that the silicon-modified alloy be beta processed if improvements in creep resistance are to be assured.

Creep resistance and thermal stability of the silicon-modified alloy are enhanced by solution treating high in the alpha-beta field (commonly at beta transus - 25F). These effects are illustrated in Figures 1.0426 and 1.0427 for rolled bar and forged upsets. The rolled bar primary-alpha grains were small, equiaxed, noncontinuous and nonaligned, surrounded by aged metastable beta products. Its thermal stability was unaffected over the range of solution temperatures from 80F to 25F below the beta transus. The forged upsets had large, elongated, aligned, and continuous primary-alpha grains, which are damaging to creep resistance and thermal stability (78). High-temperature solution treatment reduces the amount of primary alpha as shown in Figure 1.0428 (and hence the amount of continuous primary alpha), and broadens elongated grains so that they tend to become equiaxed and alignment is diminished. This improves creep resistance (Figure 1.0426), and metallurgical stability as expressed in Figure 1.0427 most notably by a rise in post-exposure reduction-of-area for the forged upsets.

Early modification of this alloy involved additions up to 0.25 weight percent silicon. Unlike the data of Figures 1.0421 and 1.0422 which show less benefit at 0.2 than at 0.1 weight percent silicon, Tables 1.0429 and 1.04210 show substantial increases in creep resistance for beta forged disks from the 0.25 weight percent silicon alloy. Thermal stability, however, is far inferior to the base alloy (Tables 1.04211 thru 1.04213). Other mechanical properties are given for the 0.25 weight percent silicon alloy in Figures and Tables 1.04214 thru 1.04220, and only the conventional tensile strength and smooth low cycle fatigue properties are improved by the additional silicon. Ductility, high cycle fatigue, fretting fatigue, notch rupture and hot salt stress corrosion resistance are either unchanged or damaged by the silicon addition. As a consequence of the limited benefit, 0.25 weight percent silicon addition is generally not used, although some specifications (40) (74) (75) still allow it.

Molybdenum additions beyond current specified limits slightly increase strength, but with substantial sacrifice in creep resistance (Table 1.04221).

Because boron in concentrations that could produce segregated borides can be introduced during sponge refurbishment and master alloy preparation (51) (53), their levels are limited to 10, 30 or 50 ppm in recently revised specifications (40) (43) (50) (72) (73). Similarly, yttrium is limited to the same levels in recent specifications (41 thru 46) (50) (72 thru 75). Based on a common experience with tramp element introduction in the production of superalloys (53), concentrations of copper and manganese are limited each to 100 ppm in several specifications (46) (50) (73).

1.0421 Effect of silicon content on time to 0.1 percent creep deformation at 950F, 35 ksi, for duplex annealed bar, Figure 1.0421.

1.0422 Effect of silicon content on 100-hour creep deformation at 950F and 35 ksi for duplex annealed bar, Figure 1.0422.

1.0423 Effect of 100-hour exposure at 950F, 35 ksi on room temperature tensile properties of duplex annealed bar of varying silicon content, Figure 1.0423.

1.0424 Effect of silicon content on the room temperature and 900F tensile properties of duplex annealed bar, Figure 1.0424

1.0425 Effect of silicon content on -40F Charpy-V impact energy of duplex annealed bar, Figure 1.0425.

1.0426 Effect of solution annealing temperature on 100-hour, 1000F, 25 ksi creep deformation of duplex annealed Ti-6Al-2Sn-4Zr-2Mo-0.9Si rolled bar and forged upsets, Figure 1.0426.

1.0427 Effect of solution annealing temperature on room temperature tensile properties of duplex annealed Ti-6Al-2Sn-4Zr-2Mo-0.9Si rolled bar and forged upsets subsequent to 100-hour creep exposure at 1000F, 25 ksi, Figure 1.0427.

1.0428 Effect of solution annealing temperature on percent primary alpha in Ti-6Al-2Sn-4Zr-2Mo-0.9Si alloy, Figure 1.0428.

1.0429 Combined effect of 0.25% silicon addition and forge/heat treat combinations on time to 0.1% creep at 1000F, 35 ksi, of duplex annealed forged disks, Table 1.0429.

1.04210 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on time to 0.1% creep at various temperatures and stresses, of duplex annealed forged disks, Table 1.04210.

1.04211 Combined effect of 0.25% silicon addition and forge/heat treat combinations on room temperature tensile properties of duplex annealed forged disks subsequent to 0.1% creep exposure at 1000F, 35 ksi, Table 1.04211.

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1.04212 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on room temperature tensile properties of duplex annealed forged disks subsequent to 0.1% creep exposure at various exposure temperatures and stresses, Table 1.04212.

1.04213 Effect of exposure to elevated temperature with load on room temperature tensile properties of beta forged, duplex annealed Ti-6Al-2Sn-4Zr-2Mo + 0.25Si forged disks, Table 1.04213.

1.04214 Combined effect of 0.25% silicon addition and forge/heat treat combinations on room temperature tensile properties of duplex annealed forged disks, Table 1.04214.

1.04215 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on the elevated temperature tensile properties of duplex annealed forged disks, Figure 1.04215.

1.04216 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on 900F axial load smooth and mild notch low cycle fatigue properties of duplex annealed forged disks, Figure 1.04216.

1.04217 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on 900F smooth and mild notch fatigue properties of duplex annealed forged disks, Figure 1.04217.

1.04218 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on 1100F smooth and mild notch fatigue properties of duplex annealed forged disks, Figure 1.04218.

1.04219 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on 900F fretting fatigue resistance of duplex annealed forged disks, Figure 1.04219.

1.04220 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on room temperature mild-notch stress rupture properties of duplex annealed forged disks, Table 1.04220.

1.04221 Effect of molybdenum addition and solution annealing temperature on strength and creep resistance of duplex annealed forged bar, Table 1.04221.

1.04222 Effect of oxygen content on room temperature tensile properties of consumable electrode melted castings, (see Figure 1.0811).

1.04223 Effect of oxygen content on room temperature mild-notch strength of consumable electrode melted castings, (see Table 1.0812).

1.04224 Effect of oxygen content on room temperature Charpy-V impact energy for consumable electrode melted castings, (see Figure 1.0813).

1.04225 Effect of oxygen content on room temperature step-loaded mild-notch creep rupture properties of consumable electrode melted castings, (see Table 1.0814).

1.04226 Effect of iron content on room temperature tensile properties of consumable electrode melted castings, (see Figure 1.0815).

1.04227 Effect of iron content on room temperature mild-notch strength of consumable electrode melted castings, (see Figure 1.0816).

1.04228 Effect of iron content on room temperature Charpy-V impact energy for consumable electrode melted castings, (see Table 1.0817).

1.04229 Effect of iron content on room temperature step-loaded mild-notch creep rupture properties of consumable electrode melted castings, (see Table 1.0818).

1.05 Heat Treatment

1.051 General. This alloy is used in either a duplex or triplex annealed condition. The first cycle of either treatment is a solution anneal (1650F, alpha solution anneal, or 1750F, alpha + beta solution anneal). The subsequent 1450F heating cycle for sheet is a stabilization anneal having little or no effect on room temperature tensile properties. The final 1100F heating cycle for triplex annealed sheet and duplex annealed bar and forgings produces a modest improvement in room temperature tensile strength indicating some aging takes place; this treatment is sometimes referred to as a stabilization age.

1.052 Anneal.

1.0521 Sheet: Duplex; 1650F, ½ hour, air cool + 1450F, ½ hour, air cool. Triplex: 1650F, ½ hour, air cool + 1450F, ½ hour, air cool + 1100F, 2 hours, air cool. The second cycle of either treatment is designed to be compatible with forming operations such as hot sizing. The additional 1100F, 2 hours treatment is also compatible with certain hot forming operations or may be added as an aging treatment following the hot sizing operation if higher uniaxial strength at room and elevated temperatures is desired. This triplex treatment has little if any effect on sharp notch tensile strength and produces superior creep resistance and smooth tensile strength stability. Sharp notch strength stability without load is extended to higher exposure temperatures by triplex annealing, but embrittlement is more pronounced at those temperatures where embrittlement occurs. The triplex treatment is damaging to sustained load failure characteristics in salt water environment (see Table 2.0331).

1.0522 Bar and Forgings: Less than 2½ inch section; 1750F, 1 hour, air cool + 1100F, 8 hours, air cool. Greater than 2½ inch section; 1650F, 1 hour, air cool + 1100F, 8 hours, air cool; or, 1750F, 1 hour, air cool + 1100F, 8 hours, air cool.

The 1650F solution anneal with an 1100F, 8 hour stabilization age provides somewhat higher tensile strengths at room and elevated temperatures and fatigue strength as good or better than that for the higher solution anneal temperature (1750F). The higher solution anneal with the same stabilization age provides superior creep resistance, but no demonstrated improvement in smooth tensile strength stability. Room temperature notch stress rupture strength is somewhat improved, as is the Charpy-V impact energy at room temperature and -80F.

Solution annealing at 1790F (beta transus - 25F) can further improve creep resistance, but not consistently. However, its potential benefit warrants its use. As discussed in section 1.042, solution treating at 1790F in combination with 0.08 to 0.1 weight percent silicon addition and beta processing substantially improves creep resistance and stability. The higher solution treatment for the standard composition benefits room and elevated temperature strength, room temperature plane strain fracture toughness, room temperature and -80F Charpy-V impact energy, and room temperature mild-notch stress rupture life.

Solution treating above the beta transus is not beneficial.

Faster quenching from the solution temperature in media other than air improves tensile strength but with a sacrifice in creep resistance.

1.053 Stress relief. An 1100F, 2 hour stress relief cycle provides nearly 100 percent relief of residual stresses (see Figure 1.0531) and is identical to the final cycle of the triplex anneal treatment for sheet. Depending on convenience and need, lesser stress relief at lower temperatures may be satisfactory.

1.0531 Effect of stress relief time and temperature on relaxation of restrained bend specimens of triplex annealed sheet, (see Figure 3.0531)

1.054 Mill anneal. 1300-1550F, 1-8 hours, slow cool to 1050F, air cool. (17) (37)

1.06 Hardness

Stabilization aging at 1100F raises the solution annealed tensile strength of this alloy about 10 ksi indicating only slight hardenability. Sections up to 3 inch, in the recommended duplex condition, exhibit uniform tensile properties throughout; however, water quenching from the solution anneal treatment followed by a stabilization age produces a 15-ksi strength differential from center to outside. Thus the alloy has hardening characteristics

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about like Ti-6Al-4V, (7).

1.061 Effect of exposure to elevated temperature on room temperature hardness of duplex annealed sheet, Figure 1.061.

1.07 Forms and Conditions Available

Ingot, bloom, bar, billet, sheet, plate, wire, (79).

1.08 Melting and Casting Practice

1.081 Wrought products. Multiple melted using consumable electrode vacuum practice: standard quality, double melted; premium quality, triple melted.

1.082 Castings. Two recent programs (Air Force Contracts F33615-70-C-1409 with TRW, Inc. and F33615-70-1410 with REM Metals Corp.) have been carried out to study various aspects of casting this alloy, including foundary variables, alloy chemistry and heat treatment effects, casting defects and cast properties. The programs are distinguished principally by the melting methods used: induction melting by TRW and consumable electrode skull melting by REM. The two programs are discussed separately below according to the melting practice employed.

1.083 Induction melting. Chemical interaction between molten alloy and crucible has been a major deterent to induction melting titanium-base alloys. TRW, however, has recently developed a semi-levitation induction melting process which purportedly allows for good control of power input and limits the amount of crucible contamination by making use of levitation forces generated during induction melting, (54). Graphite crucibles are used, with minimized molten metal/crucible contact time, and direct pour into the mold. Melt temperature is uniform and constant during pouring, and fixed for a given setup. Unlike consumable electrode melting, superheating is possible with induction melting, an important feature considering titanium alloys' limited solidification range. Molten metal temperature is measured using infrared pyrometers which have rapid response and, unlike optical pyrometers operating in the visible portion of the spectrum, are relatively insensitive to emissivity changes with temperature.

Using this melting technique, castings were made to determine the castability (fluidity) of this alloy and the mechanical properties of the cast metal. Pyrolytic graphite faced silicate bonded molds produced by a patented process (55) were used. Castability castings weighed six pounds and consisted of two clusters of four bars each. Bar sizes were 0.75-inch wide x 4-inch long x 0.030-, 0.060-, 0.090- and 0.250-inch thick. One cluster was gated at both top and bottom, the other gated only at the bottom. Two pour temperatures were used: low superheat (liquidus + 100-200F) and high superheat (liquidus + 200-350F). Liquid metal temperature was determined in the pour cup using tungsten-rhenium thermocouples in molybdenum tubes. Mold preheat temperatures of 1000, 1500 and 2000F were investigated. The effects of these casting variables on mold fill are presented in Table 1.085. These results reveal difficulty in filling sections as thin as 0.060 inch. Filling was complete for the heavier gages, but radiographic analyses revealed internal defects: 0.090 inch sections were porous; 0.250 inch sections contained microshrink or slight porosity.

Six-pound tensile bar cluster castings were made to determine the room temperature and 600F tensile properties of the cast metal. Each casting contained six standard 0.250-inch diameter test specimens, three bottom gated and three top and bottom gated. The same combinations of pour and mold preheat temperatures used in the castability determinations were used for these castings. Complete mold fill was achieved in every case; however some minor surface reaction was evident on all test bars. Companion specimens of Ti-6Al-4V alloy had 0.0001-inch surface reaction layers of TiC which caused marked reductions in conventional tensile ductility. On the basis of this experience, test bars of the present alloy were sand-blasted to remove 0.001 inch of the test section surface prior to testing. Test results for selected specimens are presented in Table 1.086. The castings were not completely sound, showing some evidence of centerline microshrink or slight porosity. These defects appear to have no effect on the strength properties of the cast alloy, but may be presumed responsible for the observed scatter in ductility values.

Production of a shaped casting was attempted using a quarter-section of the #2 bearing housing of the General Electric TF-39 engine. Casting weight was 10 pounds; minimum casting wall thickness was 0.125 inch. Castings were poured using the same techniques used for the castability and tensile bar castings. In all instances complete mold fill was achieved; however the quality of the castings produced was generally disappointing. Particular problems were surface defects and porosity. Surface defects were similar to those encountered in more conventional casting processes: hot tears caused by mold cracking during solidification; cold shuts resulting from the use of too cold a mold; fold-type defects produced by titanium carbide formation on the surface of the liquid as it entered the mold and, due to stream turbulence, folding at the casting surface; inclusions caused by spalling of the pyrolytic graphite mold coating; and rattails resulting from entrapment of zirconium silicate mold material disrupted by the molten metal.

The gas porosity encountered in these casting trials is not uncommon in the casting of titanium-base alloys, arising in part from the large difference in gas solubility between liquid and solid. Pouring under vacuum magnifies the effect, as does the lightness of titanium which keeps it from developing a high metallostatic head. In the present case, gas porosity occurred randomly throughout the castings and efforts to eliminate it by gating and venting modifications of the casting were unsuccessful. Void pocket analyses identified the entrapped gas as hydrogen. The use of degassed charge material and vacuum degassing the molds and crucibles prior to pouring had no appreciable effect in reducing porosity. It was concluded that the only effective means for eliminating gas pores would be the use of massive gating systems for static casting, or resort to centrifugal or other nonstatic forms of casting.

Conventional mechanical properties were determined on specimens extracted from the sidewalls of the bearing castings and found to be little different from the properties of cast tensile bars, except for reduced ductility associated with gas porosity and/or massive alpha grain microstructures. Weld repairability was cursorily investigated with the result that, using the maximum bend angle to fracture in three-point loading as criterion, TIG welding reduced the ductility of the cast product.

General problems with the use of graphite crucibles and molds were pervasive in the attempt to produce acceptable castings by the induction melting technique. Surface reaction with the mold, as indicated by the titanium carbide surface layer, subsurface carbide network and alpha case, was prevalent and appeared to increase with increasing melt superheat and mold preheat temperature (see Table 1.087). Carbon pick-up during melting due to crucible dissolution was appreciable and independent of superheat. Determinations on castings poured into steel molds showed increases from an initial value of 0.02 weight percent to between 0.10 and 0.15 weight percent. These values not only exceed present allowables for wrought stock, but have an unfavorable effect on castability (see Fig-

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ure 1.088). Remelting further increased carbon pick-up, but less than during initial melting (see Figure 1.089). On the basis of these results (using 6 to 10 pound charges), it appears that carbon pickup associated with this melting process cannot be reliably controlled to currently accepted levels, and the prospect of reclaiming sprues, gates, scrap castings, etc., is dim. No changes were found in the oxygen or nitrogen levels during melting. As expected for vacuum melting processes, hydrogen levels dropped from the as-received melt stock levels.

Consumable electrode melting. The problem of molten metal reaction with the furnace crucible is purportedly circumvented by consumable electrode vacuum "skull" melting in water cooled copper crucibles, (56). A skin of solid titanium, called a "skull", is formed which provides a nonreactive wall between the molten titanium and the copper crucible. This melting method is used by REM Metals Corporation.

The basic operation of skull melting is identical to conventional consumable arc melting, except the arc power (current) requirements are about twice that of conventional arc melting. This is so that a large molten pool forms rapidly and that a minimum of alloy solidifies before the melt is poured. The size of the molten pool will depend on melt rate, crucible size, and electrode configuration. When a sufficient pool is formed, the power is cut, the electrode stub withdrawn, and the charge poured into the mold by tilting the copper crucible. The complete sequence takes only a matter of minutes, with the casting portion taking only seconds. The time from electrode withdrawal to the completion of pour is very critical due to the narrow solidification range of most titanium alloys. Following pouring, the furnace is backfilled with a partial pressure of argon to promote cooling. When the mold has cooled sufficiently to avert harmful reaction with air, the furnace is opened and the mold removed.

The temperature of the melt is a continuous gradient from the hottest region (near the arc) to the coldest (near the crucible wall). No attempt is made to determine melt temperature before pouring, but pour conditions are replicated by controlling power input and coolant flow rate.

All castings produced by REM in their program were by their patented "REMET" investment casting process using tungsten lined ceramic molds preheated to 700F (except when mold preheat was an experimental variable). Fluidity was determined as the ability to fill either 0.030-inch or 0.060-inch thick "wings" appended to combination tensile bar/Charpy bar cluster castings. Like TRW's experience, the results indicated difficulty in filling sections as thin as 0.060 inch.

Four foundary practice variables were studied: mold preheat temperature, electrode size, crucible size and melt weight. Each of these factors could be expected to influence metal temperature, or heat content, and thereby affect surface finish and internal soundness and, consequently, mechanical properties. Triplicate variable-thickness, step-plate castings were poured for each foundary variable. Throughout, power input, cooling water flow rate, pour speed and mold configuration (except for a slightly larger pouring cup when enlarged melt size was studied) were held constant. Castings were heat treated (1650F, 1 hour, HeC + 1100F, 8 hours, HeC) in full section prior to sectioning for smooth tensile specimens.

Casting quality as influenced by foundary practice is documented in Table 1.0810. Despite the inability to superheat by consumable electrode melting (increasing arc power merely increases electrode consumption rate) and the alloy's limited solidification range, all castings were completely filled. However, some evidence of cold metal was observed as lines (cold laps or cold shuts) or circles (cold shot) on casting surfaces. Most of these surface imperfections were slight, many requiring directional lighting to even be seen. This accounts for the disparity between the reported visual and fluorescent penetrant surface imperfection indications in Table 1.0810. The "reference" and "hot mold" conditions gave the least number of indications and the least internal shrinkage (porosity) in the thinnest cast sections. All other changes in foundary practice reduced casting quality by these measures. Overall dimensional shrinkage was the only quality index unaffected by variations in foundary practice, the uniformity being well within the normal casting tolerance of $\pm$0.005 in/in.

Room temperature smooth tensile properties were generally unaffected by variations in foundary practice variables, except that in a few cases thin-section shrinkage markedly reduced ductility. Grain size for the step castings rose smoothly from the thinnest to the thickest section. Average grain diameter was unaffected by foundary variables, as were macrostructure and microhardness.

An attempt was made, using microhardness measurements, to determine the extent of possible casting surface reaction with the mold or other processing environments. Average hardness was essentially uniform from about 0.002 inch to as much as 0.250 inch below the casting surface. Scatter in the data was considerable; however, no attempt was made to identify its source (i.e., compositional or microstructural differences, or both). It should be recalled that TRW observed metallographic indications of surface reaction by their casting process at depths nearer the surface than explored here and that such a possibility cannot be ruled out here. The conventional smooth tensile properties of stabilization aged bars (1100F, 8 hours, HeC) with and without test section machining indicated, however, no evidence of surface reaction as regards its influence on these properties.

The separate influences of oxygen and iron contents on the stabilization aged mechanical properties of cast bars are presented in Figures 1.0811 thru 1.0818. Increasing oxygen has the anticipated effect of increasing strength and reducing ductility, toughness and mild-notch creep rupture strength. Increasing iron had no practical effect over the range studied.

An important consideration in the usefulness of cast products is weldability. Welding is essential in removing harmful defects, affecting the economics of production particularly as the casting size and complexity increase, and in the ability to join cast parts to mating components. Weld repairability was determined by comparing unwelded cast specimens with those whose test cross section was 50 percent TIG repair weld. Results, for specimens with and without post weld heat treatment, are given in Table 1.0819. The elongation of repair welded samples without post weld heat treatment and those alpha solution annealed plus stabilization aged (1650F, 1 hour, HeC + 1100F, 8 hours, HeC) were below companion unwelded values. Isothermal treatment of 1900F, 1 hour + 1650F, 1 hour + 1100F, 4 hours, HeC restored repair weld ductility, but at a reduced strength level for both welded and unwelded specimens (compared to as-cast values). Beta solution treating plus aging (1900F, 1 hour, HeC + 1100F, 4 hours, HeC) produces strengths and ductilities for repair welded and unwelded specimens equal to each other and to the as-cast values. It is claimed that this treatment produces microstructural uniformity throughout the repair welded stock. However, all mechanical properties do not benefit from this heat treatment as do

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the smooth tensile properties. Charpy impact energy, 100-hour creep strain at 1000F, 35 ksi, and post-creep tensile properties were all equivalent for repair welded and unwelded specimens given the beta solution anneal plus age treatment; but repair weld damage to the room temperature step-loaded mild notch creep rupture and smooth axial fatigue strengths was not remedied by the heat treatment.

Difficulty was experienced in weld joining thin-to-thin and thin-to-thick sections; lack of penetration and/or severe porosity were particularly damaging to ductility, and the situation was only partially improved by modifications in welding technique. Problems with welding this alloy, discussed in section 4.03, cast doubt on the investigators' claim that further improvements in technique will eventually produce acceptable weld joints.

The effects of heat treatment on the mechanical properties of the cast product are presented in Tables 1.0820 thru 1.0823. Test specimens were machined from cast-oversize bars following heat treatment. The smooth tensile properties of bars stabilization aged 1100F, 8 hours, AC (Table 1.0820) are in agreement with those determined in the TRW program for induction melted cast bars similarly aged. Prior alpha-beta solutioning at 1750F has no affect on aged strength, but produces considerable scatter in ductility (not withstanding the possibility of variable cast bar quality). Other mechanical properties reported in Tables 1.0821 thru 1.0823 appear either unaffected or somewhat improved by the alpha-beta solution treatment preceding aging.

In an attempt to produce a more uniform structure (alpha precipitate) than was initially established on cooling the newly frozen alloy, a beta solution treatment at 1900F was applied to two groups of specimens. This treatment requires less careful control of the temperature than is required for alpha-beta solutioning, where small variations can produce large differences in aged properties. Water quenching from the beta solution temperature, and subsequently aging, produces substantial strengthening but has a calamitous effect on ductility and those properties reported in Tables 1.0821 thru 1.0823. Slower cooling from the solution treatment followed by an abbreviated age produces properties little different from those obtained by simple stabilization aging except to scatter the results a bit more. This latter treatment, however, is considered necessary for repair welds as described previously in connection with weld repair studies. Consequently, the mechanical properties reported in the balance of this section on castings (Figures and Tables 1.0824 thru 1.0828) are for this heat treated condition.

To check the suitability of this casting technique to actual hardware, production of several C-5A cargo tie down rings was attempted. Casting quality was judged satisfactory by the producer and smooth tensile properties matched those of cast-to-size bars and bars extracted from step castings.

1.085 Effect of metal pour temperature and mold preheat temperature on mold fill for induction melted castings, Table 1.085.

1.086 Room temperature and 600F tensile properties of induction melted cast bars, Table 1.086.

1.087 Surface reaction of ½-inch-thick single-gated castability sections induction melted in graphite crucibles and cast into pyrolytic faced silicate bonded molds, Table 1.087.

1.088 Effect of carbon content on mold fill for castings induction melted in graphite crucibles and cast into stainless steel molds, Figure 1.088.

1.089 Effect of induction remelting in graphite crucibles on carbon content of castings poured into stainless steel molds, Figure 1.089.

1.0810 Influence of foundary practice (casting conditions) on nondestructive testing (NDT) quality of consumable electrode melted castings, Table 1.0810.

1.0811 Effect of oxygen content on room temperature tensile properties of consumable electrode melted castings, Figure 1.0811.

1.0812 Effect of oxygen content on room temperature mild-notch strength of consumable electrode melted castings, Table 1.0812.

1.0813 Effect of oxygen content on room temperature Charpy-V impact energy for consumable electrode melted castings, Figure 1.0813.

1.0814 Effect of oxygen content on room temperature step-loaded mild-notch creep rupture properties of consumable electrode melted castings, Table 1.0814.

1.0815 Effect of iron content on room temperature tensile properties of consumable electrode melted castings, Figure 1.0815.

1.0816 Effect of iron content on room temperature mild-notch strength of consumable electrode melted castings, Figure 1.0816.

1.0817 Effect of iron content on room temperature Charpy-V impact energy for consumable electrode melted castings, Table 1.0817.

1.0818 Effect of iron content on room temperature step-loaded mild-notch creep rupture properties of consumable electrode melted castings, Table 1.0818.

1.0819 Effect of post-weld heat treatment on room temperature smooth tensile properties of TIG repair welded, consumable electrode melted cast specimens, Table 1.0819.

1.0820 Room temperature tensile properties of consumable electrode melted castings variously heat treated, Table 1.0820.

1.0821 Room temperature mild notch strength of consumable electrode melted castings variously heat treated, Table 1.0821.

1.0822 Room temperature step-loaded mild-notch creep rupture properties of consumable electrode melted castings variously heat treated, Table 1.0822.

1.0823 Room temperature Charpy-V impact energy for consumable electrode melted castings variously heat treated, Table 1.0823.

1.0824 Effect of test temperature on tensile properties of consumable electrode melted castings, Figure 1.0824.

1.0825 Effect of exposure to elevated temperature with load on room temperature tensile properties of consumable electrode melted castings, Table 1.0825.

1.0826 Effect of cast section thickness on the creep deformation of a consumable electrode melted casting, Table 1.0826.

1.0827 Effect of 100-hour exposure under load to hot solid salt on subsequent room temperature tensile properties of consumable electrode melted castings, Table 1.0827.

1.0828 Effect of cast section thickness on the fatigue properties of consumable electrode melted castings, Figure 1.0828.

1.09 Special Considerations

Stability - General. For many high-temperature applications, the usefulness of a particular alloy is limited by its elevated-temperature stability. This property is commonly evaluated from room temperature tensile tests on specimens previously exposed to elevated temperatures with and without load. Because of the importance of this property for critical applications, a large body of such information has been accumulated for Ti-6Al-2Sn-4Zr-2Mo alloy. The effect of exposure on room temperature smooth tensile properties for sheet, bar and forgings in the whole range of commercial sizes are presented in Figures and Tables 3.02114 through 3.02132. Exposure effects on room temperature notch tensile properties of sheet are presented in Figures 3.02718 through 3.027111. Limited data on the effect of exposure on the room temperature shear strength of sheet are presented in Figure 3.0251. The influence of forging and solution annealing temperatures on the elevated temperature

	Ti
6	Al
2	Sn
4	Zr
2	Mo

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stability of forgings is given in Tables 4.0121 and 4.0122. A single set of data on the effect of elevated temperature exposure on the smooth tensile properties of sheet at the exposure temperature is presented in Figure 3.03126.

The extent to which room temperature properties will be affected by previous exposure will depend on the form and condition of the product as well as the time, temperature and stress level of exposure. While the available data are extensive, they are not systematic and no firm generalizations can be made at this time. However, the following conclusions appear to be supported by the present results.

Stability - 150-hour: For sheet in both the duplex and triplex annealed conditions, 150-hour exposure at 1000F, 25-ksi produces no deleterious effect on subsequent room temperature tensile properties. This is also true for exposure at lower temperatures and higher stress levels; for example 900F at 45-ksi and 800F at 65-ksi (Figure 3.02116, Table 3.02117 and Figure 3.02119). Likewise 100-hour exposure to 1000F without load produces no loss in room temperature sharp notch tensile strength of either duplex or triplex annealed sheet (Figures 3.02718 and 3.027110).

Duplex annealed rolled bar may or may not be affected by exposures of 150 hours with load at temperatures up to 1000F depending on the exposure stress. At 25 ksi stress level no practical loss in room temperature smooth tensile properties is observed (Table 3.02121) while at 30 ksi a sensible loss in ductility is observed (Figure 3.02120). Bar rolled in the beta region is unaffected by 150 hour exposure at 1000F, 30 ksi (Table 3.02124).

Forged bar in the recommended duplex annealed condition exposed 150 hour up to 1000F, 25 ksi exhibits no loss in subsequent room temperature smooth tensile properties (Figure 3.02126 and Table 3.02127). Contrasting results were obtained from forged compressor wheels (Tables 3.02128 and 3.02129). The hub location in one wheel exposed at 800F, 70 ksi, 150 hour showed losses in elongation and reduction of area (Table 3.02128). Other locations in the same forging, however, were essentially unaffected. A second wheel forging, water quenched from the solution anneal, showed losses in ductility after exposures at 900F/55 ksi, 1000 F/35 ksi or 1100 F/15 ksi (Table 3.02129).

Stability - Long Time. 1000 hour exposure up to 1000F without load has no deleterious effect on subsequent room temperature tensile properties of duplex annealed sheet (Figure 3.02115). In contrast, 1000 hour exposure with load produces a serious loss in ductility at 900F, 20 ksi for duplex annealed sheet and at 1000F, 10 ksi for triplex annealed sheet (Table 3.02118). At 950F, 15 ksi no damage is done to triplex annealed sheet for 1000 hour exposure (Table 3.02118). It appears from these limited results that the triplex annealed condition is more stable than the duplex condition. As expected, no change in tensile properties at the exposure temperatures is observed after 1000 hour exposure without load up to 1000F and perhaps beyond (Figure 3.03126).

Figures 3.02718 to 3.027111 show the influence of exposure to elevated temperature without load on the subsequent room temperature sharp notch strength of sheet. This property is a sensitive indicator of instability and reveals the onset of serious embrittlement at 900F for 1000 hour exposure for both duplex and triplex annealed conditions.

Bar in the recommended duplex annealed condition exposed 1000 hours with load at temperatures up to 1000F exhibits no significant instability (Table 3.02122). However, for longer exposure times a loss in room temperature tensile ductility is observed for lower exposure temperatures (Table 3.02123). Thus a marked reduction in ductility results from 3000 hours exposure at 825F, 47.5 ksi.

Substantial losses in ductility are observed for forgings in the recommended duplex annealed condition following 500 hours exposure at 800F, 75 ksi (Table 3.02131). A single result for the same forgings showed no ductility loss for 1000 hours exposure at 800F, 80 ksi; however, additional forgings (Figure 3.02130) substantiate the onset of instability at exposure temperatures as low as 800F as indicated by losses in reduction-of-area. These results (Figure 3.02130) were independent of specimen surface machining following exposure, indicating metallurgical changes rather than mere surface damage. The results of Figure 3.02130 also seem to contradict the suggestion (78) (79) (85) that solution annealing temperatures approaching the beta transus temperature improve metallurgical stability. On the other hand, high solution temperatures (below the beta transus) are not damaging, and their beneficial effect on creep resistance and stability when combined with modest silicon additions warrants their use as discussed in section 1.042. Solution annealing above the beta transus temperature is also ineffectual in improving thermal stability (Table 4.0121), as is beta forging followed by the recommended duplex anneal treatment (Table 4.0122). As discussed in section 1.042, however, beta processing in combination with added silicon is effective (indeed considered essential (79)) in improving creep resistance.

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range, Table 2.011.

2.012 Phase changes. Beta transus, 1820 to 1830F, (70) (71). Variations in oxygen level will affect the beta transus temperature, as oxygen is a strong alpha stabilizer. Results in Figure 2.0121 show rapid changes in beta transus temperature with silicon variations in the normal specification range.

According to the isothermal TTT diagram (Figure 2.0122), M_s temperature is about 1470F and M_f temperature is about 1415F. Under continuous cooling (nonequilibrium) conditions, these temperatures are lowered substantially (see comparison of TTT and CCT diagrams in Figure 4.0317). The transformation kinetics of this alloy are discussed at length in section 4.03 on welding.

2.0121 Effect of silicon content on beta transus temperature, Figure 2.0121.

2.0122 Isothermal time-temperature-transformation (TTT) diagram for Ti-6Al-2Sn-4Zr-2Mo, Figure 2.0122.

2.0123 Continuous-cooling-transformation (CCT) diagram for Ti-6Al-2Sn-4Zr-2Mo, (see Figure 4.0315).

2.0124 Effect of compositional variations within specification on continuous-cooling-transformation (CCT) diagram for Ti-6Al-2Sn-4Zr-2Mo, (see Figure 4.0316).

2.0125 Comparison of continuous-cooling-transformation (CCT) diagram and isothermal-transformation (TTT) diagram for Ti-6Al-2Sn-4Zr-2Mo alloy, (see Figure 4.0317).

2.013 Thermal conductivity.

2.0131 Thermal conductivity of duplex annealed sheet, Figure 2.0131.

2.0132 Thermal conductivity of duplex annealed bar, Figure 2.0132.

2.014 Thermal expansion.

2.0141 Thermal expansion for duplex annealed sheet, Figure 2.0141.

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6	Al
2	Sn
4	Zr
2	Mo

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2.0142 Thermal expansion for duplex annealed bar, Figure 2.0142.
2.0143 Thermal expansion for cast compressor casing and duplex annealed pancake forging, Figure 2.0143.
2.015 Specific heat.
2.0151 Specific heat for duplex annealed sheet, Figure 2.0151.
2.0152 Specific heat for duplex annealed bar, Figure 2.0152.

2.02 Other Physical Properties
2.021 Density. 0.164 lb per cu in, 4.54 gr per cu cm.
2.022 Electrical resistivity.
2.0221 Electrical resistivity of duplex annealed sheet, Figure 2.0221.
2.023 Magnetic properties. Alloy is nonmagnetic.
2.024 Emittance.
2.025 Damping capacity.

2.03 Chemical Properties
2.031 Corrosion resistance. General. In common with other titanium alloys, Ti-6Al-2Sn-4Zr-2Mo is susceptible to solid salt stress corrosion at elevated temperatures and exhibits delayed failure of cracked specimens at room temperature in aqueous salt environments.

2.032 Solid salt corrosion. Embrittlement and/or cracking of titanium alloys while stressed in salt environments at elevated temperatures is well known and commonly referred to as hot-salt stress corrosion. Measured salt deposits and operating stresses and temperatures of compressor components in current aircraft turbine engines are sufficient to cause failure by this mode in laboratory specimens, but no such service failures have been reported in the literature. It is presumed that the lack of correspondence between predicted behavior and service experience lies in a lack of correspondence between laboratory simulation and actual engine operation. Added to this, there is a distressing lack of test standardization which makes any prediction of service failure open to question.

A common test for hot-salt stress corrosion involves exposure of salt-coated specimens to elevated temperature under load (usually static tension) and subsequent visual examination for corrosion or cracking, and/or measurement of residual room temperature mechanical properties for indications of embrittlement. On a plot of exposure stress versus exposure temperature, threshold curves separate regions of cracking from no cracking, or embrittlement from nonembrittlement. Substantial variations in test procedure and stress corrosion criteria account for substantial differences in thresholds reported by different investigators.

A particularly interesting series of tests by Gray and Johnston (57) (58) (61) (62) (63) (64) has been directed toward the problems of hot-salt stress corrosion testing and to the disparity between laboratory and service experience. Most of the work was done on Ti-8Al-1Mo-1V alloy because of its known sensitivity to hot-salt stress corrosion and because of its early consideration for application in hot-salt environments. A substantial amount of information was also developed in those studies for Ti-6Al-2Sn-4Zr-2Mo alloy. The data are combined in what follows in a general discussion of hot-salt stress corrosion testing, with particular emphasis on the behavior of Ti-6Al-2Sn-4Zr-2Mo alloy.

In Gray and Johnston's studies, tubular specimens were used in conjunction with a dynamic air apparatus which simulated salt deposition and exposure conditions of actual aircraft turbine engines. The influences of both specimen preparation and specimen exposure conditions on hot-salt stress corrosion behavior were examined. Specimen preparation variables were residual machining stresses, salt deposition temperature and salt concentration. Exposure variables were airflow, air pressure, air dewpoint (humidity), salt-in-air concentration, temperature and stress. Post-exposure tensile tests were performed at a constant test machine crosshead speed to specimen failure of 0.005 in/min. This loading was considered essential to the believed stress corrosion mechanism of hydrogen production, absorption, diffusion and embrittlement, observable only at temperatures at or slightly exceeding room temperature and at loading rates compatible with hydrogen diffusion rates (62). Stress corrosion thresholds were based either on cracking during exposure or on an arbitrarily-assigned reduction in subsequently-measured room temperature tensile ductility; elongation less than 15% and reduction of area (based on change in outside diameter) less than 25%. Cracking during exposure was evidenced by the presence on the fracture surface of regions covered with oxides and corrosion products. It is claimed that cracks as small as 0.001 inch were easily detected under X30 magnification. Specimen cylindrical surfaces were not inspected for damage, and the possibility of microcracks contributing to reduced ductility (embrittlement) was not explored. Specimens customarily were coated by exposing, without applied load, the inner bore for one hour to a salt-in-air concentration of 40 parts per billion at an air velocity of 1000 feet per second at 400F and dewpoint of -120F and 30 psia pressure. This elaborate procedure produced uniform deposits of 0.6 mg/in^2, which was within the range measured on service airfoils (59) (60). Higher deposition temperatures, or continuous deposition during test exposure, were examined only for mill annealed Ti-8Al-1Mo-1V and were seen to raise the apparent embrittlement threshold (61); data for Ti-6Al-2Sn-4Zr-2Mo were not obtained.

Salt concentrations of 0.2 and 2.0 mg/in^2, bracketing the range measured on actual airfoils, produced substantially identical embrittlement thresholds for Ti-8Al-1Mo-1V alloy in Gray and Johnston's experiments (61). However, earlier studies (65) (66) (67) showed that light coatings were more damaging than heavy coatings (purportedly due to the greater availability of moisture and oxygen in the case of the light coatings). Puffer et al (60) show cracking for Ti-6Al-2Sn-4Zr-2Mo increases continually with increasing salt concentration from very light to very heavy concentrations (0.05 to 50 mg/in^2).

Compressive surface stresses can raise the stress corrosion threshold, sometimes substantially. For Ti-8Al-1Mo-1V, the embrittlement threshold, for as-machined specimens (presumably with residual compressive machining stresses) exceeded that for specimens annealed either by heat treatment or by chemically milling (dissolving) the surface, by a factor of two. For Ti-6Al-2Sn-4Zr-2Mo mill annealed bar, much smaller effects were observed, as shown for dynamic exposures in Figure 2.0324. Attempts to confirm the presence of residual machining stresses in these tests with x-ray analyses were unsuccessful, and the equally plausible effect of contamination and/or attack during heat treatment or chemically milling was not disposed of. However, the very substantial benefit from glass bead blasting compressor disc forgings shown in Figure 2.03212 seems to substantiate the presumption of residual compressive stresses in the previous work, and attests to the potentially significant benefit of same. One should be advised, however, that initial benefits from compressive surface stresses could disappear in service due to stress relief during exposure.

Actual engine environmental conditions are unique and considered less conducive to stress corrosion than laboratory exposure conditions. This in fact appears borne out by the lack of recorded service failures. Possible ameliorating engine conditions are high air

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velocities, high pressures, salt-air conditions, oil contamination and/or unique operating cycles. In the same relevant studies of Gray and Johnston, air velocity of 1100 ft/sec and air pressure increase from 30 to 52 psia were each determined to have only a minor effect on the embrittlement threshold of Ti-8Al-1Mo-1V alloy (61). Essentially no effect of air velocity is seen for the Ti-6Al-2Sn-4Zr-2Mo alloy in Figure 2.0324 (compare dynamic and static air exposures for chemically-milled specimens). Gray and Johnston report no systematic influence of exposure air moisture in the range -120 to +40F dewpoint for Ti-8Al-1Mo-1V, but this is at variance with numerous experiments reported in the literature which show increased hot-salt stress corrosion with increasing moisture in the environment. As expected, increased exposure times universally produce increased indications of stress corrosion.

The influence of exposure cycling was studied for Ti-8Al-1Mo-1V (64). Temperature and stress were cycled separately and in combination, the latter simulating a service cycle of current aircraft turbine engine compressor components. Cyclic exposure in which both temperature and stress were applied for 1 hour and removed for 3 hours, for a total of 96 hours at temperature, had associated crack threshold stresses twice those for continuous 96-hour exposure. The same was true for cycles of temperature, 1 hour on and 3 hours off, at constant stress. Other temperature cycles (3 hours on/ 3 hours off, 1 hour on/ 1 hour off, and 3 hours on/ 1 hour off) at constant stress, and a stress cycle of 1 hour on and 3 hours off at constant temperature raised the continuous-exposure (for the same total time at temperature) threshold by 60 to 90% at the lowest exposure temperature, but these improvements disappeared as the exposure temperature increased. It has been suggested that temperature cycling interferes with the production and decomposition of the intermediate corrosion product titanium dichloride ($TiCl_2$), necessary for the production of the embrittling corrosion product, hydrogen. Stress cycling is thought to lessen the buildup of diffused hydrogen by virtue of homogenization during off-cycles. It is quite believable that these cycles, plus repeated errosion (washing) of the engine components plays an important role in engine reliability.

Stress corrosion characteristics can depend on alloy processing and heat treatment, and can vary from heat to heat. There appears little difference between mill annealing and duplex annealing bar of Ti-6Al-2Sn-4Zr-2Mo (compare Figures 2.0324 and 2.0325). Heavy forging can reduce the embrittlement and cracking thresholds, as shown in Figure 2.0326. The cracking thresholds reported for sheet at 100-hour exposure in Figures 2.0321 and 2.0322 are generally lower than those reported for bar in Figures 2.0324 through 2.0326 and the compressor wheel forging in Table 2.03211, but no worse than the compressor disc forging in Figure 2.03212.

No stress corrosion experiments have been conducted wherein salt-free specimens were exposed to the same high stresses and temperatures producing embrittlement or cracking in salt-coated specimens. In this regard the representations of Figures 2.0327 through 2.03210 are of unusual interest. Associated with the exposure of salt-coated specimens to elevated temperatures under load, are changes in residual room temperature properties not unlike those one might expect from accelerated aging under stress. It would be interesting, indeed, to perform such salt-free specimen tests. Interesting, too, would be the use of more sensitive indicators of embrittlement such as sustained-load notch tests.

It is clear from the foregoing that no single hot-salt stress corrosion threshold can be claimed for this alloy. Material condition, exposure variables, post-exposure test procedure and corrosion criteria are all influential and account for the variability of results from one investigator to another. Some insights have been gained in resolving the disparity between laboratory and service experiences, but no assurance can be given that increased service requirements might not one day penetrate the region of unsafe combinations of stress, temperature and time in salt environments.

Results for resistance spot-welded sheet in Figure 4.0310 show freedom from salt corrosion cracking within the range of exposure conditions investigated. Significant loss of strength accompanies the elevated temperature exposure above 600F. The influence of a 1100F, 2 hour postweld treatment is to reduce initial cross tension strength but minimize further reduction when exposed to elevated temperature.

2.0321 Hot-salt stress corrosion cracking characteristics of duplex annealed sheet at 550, 800 and 1000F, Figure 2.0321.

2.0322 Short-time hot-salt stress corrosion cracking characteristics of triplex annealed sheet subjected to static or cyclic exposure temperatures, Figure 2.0322.

2.0323 Effect of heat treatment and thermal exposure, with and without a salt environment, on room temperature cross-tension strength of single resistance spot welds, (see Figure 4.0310).

2.0324 100-hour embrittlement and crack threshold curves for NaCl-coated (aerosol deposit on hot surface) as-machined or chemically-milled tubular specimens (from mill annealed bar) exposed to elevated temperature with load in either a laboratory or simulated aircraft turbine engine compressor environment and subsequently tensile tested at room temperature, Figure 2.0324.

2.0325 100-hour embrittlement and crack threshold curves for NaCl-coated (aerosol deposit on hot surface) as-machined or chemically-milled tubular specimens (from duplex annealed bar) exposed to elevated temperature with load in either a laboratory or simulated aircraft turbine engine compressor environment and subsequently tensile tested at room temperature, Figure 2.0325.

2.0326 Effect of alloy processing on 100-hour embrittlement and crack threshold curves for NaCl-coated (aerosol deposit on hot surface) chemically-milled tubular specimens (from duplex annealed bar) exposed to elevated temperature with load in a laboratory environment and subsequently tensile tested at room temperature, Figure 2.0326.

2.0327 Effect of 100-hour exposure to elevated temperature with load in a simulated aircraft turbine engine compressor environment on subsequent room temperature tensile properties of NaCl-coated (aerosol deposit on hot surface) as-machined tubular specimens from mill annealed bar, Figure 2.0327.

2.0328 Effect of 100-hour exposure to elevated temperature with load in either a laboratory or simulated aircraft turbine engine compressor environment on subsequent room temperature tensile properties of NaCl-coated (aerosol deposit on hot surface) chemically-milled tubular specimens from mill annealed bar, Figure 2.0328.

2.0329 Effect of 100-hour exposure to elevated temperature with load in a simulated aircraft turbine engine compressor environment on subsequent room temperature tensile properties of NaCl-coated (aerosol deposit on hot surface) as-machined tubular specimens from duplex annealed bar, Figure 2.0329.

2.03210 Effect of 100-hour exposure to elevated temperature with load in a laboratory environment on subsequent room temperature tensile properties of NaCl-coated (aerosol deposit on hot surface) chemically-milled tubular specimens from duplex annealed bar, Figure 2.03210.

2.03211	Effect of 100-hour exposure to elevated temperature with load on stress corrosion cracking and subsequent room temperature tensile properties of NaCl-coated specimens from duplex annealed compressor wheel forging, Table 2.03211.
2.03212	Effect of glass bead blasting on 100-hour hot-salt stress corrosion cracking characteristics of duplex annealed compressor forging, Figure 2.03212.
2.03213	Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on hot salt stress corrosion characteristics of duplex annealed forged disks, Table 2.03213.
2.03214	Effect of 100-hour exposure under load to hot solid salt on subsequent room temperature tensile properties of consumable electrode melted castings, (see Table 1.0827).
2.033	Delayed failure. The tendency for delayed failure of cracked specimens under sustained load in aqueous salt environments appears to be less for the duplex than for the mill or triplex annealed sheet conditions. For either duplex or triplex annealed condition, the tendency for delayed failure increases with increases in sheet thickness (Table 2.0331). This thickness dependence has also been observed for Ti-8Al-1Mo-1V alloy (21). One study (56) indicates a substantial (at least 50%) reduction in the plane strain fracture toughness for monotonic loading in ASTM D1141-52 (reapproved 1965) substitute ocean water as compared to air for consumable electrode melted castings.
2.0331	Delayed failure in salt water of fatigue-cracked specimens from duplex and triplex annealed sheet, Table 2.0331.
2.0332	Delayed failure in salt water of fatigue-cracked specimens from sheet variously heat treated, Table 2.0332.
2.034	Fretting Fatigue.
2.0341	Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on 900F fretting fatigue resistance of duplex annealed forged disks, (see Figure 1.04219).

3.	MECHANICAL PROPERTIES
3.01	Specified Mechanical Properties
3.011	AMS specified mechanical properties, Table 3.011.
3.012	Producer's guaranteed mechanical properties, Table 3.012.
3.013	User's specified mechanical properties for sheet, strip, plate, bars, forgings, rings, extrusions, forged parts, compressor blades and vanes, and premium forged parts, Table 3.013.
3.014	Users' specified mechanical properties for bars, forgings and forging stock, premium quality bars, forgings and forging stock, and investment castings, Table 3.014.
3.015	User's specified mechanical properties for bars, forgings, forging stock, forged parts, and compressor blades and vanes, Table 3.015.
3.016	User's specified mechanical properties for bars, forgings and forging stock from Ti-6Al-2Sn-4Zr-2Mo-0.25Si, Table 3.016.
3.02	Mechanical Properties at Room Temperature
3.021	Tension. Stress-strain diagrams and tension properties. See also 3.031.
3.0211	Stress-strain curves in tension for duplex annealed forged compressor discs at room temperature, Figure 3.0211.
3.0212	Effect of solution anneal temperature on room temperature tensile properties of solution annealed sheet, Figure 3.0212.
3.0213	Effect of solution anneal temperature on room temperature tensile properties of duplex and triplex annealed sheet, Figure 3.0213.
3.0214	Effect of stabilization anneal temperature on room temperature tensile properties of duplex annealed plate, Figure 3.0214.
3.0215	Effect of solution anneal temperature on room temperature tensile properties of solution annealed bar, (see Figure 3.0212).
3.0216	Effect of solution annealing near the beta transus temperature on room temperature tensile properties of duplex annealed bar, Table 3.0216.
3.0217	Effect of solution annealing at temperatures up to and beyond the beta transus temperature on room temperature tensile properties of duplex annealed bar, Figure 3.0217.
3.0218	Effect of section size on room temperature tensile properties of duplex annealed bar, Table 3.0218.
3.0219	Effect of stabilization age time and temperature on room temperature tensile properties of duplex annealed rolled bar, Figure 3.0219.
3.02110	Effect of solution anneal temperature on room temperature tensile properties of solution annealed forging, (see Figure 3.0212).
3.02111	Effect of solution anneal temperature on room temperature tensile properties of duplex annealed forging, Figure 3.02111.
3.02112	Room temperature tensile properties of duplex annealed upset forging, Table 3.02112.
3.02113	Typical room temperature tensile properties of forged jet engine compressor discs, Table 3.02113.
3.02114	Effect of exposure to elevated temperature with load on room temperature tensile properties of solution annealed sheet, Figure 3.02114.
3.02115	Effect of exposure to elevated temperature on room temperature tensile properties of duplex annealed sheet, Figure 3.02115.
3.02116	Effect of exposure to elevated temperature with load on room temperature tensile properties of duplex annealed sheet given various solution anneal treatments, Figure 3.02116.
3.02117	Effect of exposure to elevated temperature with load on room temperature tensile properties of duplex and triplex annealed sheet, Table 3.02117.
3.02118	Effect of long time exposure to elevated temperature with load on room temperature tensile properties of duplex and triplex annealed sheet, Table 3.02118.
3.02119	Effect of exposure to elevated temperature with load on room temperature tensile properties of triplex annealed sheet of various thicknesses, Figure 3.02119.
3.02120	Effect of exposure to elevated temperature with load on room temperature tensile properties of duplex annealed bar given various solution anneal treatments, Figure 3.02120.
3.02121	Effect of exposure to elevated temperature with load on room temperature tensile properties of duplex annealed rolled bar of various sizes, Table 3.02121.
3.02122	Effect of exposure to elevated temperature with load on room temperature tensile properties of duplex annealed rolled bar variously heat treated, Table 3.02122
3.02123	Effect of long time exposure to elevated temperature with load on room temperature tensile properties of duplex annealed rolled bar, Table 3.02123.
3.02124	Effect of exposure to elevated temperature with load on room temperature tensile properties of beta-rolled duplex annealed bar, Table 3.02124.
3.02125	Effect of exposure to elevated temperature with load on room temperature tensile properties of solution annealed forging, Figure 3.02125.
3.02126	Effect of exposure to elevated temperature with load on room temperature tensile properties of duplex annealed forging, Figure 3.02126.
3.02127	Effect of exposure to elevated temperature with load on room temperature tensile properties of duplex annealed forged bar, Table 3.02127.
3.02128	Effect of exposure to elevated temperature with load on room temperature tensile properties of duplex annealed compressor hub forging, Table 3.02128.
3.02129	Effect of exposure to elevated temperature with load on room temperature tensile properties of duplex annealed compressor wheel forgings, Table 3.02129.

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4	Zr
2	Mo

Ti-6-2-4-2

	Ti
6	Al
2	Sn
4	Zr
2	Mo

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3.02130 Effect of solution anneal temperature on room temperature tensile properties of duplex annealed compressor disk forgings subsequent to long-time exposure to elevated temperature with load, Figure 3.02130.

3.02131 Effect of long-time exposure to elevated temperature with load on room temperature tensile properties of duplex annealed pancake forgings, Table 3.02131.

3.02132 Effect of high solution annealing temperature (beta transus - 25F) on exposure stability properties of duplex annealed forged disk, Table 3.02132.

3.02133 Combined effect of 0.25% silicon addition and forge/heat treat combinations on room temperature tensile properties of duplex annealed forged disks, (see Table 1.04214).

3.02134 Effect of molybdenum addition and solution annealing temperature on strength and creep resistance of duplex annealed forged bar, (see Table 1.04221).

3.02135 Effect of oxygen content on room temperature tensile properties of consumable electrode melted castings, (see Figure 1.0811).

3.02136 Effect of iron content on room temperature tensile properties of consumable electrode melted castings, (see Figure 1.0815).

3.02137 Effect of post-weld treatment on room temperature smooth tensile properties of TIG repair welded, consumable electrode melted cast specimens, (see Table 1.0819).

3.02138 Room temperature tensile properties of consumable electrode melted castings variously heat treated, (see Table 1.0820).

3.02139 Effect of heat treatment and filler wire composition on room temperature tensile and bend properties of welded sheet, (see Figure 4.036).

3.02140 Effect of exposure to elevated temperature with load on room temperature tensile properties of welded sheet given various heat treatments, (see Table 4.038).

3.02141 Effect of postweld anneal temperature and time on tensile properties of welded duplex annealed 0.025-inch sheet, (see Figure 4.0318).

3.02142 Effect of postweld anneal temperature and time on tensile properties of welded duplex annealed 0.080-inch sheet, (see Figure 4.0319).

3.02143 Effect of exposure to elevated temperature on room temperature tensile properties of welded duplex annealed sheet postweld annealed for two hours at various temperatures, (see Table 4.0320).

3.02144 Effect of loading rate on room temperature and 900F tensile properties of duplex annealed bar, (see Table 3.03113).

3.022 Compression. Stress-strain diagrams and compression properties. See 3.032.

3.023 Impact. See also 3.033.

3.0231 Standard Charpy-V impact energy of duplex annealed compressor wheel forging, Table 3.0231.

3.0232 Effect of oxygen content on room temperature Charpy-V impact energy for consumable electrode melted castings, (see Figure 1.0813).

3.0233 Effect of iron content on room temperature Charpy-V impact energy for consumable electrode melted castings, (see Table 1.0817).

3.0234 Room temperature Charpy-V impact energy for consumable electrode melted castings variously heat treated, (see Table 1.0823).

3.024 Bending.

3.0241 Effect of solution anneal temperature on room temperature minimum bend radius of solution annealed, duplex annealed and triplex annealed sheet, Figure 3.0241.

3.0242 Effect of sheet thickness on minimum bend radius of duplex and triplex annealed sheet, Table 3.0242.

3.0243 Effect of heat treatment and filler wire composition on room temperature tensile and bend properties of welded sheet, (see Figure 4.036).

3.0244 Minimum bend radii of duplex and triplex annealed sheet of various thicknesses from several heats, welded and cooled at two different rates from the weld cycle, (see Table 4.0312).

3.025 Torsion and shear. See also 3.035.

3.0251 Effect of exposure to elevated temperature on room temperature ultimate shear strength of duplex annealed sheet, Figure 3.0251.

3.026 Bearing. See 3.036

3.027 Stress concentration.

3.0271 Notch properties.

3.02711 Effect of solution anneal temperature on room temperature sharp notch properties of solution annealed sheet, Figure 3.02711.

3.02712 Effect of solution anneal temperature on room temperature sharp notch properties of duplex annealed sheet, Figure 3.02712.

3.02713 Effect of solution anneal temperature on room temperature sharp notch properties of triplex annealed sheet, Figure 3.02713.

3.02714 Effect of annealing time on smooth and sharp notch tensile properties of duplex and triplex annealed sheet, Table 3.02714.

3.02715 Effect of stabilization age time and temperature on room temperature smooth and sharp notch tensile properties of triplex annealed sheet, Figure 3.02715.

3.02716 Effect of thickness on room temperature smooth and sharp notch tensile properties of duplex and triplex annealed sheet, Table 3.02716.

3.02717 Effect of thickness on room temperature smooth and sharp notch tensile properties of triplex annealed sheet, Figure 3.02717.

3.02718 Effect of exposure to elevated temperature on room temperature sharp notch strength of duplex annealed sheet, Figure 3.02718.

3.02719 Effect of exposure to elevated temperature on room temperature smooth and sharp notch tensile properties of duplex annealed sheet, Figure 3.02719.

3.027110 Effect of exposure to elevated temperature on room temperature sharp notch strength of triplex annealed sheet, Figure 3.027110.

3.027111 Effect of exposure to elevated temperature on room temperature smooth and sharp notch tensile properties of triplex annealed sheet, Figure 3.027111.

3.027112 Effect of oxygen content on room temperature mild-notch strength of consumable electrode melted castings, (see Table 1.0812).

3.027113 Effect of iron content on room temperature mild-notch strength of consumable electrode melted castings, (see Figure 1.0816).

3.027114 Room temperature mild notch strength of consumable electrode melted castings variously heat treated, (see Table 1.0821).

3.027115 Effect of heat treatment on room temperature sharp notch tensile properties of welded sheet, (see Table 4.037).

3.0272 Fracture toughness.

3.02721 The plane strain fracture toughness of as-received and (unconventionally) duplex annealed 2-inch plate is reported in Figure 3.02722. The data exhibit the usual strong inverse relation between strength and toughness. An attempt (80) to characterize the toughness of heavy sections in two useful duplex annealed conditions was largely frustrated by the selection of an inadequately-thick specimen. Those results are given in Table 3.02723. Only one value qualifies in every respect as valid according to ASTM Method E-399-74: TS orientation toughness of 52 ksi-$in^{\frac{1}{2}}$ for the 1650F solution annealed (plus stabilization aged) stock. All other values in the Table may be compared to that result, from which it appears that the higher 1790F solution temperature produces a tougher duplex condition with no significant sacrifice in strength, and that directionality is inconsistent and only moderate.

3.02722 Effect of specimen thickness on plane strain fracture toughness of as-received and duplex annealed plate, Figure 3.02722.

3.02723 Plane strain fracture toughness of duplex annealed bar, Table 3.02723.

3.028 Combined properties.

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

3.03 Mechanical Properties at Various Temperatures

3.031 Tension. Stress-strain diagrams and tension properties. See also 3.021.

3.0311 Typical stress-strain curves at elevated temperatures for duplex annealed bar, Figure 3.0311.

3.0312 Stress-strain curves in tension for duplex annealed forged compressor discs at 600F, Figure 3.0312.

3.0313 Stress-strain curves in tension for duplex annealed forged compressor discs at 800F, Figure 3.0313.

3.0314 Stress-strain curves in tension for duplex annealed forged compressor discs at 1000F, Figure 3.0314.

3.0315 Effect of test temperature on tensile properties of duplex annealed sheet, Figure 3.0315.

3.0316 Spread of tensile properties at elevated temperatures for duplex annealed sheets from two heats, Figure 3.0316.

3.0317 Effect of test temperature on tensile properties of triplex annealed sheet, Figure 3.0317.

3.0318 Smooth tensile properties at room and elevated temperatures for duplex and triplex annealed sheet, Figure 3.0318.

3.0319 Tensile properties at very high temperatures for triplex annealed sheet, Figure 3.0319.

3.03110 Effect of test temperature on tensile properties of solution annealed bar, Figure 3.03110.

3.03111 Effect of test temperature on tensile properties of duplex annealed bar, Figure 3.03111.

3.03112 Effect of section size on elevated temperature tensile properties of duplex annealed bar, Figure 3.03112.

3.03113 Effect of loading rate on room temperature and 900F tensile properties of duplex annealed bar, Table 3.03113.

3.03114 Spread of tensile properties at room and elevated temperature for thirteen duplex annealed pancake forgings from three heats, Figure 3.03114.

3.03115 Effect of test temperature on tensile properties of duplex annealed compressor wheel forging, Figure 3.03115.

3.03116 Total variation in tensile properties for duplex annealed compressor hub, Table 3.03116.

3.03117 Typical 900F tensile properties of forged jet engine compressor discs, Table 3.03117.

3.03118 Room and elevated temperature tensile properties of beta-forged upset, Table 3.03118.

3.03119 Effect of solution anneal temperature on 800F tensile properties of solution annealed and duplex annealed bar, Figure 3.03119.

3.03120 Effect of quench rate from solution anneal on 800F tensile properties of duplex annealed bar, Figure 3.03120.

3.03121 Effect of heat treatment on elevated temperature tensile properties of duplex annealed rolled bar, Figure 3.03121.

3.03122 Effect of solution annealing temperature on elevated temperature tensile properties of forged compressor disks, Figure 3.03122.

3.03123 Effect of solution anneal treatment on room temperature and 1000F tensile properties of beta-forged, duplex annealed compressor wheel, Table 3.03123.

3.03124 Effect of quench rate from solution anneal on elevated temperature tensile properties of duplex annealed forging, Table 3.03124.

3.03125 Effect of forging and annealing temperatures on the elevated temperature tensile properties of forged bar, Figure 3.03125.

3.03126 Effect of exposure to elevated temperature on tensile properties of duplex annealed sheet at the exposure temperature, Figure 3.03126.

3.03127 Effect of silicon content on the room temperature and 900F tensile properties of duplex annealed bar, (see Figure 1.0424).

3.03128 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on the elevated temperature tensile properties of duplex annealed forged disks, (see Figure 1.04215).

3.03129 Room temperature and 600F tensile properties of induction melted cast bars, (see Table 1.096).

3.03130 Effect of test temperature on tensile properties of consumable electrode melted castings, (see Figure 1.0824).

3.03131 Elevated temperature tensile properties of welded sheet, (see Table 4.039).

3.032 Compression. Stress-strain diagrams and compression properties.

3.0321 Effect of test temperature on compressive yield strength of duplex annealed sheet, Figure 3.0321.

3.033 Impact. See also 3.023.

3.0331 Effect of solution anneal temperature on standard Charpy-V impact energy for solution annealed and duplex annealed bar at room temperature and -80F, Figure 3.0331.

3.0332 Effect of silicon content on -40F Charpy-V impact energy of duplex annealed bar, (see Figure 1.0425).

3.034 Bending. See 3.024.

3.035 Torsion and shear. See also 3.025.

3.0351 Effect of test temperature on ultimate shear strength of duplex annealed sheet, Figure 3.0351.

3.0352 Effect of exposure to elevated temperature on ultimate shear strength of duplex annealed sheet at the exposure temperature, Figure 3.0352.

3.036 Bearing.

3.0361 Effect of test temperature on bearing properties of duplex annealed sheet, Figure 3.0361.

3.037 Stress concentration.

3.0371 Notch properties. See also 3.0271.

3.03711 Mild-notch strength of duplex annealed sheet at room and elevated temperatures, Table 3.03711.

3.03712 Effect of test temperature on center-crack tensile and yield strengths of duplex annealed sheet, Figure 3.03712.

3.03713 Smooth and mild-notch tensile properties of duplex annealed compressor disc forgings at room and elevated temperatures, Figure 3.03713.

3.0372 Fracture toughness. See 3.0272.

3.038 Combined properties.

3.04 Creep and Creep Rupture Properties

3.041 Creep rates.

3.0411 Minimum creep rate curves at 800, 900 and 1000F, for duplex annealed sheet, Figure 3.0411.

3.042 Creep deformation.

3.0421 Creep deformation curves at 800F for duplex annealed sheet, Figure 3.0421.

3.0422 Creep deformation curves at 900F for duplex annealed sheet, Figure 3.0422.

3.0423 Creep deformation curves at 1000F for duplex annealed sheet, Figure 3.0423.

3.0424 Effect of sheet thickness on 150-hour creep deformation of duplex and triplex annealed sheet, Table 3.0424.

3.0425 Effect of stabilization aging temperature on creep deformation of triplex annealed sheet of various thicknesses, Table 3.0425.

3.0426 Effect of solution anneal temperature on 150-hour creep of duplex annealed rolled bar, Table 3.0426.

3.0427 Effect of stabilization anneal temperature on 150-hour creep of duplex annealed rolled bar, Table 3.0427.

3.0428 Creep properties of duplex annealed bar, Table 3.0428.

3.0429 Effect of silicon content on time to 0.1 percent creep deformation at 950F, 35 ksi, for duplex annealed bar, (see Figure 1.0421).

3.04210 Effect of silicon content on 100-hour creep deformation at 950F and 35 ksi for duplex annealed bar, (see Figure 1.0422).

3.04211 Effect of molybdenum addition and solution annealing temperature on strength and creep resistance of duplex annealed forged bar, (see Table 1.04221).

3.04212 Creep deformation curves at 800F to 1000F for duplex annealed pancake forgings, Figure 3.04212.

3.04213 Effect of solution anneal temperature and quench rate on creep properties at 900F to 1100F for duplex annealed compressor wheel forging, Table 3.04213.

3.04214 Effect of solution annealing temperature on time to 0.1 percent creep deformation at 800F, 900F and 1000F for duplex annealed forgings, Figure 3.04214.

3.04215 Effect of solution anneal temperature on time to 2.0

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

percent creep at 1000F, 30 ksi, for duplex annealed forgings, Table 3.04215.

3.04216 Effect of solution annealing at high temperature (beta - 25F) on creep deformation for duplex annealed forging, Table 3.04216.

3.04217 Effect of solution annealing temperature on 100-hour, 1000F, 25 ksi creep deformation of duplex annealed Ti-6Al-2Sn-4Zr-2Mo-0.9Si rolled bar and forged upsets, (see Figure 1.0426).

3.04218 Combined effect of 0.25% silicon addition and forge/heat treat combinations on time to 0.1% creep at 1000F, 35 ksi, of duplex annealed forged disks, (see Table 1.0429).

3.04219 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on time to 0.1% creep at various temperatures and stresses, of duplex annealed forged disks, (see Table 1.04210).

3.04220 Effect of cast section thickness on the creep deformation of a consumable electrode melted casting, (see Table 1.0826).

3.043 Creep rupture.

3.0431 Short-time creep rupture strength of triplex annealed sheet specimens preloaded and rapidly heated to test temperature, Figure 3.0431.

3.0432 1000F stress rupture properties of duplex annealed bar, Table 3.0432.

3.0433 Monotonic creep-rupture and strain-limited cyclic creep-rupture curves at 900F and 1100F for duplex annealed bar, Figure 3.0433.

3.0434 Effect of solution anneal treatment on 1000F stress rupture properties of duplex annealed forgings, Figure 3.0434.

3.0435 Effect of solution anneal temperature on room temperature mild-notch stress rupture properties of duplex annealed compressor wheel forging, Table 3.0435.

3.0436 Effect of solution anneal temperature on room temperature mild-notch stress rupture properties of duplex annealed, beta forged compressor wheel forging, Table 3.0436.

3.0437 Effect of solution annealing at high temperature (beta - 25F) on room temperature tensile and mild-notch stress rupture properties of duplex annealed compressor hub forging, Table 3.0437.

3.0438 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on room temperature mild-notch stress rupture properties of duplex annealed forged disks, (see Table 1.04220).

3.0439 Stress rupture properties at 700F to 1000F for duplex annealed pancake forgings and as-cast compressor casing, Figure 3.0439.

3.04310 Effect of oxygen content on room temperature step-loaded mild-notch creep rupture properties of consumable electrode melted castings, (see Table 1.0814).

3.04311 Effect of iron content on room temperature step-loaded mild-notch creep rupture properties of consumable electrode melted castings, (see Table 1.0818).

3.04312 Room temperature step-loaded mild-notch creep rupture properties of consumable electrode melted castings variously heat treated, (see Table 1.0822).

3.05 Fatigue Properties

3.051 Axial load smooth and notch fatigue properties at 70F for duplex annealed sheet, Figure 3.051.

3.052 Axial load smooth and notch fatigue properties at 400F for duplex annealed sheet, Figure 3.052.

3.053 Axial load smooth and notch fatigue properties at 800F for duplex annealed sheet, Figure 3.053.

3.054 Room temperature stress range diagram at 10^7 cycles for smooth specimens of duplex annealed sheet, Figure 3.054.

3.055 Room temperature and 900F smooth fatigue properties for duplex annealed bar, Figure 3.055.

3.056 900F smooth and notch fatigue properties for duplex annealed bar, Figure 3.056.

3.057 High-frequency axial-load fatigue properties at room temperature and 900F for duplex annealed bar, Figure 3.057.

3.058 Notch fatigue strength at 600F and 900F for duplex annealed compressor disk forging, Figure 3.058.

3.059 400F smooth and notch fatigue properties for duplex annealed compressor disk forgings, Figure 3.059.

3.0510 850F smooth and notch fatigue properties for duplex annealed compressor disk forgings, Figure 3.0510.

3.0511 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on 900F axial load smooth and mild notch low cycle fatigue properties of duplex annealed forged disks, (see Figure 1.04216).

3.0512 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on 900F smooth and mild notch fatigue properties of duplex annealed forged disks, (see Figure 1.04217).

3.0513 Combined effect of 0.25% silicon addition, beta forging and solution annealing variation on 1100F smooth and mild notch fatigue properties of duplex annealed forged disks, (see Figure 1.04218).

3.0514 Effect of cast section thickness on the fatigue properties of consumable electrode melted castings, (see Figure 1.0828).

3.06 Elastic Properties

3.061 Poisson's ratio. (see also Figure 3.0433)

3.0611 Poisson's ratio for duplex annealed pancake forging, Figure 3.0611.

3.062 Modulus of elasticity.

3.0621 Static tensile modulus of elasticity at room and elevated temperatures for duplex annealed sheet, Figure 3.0621.

3.0622 Static compressive modulus of elasticity at room and elevated temperatures for duplex annealed sheet, Figure 3.0622.

3.0623 Dynamic tensile modulus of elasticity of duplex annealed sheet at room and elevated temperature, Figure 3.0623.

3.0624 Static tensile modulus of elasticity at room and elevated temperatures for duplex annealed bar, Figure 3.0624.

3.0625 Effect of loading rate on room temperature and 900F tensile properties (including tensile modulus of elasticity) of duplex annealed bar, (see Table 3.03113).

3.0626 Dynamic tensile modulus of elasticity at room and elevated temperatures for duplex annealed pancake forging, Figure 3.0626.

3.063 Modulus of rigidity.

3.064 Tangent modulus.

3.065 Secant modulus.

4. FABRICATION

4.01 Forming

4.011 Bending. Bend properties are equivalent to those for competitive alpha or alpha-beta alloys. See bend properties, section 3.024.

4.012 Forging. The producer of this alloy classifies its forgeability as similar to Ti-6Al-4V, (2). Others classify the forgeability of this alloy as better than that of Ti-8Al-1Mo-1V, not as good as Ti-6Al-4V, (11), and comparable to Ti-6Al-6V-2Sn, (4). Current specifications limit the forging temperature of this alloy to 1750F or beta transus temperature - 50F. One investigator reports that this produces a structure having superior fatigue properties. At these low temperatures, however, cracking can occur. (12). Forging high in the alpha-beta region reduces cracking tendency and imparts higher creep resistance. Creep resistance is further increased by forging well into the beta region, with no essential difference in the conventional tensile properties or in post-creep tensile properties (12) (Tables 4.0121 and 4.0122). As discussed in section 1.042, beta processing is considered essential if improved creep resistance of the silicon-modified variant of this alloy is to be assured, (79).

Beta recrystallization results in Tables 4.0123 and 4.0124 indicate that high temperature, large reduction forging processes are effective in refining the beta grain size. Low temperature forging and beta annealing is also useful in refining the beta grain size (86), but it appears considerable work is required to obtain complete recrystallization.

4.0121 Effect of beta forging and beta annealing on elevated temperature stability of duplex annealed forged bar, Table 4.0121.

4.0122 Effect of processed structure on elevated temperature stability of duplex annealed forging, Table 4.0122.

4.0123 High temperature forging and recrystallization results, Table 4.0123.

4.0124 Lower temperature forging and recrystallization results, Table 4.0124.

4.02 Machining and Grinding

Refer to Machinability Data Center, Metcut Research Associates, 390 Rosslyn Drive, Cincinnati, OH 45209.

4.03 WELDING

4.031 General. Two phase, alpha-beta titanium alloys characteristically produce welds with properties different from those of the unwelded metal. Generally, as the amount of stable beta phase increases, weld strength increases and ductility and toughness decrease. The normal annealed microstructure of Ti-6Al-2Sn-4Zr-2Mo alloy is alpha phase with a small amount of beta phase. It would be expected that, with such slight beta stabilization, the alloy would have excellent weldability. This, however, is not the case. The alloy produces a weld, the properties of which are difficult to predict and markedly different from the unwelded metal. (30).

Weld properties for this alloy have been reported in references (10) (13) (27) and (30). The results are summarized here. Sizeable differences have been observed in room temperature strength and notch toughness for fusion welded sheet of two thicknesses from separate heats (Figure 4.036 and Table 4.037). Postweld heat treatment in the stress relief range (i.e., 1100F, 2 hours) aged the welds, increasing their strength and reducing their notch toughness. In contrast to the results of Figure 4.036 and Table 4.037, Figures 4.0318 and 4.0319 show essentially no differences in ordinary tensile properties for welds of two different sheet gages from a single heat, and that possible benefits may derive from postweld annealing (this is discussed at greater length in Section 4.035). By comparison with creep data for parent sheet in Tables 3.0424 and 3.0425, poor creep resistance is seen for welded sheet in Table 4.038. Some evidence of thermal instability is also seen for welded sheet in Table 4.038. Postweld heat treatment at 1100F for 2 hours (stress relief cycle) improves creep resistance but not elevated temperature stability (also shown in Table 4.038). The elevated temperature weld strengths reported in Table 4.039 represent 100 percent weld efficiencies. Room temperature strengths of unexposed, as-welded spot welds presented in Figure 4.0310 and Table 4.0311 are considered "satisfactory" by the alloy producer (30). Postweld heat treatment (1100F, 2 hours) and elevated temperature exposure in air or salt environments, however, have deleterious effects on spot weld strength (again see Figure 4.0310).

It has been suggested (27) (30) that the variable weld properties of this alloy are attributable to nonequilibrium transformations which accompany weld cooling. Series of tests designed to study the influences of weld cooling rate (varied by altering sheet thickness, welding speed, and copper chill fixturing), base metal composition and heat treated condition on structure and properties have been conducted (27) (30). Results of bend tests in Table 4.0312, though sometimes not very pronounced, are consistent in suggesting that for this alloy the weld properties may vary with ingot source (composition), gage of material welded, weld cooling rate, and possibly, prior heat treatment. Variability of weld properties may be explained in part by reference to the transformation kinetics of this alloy as follows.

4.032 Nonequilibrium Beta Phase Decomposition. In titanium alloys, which are allotropic, there occur nonequilibrium transformations during relatively rapid cooling (or heating). The familiar time-temperature-transformation (TTT) diagram is frequently used for the study of such nonequilibrium transformations. However, the TTT diagram is usually determined by isothermal quench techniques, and can only be used as a guide to the phase changes which take place during continuous cooling: the continuous-cooling-transformation (CCT) diagram is necessary for this purpose. As the name implies, the CCT diagram describes the phase changes which take place while the metal is cooling, as a function of its cooling rate.

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

A schematic CCT diagram for alpha-lean beta titanium alloys is shown in Figure 4.0313. Curve A represents very slow cooling with transformation occurring in the neighborhood of the beta transus. The reaction is a near-equilibrium transformation of beta to alpha platelets. Cooling indicated by curve B is more rapid than that represented by curve A (but still slow) and results in an alpha structure more serrated in nature. Cooling indicated by curve C produces fine (acicular) alpha, but insufficient time in the upper range of temperature prevents the completion of this transformation. Some beta thus transforms to martensite (α') at the lower temperature. This split transformation, a nonequilibrium beta phase decomposition, occurs between rates C_1 and C_2. Variable cooling rates within this range result in variable transformations believed to cause many structural and mechanical uncertainties in Ti-6Al-2Sn-4Zr-2Mo welds. At sufficiently fast cooling rates, as indicated by curve D, transformation does not occur until a low temperature is reached. Here a uniform fully-martensitic structure is obtained.

4.033 Mechanical Properties. On the basis of the CCT diagram, maximum hardness for this alloy would be expected for intermediate cooling rates. Faster rates would not permit transformation to alpha, but rather martensite, which in titanium is usually considered a soft, ductile structure. Slower rates would result in alpha precipitates increasingly massive, soft and ductile, the slower the cooling rate.

Hardness measurements have been made on specimens cooled at various rates from above the beta transus. At slow cooling rates, transformation takes place at high temperatures and approaches equilibrium. The alpha growth rate exceeds the nucleation rate and the resultant structure is relatively soft. As the cooling rate is increased from the slowest rate, hardness increases as alpha platelet size diminishes. The nucleation rate for alpha transformation exceeds the growth rate. Hardness continues to increase with cooling rate as the "knee" of the curve is approached and the region of precipitation from an unstable beta is entered. (In actual welding situations the heat affected zone may be further complicated by an incomplete transformation upon heating due to the short times involved - see the CCT diagram for this alloy in Figure 4.0315.) To the left of the "knee", martensite is formed, characterized by a criss-cross needle appearance. Titanium martensite is usually soft, and therefore the hardness would be expected to fall for cooling rates to the left of the "knee". However, for this alloy it does not. One authority (35) feels that this is to be expected for stock cooled from above the beta transus. The "soft" martensite is produced by quenching from below the beta transus. These two martensites differ in hardness, lattice parameters and transformation mechanism. These hardness observations are consistent with hardness surveys made on weldments, a typical result shown in Figure 4.0314. The cooling rate increases with distance from the weld centerline, and so does the hardness before it falls to the base plate value. There is no drop in the heat affected zone to a value less than the base plate value as would be expected were the

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

4.034 martensite in this region "soft". The full range of mechanical properties as a function of cooling rate for this alloy has not yet been developed.

Composition. The nominal CCT diagram for this alloy is shown in Figure 4.0315. Figure 4.0316 shows that variations in chemical composition within normal specification tolerances can cause significant changes in the positions of the CCT diagram curves (i.e., M_s, M_f and times to start and finish transformations). While the differences shown may appear small, they are of considerable practical significance. A cooling rate considered slow enough to miss the region of nonequilibrium beta phase decomposition for one heat may, in fact, not be slow enough to miss it due to the curves' shift with slight chemistry changes. The heat affected zone which cools at quite a variable rate can be expected to consist of an equally broad range of microstructures and consequent mechanical properties.

The CCT diagram for this alloy is positioned to the right and below the TTT diagram (see Figure 4.0317). This is to be expected since the CCT diagram is essentially nonequilibrium and the TTT diagram is pseudoequilibrium. The time required to start the beta-to-alpha transformation is greater at higher temperatures. At a given transformation temperature, the continuously cooled specimen has been above the temperature throughout its entire cooling cycle, whereas the isothermally treated sample has been at the given reaction temperature for a finite time. Thus, the continuously cooled sample is not ready to form alpha at this given temperature in the time interval the isothermally treated sample is; that is, more time is required for transformation to begin. This explains why the CCT diagram lies below and to the right of the TTT diagram. It is a more difficult and abstract case to rationalize the discrepancy in M_s temperatures.

The transformation kinetics of martensite formation are different from those of the beta-to-alpha reaction. The former is by a shear mechanism (which defines martensite) and results in a supersaturated microstructure; the latter by a nucleation and growth process. It has been shown (31) (32) that the M_s temperature for titanium alloys is virtually independent of cooling rate at rates faster than critical (i.e., C_1 in Figure 4.0313). Thus the M_s temperature determined from either isothermal quenching or continuous cooling procedures should be the same. However, the CCT diagram shows an M_s temperature of about 1300F; the TTT diagram, 1475F. Two explanations for this disagreement have been offered.

Armitage (33) suggests that martensite may form isothermally above the apparent M_s temperature. The possible formation of small dispersed particles of omega phase (even after cold water quenching) would produce zones of transitory enriched beta. This segregation of beta stabilizing solute elements (here molybdenum) could then promote isothermal martensite transformation by increasing M_s temperature of small solute depleted regions.

Another source (30) suggests that heat to heat differences might also contribute to M_s differences. A variation of 1 weight percent molybdenum can depress the M_s of the Ti-Mo binary by about 50F in the range of 2 to 3 weight percent molybdenum, (31) (32) (34). Conceivably, the combined effects of compositional variations in Ti-6Al-2Sn-4Zr-2Mo might account for the observed difference in M_s temperature for the two transformation diagrams.

4.035 Postweld Annealing. The martensite formed by rapid cooling is unstable and reverts to alpha and beta upon reheating. If the reheat temperature is relatively low, the weld "age hardens". At higher reheat temperatures, the weld equilibrates and softens - commonly called annealing.

The variable structure (of variable hardness) produced at slower cooling rates is unstable due to the retention of unstable beta and ages when reheated to moderate temperatures. Reheating to sufficiently high temperatures, on the other hand, causes some of the alpha products producing hardening during cooling to be partially taken into solution. Others coalesce, equilibrium is approached, and general softening occurs - this again is called annealing.

The large alpha plates formed at cooling rates slower than those in the unstable transformation range is a "soft structure" - reheating to moderate temperatures has little effect. At higher reheat temperatures, in the annealing range, some hardening may occur due to redistribution of elements between the alpha and beta phases.

The effects of postweld annealing temperature and time on the room temperature tensile properties of duplex annealed 0.025-inch and 0.080-inch sheet are shown in Figures 4.0318 and 4.0319. The welds in the 0.025-inch sheet were thought (30) to have quenched to a martensitic (alpha prime) structure; welds in the 0.080-inch sheet cooled at a slower rate producing an "indefinite" structure. Both gages exhibited essentially identical properties in the as-welded condition. Structural differences, however, account for quite different property trends with time at the annealing temperature for the two gages. It appears, nevertheless, that both sheet aged at all annealing temperatures. Overaging (or annealing) occurred, however, in a very short time at the higher temperatures.

The effect of 150-hour exposure at 1000F without load on the subsequent room temperature tensile properties of both sheet gages annealed for 2 hours over the same range of annealing temperatures is shown in Table 4.0320. It is not surprising that the instability shown was not fully eliminated by annealing even at 1400F for 2 hours, since, as shown in Figures 4.0318 and 4.0319, four hours are required for the overaged properties to return to the unaged values. That some thermal instability might not be observed for fully annealed stock similarly exposed has not been demonstrated. It should be cautioned, however, that the specimen type used for this study (longitudinal weld orientation) tends to integrate the properties of the weld fusion and heat affected zones as well as the unwelded sheet and that the possibility that the base metal was controlling the tensile properties of the exposed specimens can not be ruled out.

While the data are incomplete, it appears that postweld annealing may be a useful method of approaching uniform weld properties in an alloy that has demonstrated wide variability. A cycle of 1300-1400F for at least one hour seems indicated. This tends to equilibrate the weld; however, its effect on base metal properties is unknown. Undoubtedly, the advantages gained by the 1100F part of the triplex anneal would be lost.

4.036 Effect of heat treatment and filler wire composition on room temperature tensile and bend properties of welded sheet, Figure 4.036.

4.037 Effect of heat treatment on room temperature sharp notch tensile properties of welded sheet, Table 4.037.

4.038 Effect of exposure to elevated temperature with load on room temperature tensile properties of welded sheet given various heat treatments, Table 4.038.

4.039 Elevated temperature tensile properties of welded sheet, Table 4.039.

4.0310 Effect of heat treatment and thermal exposure, with and without a salt environment, on room temperature cross-tension strength of single resistance spot welds, Figure 4.0310.

4.0311	Room temperature shear-tension and cross-tension strengths of single resistance spot welds given various heat treatments, Table 4.0311.
4.0312	Minimum bend radii of duplex and triplex annealed sheet of various thicknesses from several heats, welded and cooled at two different rates from the weld cycle, Table 4.0312.
4.0313	Hypothetical cooling curves A, B, C_2, C, C_1 and D, superimposed on schematic continuous-cooling-transformation (CCT) diagram for an alpha-lean beta titanium alloy, Figure 4.0313.
4.0314	Microhardness of weld cross section in 0.025-inch thick Ti-6Al-2Sn-4Zr-2Mo sheet, Figure 4.0314.
4.0315	Continuous-cooling-transformation (CCT) diagram for Ti-6Al-2Sn-4Zr-2Mo, Figure 4.0315.
4.0316	Effect of compositional variations within specification on continuous-cooling-transformation (CCT) diagram for Ti-6Al-2Sn-4Z4-2Mo, Figure 4.0316.
4.0317	Comparison of continuous-cooling-transformation (CCT) diagram and isothermal-transformation (TTT) diagram for Ti-6Al-2Sn-4Zr-2Mo alloy, Figure 4.0317.
4.0318	Effect of postweld anneal temperature and time on tensile properties of welded duplex annealed 0.025 inch sheet, Figure 4.0318.
4.0319	Effect of postweld anneal temperature and time on tensile properties of welded duplex annealed 0.080 inch sheet, Figure 4.0319.
4.0320	Effect of exposure to elevated temperature on room temperature tensile properties of welded duplex annealed sheet postweld annealed for two hours at various temperatures, Table 4.0320.

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

FORM	CONDITION	SPECIFICATION
Bars, Wire and Rings	Duplex Annealed	Aerospace Material Specification AMS-4975B (11-15-71)
Forgings and Forging Stock	Duplex Annealed	Aerospace Material Specification AMS-4976 (5-1-68)
Sheet, Strip and Plate	Mill Annealed, Solution Annealed and Duplex Annealed	Military Specification MIL-T-9046H (3-14-74)
Bars and Forging Stock	Mill Annealed, Solution Annealed and Duplex Annealed	Military Specification MIL-T-009047F(USAF) (9-19-72)
Premium Quality Forgings	Mill Annealed and Duplex Annealed	Military Specification MIL-F-83142A(USAF) (12-1-69)
Investment Castings	Mill Annealed	Military Specification MIL-T-81915 (3-16-73)
Bars and Forgings	Duplex Annealed	AVCO Corporation Lycoming Division M3406 (7-20-66)
Premium Quality Bars and Forgings	Duplex Annealed	AVCO Corporation Lycoming Division M3406A (1-6-72)
Investment Castings	As-Cast	AVCO Corporation Lycoming Division M34AB (9-14-66)
Sheet, Strip and Plate	Duplex Annealed and Triplex Annealed	General Electric Company B50TF21-S3 Amend 1 (6-24-76)
Bars, Rings and Forgings	Solution Annealed and Duplex Annealed	General Electric Company B50TF22-S4 Amend 1 (6-24-76)
Forged Parts	Duplex Annealed	General Electric Company C50TF7-S7 Amend 1 (6-24-76)
Premium Quality Forged Parts	Duplex Annealed	General Electric Company C50TF39-S4 Amend 1 (6-24-76)
Compressor Blades and Vanes	Duplex Annealed	General Electric Company C50TF8-S7 Amend 1 (6-24-76)
Extrusions	Mill Annealed, Solution Annealed and Duplex Annealed	General Electric Company B50TF91-S2 Amend 1 (6-24-76)
Bars	Duplex Annealed	United Technologies Corporation Pratt & Whitney Aircraft Division PWA-1210E (8-4-75)
Bars, Forgings, Forging Stock, Forged Parts and Compressor Blades and Vanes	Duplex Annealed	United Technologies Corporation Pratt & Whitney Aircraft Division PWA-1209L (8-4-75)
Forgings and Forging Stock	Duplex Annealed	United Technologies Corporation Pratt & Whitney Aircraft Division PWA-1214F (8-4-75)
Bars, Forgings and Forging Stock from Alpha-Beta Processed Ti-6Al-2Sn-4Zr-2Mo-0.25Si	Duplex Annealed	United Technologies Corporation Pratt & Whitney Aircraft Division PWA-1211A (8-8-75)
Forgings and Forging Stock from Beta Processed Ti-6Al-2Sn-4Zr-2Mo-0.25Si	Duplex Annealed	United Technologies Corporation Pratt & Whitney Aircraft Division PWA-1218A (8-8-75)

TABLE 1.03 SPECIFICATIONS

Source	AMS (19)		AMS (20)	
Form	Bars and Rings		Forgings	
	Weight Percent			
	Min	Max	Min	Max
Aluminum	5.50	6.50	5.50	6.50
Tin	1.80	2.20	1.80	2.20
Zirconium	3.60	4.40	3.60	4.40
Molybdenum	1.80	2.20	1.80	2.20
Iron		0.25		0.25
Carbon		0.05		0.05
Oxygen		0.15		0.15
Nitrogen		0.05		0.05
Hydrogen		0.0125		0.0150[a]
Others Each[b]		0.10		0.10
Others Total[b]		0.30		0.30
Titanium	balance		balance	

(a) 0.0125 max for forging stock.
(b) Determination not required for routine acceptance.

TABLE 1.041 AMS SPECIFIED COMPOSITION

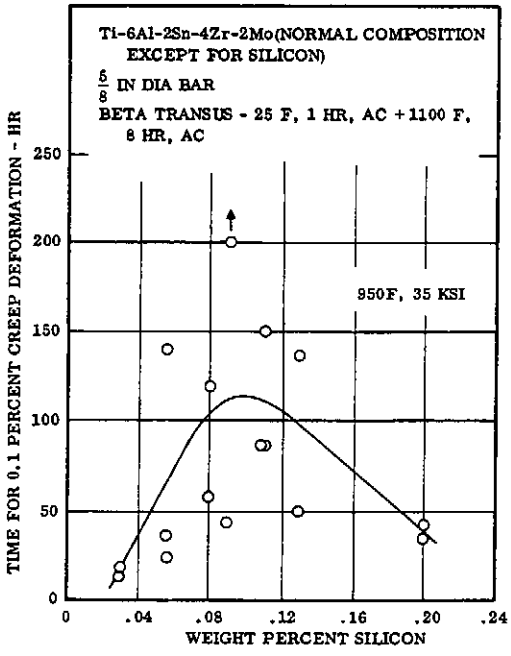


FIG. 1.0421. EFFECT OF SILICON CONTENT ON TIME TO 0.1 PERCENT CREEP DEFORMATION AT 950 F, 35 KSI, FOR DUPLEX ANNEALED BAR. (78)

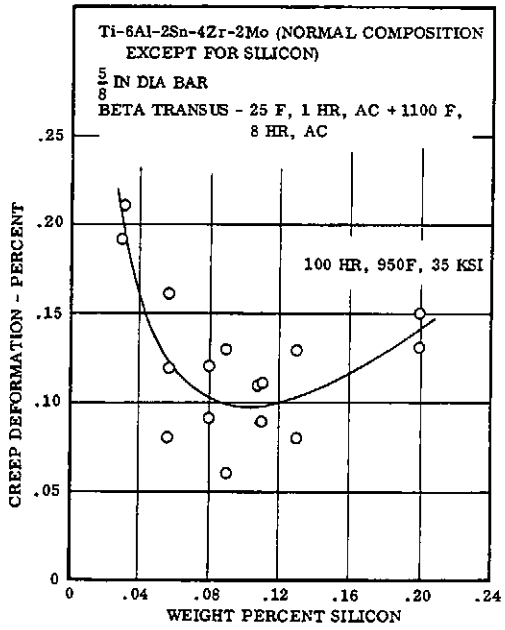


FIG. 1.0422. EFFECT OF SILICON CONTENT ON 100-HR CREEP DEFORMATION AT 950 F AND 35 KSI, FOR DUPLEX ANNEALED BAR. (78)

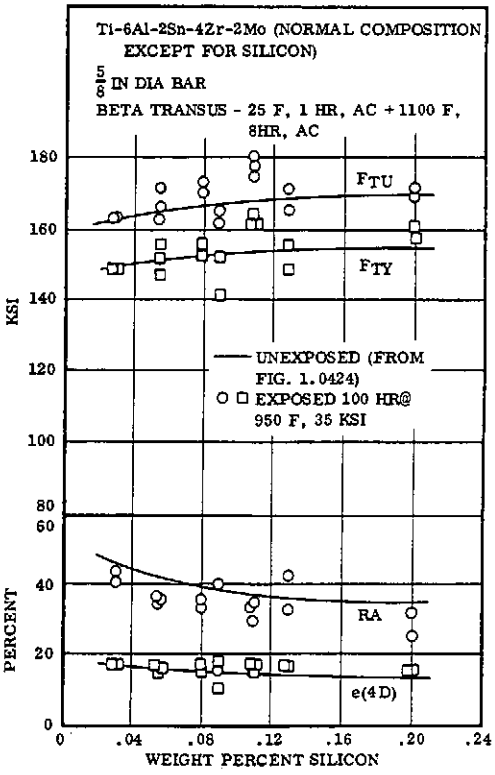


FIG. 1.0423. EFFECT OF 100 HR EXPOSURE AT 950 F, 35 KSI, ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED BAR OF VARYING SILICON CONTENT. (78)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

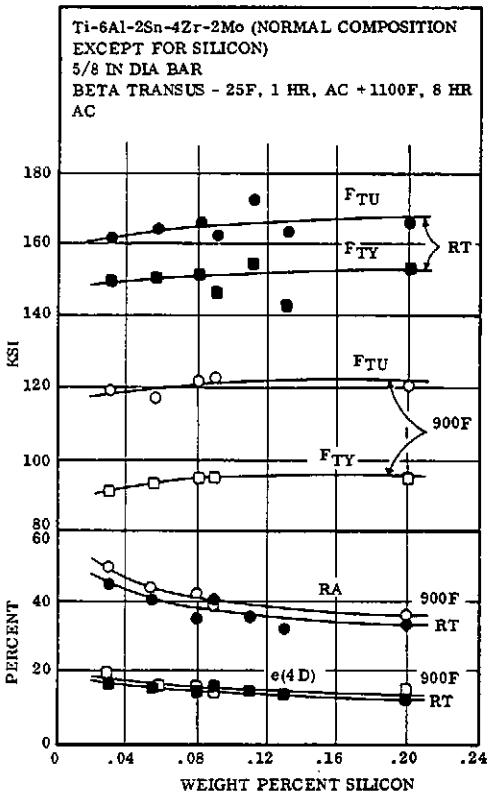


FIG. 1.0424 EFFECT OF SILICON CONTENT ON THE ROOM TEMPERATURE AND 900F TENSILE PROPERTIES OF DUPLEX ANNEALED BAR (78)

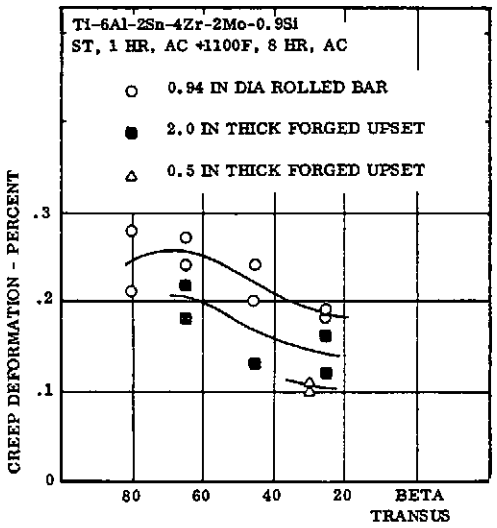


FIG. 1.0426 EFFECT OF SOLUTION ANNEALING TEMP ON 100 HR, 1000F, 25 KSI CREEP DEFORMATION OF DUPLEX ANNEALED Ti-6Al-2Sn-4Zr-2Mo-0.9Si ROLLED BAR AND FORGED UPSETS (78)

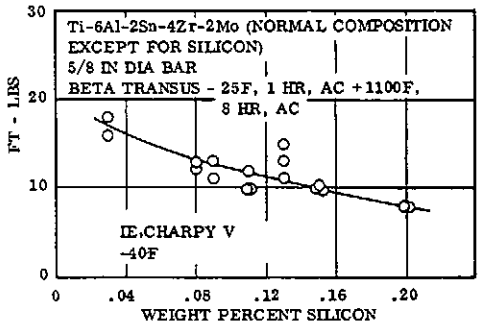


FIG. 1.0425 EFFECT OF SILICON CONTENT ON -40F CHARPY-V IMPACT ENERGY OF DUPLEX ANNEALED BAR (78)

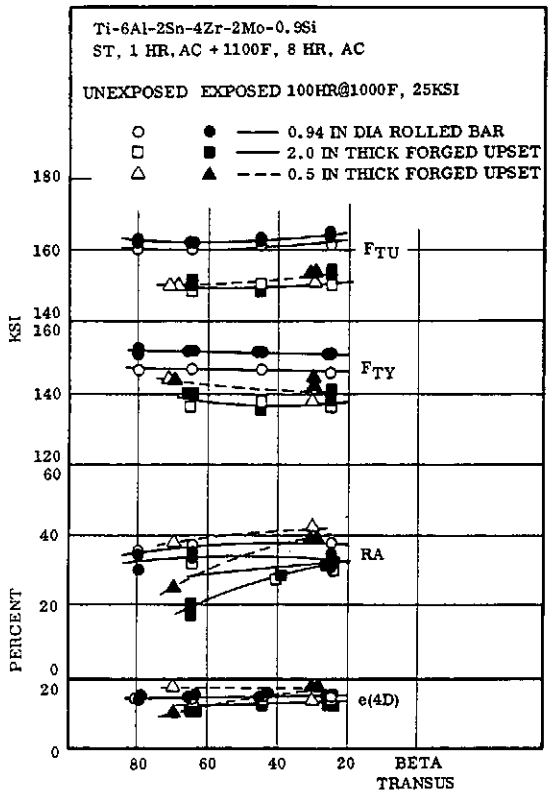


FIG. 1.0427. EFFECT OF SOLUTION ANNEALING TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED Ti-6Al-2Sn-4Zr-2Mo-0.9Si ROLLED BAR AND FORGED UPSETS SUBSEQUENT TO 100-HR CREEP EXPOSURE AT 1000 F, 25 KSI. (78)

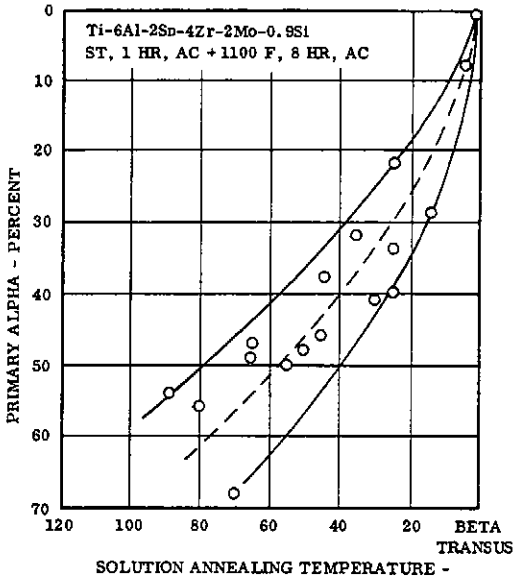


FIG. 1.0428. EFFECT OF SOLUTION ANNEALING TEMPERATURE ON PERCENT PRIMARY ALPHA IN Ti-6Al-2Sn-4Zr-2Mo-0.9Si ALLOY. (78)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Form		1½-in x 15-in dia pancake type forged disks	
Beta Transus F	Forge Temp F	Duplex Anneal Treatment	Time to 0.1% Creep at 1000F, 35 ksi hrs
		Ti-6Al-2Sn-4Zr-2Mo	
1830	1750	1805F, 1 hr, AC + 1100F, 8 hrs, AC	14.4 23.4
		Ti-6Al-2Sn-4Zr-2Mo + 0.25Si	
1820	1770	1770F, 1 hr, AC + 1100F, 8 hrs, AC	10.9 10.7
1820	1770	1770F, 1 hr, OQ + 1100F, 8 hrs, AC	15.3 20.3
1820	1870	1770F, 1 hr, AC + 1100F, 8 hrs, AC	127.8 117.2
1820	1870	1770F, 1 hr, OQ + 1100F, 8 hrs, AC	131.1 187.6

TABLE 1.0429 COMBINED EFFECT OF 0.25% SILICON ADDITION AND FORGE/HEAT TREAT COMBINATIONS ON TIME TO 0.1% CREEP AT 1000F, 35 KSI, OF DUPLEX ANNEALED FORGED DISKS, (70).

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Form	1½-in x 15-in dia pancake type forged disks	
Condition	Duplex Annealed	
Temp F	Stress ksi	Hrs to 0.1% Creep
	Ti-6Al-2Sn-4Zr-2Mo[a]	
800	60	313.5
800	65	110.0
1000	25	128.0
1000	30	55.0
1000	35	14.4
1000	35	23.4
1200	10	8.0
1200	15	3.4
	Ti-6Al-2Sn-4Zr-2Mo + 0.25Si[b]	
800	60	1000.0(c)
800	65	1000.0(d)
1000	25	396.0
1000	30	96.0
1000	35	131.1
1000	35	187.6
1200	10	5.4
1200	15	on Loading

(a) Forged: 1750F. Duplex Annealed: 1805F, 1 hr, AC + 1100F, 8 hrs, AC. Beta transus = 1830F.
(b) Forged: 1870F. Duplex Annealed: 1770F, 1 hr, OQ + 1100F, 8 hrs, AC. Beta transus = 1820F.
(c) 0.081% creep deformation.
(d) 0.092% creep deformation.

TABLE 1.04210 COMBINED EFFECT OF 0.25% SILICON ADDITION, BETA FORGING AND SOLUTION ANNEALING VARIATION ON TIME TO 0.1% CREEP AT VARIOUS TEMPERATURES AND STRESSES, OF DUPLEX ANNEALED FORGED DISKS, (70).

Form		1½-in x 15-in dia pancake type forged disks					
Beta Transus F	Forge Temp F	Duplex Anneal Treatment	Exposure Condition	Subsequent RT Tensile Properties[a] F_{tu} ksi	F_{ty} ksi	e(1-in) percent	RA percent
		Ti-6Al-2Sn-4Zr-2Mo					
1830	1750	1805F, 1 hr, AC + 1100F, 8 hrs, AC	Unexposed	147.0	133.5	16.0	35.6
				150.0	137.9	16.5	33.7
			Exposed[b]	145.5	135.1	19.0	44.6
				149.5	138.2	18.5	42.4
		Ti-6Al-2Sn-4Zr-2Mo + 0.25Si					
1820	1770	1770F, 1 hr, AC + 1100F, 8 hrs, AC	Unexposed	153.7	146.2	12.0	34.3
				155.0	147.0	13.0	33.0
			Exposed[b]	156.7	147.7	16.0	30.6
				158.0	148.1	14.0	28.1
1820	1770	1770F, 1 hr, OQ + 1100F, 8 hrs, AC	Unexposed	172.0	157.5	10.0	12.3
				173.0	158.0	15.0	27.7
			Exposed[b]	177.3	166.3	9.0	13.8
				174.7	164.9	16.0	31.6
1820	1870	1770F, 1 hr, AC + 1100F, 8 hrs, AC	Unexposed	149.7	138.1	9.0	27.2
				151.7	138.9	13.0	23.0
			Exposed[b]	153.5	142.0	13.0	18.2
				153.6	140.5	11.5	12.0
1820	1870	1770F, 1 hr, OQ + 1100F, 8 hrs, AC	Unexposed	166.8	151.8	7.0	15.0
				165.0	149.5	7.0	15.8
			Exposed[b]	176.4	153.5	6.0	9.3
				171.7	156.5	8.0	11.6

(a) Tested after exposure without surface conditioning.
(b) 0.1% creep deformation at 1000F, 35 ksi.

TABLE 1.04211 COMBINED EFFECT OF 0.25% SILICON ADDITION AND FORGE/HEAT TREAT COMBINATIONS ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED FORGED DISKS SUBSEQUENT TO 0.1% CREEP EXPOSURE AT 1000F, 35 KSI, (70).

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti·6·2·4·2

Form	1½-in x 15-in dia pancake type forged disks
Condition	Duplex Annealed
0.1% Creep Exposure at	Subsequent RT Tensile Properties[a]

Temp F	Stress ksi	Time hr	F_{tu} ksi	F_{ty} ksi	e(1-in) percent	RA percent
		Ti-6Al-2Sn-4Zr-2Mo[b]				
	Unexposed		147.0	133.5	16.0	35.6
	Unexposed		150.0	137.9	16.5	33.7
800	60	313.5	146.7	132.9	19.0	34.0
800	65	110.0	145.9	129.9	13.5	32.5
1000	25	128.0	146.7	135.5	16.0	24.9
1000	30	55.0	146.1	136.2	19.0	39.6
1000	35	14.4	145.5(c)	135.1(c)	19.0(c)	44.6(c)
1000	35	23.4	149.5(c)	138.2)c)	18.5(c)	42.4(c)
1200	10	8.0	145.4	132.6	16.5	32.9
1200	15	3.4	144.9	135.6	17.5	37.6
		Ti-6Al-2Sn-4Zr-2Mo + 0.25Si[d]				
	Unexposed - Disk #1		166.8	151.8	7.0	15.0
	Unexposed - Disk #1		165.0	149.5	7.0	15.8
	Unexposed - Disk #2		165.1	149.1	10.0	14.6
	Unexposed - Disk #2		169.0	153.4	8.5	13.0
800	60	1000.0[e]	175.1	160.7	6.0	8.5
800	65	1000.0[f]	165.8	149.4	8.0	11.0
1000	25	396.0	168.2	154.3	5.5	6.8
1000	30	96.0	165.8	150.0	11.5	11.4
1000	35	131.1	167.4[c]	153.5[c]	6.0[c]	9.3[c]
1000	35	187.6	171.7[c]	156.5[c]	8.0[c]	11.6[c]
1200	10	5.4	163.6	150.0	7.5	9.7
1200	15	on Loading	158.7	148.0	7.5	8.0

(a) 0.020 in removed from surface after exposure and before RT test, except where noted.
(b) Forged: 1750F. Duplex annealed: 1805F, 1hr, AC + 1100F, 8 hrs, AC.
Beta transus = 1830F.
(c) Tested after exposure without surface removal.
(d) Forged: 1870F. Duplex annealed: 1770F, 1 hr, OQ + 1100F, 8 hrs, AC.
Beta transus = 1820F.
(e) 0.081% creep deformation.
(f) 0.092% creep deformation.

TABLE 1.04212. COMBINED EFFECT OF 0.25% SILICON ADDITION, BETA FORGING AND SOLUTION ANNEALING VARIATION ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED FORGED DISKS SUBSEQUENT TO 0.1% CREEP EXPOSURE AT VARIOUS EXPOSURE TEMPERATURES AND STRESSES, (70).

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Alloy	Ti-6Al-2Sn-4Zr-2Mo + 0.25Si						
Form	1½-in x 15-in dia pancake type forged disks						
Condition	Beta Forged + Duplex Annealed[a]						
Creep Exposure				Subsequent RT Tensile Properties [b]			
Temp F	Stress ksi	Time hr	Deformation percent	F_{tu} ksi	F_{ty} ksi	e(1-in) percent	RA percent
	Unexposed			165.1	149.1	10.0	14.6
	Unexposed			169.0	153.4	8.5	13.8
800	60	1000	0.081	175.1	160.7	6.0	8.5
800	65	1000	0.092	165.8	149.4	8.0	11.0
800	90	896	0.173	170.5	163.0	9.0	9.3
900	30	130	0.026	167.6	151.1	10.0	12.7
900	30	130	0.059	161.8	144.6	10.0	13.4
900	30	300	0.062	173.7	158.3	7.0	8.3
900	30	300	0.068	165.5	152.3	8.5	10.6
900	30	600	0.032	164.5	149.1	11.5	13.2
900	30	600	0.034	167.5	150.0	10.0	13.0
1000	20	50	0.017	165.7	150.0	9.0	11.3
1000	20	50	0.018	164.0	146.8	10.0	12.1
1000	20	150	0.042	165.0	149.0	9.0	11.0
1000	25	396	0.100	168.2	154.3	5.5	6.8
1000	25	500	----	164.8	148.6	10.5	12.7
1000	30	96	0.100	165.8	150.0	11.5	11.4
1000	45	295	0.202	173.6	165.0	4.0	6.0
1100	5	25	0.034	161.0	146.0	8.5	9.6
1100	5	25	0.049	166.5	151.2	6.0	6.0
1200	10	5.4	0.100	163.6	150.0	7.5	9.7
1200	15	on Loading	0.100	158.7	148.0	7.5	8.0

(a) Forged: 1870F. Duplex annealed: 1770F, 1 hr, OQ + 1100F, 8 hrs, AC. Beta transus = 1820F.
(b) 0.020 in removed from surface after exposure and before RT tensile test.

TABLE 1.04213. EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF BETA FORGED, DUPLEX ANNEALED Ti-6Al-2Sn-4Zr-2Mo + 0.25Si FORGED DISKS, (70).

Form	1½-in x 15-in dia pancake type forged disks					
Beta Transus F	Forge Temp F	Duplex Anneal Treatment	RT Tensile Properties			
			F_{tu} ksi	F_{ty} ksi	e(1-in) percent	RA percent
		Ti-6Al-2Sn-4Zr-2Mo				
1830	1750	1805F, 1 hr, AC + 1100F, 8 hrs, AC	147.0	133.5	16.0	35.6
			150.0	137.9	16.5	33.7
		Ti-6Al-2Sn-4Zr-2Mo + 0.25Si				
1820	1770	1770F, 1 hr, AC + 1100F, 8 hrs, AC	153.7	146.2	12.0	34.3
			155.0	147.0	13.0	33.0
1820	1770	1770F, 1 hr, OQ + 1100F, 8 hrs, AC	172.0	157.5	10.0	12.3
			173.0	158.0	15.0	27.7
1820	1870	1770F, 1 hr, AC + 1100F, 8 hrs, AC	149.7	138.1	9.0	27.2
			151.7	138.9	13.0	23.0
1820	1870	1770F, 1 hr, OQ + 1100F, 8 hrs, AC	166.8	151.8	7.0	15.0
			165.0	149.5	7.0	15.8

TABLE 1.04214. COMBINED EFFECT OF 0.25% SILICON ADDITION AND FORGE/HEAT TREAT COMBINATIONS ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED FORGED DISKS, (70).

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

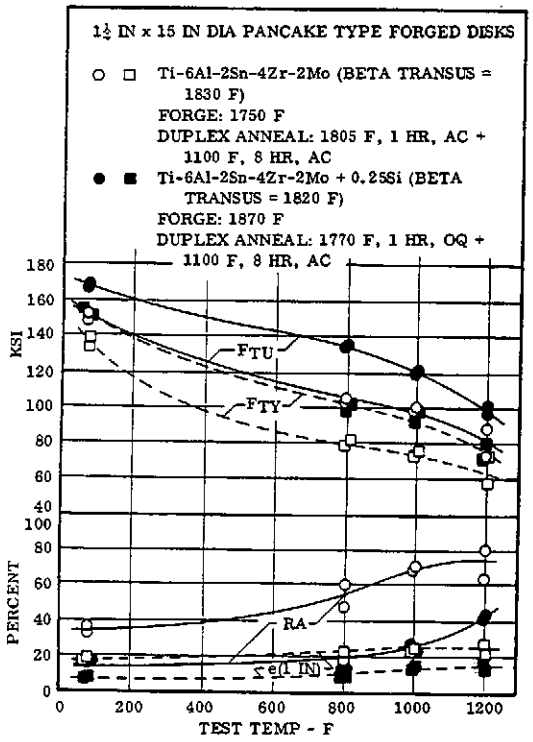


FIG. 1.04215. COMBINED EFFECT OF 0.25% SILICON ADDITION, BETA FORGING AND SOLUTION ANNEALING VARIATION ON THE ELEVATED TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED FORGED DISKS (70)

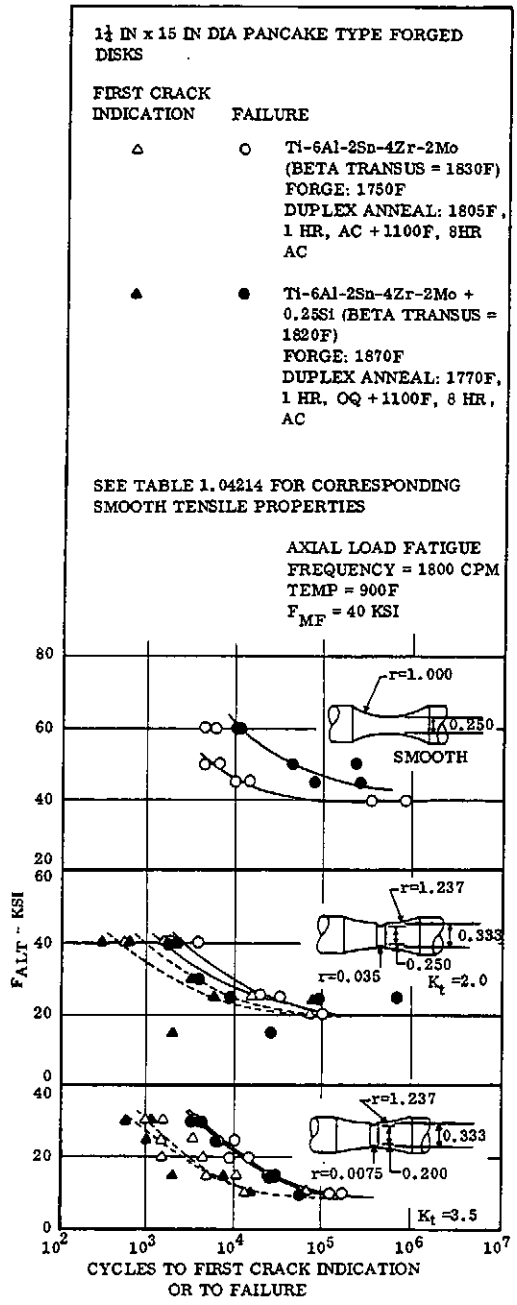


FIG. 1.04216 COMBINED EFFECT OF 0.25 PERCENT SILICON ADDITION, BETA FORGING AND SOLUTION ANNEALING VARIATION ON 900 F AXIAL LOAD SMOOTH AND MILD NOTCH LOW CYCLE FATIGUE PROPERTIES OF DUPLEX ANNEALED FORGED DISKS (70)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

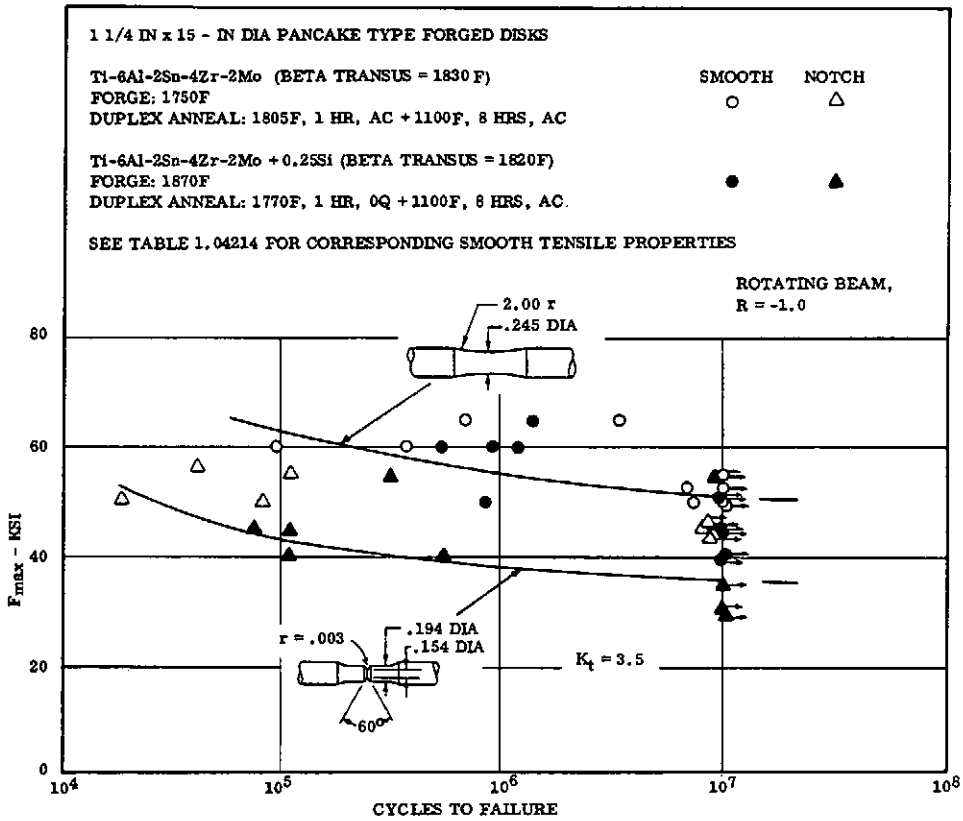


FIG. 1.04217 COMBINED EFFECT OF 0.25% SILICON ADDITION, BETA FORGING AND SOLUTION ANNEALING VARIATION ON 900F SMOOTH AND NOTCH FATIGUE PROPERTIES OF DUPLEX ANNEALED FORGED DISKS (70)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

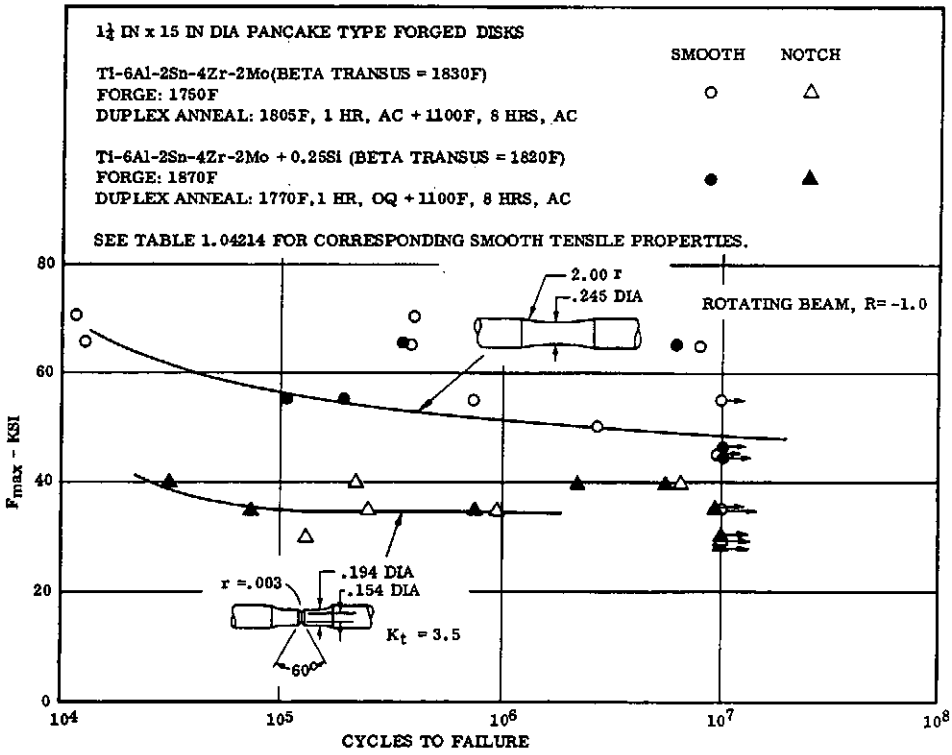


FIG. 1.04218 COMBINED EFFECT OF 0.25% SILICON ADDITION, BETA FORGING AND SOLUTION ANNEALING VARIATION ON 1100F SMOOTH AND MILD NOTCH FATIGUE PROPERTIES OF DUPLEX ANNEALED FORGED DISKS. (70)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

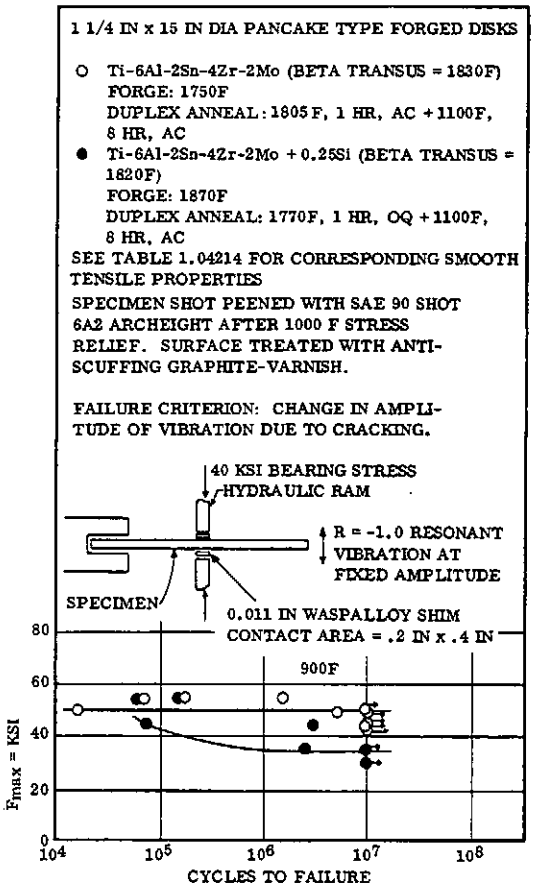
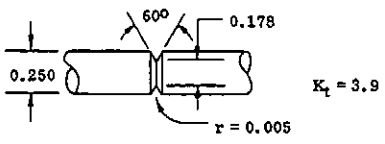


FIG. 1.04219 COMBINED EFFECT OF 0.25% SILICON ADDITION, BETA FORGING AND SOLUTION ANNEALING VARIATION ON 900F FRETTING FATIGUE RESISTANCE OF DUPLEX ANNEALED FORGED DISKS. (70)

Form	1¼-in x 15-in dia pancake type forged disks	
Alloy/Condition	RT Notch Stress Rupture	
	Stress at Failure[a] ksi	Time at Failure Stress hr
Ti-6Al-2Sn-4Zr-2Mo (Beta transus = 1830F)		
Forge: 1750F	200	2.3
Duplex Anneal: 1805F, 1 hr, AC + 1100F, 8 hrs, AC	200	2.5
Ti-6Al-2Sn-4Zr-2Mo + 0.25Si (Beta transus = 1820F)		
Forge: 1870F	190	0.1
Duplex Anneal: 1770F, 1 hr, OQ + 1100F, 8 hrs, AC	190	0.6

(a) Stress increased from 160 ksi in 5-ksi increments every 5 hours.



See Table 1.04214 for corresponding smooth tensile properties.

TABLE 1.04220 COMBINED EFFECT OF 0.25% SILICON ADDITION, BETA FORGING AND SOLUTION ANNEALING VARIATION ON ROOM TEMPERATURE MILD NOTCH STRESS RUPTURE PROPERTIES OF DUPLEX ANNEALED FORGED DISKS, (70).

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Form			3-in Forged Bar					
Condition[a]			1650F, 1 hr, AC + 1100F, 8 hrs, AC			1750F, 1 hr, AC + 1100F, 8 hrs, AC		
Alloy	150-hr Creep Exposure Temp F	150-hr Creep Exposure Stress ksi	Creep Deformation percent	F_{tu} ksi	F_{ty} ksi	Creep Deformation percent	F_{tu} ksi	F_{ty} ksi
Ti-6Al-2Sn-4Zr-2Mo	900	45	0.10-0.12	141-142	131-132	0.11-0.12	137-138	127-129
Ti-6Al-2Sn-4Zr-3Mo	900	45	0.40-0.52	144-145	132-135	0.27-0.40	142-143	131-133
Ti-6Al-2Sn-4Zr-4Mo	900	45	0.28-0.60	148-150	134-139	0.21-0.23	150-151	134-135
Ti-6Al-2Sn-4Zr-2Mo	1000	25	0.14-0.21	142-145	134-136	0.05-0.12	138-139	130-131
Ti-6Al-2Sn-4Zr-3Mo	1000	25	1.00-1.29	145	135	0.61-1.07	142	131
Ti-6Al-2Sn-4Zr-4Mo	1000	25	0.51-1.12	148-151	137-141	0.25-0.35	150-151	134-135

[a] Duplex annealed as 7-in long specimens.

TABLE 1.04221. EFFECT OF MOLYBDENUM ADDITION AND SOLUTION ANNEALING TEMPERATURE ON STRENGTH AND CREEP RESISTANCE OF DUPLEX ANNEALED FORGED BAR, (85).

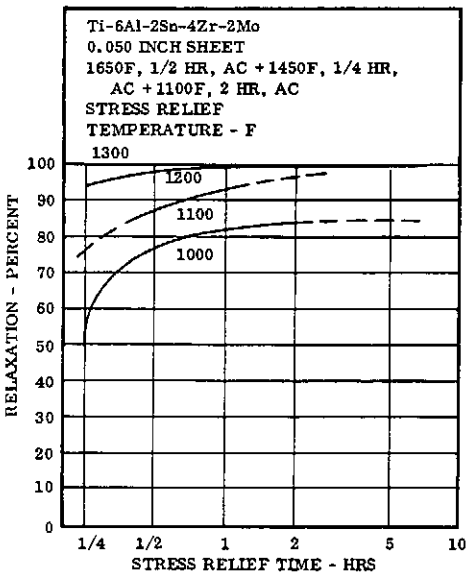


FIG. 1.0531 EFFECT OF STRESS RELIEF TIME AND TEMPERATURE ON RELAXATION OF RESTRAINED BEND SPECIMENS OF TRIPLEX ANNEALED SHEET. (30, p. 23)

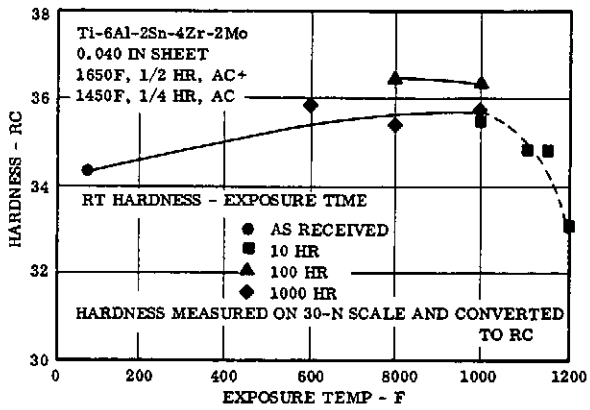


FIG. 1.061 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ROOM TEMPERATURE HARDNESS OF DUPLEX ANNEALED SHEET. (1, P.268)

Alloy		Ti-6Al-2Sn-4Zr-2Mo							
Form		Castability Casting[1]							
Metal Pour Temp	Mold Preheat Temp-F	Percent Mold Fill[2]							
		Bottom Gated Section Thickness - inch[3]				Top & Bottom Gated, Section Thickness - inch[3]			
		0.250	0.090	0.060	0.030	0.250	0.090	0.060	0.030
High (4)	1000	100	100	20.7	22.4	100	100	100	9.0
Low (5)	1000	100	100	50.7	18.6	100	100	96.0	43.2
High	1500	100	100	58.4	41.5	100	100	76.2	22.8
Low	1500	100	100	70.3	32.4	100	100	100	22.8
High	2000	100	100	100	14.5	100	100	100	20.4
Low	2000	100	100	67.1	23.4	100	100	100	18.2

(1) Induction melted in graphite crucibles and cast into pyrolytic graphite faced silicate bonded molds.
(2) Determined as percent of total section surface.
(3) 0.75-inch wide x 4-inch long bars (see Section 1.083 for description).
(4) Liquidus + 200-350F.
(5) Liquidus + 100-200F.

TABLE 1.085 EFFECT OF METAL POUR TEMPERATURE AND MOLD PREHEAT TEMPERATURE ON MOLD FILL FOR INDUCTION MELTED CASTINGS, (54).

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy		Ti-6Al-2Sn-4Zr-2Mo		
Form		0.250-inch Dia Cast Tensile Bars[1]		
Condition		Cast + Sandblasted + 1100F, 8 hrs, Rapid FC		
Test Temp F	F_{tu} ksi	F_{ty} ksi	e(1-in) percent	RA percent
RT	141.5	123.7	15.0	19.6
RT	138.9	125.3	11.0	6.2
RT	139.7	122.3	18.0	13.3
RT	139.0	123.1	9.5	13.8
600	96.0	74.3	18.5	27.0
600	90.8	71.7	10.0	17.0
600	94.2	75.1	10.5	16.6
600	92.1	71.3	13.0	23.9

(1) Induction melted in graphite crucibles and cast into pryolytic graphite faced silicate bonded molds. Castings not completely sound - some centerline microshrink or porosity evident.

TABLE 1.086 ROOM TEMPERATURE AND 600F TENSILE PROPERTIES OF INDUCTION MELTED CAST BARS, (54).

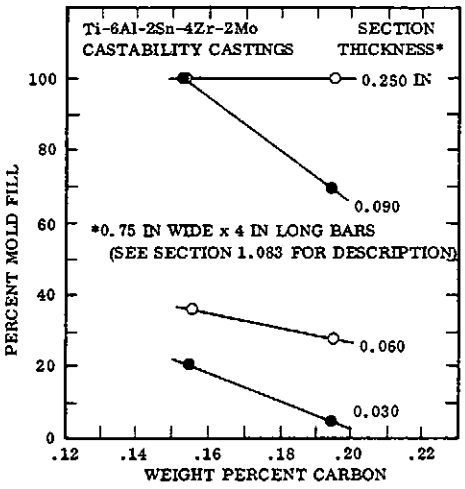


FIG. 1.088. EFFECT OF CARBON CONTENT ON MOLD FILL FOR CASTINGS INDUCTION MELTED IN GRAPHITE CRUCIBLES AND CAST INTO STAINLESS STEEL MOLDS. (54)

Alloy		Ti-6Al-2Sn-4Z4-2Mo		
Form		1/4-inch-Thick Single-Gated Castability Section[1]		
Metal Pour Temp	Mold Preheat Temp F	Surface Carbide Layer inch	Carbide Network inch	Alpha Case inch
High[2]	1000	Trace	None	None
High	1500	0.00012	0.007	0-0.002 intermittent
High	2000	0.00025	0.020	0.005
Low[3]	2000	0.00025	0.0075	0.001-0.0015 intermittent

(1) 0.75-inch wide x 4-inch long bar (see Section 1.083 for description).
(2) Liquidus + 200-350F.
(3) Liquidus + 100-200F.

TABLE 1.087 SURFACE REACTION OF 1/4-INCH-THICK SINGLE-GATED CASTABILITY SECTIONS INDUCTION MELTED IN GRAPHITE CRUCIBLES AND CAST INTO PYROLTYIC GRAPHITE FACED SILICATE BONDED MOLDS, (54).

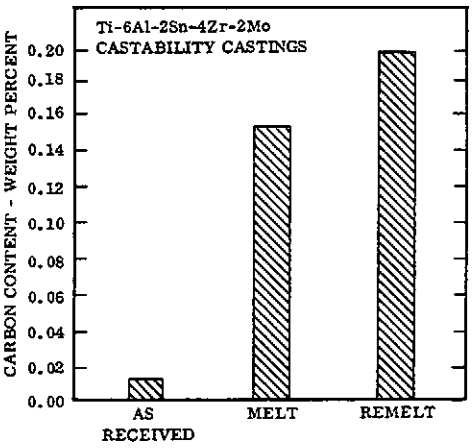


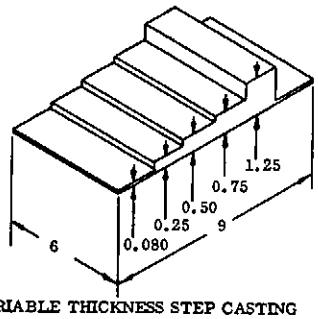
FIG. 1.089 EFFECT OF INDUCTION REMELTING IN GRAPHITE CRUCIBLES ON CARBON CONTENT OF CASTINGS POURED INTO STAINLESS STEEL MOLDS. (54)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Alloy	Ti-6Al-2Sn-4Zr-2Mo							
Form	Cast(1)							
Casting Conditions					Casting Quality(2)			
Foundary Practice Variable	Mold Temperature	Electrode Diameter	Crucible Size (Capacity)	Melt Size (Weight)	Linear Indications of Surface Imperfections(3)		X-Ray Shrink Indications(4) (Porosity)	Overall Dimensional Shrinkage
	F	in	lb	lb	Visual	Fluorescent Penetrant		in/in
Reference Foundary Conditions	700	5	50	11	31	7	8	0.016
Cold Mold	RT	5	50	12	72	10	101	0.015
Hot Mold	1400	5	50	12	26	6	8	0.014
Smaller Electrode	700	3	50	15	41	5	12	0.016
Smaller Crucible	700	3	25	10	47	9	44	0.017
Larger Melt	700	3	25	>17(5)	82	9	30	0.016

(1) Consumable electrode skull melted in water-cooled copper crucibles and cast into tungsten lined ceramic molds.
(2) All values average for three castings for each foundary practice variable.
(3) Surface blemishes linearized and expressed as number of one-quarter-inch lengths.
(4) Internal shrinkage in 0.080-inch thick sections. Shrunk areas typically 0.020 to 0.030-inch in length.
(5) Excessive metal splash during pour: melt weight, determined as weight of casting plus pour cup, is conservative.



VARIABLE THICKNESS STEP CASTING

TABLE 1.0810 INFLUENCE OF FOUNDARY PRACTICE (CASTING CONDITIONS) ON NONDESTRUCTIVE TESTING (NDT) QUALITY OF CONSUMABLE ELECTRODE MELTED CASTINGS, (56).

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

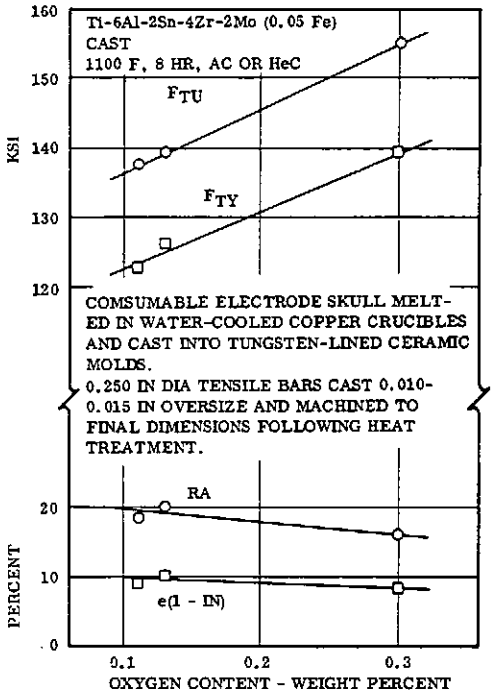


FIG. 1.0811. EFFECT OF OXYGEN CONTENT ON ROOM TEMPERATURE TENSILE PROPERTIES OF CONSUMABLE ELETRODE MELTED CASTINGS. (56)

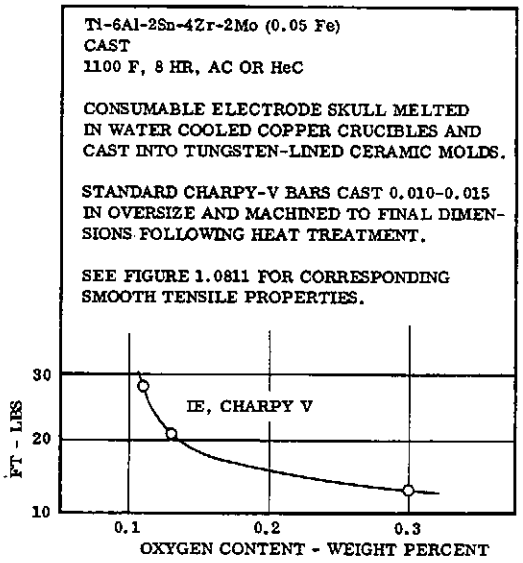


FIG. 1.0813 EFFECT OF OXYGEN CONTENT ON ROOM TEMPERATURE CHARPY-V IMPACT ENERGY FOR COMSUMABLE ELECTRODE MELTED CASTINGS. (56)

Alloy	Ti-6Al-2Sn-4Zr-2Mo (0.05 Fe)	
Form	Cast(1)	
Condition	1100F, 8 hrs, AC or HeC	
Oxygen Content weight percent	F_{ty}(2) ksi	NTS(3) ksi
0.11	123	206.8 215.7 218.1
0.13	126	206.3 211.1 210.4
0.30	139	217.7 223.3 224.1

(1) Consumable electrode skull melted in water-cooled copper crucibles and cast into tungsten-lined ceramic molds.
(2) See Figure 1.0811 for balance of smooth tensile properties.
(3) Mild-notch tensile bars cast 0.010-0.015 inch oversize and machined to configuration shown below following heat treatment.

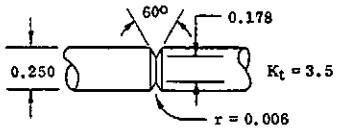


TABLE 1.0812 EFFECT OF OXYGEN CONTENT ON ROOM TEMPERATURE MILD-NOTCH STRENGTH OF CONSUMABLE ELECTRODE MELTED CASTINGS. (56).

Alloy	Ti-6Al-2Sn-4Zr-2Mo (0.05 Fe)	
Form	Cast(1)	
Condition	1100F, 8 hrs, AC or HeC	
Oxygen Content weight percent	RT Mild-Notch Creep Rupture Properties(2)(3)(4)	
	Stress at Failure ksi	Time at Failure Stress hrs
0.11	180	0.9
0.13	170	0.7
0.30	160	0.2

(1) Consumable electrode skull melted in water-cooled copper crucibles and cast into tungsten-lined ceramic molds.
(2) Stress increased from 160 ksi in 10 ksi increments every five hours until failure. Least value from three tests reported.
(3) See Figure 1.0811 for corresponding smooth tensile properties.
(4) Mild-notch tensile bars cast 0.010-0.015 inch oversize and machined to configuration shown below following heat treatment.

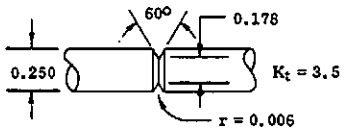


TABLE 1.0814 EFFECT OF OXYGEN CONTENT ON ROOM TEMPERATURE STEP-LOADED MILD-NOTCH CREEP RUPTURE PROPERTIES OF CONSUMABLE ELECTRODE MELTED CASTINGS, (56).

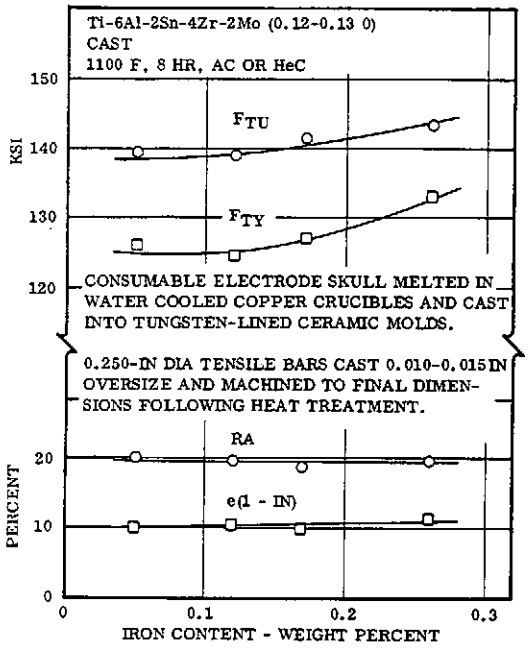


FIG. 1.0815. EFFECT OF IRON CONTENT ON ROOM TEMPERATURE TENSILE PROPERTIES OF CONSUMABLE ELECTRODE MELTED CASTINGS. (56)

Alloy	Ti-6Al-2Sn-4Zr-2Mo (0.12-0.13 O)	
Form	Cast(1)	
Condition	1100F, 8 hrs, AC or HeC	
Iron Content weight percent	F_{ty}(2) ksi	IE, Charpy-V(3) ft-lbs
0.05	126	21.8 20.8 21.2
0.12	124	27.5 24.0 24.5
0.17	126	24.0 22.5 21.0
0.26	133	19.5 19.5 21.0

(1) Consumable electrode skull melted in water-cooled copper crucibles and cast into tungsten-lined ceramic molds.
(2) See Figure 1.0815 for corresponding smooth tensile properties.
(3) Standard Charpy-V bars cast 0.010-0.015 inch oversize and machined to final dimensions following heat treatment.

TABLE 1.0817 EFFECT OF IRON CONTENT ON ROOM TEMPERATURE CHARPY-V IMPACT ENERGY FOR CONSUMABLE ELECTRODE MELTED CASTINGS, (56).

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

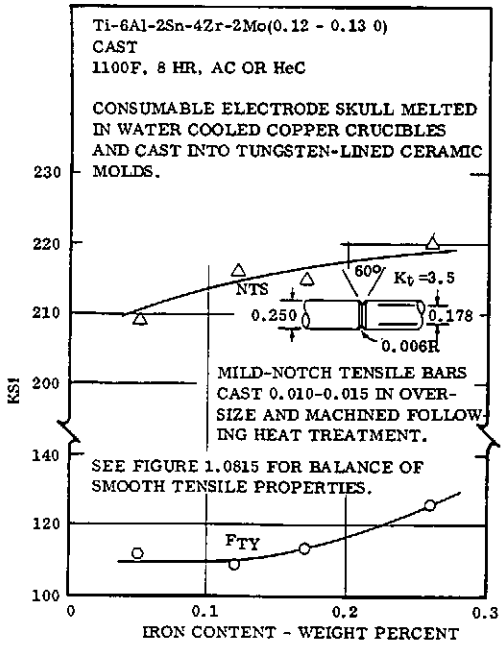


FIG. 1.0816. EFFECT OF IRON CONTENT ON ROOM TEMPERATURE MILD-NOTCH STRENGTH OF CONSUMABLE ELECTRODE MELTED CASTINGS. (56)

Alloy	Ti-6Al-2Sn-4Zr-2Mo (0.12-0.13 O)	
Form	Cast(1)	
Condition	1100F, 8 hrs, AC or HeC	
Iron Content weight percent	RT Mild-Notch Creep Rupture Properties(2)(3)(4)	
	Stress at Failure ksi	Time at Failure Stress hrs
0.05	170	0.7
0.12	180	2.5
0.17	180	1.5
0.26	180	2.5

(1) Consumable electrode skull melted in water-cooled copper crucibles and cast into tungsten-lined ceramic molds.
(2) Stress increased from 160 ksi in 10 ksi increments every five hours until failure. Least value from three tests reported.
(3) See Figure 1.0815 for corresponding smooth tensile properties.
(4) Mild-notch tensile bars cast 0.010-0.015 inch oversize and machined to configuration shown below following heat treatment.

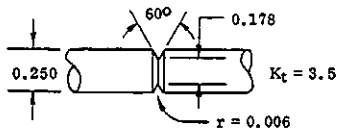


TABLE 1.0818 EFFECT OF IRON CONTENT ON ROOM TEMPERATURE STEP-LOADED MILD-NOTCH CREEP RUPTURE PROPERTIES OF CONSUMABLE ELECTRODE MELTED CASTINGS, (56).

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Alloy		Ti-6Al-2Sn-4Zr-2Mo			
Form		0.250-inch Dia Tensile Bars			
Condition		Cast(1) + TIG Repair Welded(2) + Heat Treated			
Heat Treatment		RT Tensile Properties(3)			
		F_{tu} ksi	F_{ty} ksi	e(1-in) %	RA %
None	Repair Welded	149.5	127.1	6.8	12.5
	Not Repair Welded	147.2	130.2	9.3	18.8
1650F, 1 hr, HeC + 1100F, 8 hrs, HeC	Repair Welded	150.8	140.5	5.3	16.2
	Not Repair Welded	148.1	133.9	9.7	15.6
1900F, 1 hr + 1650F, 1 hr + 1100F, 4 hrs, HeC	Repair Welded	134.9	122.6	9.2	24.5
	Not Repair Welded	134.0	121.1	10.7	22.2
1900F, 1 hr, HeC + 1100F, 4 hrs, HeC	Repair Welded	145.5	132.5	10.7	18.3
	Not Repair Welded	143.6	131.8	9.0	19.2

(1) Consumable electrode skull melted in water-cooled copper crucibles and cast into tungsten-lined ceramic molds.
(2) 50 percent of specimen test cross section machined away and replaced with weld metal.
(3) Each value average of three tests.

TABLE 1.0819 EFFECT OF POST-WELD HEAT TREATMENT ON ROOM TEMPERATURE SMOOTH TENSILE PROPERTIES OF TIG REPAIR WELDED, CONSUMABLE ELECTRODE MELTED CAST SPECIMENS, (56).

Alloy		Ti-6Al-2Sn-4Zr-2Mo				
Form		Cast(1)				
Heat Treatment		F_{tu} ksi	F_{ty} ksi	e(1-in) percent	RA percent	E 10^3 ksi
1100F, 8 hrs, AC	(2)	137.5	123.7	10.5	21.4	
		139.2	130.0	9.0	20.5	
		140.4	123.7	10.0	18.2	
1750F, 1 hr, AC + 1100F, 8 hrs, AC	(2)	146.5	129.7	8.0	21.5	18.4
		142.7	127.6	5.0	13.3	17.2
		144.1	129.4	4.0	8.1	17.1
1900F, 1 hr, WQ + 1100F, 8 hrs, AC	(2)	164.5	178.2	1.0	3.9	
		187.7	(3)	1.0	3.9	
		179.4	179.4	1.0	3.1	
1900F, 1 hr, HeC + 1100F, 4 hrs, HeC	(4)(5)	141.2	127.4	7.8	19.3	
	(4)(6)	138.8-143.6	125.0-130.5	5.0-12.0	10.9-24.6	

(1) Consumable electrode skull melted in water-cooled copper crucibles and cast into tungsten-lined ceramic molds.
(2) 0.250-inch dia tensile bars cast 0.010-0.015 inch oversize and machined to final dimensions following heat treatment.
(3) Failed at less than 0.2 percent indicated strain.
(4) 0.250-inch dia tensile bars machined from three thickest sections of heat treated, variable thickness step castings of the type shown in Table 1.0810.
(5) Average of nine values from three castings.
(6) Range of nine values from three castings.

TABLE 1.0820 ROOM TEMPERATURE TENSILE PROPERTIES OF CONSUMABLE ELECTRODE MELTED CASTINGS VARIOUSLY HEAT TREATED, (56).

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy		Ti-6Al-2Sn-4Zr-2Mo	
Form		Cast(1)	
Heat Treatment		F_{ty}(2) ksi	NTS ksi
1100F, 8 hrs, AC	(3)	126	206.3 211.1 210.4
1750F, 1 hr, AC + 1100F, 8 hrs, AC	(3)	129	200.8 205.6 211.5
1900F, 1 hr, WQ + 1100F, 8 hrs, AC	(3)	179	187.2 179.4 174.2
1900F, 1 hr, HeC + 1100F, 4 hrs, HeC	(4)(5)	127	219.8
	(4)(6)		212.0 - 226.9

(1) Consumable electrode skull melted in water-cooled copper crucibles and cast into tungsten-lined ceramic molds.
(2) See Table 1.0820 for balance of smooth tensile properties.
(3) Mild notch tensile bars cast 0.010-0.015 inch oversize and machined to configuration shown below following heat treatment.
(4) Mild notch tensile bars of configuration shown below machined from three thickest sections of heat treated, variable thickness step castings of the type shown in Table 1.0810.
(5) Average of nine values from three castings.
(6) Range of nine values from three castings.

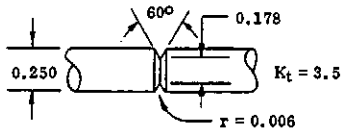


TABLE 1.0821 ROOM TEMPERATURE MILD NOTCH STRENGTH OF CONSUMABLE ELECTRODE MELTED CASTINGS VARIOUSLY HEAT TREATED. (56).

Alloy		Ti-6Al-2Sn-4Zr-2Mo	
Form		Cast(1)	
		RT Mild-Notch Creep Rupture Properties(2)(3)	
Heat Treatment		Stress at Failure ksi	Time at Failure Stress hrs
1100F, 8 hrs, AC	(4)	170	0.7
1750F, 1 hr, AC + 1100F, 8 hrs, AC	(4)	200	1.6
1900F, 1 hr, WQ + 1100F, 8 hrs, AC	(4)	160	Broke on loading
1900F, 1 hr, HeC + 1100F, 4 hrs, HeC	(5)	170	4.7

(1) Consumable electrode skull melted in water-cooled copper crucibles and cast into tungsten-lined ceramic molds.
(2) Stress increased from 160 ksi in 10 ksi increments every five hours until failure.
(3) See Table 1.0820 for corresponding smooth tensile properties.
(4) Mild-notch tensile bars cast 0.010-0.015 inch oversize and machined to configuration shown below following heat treatment. Least value from three tests reported.
(5) Mild-notch tensile bars of configuration shown below machined from three thickest sections of heat treated, variable thickness step castings of the type shown in Table 1.0810. Least value from nine tests reported.

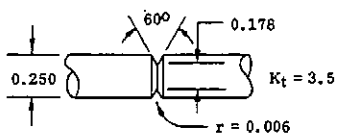


TABLE 1.0822 ROOM TEMPERATURE STEP-LOADED MILD-NOTCH CREEP RUPTURE PROPERTIES OF CONSUMABLE ELECTRODE MELTED CASTINGS VARIOUSLY HEAT TREATED. (56).

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Alloy		Ti-6Al-2Sn-4Zr-2Mo
Form		Cast(1)
Heat Treatment		IE, Charpy-V at RT(2) ft-lb
1100F, 8 hrs, AC	(3)	22 21 21
1750F, 1 hr, AC + 1100F, 8 hrs, AC	(3)	28 25 26
1900F, 1 hr, WQ + 1100F, 8 hrs, AC	(3)	6 6 6
1900F, 1 hr, HeC + 1100F, 4 hrs, HeC	(4)(5)	21
	(4)(6)	17 - 26

(1) Consumable electrode skull melted in water-cooled copper crucibles and cast into tungsten-lined ceramic molds.
(2) See Table 1.0820 for corresponding smooth tensile properties.
(3) Standard Charpy-V bars cast 0.010-0.015 inch oversize and machined to final dimensions following heat treatment.
(4) Standard Charpy-V bars machined from three thickest sections of heat treated, variable thickness step castings of the type shown in Table 1.0810.
(5) Average of nine values from three castings.
(6) Range of nine values from three castings.

TABLE 1.0823 ROOM TEMPERATURE CHARPY-V IMPACT ENERGY FOR CONSUMABLE ELECTRODE MELTED CASTINGS VARIOUSLY HEAT TREATED, (56).

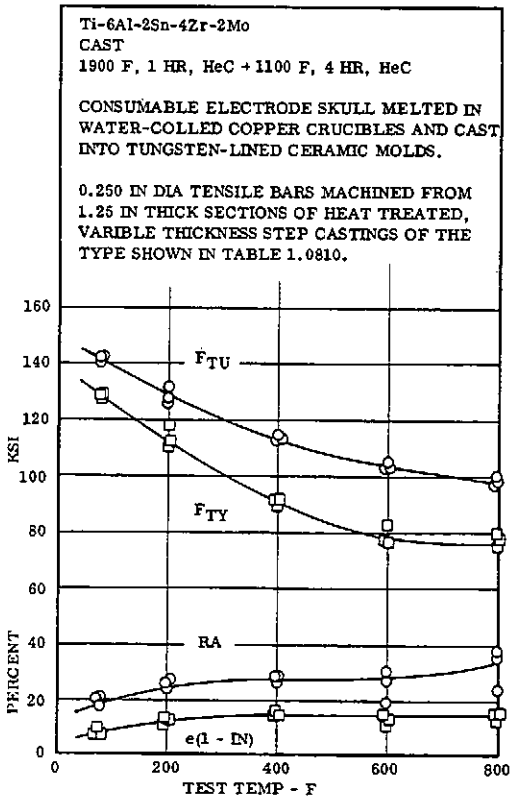


FIG. 1.0824. EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF CONSUMABLE ELECTRODE MELTED CASTINGS. (56)

Alloy		Ti-6Al-2Sn-4Zr-2Mo			
Form		Cast(1)			
Condition		1900F, 1 hr, HeC + 1100F, 4 hrs, HeC			
Exposure Conditions(2)	Deformation %	Subsequent RT Tensile Properties(3)			
		F_{tu} ksi	F_{ty} ksi	e(1-in) %	RA %
Unexposed(4)	-------	140-142	126-129	7-9	17-21
1000F, 35 ksi, 100hrs(5)	0.24 - 0.47	144-146	128-133	6-10	15-21

(1) Consumable electrode skull melted in water-cooled copper crucibles and cast into tungsten lined ceramic molds.
(2) 0.250-inch dia tensile bars machined from the three thickest sections of heat treated, variable thickness step castings of the type shown in Table 1.0810
(3) Specimen diameter reduced 0.020 inch following exposure, prior to tensile testing.
(4) Nine tests.
(5) Three tests.

TABLE 1.0825 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF CONSUMABLE ELECTRODE MELTED CASTINGS, (56).

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy			Ti-6Al-2Sn-4Zr-2Mo	
Form			Cast(1)	
Condition			1900F, 1 hr, HeC + 1100F, 4 hrs, HeC	
Creep Exposure			Cast Section Thickness	Creep Deformation(2)
Temp F	Stress ksi	Time hrs	in	%
1000	35	100	1.25	0.24
1000	35	100	0.75	0.28
1000	35	100	0.50	0.47

(1) Consumable electrode skull melted in water-cooled copper crucibles and cast into tungsten lined ceramic molds.
(2) 0.250-inch dia tensile bars machined from each of the three thickest sections of a heat treated, variable thickness step casting of the type shown in Table 1.0810.

TABLE 1.0826 EFFECT OF CAST SECTION THICKNESS ON THE CREEP DEFORMATION OF A CONSUMABLE ELECTRODE MELTED CASTING, (56).

Alloy						Ti-6Al-2Sn-4Zr-2Mo			
Form						Cast(1)			
Condition						1900F, 1 hr, HeC + 1100F, 4 hrs, HeC			
Exposure Conditions(2)						Subsequent RT Tensile Properties			
Temp F	Stress ksi	Time hrs	Medium	Deformation percent		F_{tu} ksi	F_{ty} ksi	e(1-in) percent	RA percent
--- Unexposed ---					(3)	140-142	126-12	7-9	17-21
1000	35	100	Air	0.24-0.47	(4)(5)	144-146	128-133	6-10	15-21
1000	35	100	Salt(6)	0.32	(7)	106	105	129	2.4
800	35	100	Salt(6)	0.00		112	112	3.0	7.8
600	35	100	Salt(6)	0.00		139	123	10.0	14.5

(1) Consumable electrode skull melted in water-cooled copper crucibles and cast into tungsten lined ceramic molds.
(2) 0.250-inch dia tensile bars machined from the three thickest sections of heat treated, variable thickness step castings of the type shown in Table 1.0810.
(3) Nine tests.
(4) Three tests.
(5) Specimen diameter reduced 0.020 inch following exposure, prior to tensile testing.
(6) ASTM D1141-52 (Reapproved 1965) substitute ocean water.
(7) Numerous post-exposure zyglo indications.

TABLE 1.0827 EFFECT OF 100-HOUR EXPOSURE UNDER LOAD TO HOT SOLID SALT ON SUBSEQUENT ROOM TEMPERATURE TENSILE PROPERTIES OF CONSUMABLE ELECTRODE MELTED CASTINGS, (56).

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

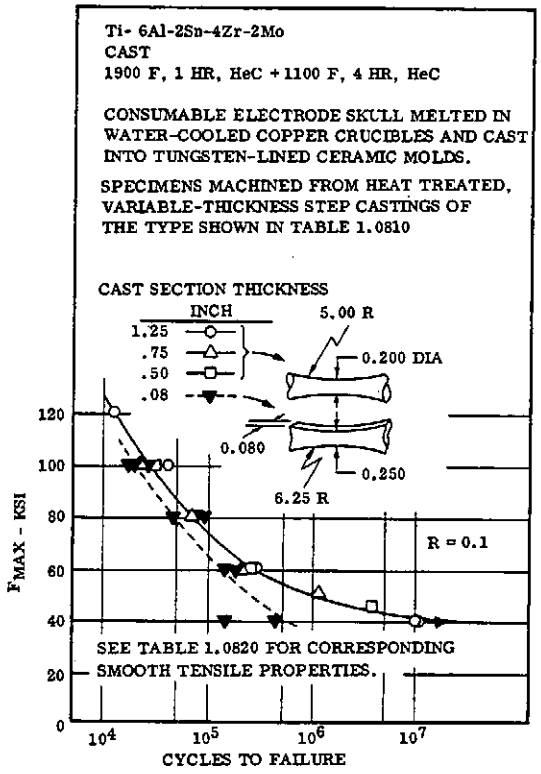


FIG. 1.0828 EFFECT OF CAST SECTION THICKNESS ON THE FATIGUE PROPERTIES OF CONSUMABLE ELECTRODE MELTED CASTINGS. (56)

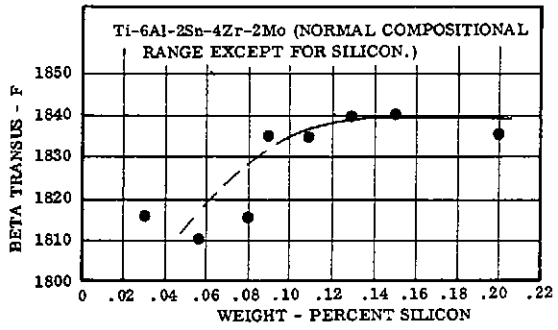


FIG. 2.0121. EFFECT OF SILICON CONTENT ON BETA TRANSUS TEMPERATURE (78)

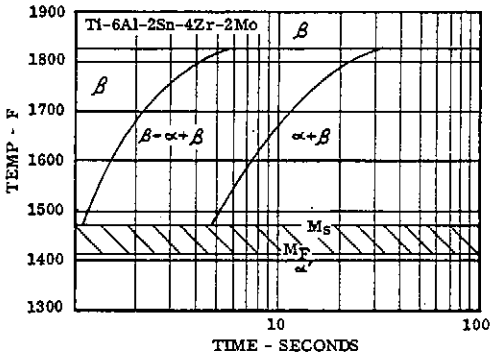


FIG. 2.0122 ISOTHERMAL TIME-TEMPERATURE-TRANSFORMATION (TTT) DIAGRAM FOR Ti-6Al-2Sn-4Zr-2Mo, (7, p. 28)

Alloy	Ti-6Al-2Sn-4Zr-2Mo[a]	
Temperature - F	Solidus (b)(d)	Liquidus (c)(d)
Range	2860 - 2935	3080 - 3160
Average	2890	3120

(a) Composition of melting range sample:

Al	Sn	Zr	Mo	Fe	O	N	H	C	Ti
6.2	2.0	4.2	1.8	0.06	0.124	0.008	0.0052	0.02	Bal.

(b) Four determinations
(c) Two determinations
(d) Temperature measurement accuracy, ± 35F. Some diffusion of support tray material (Nb) into sample may have caused slight elevation of solidus and liquidus temperatures.

TABLE 2.011 MELTING RANGE, (54).

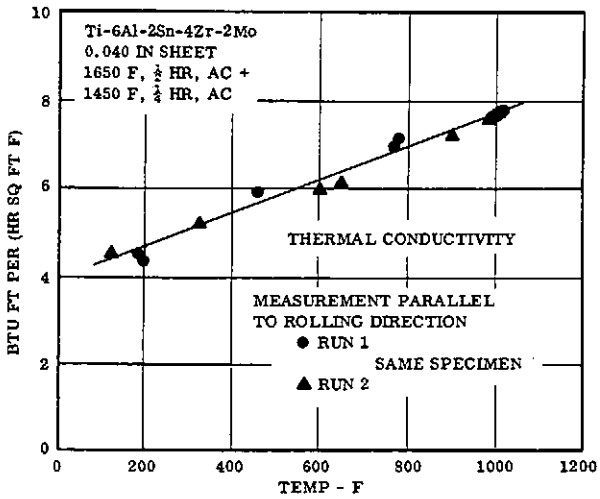


FIG. 2.0131 THERMAL CONDUCTIVITY OF DUPLEX ANNEALED SHEET. (1, P. 319)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

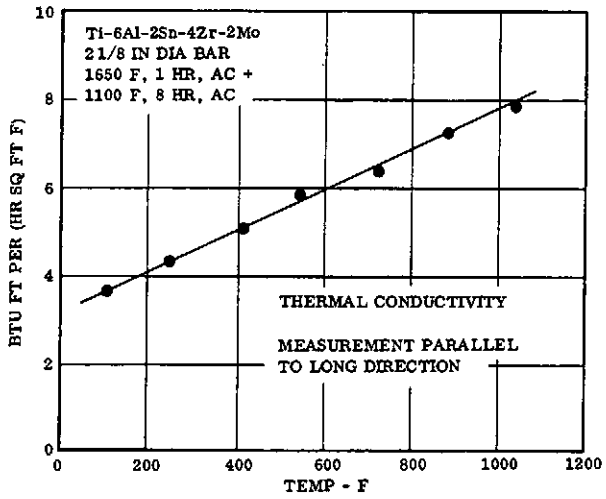


FIG. 2.0132 THERMAL CONDUCTIVITY OF DUPLEX ANNEALED BAR. (6, P.9)

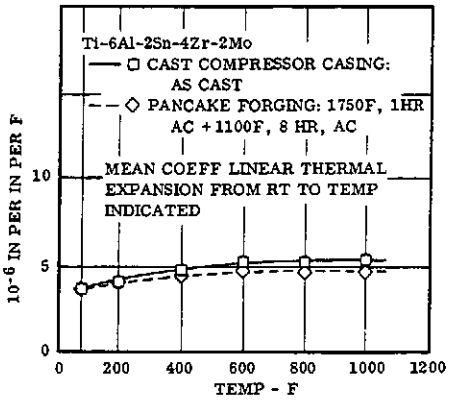


FIG. 2.0143. THERMAL EXPANSION FOR CAST COMPRESSOR CASING AND DUPLEX ANNEALED PANCAKE FORGING. (83)

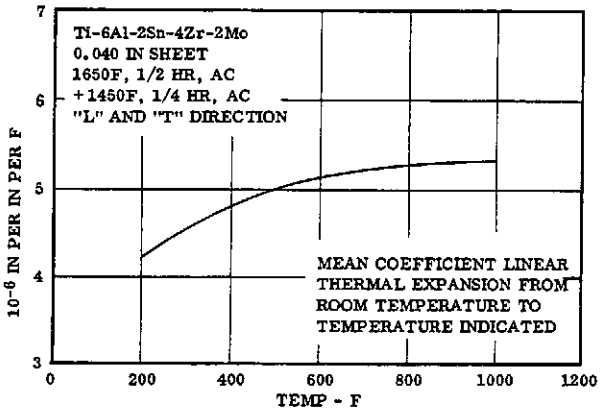


FIG. 2.0141 THERMAL EXPANSION FOR DUPLEX ANNEALED SHEET (1, PP.326-327)

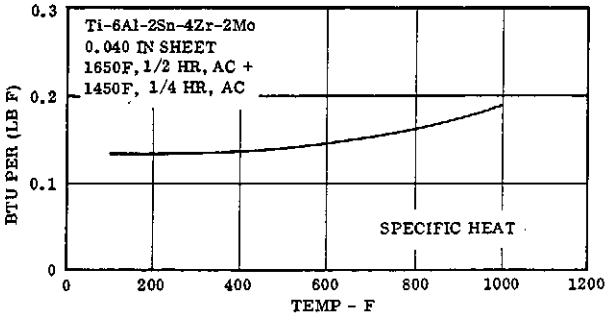


FIG. 2.0151 SPECIFIC HEAT FOR DUPLEX ANNEALED SHEET. (1, P.217)

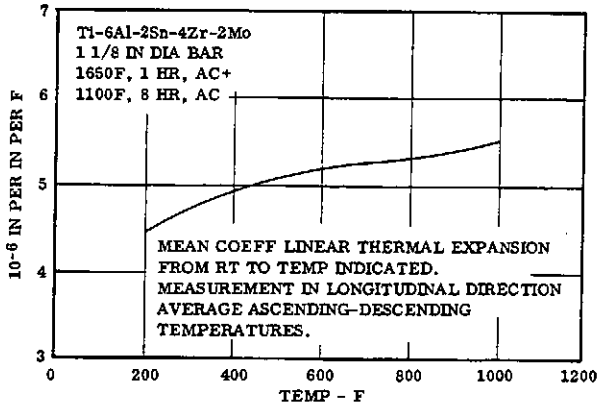


FIG. 2.0142 THERMAL EXPANSION FOR DUPLEX ANNEALED BAR (6, P.10)

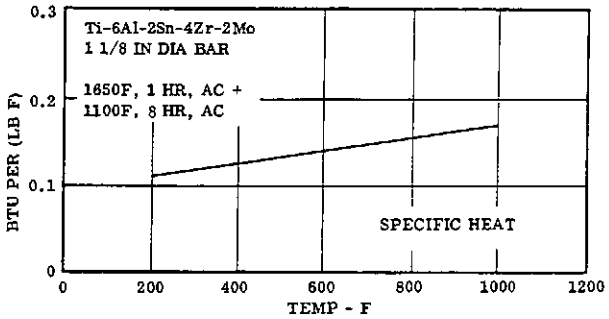


FIG. 2.0152 SPECIFIC HEAT FOR DUPLEX ANNEALED BAR (6, P.8)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

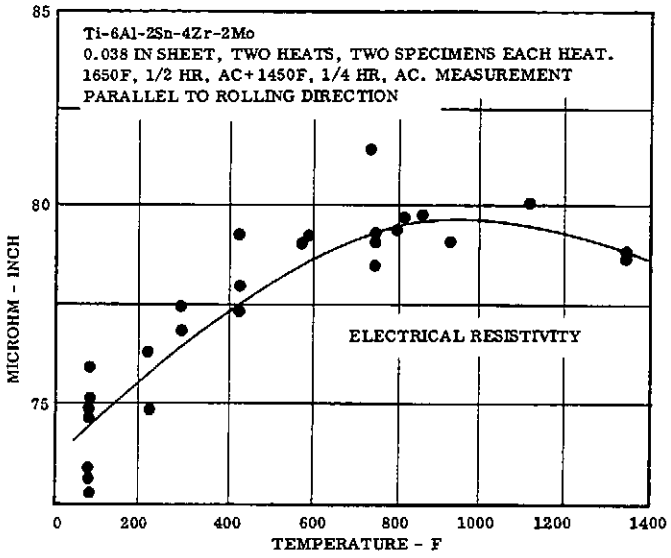


FIG. 2.0221 ELECTRICAL RESISTIVITY OF DUPLEX ANNEALED SHEET. (6, P.12)

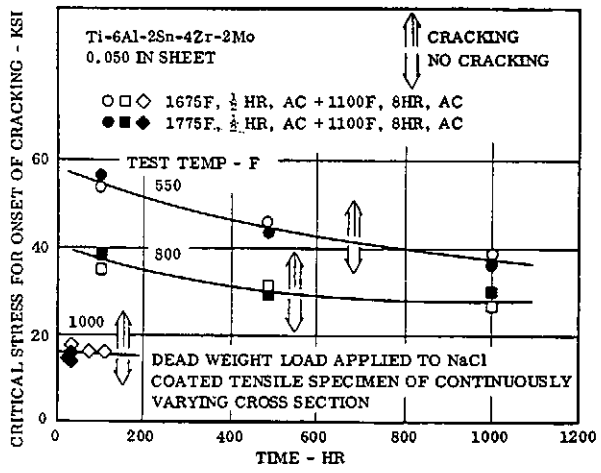


FIG. 2.0321. HOT SALT STRESS CORROSION CRACKING CHARACTERISTICS OF DUPLEX ANNEALED SHEET AT 550, 800, AND 1000 F. (7, p. 68)

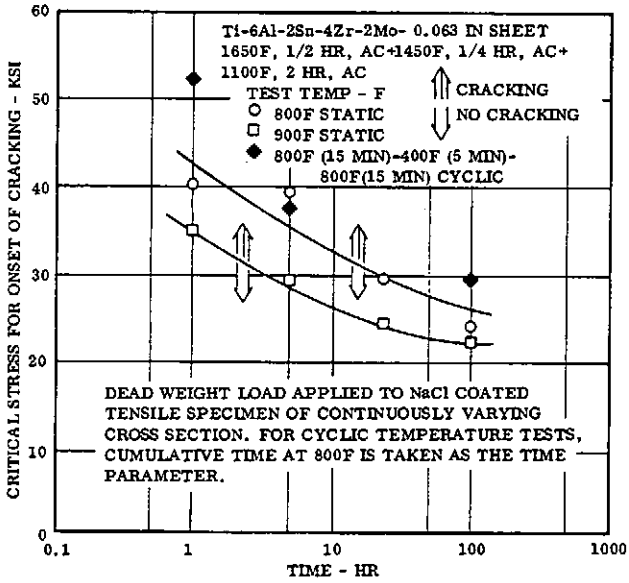
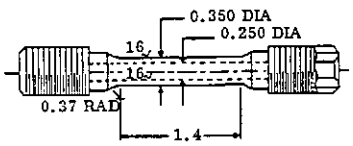


FIG. 2.0322 SHORT-TIME HOT-SALT STRESS CORROSION CRACKING CHARACTERISTICS OF TRIPLEX ANNEALED SHEET SUBJECTED TO STATIC OR CYCLIC EXPOSURE TEMPERATURES. (8, P.15)

Ti-6Al-2Sn-4Zr-2Mo
3/4 IN DIA BAR
1775 F, 1 HR, AC + 1100F, 8 HR, AC



TUBULAR TEST SPECIMAN: UNIFORM 0.6 MG/IN^2 SALT DEPOSIT PRODUCED BY EXPOSING CHEMICALLY-MILLED (APPROX. 0.001 IN METAL REMOVED) SPECIMEN BORE FOR APPROX. 1 HR, WITHOUT APPLIED STRESS TO 400F AIR WITH 40PPB NaCl AT 1000 FT/SEC VELOCITY, 30 PSIA PRESSURE AND -120F DEWPOINT.

EXPOSURE ENVIRONMENT: STATIC AIR AT AMBIENT LABORATORY PRESSURE AND HUMIDITY.

AFTER EXPOSURE, SPECIMENS TENSILE TESTED AT RT AT CONSTANT 0.005 IN/MIN TEST MACHINE CROSSHEAD SPEED.

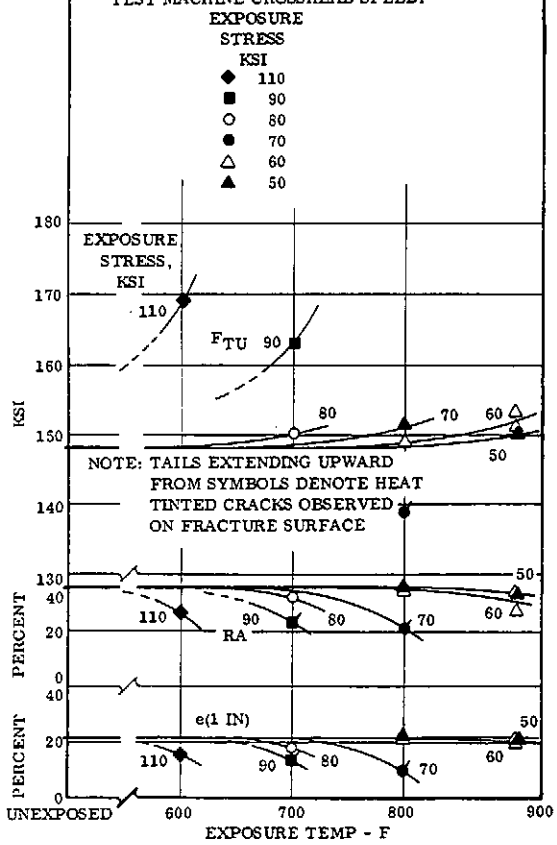
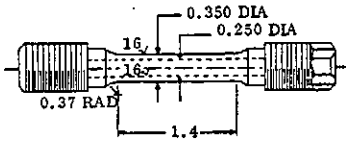


FIG. 2.03210 EFFECT OF 100-HR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD IN A LABORATORY ENVIRONMENT ON SUBSEQUENT ROOM TEMPERATURE TENSILE PROPERTIES OF NaCl-COATED(AERSOL DEPOSIT ON HOT SURFACE) CHEMICALLY-MILLED TUBULAR SPECIMENS FROM DUPLEX ANNEALED BAR. (57)

Ti-6Al-2Sn-4Zr-2Mo
3/4 IN DIA BAR
MILL ANNEALED 1650F, 1 HR, AC



TUBULAR TEST SPECIMEN: UNIFORM 0.6 MG/IN^2 SALT DEPOSIT PRODUCED BY EXPOSING AS-MACHINED OR CHEMICALLY-MILLED (APPROX. 0.001 IN METAL REMOVED) SPECIMEN BORE FOR APPROX. 1 HR, WITHOUT APPLIED STRESS, TO 400F AIR WITH 40 PPB NaCl AT 1000 FT/SEC VELOCITY, 30 PSIA PRESSURE AND -120F DEWPOINT.

EXPOSURE ENVIRONMENT: STATIC AIR AT AMBIENT LABORATORY PRESSURE AND HUMIDITY, OR DYNAMIC AIR AT 1100 FT/SEC, 30 PSIA AND -120F DEWPOINT.

AFTER EXPOSURE, SPECIMENS TENSILE TESTED AT RT AT CONSTANT 0.005 IN/MIN TEST MACHINE CROSSHEAD SPEED.

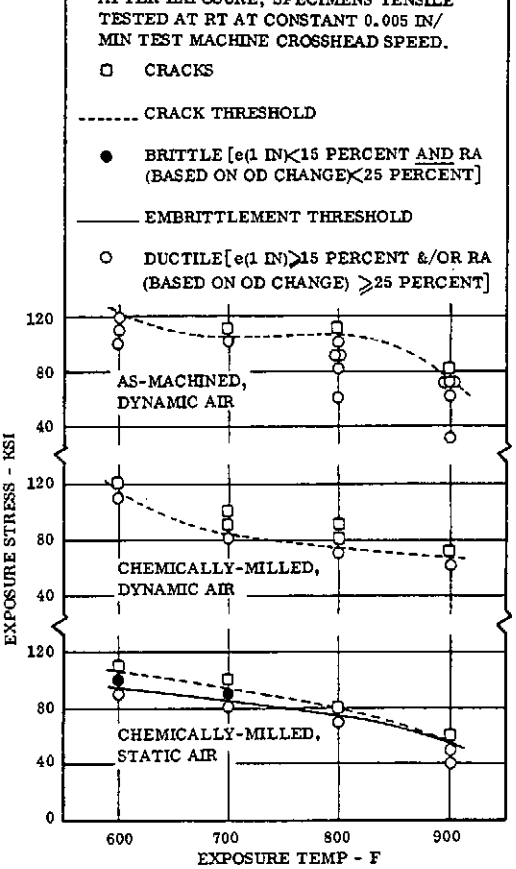


FIG. 2.0324 100-HR EMBRITTLEMENT AND CRACK THRESHOLD CURVES FOR NaCl-COATED (AERSOL DEPOSIT ON HOT SURFACE) AS-MACHINED OR CHEMICALLY-MILLED TUBULAR SPECIMENS (FROM MILL ANNEALED BAR) EXPOSED TO ELEVATED TEMPERATURE WITH LOAD IN EITHER A LABORATORY OR SIMULATED AIRCRAFT TURBINE ENGINE COMPRESSOR ENVIRONMENT AND SUBSEQUENTLY TENSILE TESTED AT ROOM TEMPERATURE. (57)

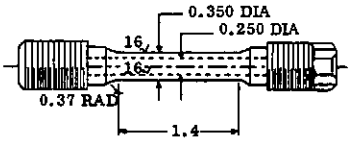
	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Ti-6Al-2Sn-4Zr-2Mo
3/4 IN DIA BAR
1775F, 1 HR, AC + 1100F, 8 HR, AC



TUBULAR TEST SPECIMEN: UNIFORM 0.6 MG/IN^2 SALT DEPOSIT PRODUCED BY EXPOSING AS-MACHINED OR CHEMICALLY-MILLED (APPROX. 0.001 IN METAL REMOVED) SPECIMEN BORE FOR APPROX. 1 HR, WITHOUT APPLIED STRESS, TO 400F AIR WITH 40 PPB NaCl AT 1000 FT/SEC VELOCITY, 30 PSIA PRESSURE AND -120F DEWPOINT.

EXPOSURE ENVIRONMENT: STATIC AIR AT AMBIENT LABORATORY PRESSURE AND HUMIDITY, OR DYNAMIC AIR AT 1100 FT/SEC, 30 PSIA AND -120F DEWPOINT.

AFTER EXPOSURE, SPECIMENS TENSILE TESTED AT RT AT CONSTANT 0.005 IN/MIN TEST MACHINE CROSSHEAD SPEED.

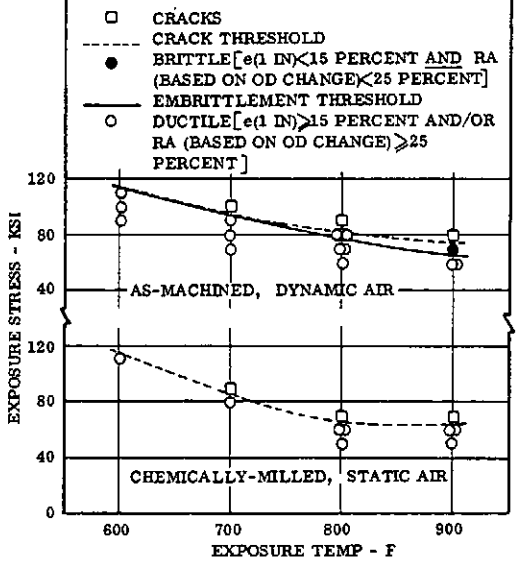
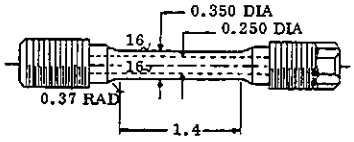


FIG. 2.0325 100-HR EMBRITTLEMENT AND CRACK THRESHOLD CURVES FOR NaCl-COATED (AERSOL DEPOSIT ON HOT SURFACE) AS-MACHINED OR CHEMICALLY-MILLED TUBULAR SPECIMENS (FROM DUPLEX ANNEALED BAR) EXPOSED TO ELEVATED TEMPERATURE WITH LOAD IN EITHER A LABORATORY OR SIMULATED AIRCRAFT TURBINE ENGINE COMPRESSOR ENVIRONMENT AND SUBSEQUENTLY TENSILE TESTED AT ROOM TEMPERATURE (57)

Ti-6Al-2Sn-4Zr-2Mo
3/4 IN DIA BAR
1775 F, 1 HR, AC + 1100F, 8 HR, AC



TUBULAR TEST SPECIMAN: UNIFORM 0.6 MG/IN^2 SALT DEPOSIT PRODUCED BY EXPOSING CHEMICALLY-MILLED (APPROX. 0.001 IN METAL REMOVED) SPECIMEN BORE FOR APPROX. 1 HR, WITHOUT APPLIED STRESS, TO 400F AIR WITH 40PPB NaCl AT 1000 FT/SEC VELOCITY, 30 PSIA PRESSURE AND -120F DEWPOINT.

EXPOSURE ENVIRONMENT: STATIC AIR AT AMBIENT LABORATORY PRESSURE AND HUMIDITY.

AFTER EXPOSURE, SPECIMENS TENSILE TESTED AT RT AT CONSTANT 0.005 IN/MIN TEST MACHINE CROSSHEAD SPEED.

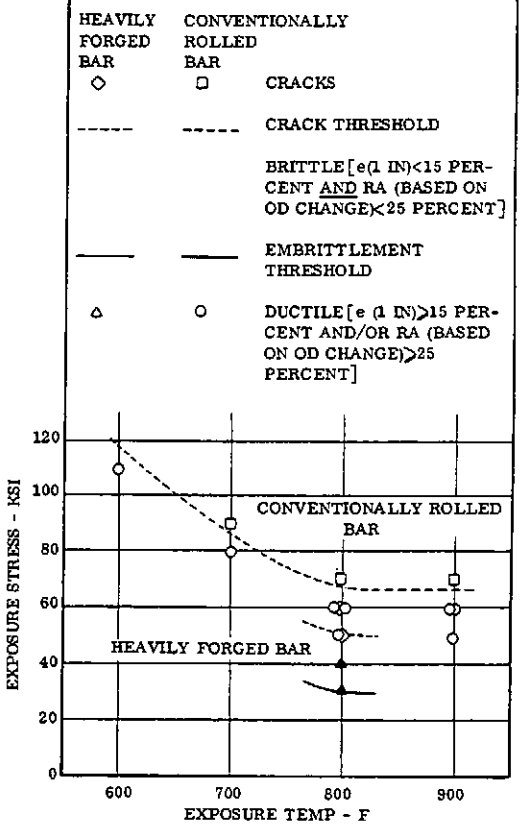


FIG. 2.0326 EFFECT OF ALLOY PROCESSING ON 100-HR EMBRITTLEMENT AND CRACK THRESHOLD CURVES FOR NaCl-COATED (AERSOL DEPOSIT ON HOT SURFACE) CHEMICALLY-MILLED TUBULAR SPECIMENS (FROM DUPLEX ANNEALED BAR) EXPOSED TO ELEVATED TEMPERATURE WITH LOAD IN A LABORATORY ENVIRONMENT AND SUBSEQUENTLY TENSILE TESTED AT ROOM TEMPERATURE (57)(58)

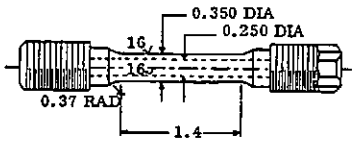
	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Ti-6Al-2Sn-4Zr-2Mo

$\frac{3}{4}$ IN DIA BAR

MILL ANNEALED 1650 F, 1 HR, AC



TUBULAR TEST SPECIMEN: UNIFORM 0.6 MG/IN^2 SALT DEPOSIT PRODUCED BY EXPOSING AS-MACHINED SPECIMEN BORE FOR APPROX. 1 HR, WITHOUT APPLIED STRESS, TO 400 F AIR WITH 40 PPB NaCl AT 1000 FT/SEC VELOCITY, 30 PSIA PRESSURE AND -120 F DEWPOINT.

EXPOSURE ENVIRONMENT: DYNAMIC AIR AT 1100 FT/SEC, 30 PSIA AND -120 F DEW POINT.

AFTER EXPOSURE, SPECIMENS TENSILE TESTED AT RT AT CONSTANT 0.005 IN/MIN TEST MACHINE CROSSHEAD SPEED.

EXPOSURE STRESS - KSI

◇ 120
◆ 110
□ 100
■ 90
○ 80
● 70
△ 60

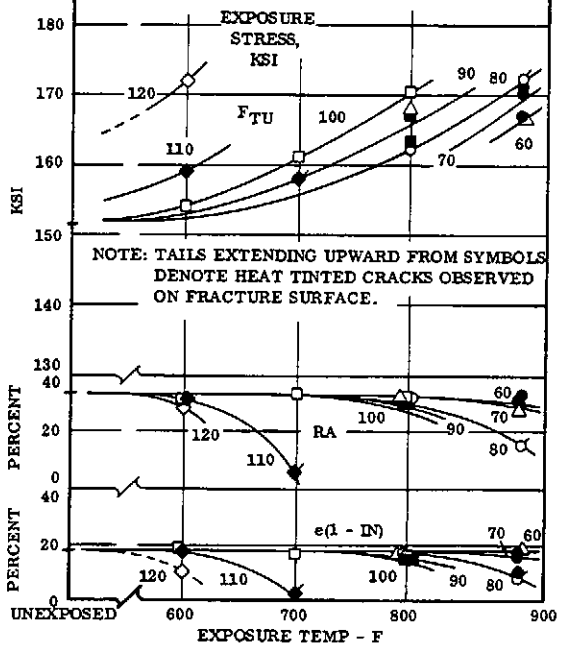
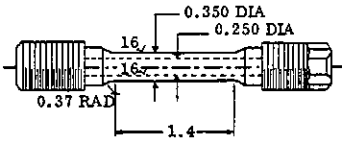


FIG. 2.0327. EFFECT OF 100-HR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD IN A SIMULATED AIRCRAFT TURBINE ENGINE COMPRESSOR ENVIRONMENT ON SUBSEQUENT ROOM TEMPERATURE TENSILE PROPERTIES OF NaCl-COATED(AERSOL DEPOSIT ON HOT SURFACE) AS-MACHINED TUBULAR SPECIMENS FROM MILL ANNEALED BAR. (57)

Ti-6Al-2Sn-4Zr-2Mo
3/4 IN DIA BAR
MILL ANNEALED 1650 F, 1 HR, AC



TUBULAR TEST SPECIMEN: UNIFORM 0.6 MG/IN^2 SALT DEPOSIT PRODUCED BY EXPOSING CHEMICALLY-MILLED (APPROX. 0.001 IN METAL REMOVED) SPECIMEN BORE FOR APPROX. 1 HR, WITHOUT APPLIED STRESS, TO 400F AIR WITH 40 PPB NaCl AT 1000FT/SEC VELOCITY, 30 PSIA PRESSURE AND -120F DEWPOINT.

EXPOSURE ENVIRONMENT: STATIC AIR AT AMBIENT LABORATORY PRESSURE AND HUMIDITY, OR DYNAMIC AIR AT 1100 FT/SEC, 30 PSIA AND -120F DEWPOINT.

AFTER EXPOSURE, SPECIMENS TENSILE TESTED AT RT AT CONSTANT 0.005 IN/MIN TEST MACHINE CROSSHEAD SPEED.

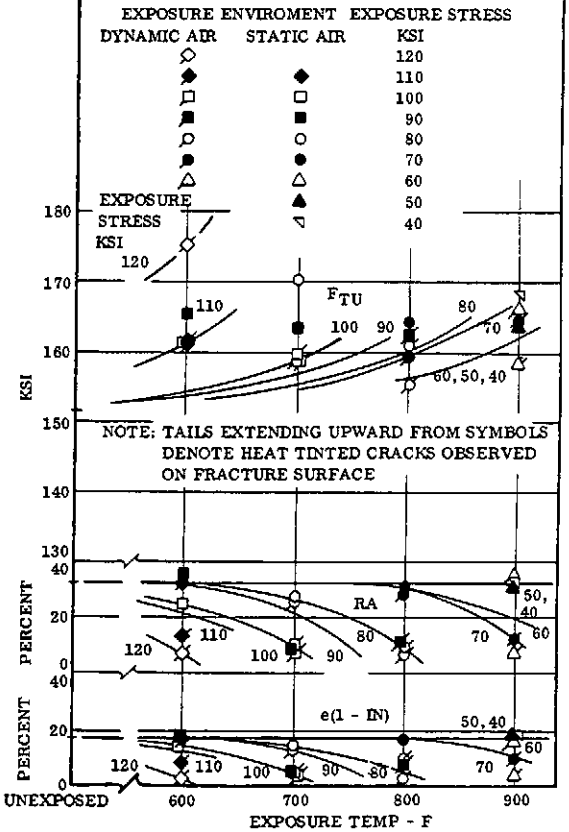


FIG. 2.0328. EFFECT OF 100-HR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD IN EITHER A LABORATORY OR SIMULATED AIRCRAFT TURBINE ENGINE COMPRESSOR ENVIRONMENT ON SUBSEQUENT ROOM TEMPERATURE TENSILE PROPERTIES OF NaCl-COATED (AERSOL DEPOSIT ON HOT SURFACE) CHEMICALLY-MILLED TUBULAR SPECIMENS FROM MILL ANNEALED BAR. (57)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

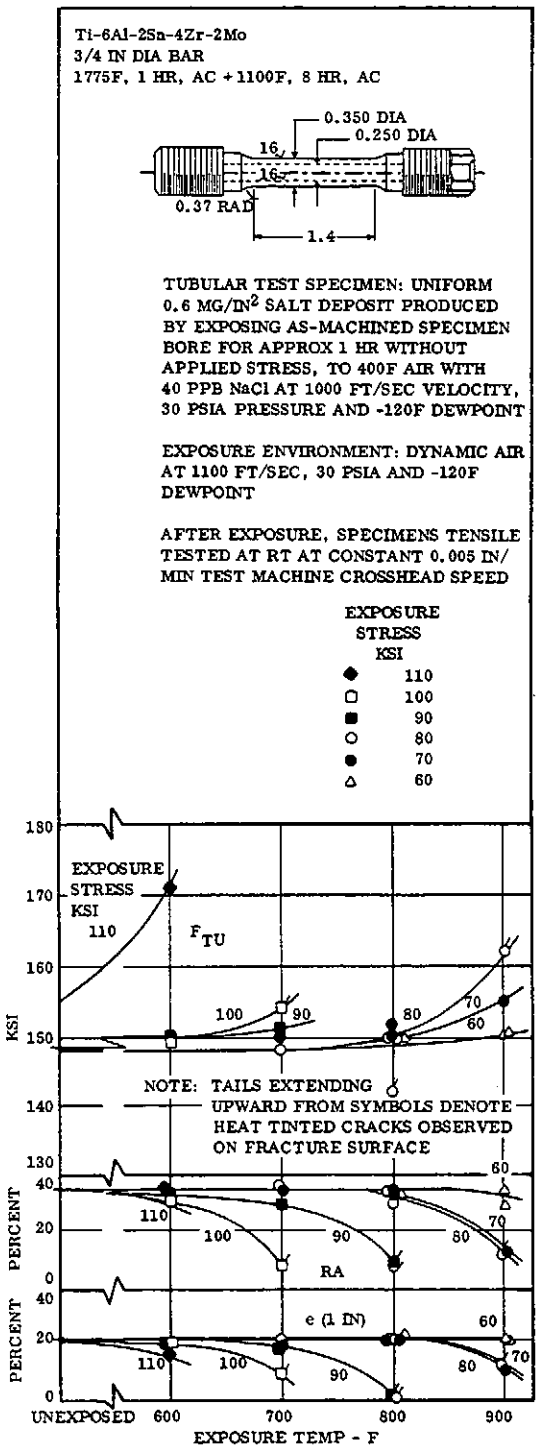


FIG. 2.0329 EFFECT OF 100 HR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD IN A SIMULATED AIRCRAFT TURBINE ENGINE COMPRESSOR ENVIRONMENT ON SUBSEQUENT ROOM TEMPERATURE TENSILE PROPERTIES OF NaCl COATED (AERSOL DEPOSIT ON HOT SURFACE) AS-MACHINED TUBULAR SPECIMENS FROM DUPLEX ANNEALED BAR (57)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy	Ti-6Al-2Sn-4Zr-2Mo				
Form	Compressor Wheel Forging[a], 20 in dia				
Condition	Duplex Annealed				
100-Hr NaCl Exposure	Subsequent R.T. Tensile Properties				
Temp F	Stress ksi	F_{tu} ksi	F_{ty} ksi	e, percent	RA percent	Cracking[b]
1750 F, 1-Hr, WQ + 1100 F, 8-Hr, AC						
— None —		165	149	14	40	--
650	40	163	149	11	36	No
650	50	162	148	11	34	No
800	32	161	147	13	39	No
800	42	161	147	3	5[c]	Yes
1000	21	164	152	5	10	Yes
1650 F, 1-Hr, AC + 1100 F, 8-Hr, AC						
— None —		141	129	17	36	--
650	60	Failed during exposure after 81 - Hrs				--
1000	11	138	128	16	40	No

[a] 0.250-in dia tensile specimens from axial wheel direction.
[b] Observed after tensile testing with aid of 100x optics.
[c] Broke outside gage length.

TABLE 2.03211 EFFECT OF 100-HOUR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON STRESS CORROSION CRACKING AND SUBSEQUENT ROOM TEMPERATURE TENSILE PROPERTIES OF NaCl-COATED SPECIMENS FROM DUPLEX ANNEALED COMPRESSOR WHEEL FORGING (2, p. 20)(7, p. 67)

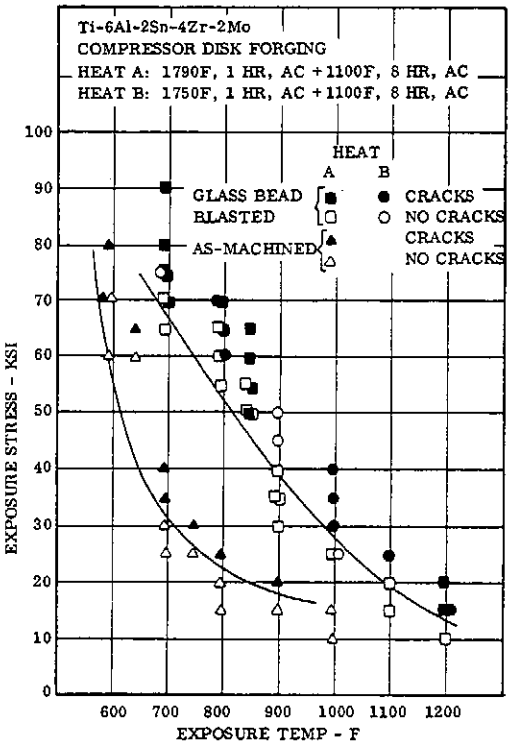


FIG. 2.03212 EFFECT OF GLASS BEAD BLASTING ON 100 HR HOT-SALT STRESS CORROSION CRACKING CHARACTERISTICS OF DUPLEX ANNEALED COMPRESSOR DISC FORGING. (68)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

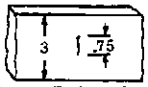
Form	1½-in x 15-in dia pancake type forged disks				
Condition	Duplex Annealed				
900F, 150-Hr NaCl Exposure Stress - ksi	Subsequent RT Tensile Properties(1) F_{tu} ksi	F_{ty} ksi	e(1-in) percent	RA percent	Remarks
	Ti-6Al-2Sn-4Zr-2Mo(2)				
Unexposed	147.0	133.5	16.0	35.6	
Unexposed	150.0	137.9	16.5	33.7	
10	145.3	137.3	6.7	13.4	No stress corrosion observed. Circumferential microcracks along gage length.
10	140.3	133.7	4.7	8.1	
15	140.9	133.9	9.3	17.1	
15	140.1	132.5	9.3	12.0	
20	140.5	133.7	3.3	10.2	Stress corrosion observed.
20	Ruptured 83.2-Hrs				Stress corrosion observed.
	Ti-6Al-2Sn-4Zr-2Mo + 0.25Si(3)				
Unexposed	165.0	149.5	7.0	15.8	
Unexposed	166.8	151.8	7.0	15.0	
10	160.2	157.0	1.3	3.8	No stress corrosion.
10	138.2	-----	---	---	Stress corrosion failure.
15	178.8	172.3	2.7	7.0	No stress corrosion observed.
15	167.3	158.6	4.0	8.2	No stress corrosion observed.
20	78.0	-----	---	---	Stress corrosion observed.
20		-----	---	---	Stress corrosion observed.

(1) 0.178-inch diameter cylindrical specimens.
(2) Forged: 1750F. Duplex annealed: 1805F, 1 hr, AC + 1100F, 8 hrs, AC. Beta transus = 1830F.
(3) Forged: 1870F. Duplex annealed: 1770F, 1 hr, OQ + 1100F, 8 hrs, AC. Beta transus = 1820F.

TABLE 2.03213 COMBINED EFFECT OF 0.25% SILICON ADDITION, BETA FORGING AND SOLUTION ANNEALING VARIATION ON HOT SALT STRESS CORROSION CHARACTERISTICS OF DUPLEX ANNEALED FORGED DISKS. (70).

Alloy	Ti-6Al-2Sn-4Zr-2Mo			
Form	Sheet			
Condition	Duplex and Triplex Annealed			
Sheet Gage in	Direction	NTS in Air, (continuously loaded) ksi	NTS in 3.5 percent NaCl Soln, (sustained load) Failure > 1-Hr (1) ksi	Failure < 1-Hr (2) ksi
1650 F, 1/2 Hr, AC + 1450 F, 1/4 Hr, AC				
0.045	T-L	—	110(3)	(4)
0.080	L-T	127	101	(4)
0.080	T-L	120	101	108
0.125	L-T	129	111	117
0.125	T-L	120	101	108
1650 F, 1/2-Hr, AC + 1450 F, 1/4-Hr, AC + 1100 F, 2-Hr, AC				
0.045	T-L	—	100	(4)
0.080	L-T	128	—	63(5)
0.080	T-L	124	87	125
0.125	L-T	120	72	80
0.125	T-L	108	—	53

(1) Maximum stress at which failure does not occur within 60 minutes
(2) Minimum stress to cause failure within 60 minutes
(3) No failure in 68 hrs
(4) Failure stress not established
(5) Failed in 5 minutes



Center Fatigue Crack

TABLE 2.0331 DELAYED FAILURE IN SALT WATER OF FATIGUE-CRACKED SPECIMENS FROM DUPLEX AND TRIPLEX ANNEALED SHEET (13, p.31)(69, p.62)

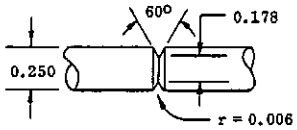
Alloy	Ti-6Al-2Sn-4Zr-2Mo		
Form	0.050 Inch Sheet		
Center fatigue cracked T-L specimens			
Heat Treatment	Applied Net Stress ksi	Time to Rupture in 3.5 percent NaCl Solution	
1350 F, 8-Hr, FC	89.5	Broke on Loading	
	67.7	1 min	
	44.7	7 min	
1350 F, 8-Hr, FC + 1650 F, 1/2-Hr, AC + 1450 F, 1/4-Hr, AC	80	> 73 Hr(a)	
	85	> 42 Hr(a)	
	100	> 43 Hr(a)	
	110	> 68 Hr(a)	
1350 F, 8-Hr, FC + 1650 F, 1/2-Hr, AC + 1450 F, 1/4-Hr, AC + 1100 F, 8-Hr, AC	80	> 48 Hr(a)	
	85	> 42 Hr(a)	
	90	> 24 Hr(a)	
	100	> 2 Hr(a)	

(a) No failure

TABLE 2.0332 DELAYED FAILURE IN SALT WATER OF FATIGUE-CRACKED SPECIMENS FROM SHEET VARIOUSLY HEAT TREATED (7, p.66)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Source	AMS (19)			AMS (20)			
Alloy	Ti-6Al-2Sn-4Zr-2Mo						
Form	Bars, Wire, Flash Welded Rings and Stock for Flash Welded Rings			Forgings and Forging Stock			
Condition	Beta Transus - 25F, 1 hr, AC (or faster) + 1100F, 8 hrs, AC						
Conventional Tensile Properties							
Room Temperature				900F(1)			
F_{tu} - min ksi	F_{ty} - min ksi	e (2-in or 4D) percent	RA - min percent	F_{tu} - min ksi	F_{ty} - min ksi	e (2-in or 4D) percent	RA - min percent
130	120(2)	10	25(2)	90	70(2)	15	(3)(2)
Room Temperature Notched Stress Rupture							
@ 170 ksi, 5 hrs min(4)				Preferred Specimen (See reference for alternate specimens)			

(1) Specimen to be held at test temperature for thirty minutes before testing.
(2) Yield strength and reduction of area requirements do not apply to wire less than 0.125 inch in diameter.
(3) Bars, wire, flash welded rings and stock for flash welded rings, 35 percent. Forgings and forging stock, 30 percent.
(4) Initial stress may be less than 170 ksi and increased to 170 ksi in 10 ksi increments at intervals of not less than 5 hours.

TABLE 3.011 AMS SPECIFIED MECHANICAL PROPERTIES.

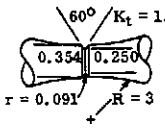
Source			T.M.C.A. (10, p.4)					
Alloy			Ti-6Al-2Sn-4Zr-2Mo					
Mill Form	Size	Heat Treatment	F_{tu}-min ksi	F_{ty}-min ksi	e-min percent L	e-min percent T	RA-min percent L	RA-min percent T
Sheet	Up to 0.187 inch	Duplex	135.0	125.0	8	8	-	-
		Triplex	140.0	130.0	8	8	-	-
Bar	Up to 16 sq inch	1750F, AC + 1100F, 8Hr, AC	130.00	120.0	10	8	20	15
Billet(1)	Up to 16 sq inch	1750F, AC + 1100F, 8Hr, AC	130.0	120.0	10	8	20	15

(1) Testing of billet is based on the results of a simulated forging, generally an upset test.

TABLE 3.012 PRODUCER'S GUARANTEED MECHANICAL PROPERTIES

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Source	General Electric (41)		General Electric (42)		General Electric (43)		General Electric(44)(45)		General Electric (46)	
Alloy	Ti-6Al-2Sn-4Zr-2Mo									
Form	Sheet, Strip and Plate		Bars[d], Forgings and Rings		Extrusions		Forged Parts and Compressor Blades and Vanes		Premium Quality Forged Parts	
Condition	1650F, 30 min, AC or faster + 1450F, 15 min, AC or faster + 1100F, 2 hrs, AC or faster		1750F, 1 hr, AC or faster + 1100F, 8 hrs, AC or faster		1775F, 1 hr, AC + 1100F, 8 hrs, AC		1775F, 1 hr, AC + 1100F, 8 hrs, AC		1775F[f], 1 hr, AC + 1100F, 8 hrs, AC	
Property	Specified Value at		Specified Value at		Specified Value at		Specified Value at		Specified Value at	
	RT	900F	RT	900F	RT	900F	RT	900F	RT	900F
F_{tu} - ksi, min	140	95	130	90	135	95	130	90	130	90
F_{ty} - ksi, min	130	75	120	70	120	70	120	70	120	70
e(2-in or 4D) -percent, min	(c)	(c)	10	15	10	15	10	15	10	15
RA - percent, min	---	---	25	30	20	30	25	30	25	30
RT Notch Stress Rupture Life	Not Specified		Not Specified		Not Specified		Not Specified		Not Specified	
Smooth Stress Rupture Life[a]	Not Specified		Not Specified		@ 975F, 70 ksi[e], 35 hrs min with 20 percent RA min		@ 975F, 70 ksi[e], 35 hrs min			
Creep Stability	Not Specified		Not Specified		Not Specified		Not Specified		Not Specified	
RT Bend Factor, r/t max, for 105° after springback without cracking[b]:										
<0.070-in gage	9									
0.070-in to 0.187-in gage	10									
K_{Ic} @RT - ksi $(in)^{\frac{1}{2}}$, min	Not Specified		Not Specified		Not Specified		Not Specified		50[g]	
RT Notched Low Cycle Fatigue Life 	Not Specified		Not Specified		Not Specified		Not Specified		@F_{max} = 90 ksi, A = 0.95, 10 to 30 cpm, 9000 cycles min	

(a) Specimen diameter 0.252 inch maximum; gage length at least three times the diameter.

(b) Axis of bend shall be parallel to rolling direction. Specimen width shall be at least ten times the nominal thickness.

(c) ≤0.187-in gage, 8; >0.187-in gage, 10.

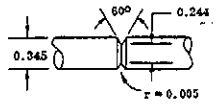
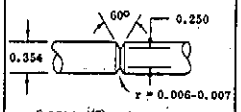
(d) For bar ≤1.5-in dia or distance between flats, specimen axis shall coincide with central axis of material. For bar >1.5-in, specimen axis shall be located midway between the center and the surface and shall be parallel to rolling direction.

(e) Test stress may exceed 70 ksi, but shall not be changed during test and life requirement shall be as specified for 70 ksi applied stress.

(f) Solution treat temperature as high as 50F below the beta transus determined for the heat may be used.

(g) To be tested in accordance with ASTM Method E-399 using 1-inch thick compact tension specimen.

TABLE 3.013 USER'S SPECIFIED MECHANICAL PROPERTIES FOR SHEET, STRIP, PLATE, BARS, FORGINGS, RINGS, EXTRUSIONS, FORGED PARTS, COMPRESSOR BLADES AND VANES, AND PREMIUM FORGED PARTS.

Source	Lycoming (47)	Lycoming (48)	Lycoming (49)
Alloy		Ti-6Al-2Sn-4Zr-2Mo	
Form	Bars, Forgings and Forging Stock	Premium Quality Bars, Forgings and Forging Stock	Investment Castings (b)
Condition	1750F, 1 hr, AC + 1100F, 8 hrs, AC	Beta Transus - 50F, 1 hr, AC + 1100F, 8 hrs, AC	As-Cast
Property	Specified Value at RT	Specified Value at RT	Specified Value at RT
F_{tu} - ksi, min	135	130	125
F_{ty} - ksi, min	125	120	110
e(4D) - percent, min	10	10	5
RA - percent, min	25	25	10
RT Notch Stress Rupture Life	 @ 170 ksi(a), 5 hrs min	 @ 170 ksi(a), 5 hrs min	Not Specified
Smooth Stress Rupture Life	Not Specified	Not Specified	At 800F, 75 ksi, 35 hrs minimum with at least 5 percent elongation. If no rupture in 48 hrs, stress may be increased to 85 ksi until rupture with at least 3 percent elongation.
Creep Resistance	Not Specified	At 950F, 35 ksi, time to 0.1 percent plastic deformation shall be 35 hrs minimum.	Not Specified
IE, Charpy V - ft-lbs, min:			
≤1-in section	16	16	Not Specified
>1-in section	13	13	
Hardness - RC, max	43	43	Not Specified

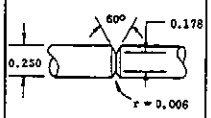
(a) Initial stress may be less than 170 ksi and increased to 170 ksi in 10 ksi increments at intervals of not less than 5 hours.

(b) 0.250-in dia cast-to-size specimens representative of cast product or 0.135-in dia specimens machined from castings.

TABLE 3.014 USERS' SPECIFIED MECHANICAL PROPERTIES FOR BARS, FORGINGS AND FORGING STOCK, PREMIUM QUALITY BARS, FORGINGS AND FORGING STOCK, AND INVESTMENT CASTINGS.

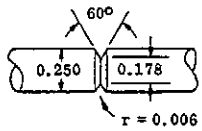
Ti 6 Al 2 Sn 4 Zr 2 Mo

Ti-6-2-4-2

Source	Pratt & Whitney (72)		Pratt & Whitney (50)				Pratt & Whitney(73)	
Alloy	Ti-6Al-2Sn-4Zr-2Mo							
Form	Bars			Forgings and Forging Stock	Forged Parts and Compressor Blades and Vanes		Forgings and Forging Stock (High Creep Strength)[b]	
Condition	Beta Transus - 25F, 1 hr, AC or faster + 1100F, 8 hrs, AC		Beta Transus - 50F, 1 hr, AC or faster + 1100F, 8 hrs, AC	Beta Transus - 25F, 1 hr, AC or faster + 1100F, 8 hrs, AC	Beta Transus - 50F, 1 hr, AC or faster + 1100F, 8 hrs, AC		Beta Transus - 25F[c], 1 hr, AC or faster + 1100F 8 hrs, AC	
Property	Specified Value at RT	900F	Specified Value at RT	900F			Specified Value at RT	900F
F_{tu} - ksi, min	130	90	130	90			130	90
F_{ty} - ksi, min	120	70	120	70			120	70
e(4D) - percent, min	10	15	10	15			10	10
RA - percent, min	25	30	20	30			20	20
RT Notch Rupture Life  (preferred specimen)	@ 170 ksi[a], 5 hrs min							
Smooth Stress Rupture Life	Not Specified							
Creep Resistance	At 950F, 35 ksi, time to 0.1 percent plastic deformation shall be 35 hrs minimum. (Applicable to Compressor Disks Only)						At 950F, 35 ksi, time to 0.1 percent plastic deformation shall be 125 hrs minimum. (Forgings Only)	
IE, Charpy V - ft-lbs, min	Not Specified							
Hardness - RC, max	43							

(a) Initial stress may be less than 170 ksi and increased to 170 ksi in 10 ksi increments at intervals of not less than 5 hours.
(b) Silicon 0.06 - 0.10 wt%, Iron 0.10 wt% max.
(c) In inert atmosphere for forgings not to be machined all over.

TABLE 3.015 USER'S SPECIFIED MECHANICAL PROPERTIES FOR BARS, FORGINGS, FORGING STOCK, FORGED PARTS, AND COMPRESSOR BLADES AND VANES.

Source	Pratt & Whitney (74)		Pratt & Whitney (75)	
Alloy	Ti-6Al-2Sn-4Zr-2Mo-0.25Si			
Form	Bars, Forgings and Forging Stock		Forgings and Forging Stock	
Condition	Alpha-Beta Processed + Beta Transus - 25F, 1 hr[a], OQ + 1100F, 8 hrs, AC		Beta Processed + Beta Transus - 25F, 1 hr[a], OQ + 1100F, 8 hrs, AC	
Property	Specified Value at RT	800F	Specified Value at RT	800F
F_{tu} - ksi, min	157.5	120	155	117
F_{ty} - ksi, min	140	95	135	92
e(4D) - percent, min	10	12	6	10
RA - percent, min	20	25	12	15
RT Notch Stress Rupture Life  (preferred specimen)	@ 170 ksi[b], 5 hrs min			
Smooth Stress Rupture Life	Not Specified			
Creep Resistance	At 900F, 59 ksi, time to 0.2 percent plastic deformation shall be 35 hrs min. (Applicable to Discs and Blades Only)		At 900F, 66 ksi, time to 0.2 percent plastic deformation shall be 35 hrs min. (Applicable to Discs and Rotor Spacers Only)	
IE, Charpy V - ft-lbs, min	Not Specified			
Hardness - RC, max	43			

(a) In inert atmosphere for forgings not to be machined all over.
(b) Initial stress may be less than 170 ksi and increased to 170 ksi in 10 ksi increments at intervals of not less than 5 hours.

TABLE 3.016 USER'S SPECIFIED MECHANICAL PROPERTIES FOR BARS, FORGINGS, AND FORGING STOCK FROM Ti-6Al-2Sn-4Zr-2Mo-0.25Si

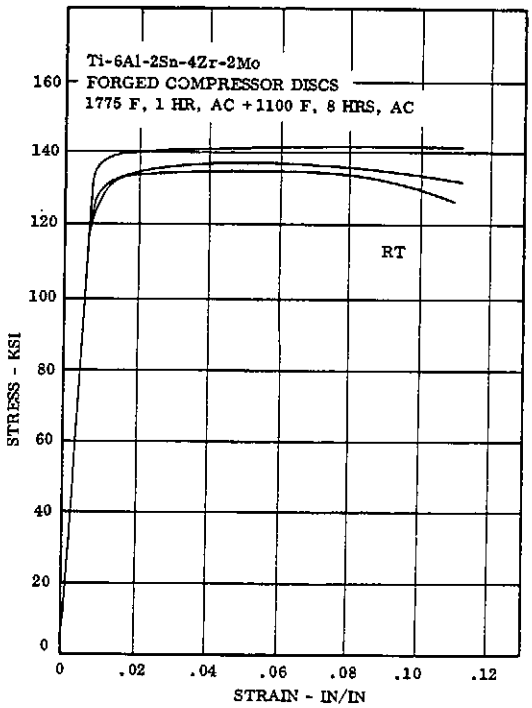


FIG. 3.0211 STRESS-STRAIN CURVES IN TENSION FOR DUPLEX ANNEALED FORGED COMPRESSOR DISCS AT ROOM TEMPERATURE. (82)

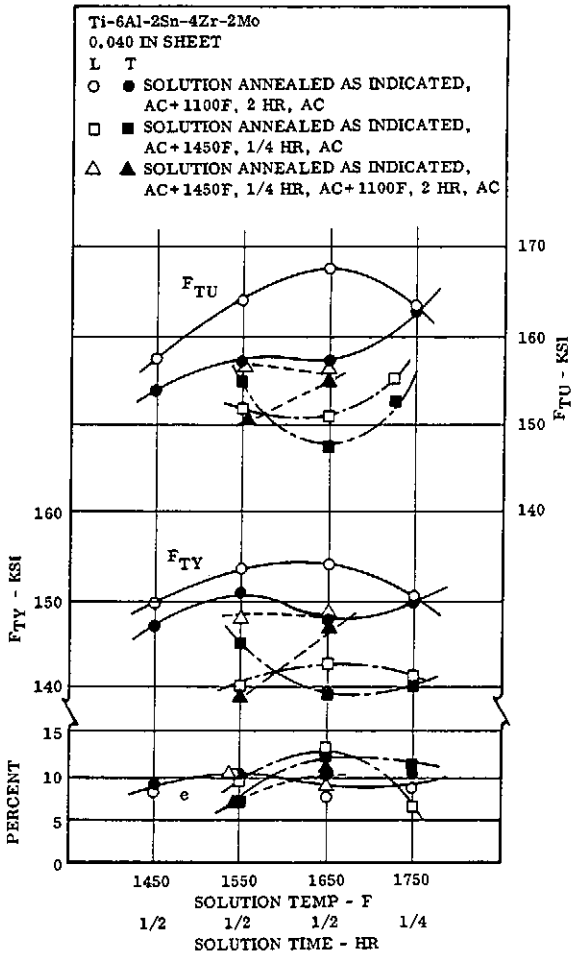


FIG. 3.0213 EFFECT OF SOLUTION ANNEAL TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX AND TRIPLEX ANNEALED SHEET. (7, P.38) (13, PP.8 AND 9)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

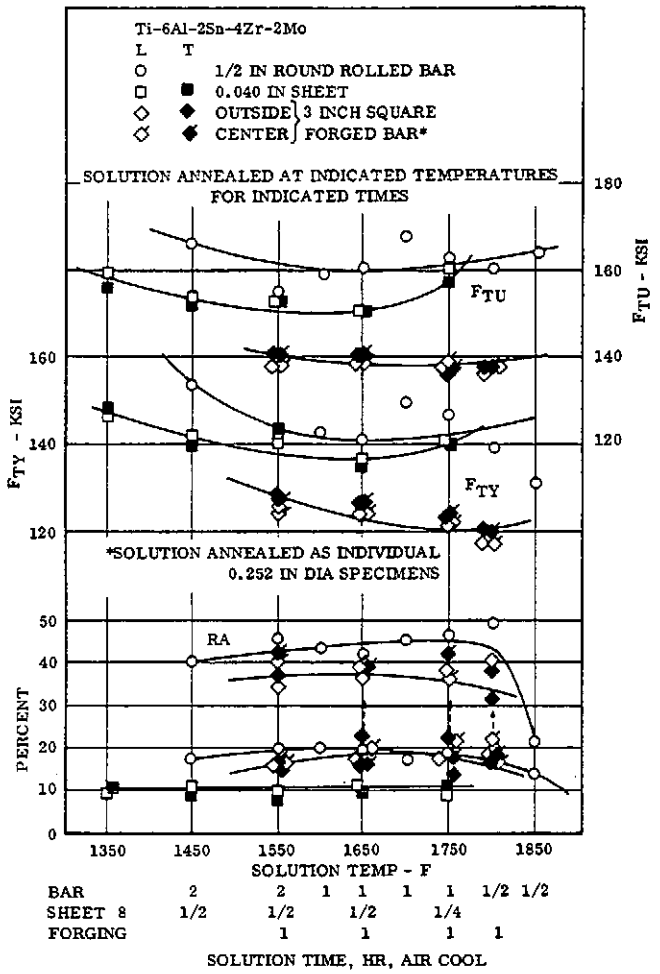


FIG. 3.0212 EFFECT OF SOLUTION ANNEAL TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF SOLUTION ANNEALED BAR, SHEET AND FORGING. (7, PP. 36,38 AND 41)

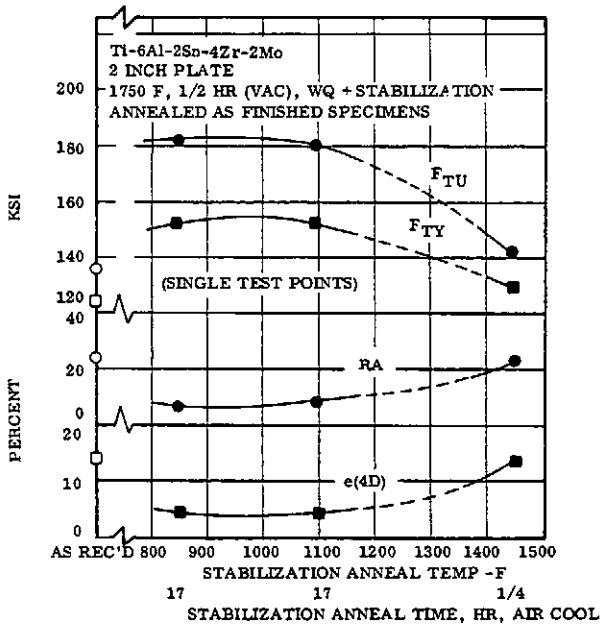


FIG. 3.0214 EFFECT OF STABILIZATION ANNEAL TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED PLATE. (25)(26)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Form	2-in x 4½-in bar					
Alloy Condition	Specimen		RT Tensile Properties(a)			
	Location	Direction	F_{tu} ksi	F_{ty} ksi	e percent	RA percent
1650F, 1 hr, AC + 1100F, 8 hrs, AC	Outside	L	137	127	15	33
	Center	L	134	122	15	32
	Outside	T	137	127	14	27
	Center	T	130	119	10	22
1790F, 1 hr, AC + 1100F, 8 hrs, AC	Outside	L	136	118	18	27
	Center	L	137	119	16	28
	Outside	T	139	125	12	23
	Center	T	140	121	10	24

(a)Each value average two tests.

TABLE 3.0216 EFFECT OF SOLUTION ANNEALING NEAR THE BETA TRANSUS TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED BAR, (80).

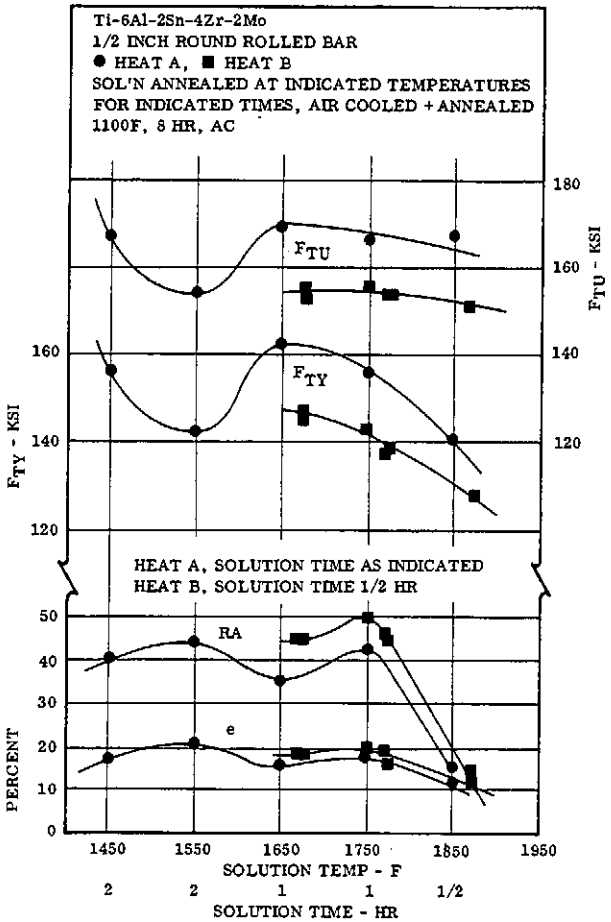


FIG. 3.0217 EFFECT OF SOLUTION ANNEALING AT TEMPERATURES UP TO AND BEYOND THE BETA TRANSUS TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED BAR, (7, P. 36)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Alloy		Ti-6Al-2Sn-4Zr-2Mo			
Product Size and Form	Location-Direction	F_{tu} ksi	F_{ty} ksi	e(4D) percent	RA percent
1650 F, 1-Hr, AC + 1100 F, 8-Hr, AC (1)					
1 1/8-in Rolled Bar	Long	152.6	140.5	20.0	41.2
2 1/4-in Rolled Bar	Outside — Long	137.0	120.7	15.5	31.2
	Center — Long	143.2	127.1	15.0	24.7
3-in Forged Bar	Outside — Long	141.2	133.1	18.0	40.9
	Center — Long	142.4	132.3	19.0	37.9
	Outside — Trans	142.3	132.8	15.0	33.3
	Center — Trans	144.5	135.5	17.0	43.3
1750 F, 1-Hr, AC + 1100 F, 8-Hr, AC (1)					
2 1/4-in Rolled Bar	Outside — Long	136.3	119.9	15.0	26.0
	Center — Long	141.4	125.8	15.0	24.7
	Center — Trans	138.9	122.7	13.5	23.4
2 1/4-in Forged Bar(2)	Outside — Long	143.3	135.3	20.0	41.5
	Center — Long	144.1	129.5	18.0	32.7
	Outside — Trans	144.7	132.6	17.5	39.3
	Center — Trans	139.3	124.1	14.5	31.3
3-in Forged Bar	Outside — Long	136.5	126.7	19.0	37.9
	Center — Long	138.5	129.3	19.0	39.2
	Outside — Trans	138.5	128.7	18.0	36.6
	Center — Trans	137.8	128.5	16.0	30.7
1750 F, 1-Hr, WQ + 1100 F, 8-Hr, AC (1)					
2 1/4-in Rolled Bar	Outside — Long	147.9	130.5	13.0	25.9
	Center — Long	151.4	134.8	12.0	21.1
3-in Forged Bar	Outside — Long	160.1	146.5	17.0	35.2
	Center — Long	146.2	132.1	20.0	45.9
	Outside — Trans	152.5	138.9	16.0	41.6
	Center — Trans	147.0	134.5	14.0	23.3

(1) All heat treated in full sections.
(2) Stabilization annealed for 24 hours.

TABLE 3.0218 EFFECT OF SECTION SIZE ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED BAR (13, p. 54)

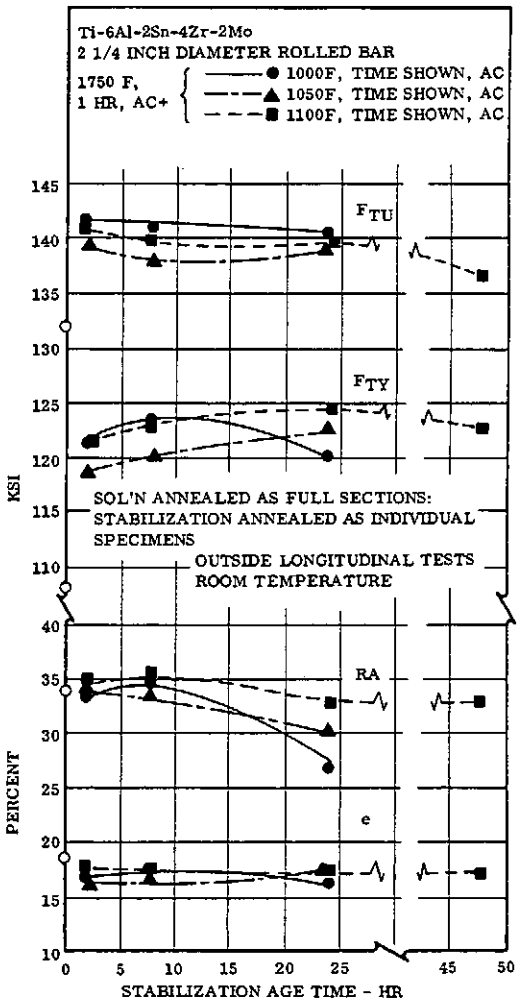


FIG. 3.0219 EFFECT OF STABILIZATION AGE TIME AND TEMPERATURE ON THE ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED ROLLED BAR. (13, P.45)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

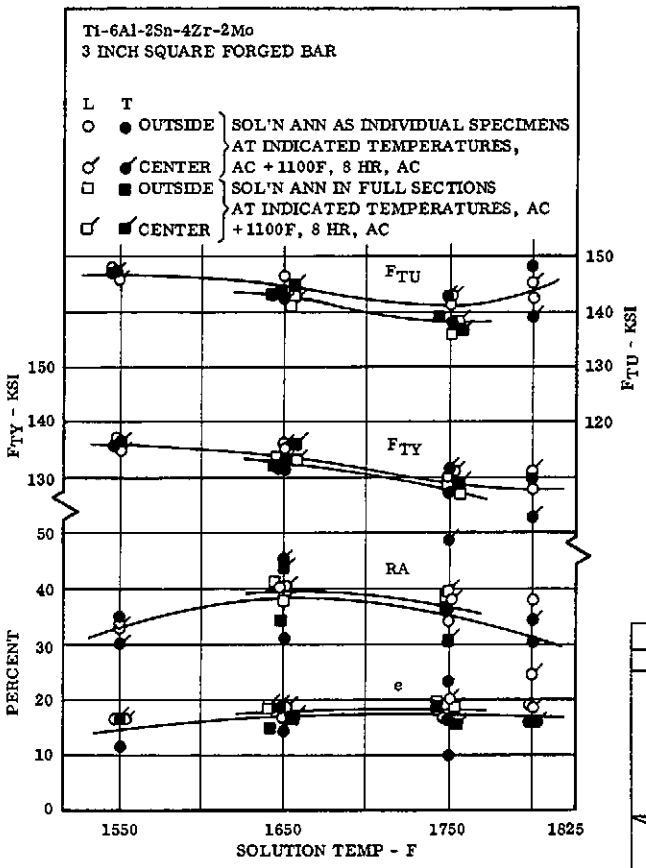


FIG. 3.02111 EFFECT OF SOLUTION ANNEAL TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED FORGING (7, pp. 41 - 42)

Alloy	Ti-6Al-2Sn-4Zr-2Mo			
Form	Forged Jet Engine Compressor Discs			
Condition	Alpha-Beta Forged + Beta Transus - 25F, 1 hr, AC or faster + 1100F, 8 hrs, AC (a)		Beta Preforged + Alpha-Beta Forged + Beta Transus - 25F, 1 hr, AC or faster + 1100F, 8 hrs, AC (b)	
Value / Property	$\bar{X}$(c)	s(d)	$\bar{X}$(c)	s(d)
F_{tu} - ksi	146.0	1.6	145.9	2.2
F_{ty} - ksi	133.8	1.6	131.3	2.6
e(1-in) - percent	15.3	1.1	11.6	1.2
RA - percent	39.5	2.6	23.3	2.1

(a) 50 tests.
(b) 199 tests.
(c) Arithmetic mean.
(d) One standard deviation.

TABLE 3.02113 TYPICAL ROOM TEMPERATURE TENSILE PROPERTIES OF FORGED JET ENGINE COMPRESSOR DISCS, (77).

Alloy	Ti-6Al-2Sn-4Zr-2Mo			
Form	Pancake Forging, Press Upset			
Condition	Forged 2-in to 3/4-in from 1750 F, + 1650 F, 1 Hr, AC + 1100 F, 8-Hr, AC			
Direction	F_{tu} ksi	F_{ty} ksi	e percent	RA percent
Radial	148.0	138.8	20.0	46.1
Tangential	145.9	137.4	21.0	48.0

TABLE 3.02112 ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED UPSET FORGING (2, p.2)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

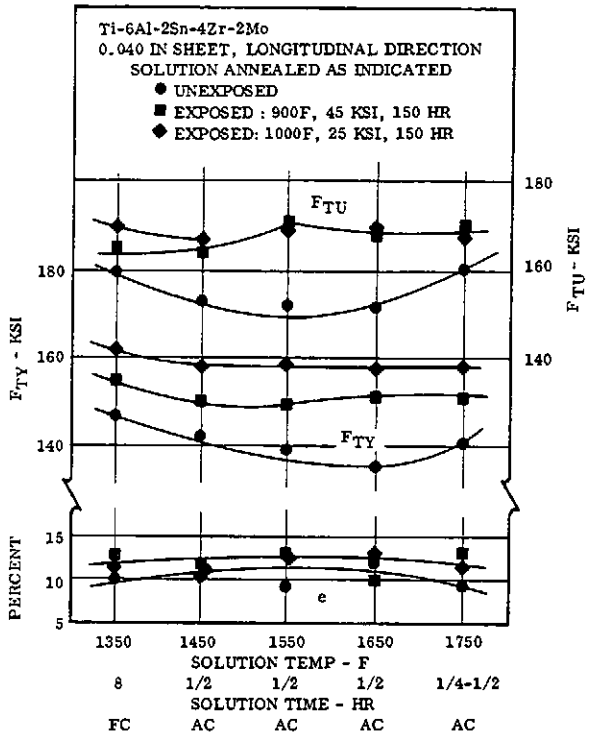


FIG. 3.02114 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF SOLUTION ANNEALED SHEET. (7, PP. 38&50)

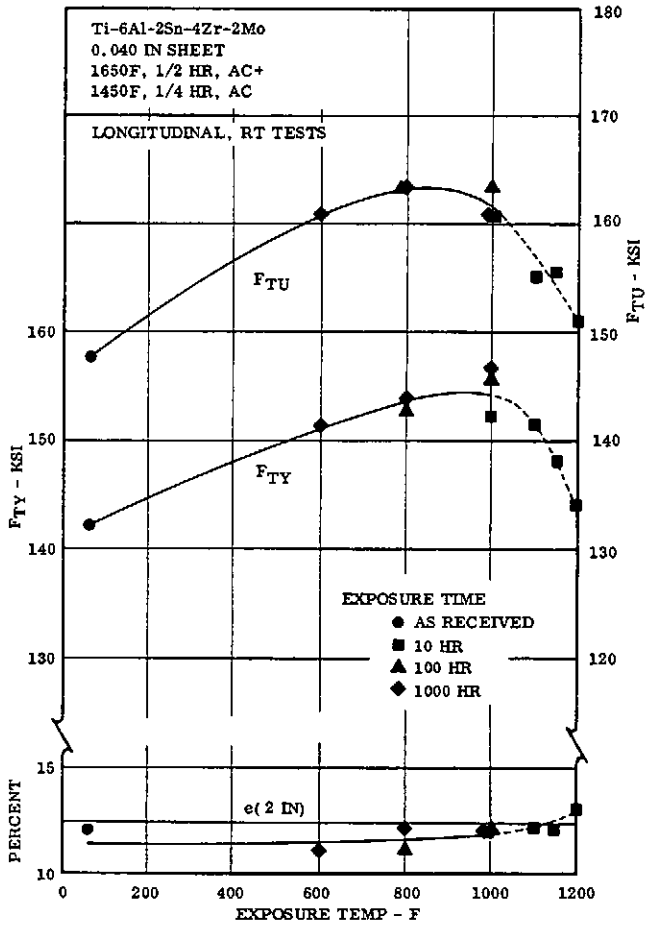


FIG. 3.02115 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED SHEET. (1, pp. 265, 266)

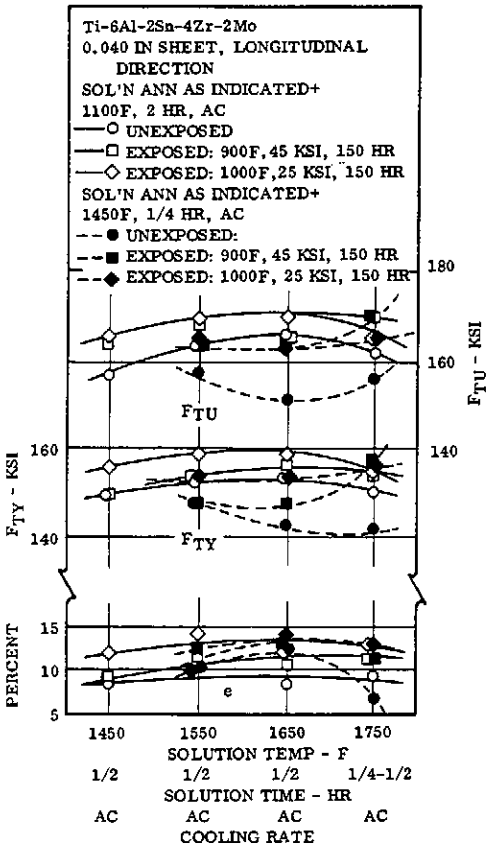


FIG. 3.02116 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED SHEET GIVEN VARIOUS SOLUTION ANNEAL TREATMENTS. (7, PP. 38&50)

Alloy			Ti-6Al-2Sn-4Zr-2Mo			
Form			0.040 in sheet			
Condition			Duplex and triplex annealed			
150-Hr exposure at			Subsequent RT tensile properties			
Temp F	Stress ksi	Deformation percent	Direction	F_{tu} ksi	F_{ty} ksi	e(1-in) percent
1650 F, 1/2-Hr, AC + 1450 F, 1/4-Hr, AC						
None			L	154.4	141.3	14.0
			T	148.9	134.4	14.0
800	65	0.16	L	168.3	144.5	12.0
		0.18	T	167.2	142.1	13.5
900	45	0.29	L	172.0	151.3	14.0
		0.22	T	167.1	147.6	13.0
1000	25	0.36	L	168.9	154.5	13.0
		0.40	T	164.7	152.0	12.0
1650 F, 1/2-Hr, AC + 1450 F, 1/4-Hr, AC + 1100 F, 2-Hr, AC						
None			L	162.4	149.2	16.0
			T	156.5	141.9	14.0
800	65	0.05	L	166.5	150.7	12.0
		0.06	T	163.7	148.6	14.0
900	45	0.17	L	167.7	152.0	12.0
		0.16	T	163.0	149.1	14.0
1000	25	0.34	L	169.8	157.1	12.5
		0.32	T	163.6	150.5	14.0

Note: Tests made after creep exposure without surface conditioning

TABLE 3.02117 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX AND TRIPLEX ANNEALED SHEET (13, p. 28)

Alloy			Ti-6Al-2Sn-4Zr-2Mo		
Form			0.040-in sheet, long. direction		
Condition			Duplex and triplex annealed		
1000-Hr exposure at			Subsequent R.T. tensile properties (1)		
Temp F	Stress ksi	Deformation percent	F_{tu} ksi	F_{ty} ksi	e percent
1650F, 1/2 Hr. AC + 1100F, 2 Hr. AC					
None			166.9	154.4	8.0
800	40	0.07	167.5	155.2	14.0
900	20	0.11	166.7	159.1	7.5
950	15	0.19	164.1	161.0	4.0
1000	10	0.50	(2)	160.5	(2)
1650 F, 1/2-Hr, AC + 1450 F, 1/4-Hr, AC					
None			150.5	142.3	12.5
800	40	0.11	164.4	149.2	13.5
900	20	0.14	162.6	154.7	6.0
950	15	0.16	162.9	157.8	7.0(3)
1000	10	0.25	160.7	159.7	3.0(3)
1650 F, 1/2-Hr, AC + 1450 F, 1/4-Hr, AC + 1100 F, 2-Hr, AC					
None			156.2	147.8	9.0
800	40	0.04	159.8	149.6	14.0
900	20	0.08	161.3	152.8	11.0
950	15	0.20	161.7	155.0	12.0
1000	10	0.20	158.5	157.0	4.5

(1) Single longitudinal tests
(2) Broke just beyond yield at end of gage length
(3) Broke at end of gage length

TABLE 3.02118 EFFECT OF LONG TIME EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX AND TRIPLEX ANNEALED SHEET (7, pp. 38 & 52)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

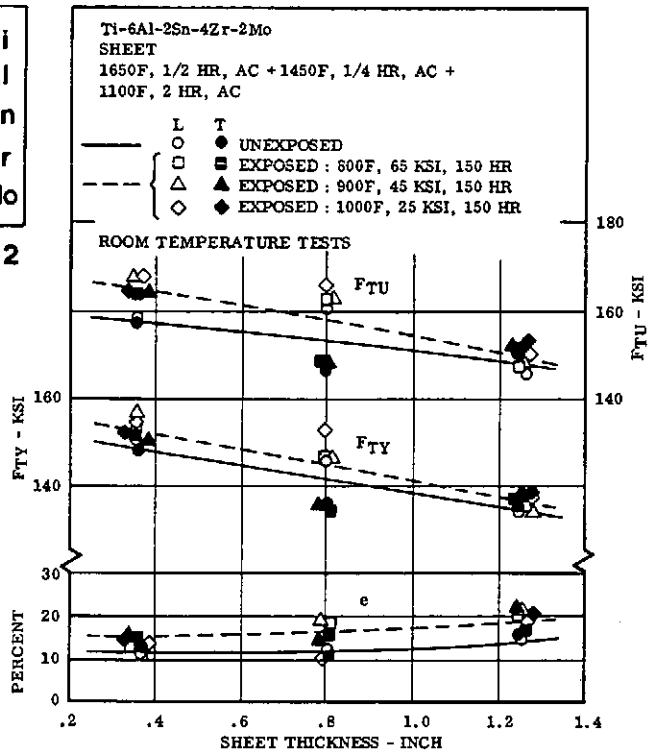


FIG. 3.02119 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF TRIPLEX ANNEALED SHEET OF VARIOUS THICKNESSES (10, p. 10)

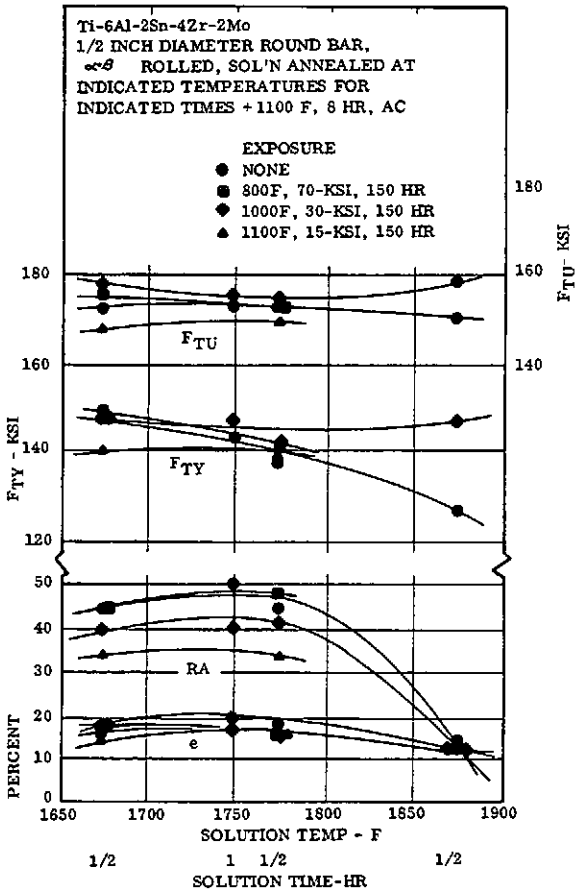


FIG. 3.02120 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED BAR GIVEN VARIOUS SOLUTION ANNEAL TREATMENTS (7, pp. 47-48)

Alloy	Ti-6Al-2Sn-4Zr-2Mo
Form	Rolled Bar
Condition	Duplex Annealed In Full Sections

Bar Size in	150-Hr Exposure At: Temp F	Stress ksi	Deformation percent	Supsequent RT Tensile Properties[a] (outside longitudinal): F_{tu} ksi	F_{ty} ksi	e(1-in) percent	RA percent
	1650 F, 1-Hr, AC + 1100 F, 8-Hr, AC						
1 1/8	None			152.6	140.5	20.0	41.2
	900	45	0.14	145.7	133.0	17.0	45.0
	1000	25	0.19	145.9	136.3	15.0	42.0
2 1/4	None			137.0	120.7	15.5	31.2
	800	65	0.17	139.6	129.3	16.0	32.1
	900	45	0.13	141.6	126.8	14.0	31.4
	1000	25	0.14	143.3	134.4	13.0	30.7
	1100	10	0.14	135.3	123.7	14.0	24.0
	1750 F, 1-Hr, AC + 1100 F, 8-Hr, AC						
2 1/4	None			136.3	119.9	15.0	26.0
	800	65	0.12	137.1	123.2	16.0	33.7
	900	45	0.12	135.8	121.7	15.0	28.2
	1000	25	0.11	140.4	127.6	18.0	33.4
	1100	10	0.11	137.8	128.2	16.5	33.5
	1750 F, 1-Hr, AC + 1100 F, 24-Hr, AC						
2 1/4	None			139.5	124.3	17.0	32.8
	850	70	0.32	138.9	129.3	18.5	33.5
	1050	30	0.46	136.1	125.7	20.0	36.1
	1750 F, 1-Hr, WQ + 1100 F, 8-Hr, AC						
2 1/4	None			147.9	130.5	13.0	25.9
	800	65	0.12	156.4	138.6	10.0	17.8
	900	45	0.22	157.7	140.0	12.0	19.1
	1000	25	0.29	153.6	137.6	11.5	19.1
	1100	10	0.20	148.9	135.2	14.0	26.0

[a] Tested after exposure without surface conditioning.

TABLE 3.02121 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED ROLLED BAR OF VARIOUS SIZES (13, pp. 67-68) (7, p. 53)

Alloy	Ti-6Al-2Sn-4Zr-2Mo
Form	2 1/4 - in Diameter Rolled Bar
Condition	Duplex Annealed In Full Sections

1000 - Hr Exposure at: Temp F	Stress ksi	Deformation Percent	Subsequent RT Tensile Properties[a] (outside longitudinal): F_{tu} ksi	F_{ty} ksi	e(1-in) Percent	RA Percent
1650 F, 1-Hr, AC + 1100 F, 8-Hr, AC						
None			137.0	120.7	15.5	31.2
800	55	0.11	147.4	132.3	15.5	34.3
850	50	0.15	143.6	132.3	18.5	34.8
900	40	0.17	142.4	129.1	17.5	28.9
1000	15	0.12	142.1	131.2	15.0	31.6
1750 F, 1-Hr, AC + 1100 F, 24-Hr, AC						
None			139.5	124.3	17.5	32.8
800	65	0.22	136.7	123.2	18.0	28.2
850	50	0.14	139.2	125.0	20.5	32.2
850	55	0.18	136.5	122.7	18.0	30.2
900	40	0.22	136.6	123.3	19.0	30.2
900	45	0.23	138.1	125.5	19.5	33.5
1000	20	0.17	138.9	128.9	16.5	30.8
1875 F, 1-Hr, AC + 1100 F, 24-Hr, AC						
None			138.4	121.0	15.0	21.2
800	65	0.19	138.5	126.1	13.5	23.4
850	55	0.14	139.6	125.8	14.5	21.9
900	45	0.16	139.8	126.7	14.5	23.4
1000	20	0.10	141.7	129.7	12.5	18.3

[a] Tested after exposure without surface conditioning

TABLE 3.02122 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED ROLLED BAR VARIOUSLY HEAT TREATED (13, pp. 67-68)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy	Ti-6Al-2Sn-4Zr-2Mo
Form	1 3/8 in Diameter Rolled Bar
Condition	1775 F, 1-Hr, AC + 1100 F, 8-Hr, AC

Exposure Conditions: Temp F	Stress ksi	Time Hrs	Time to 0.1 percent Deformation Hrs	Total Plastic Deformation Percent	Subsequent RT Tensile Properties: F_{ty} ksi	F_{tu} ksi	e percent	RA percent
		None			146.6	160.2	21.0	37.3
		None			146.2	159.7	19.0	37.7
825	47.5	3000	185	0.276	144.5	156.2	13.0	22.8
			—	0.192	142.5	155.2	14.0	18.8
925	27.5	2300	98	0.436	148.6	156.6	16.0	31.7
			—	0.240	150.8	160.2	18.0	37.7

Note: Center properties, 1/4-inch diameter specimens

TABLE 3.02123 EFFECT OF LONG TIME EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED ROLLED BAR (5, p. 10)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Alloy	Ti-6Al-2Sn-4Zr-2Mo
Form	1/2 in dia. bar, Beta rolled
Condition	Duplex annealed

150-Hr exposure at			Subsequent RT Tensile Properties			
Temp F	Stress ksi	Deformation percent	F_{tu} ksi	F_{ty} ksi	RA percent	e percent
1650 F, 1-Hr, AC			+ 1100 F, 8- Hr, AC			
None			151	140	36	18
800	70	.11	153	142	34	18
1000	30	.38	150	141	39	19
1100	15	1.83	151	144	25	14
1750 F, 1-Hr, AC			+ 1100 F, 8-Hr, AC			
None			158	140	30	17
800	70	.10	149	138	38	18
1000	30	.26	150	140	37	19
1100	15	.53	150	142	28	16

Duplicates tests

TABLE 3.02124 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF BETA-ROLLED DUPLEX ANNEALED BAR (7, p.49)

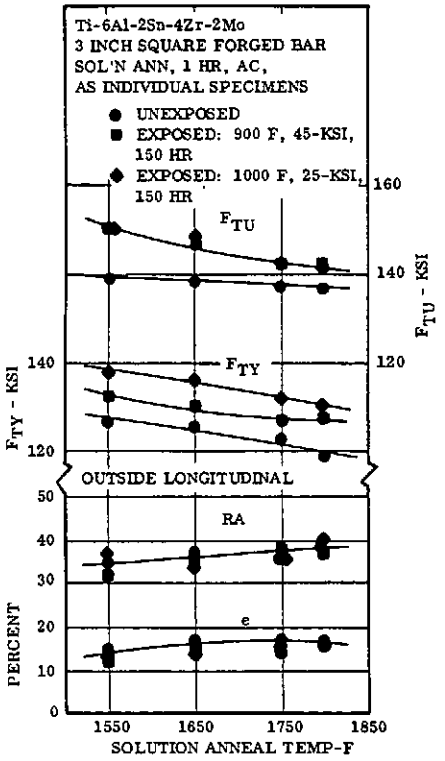


FIG. 3.02125 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF SOLUTION ANNEALED FORGING (7, pp. 41 and 54)

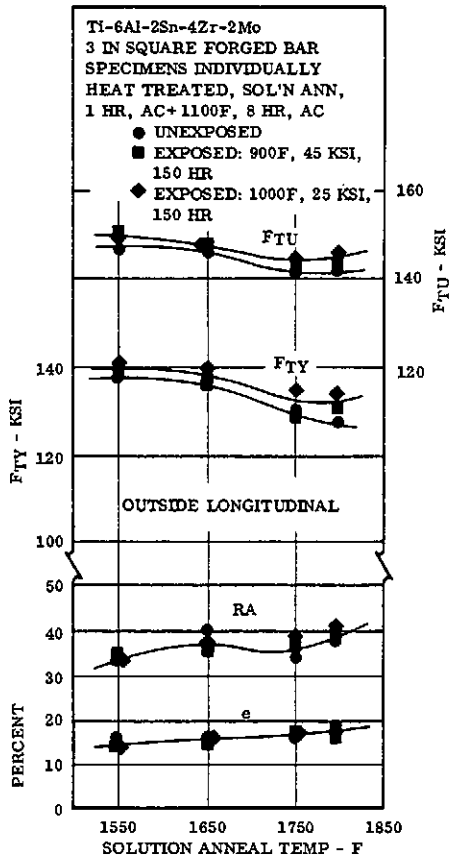


FIG. 3.02126 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED FORGING. (7, PP. 41 AND 54)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

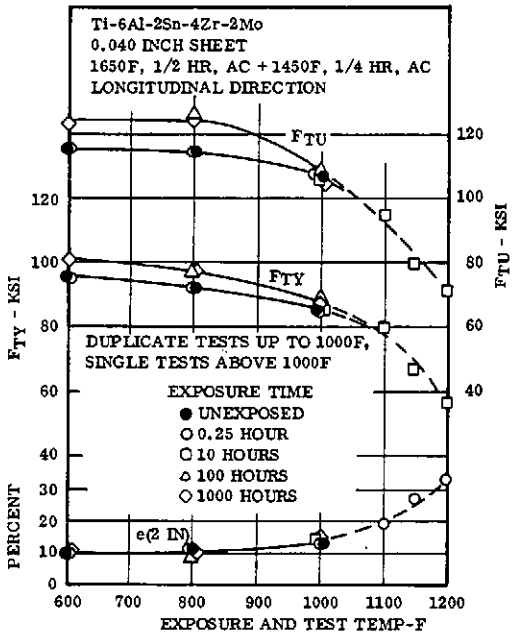


FIG 3.03126 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF DUPLEX ANNEALED SHEET AT THE EXPOSURE TEMPERATURE. (1, pp. 51 and 265-266)

Alloy			Ti-6Al-2Sn-4Zr-2Mo			
Form			3 in Square Forged Bar			
Condition			Duplex Annealed in Full Sections			
150-Hr Exposure at			Subsequent RT Tensile Properties* (outside longitudinal)			
Temp F	Stress ksi	Deformation percent	F_{tu} ksi	F_{ty} ksi	e (1-in) percent	RA percent
1650 F, 1-Hr, AC + 1100 F, 8-Hr, AC						
——	None	——	141.2	133.1	18.0	40.9
800	65	0.01	143.0	134.0	19.0	41.6
900	45	0.12	142.2	131.1	16.0	39.2
1000	25	0.18	142.6	133.9	16.0	41.6
1100	10	0.23	141.0	134.1	16.5	35.4
1750 F, 1-Hr, AC + 1100 F, 8-Hr, AC						
——	None	——	136.5	126.7	19.0	37.9
800	65	0.08	139.6	129.5	18.0	37.3
900	45	0.12	136.8	127.0	17.0	42.1
1000	25	0.09	137.9	130.0	17.0	41.6
1100	10	0.32	138.5	131.2	17.0	35.4
1750 F, 1-Hr, WQ + 1100 F, 8-Hr, AC						
——	None	——	160.1	146.5	17.0	35.2
800	65	0.10	156.6	142.8	14.0	38.4
900	45	0.57	154.0	142.2	14.0	28.8
1000	25	0.17	147.7	134.5	14.5	34.1
1100	10	0.30	153.2	141.2	14.0	22.0

* Tested after exposure without surface treatment

TABLE 3.02127 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED FORGED BAR (13, p. 69)(7, p. 56)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy		Ti-6Al-2Sn-4Zr-2Mo								
Form		18.5 in Dia Compressor Hub Forging								
Condition		1750F, 1 Hr, AC + 1100F, 8 Hr, AC								
		150-Hr Exposure at		Time to 0.1percent	Time to 0.2percent	Creep in 150-Hr	Subsequent RT Tensile Properties			
Location	Direction	Temp F	Stress ksi	Creep Hr	Creep Hr	percent	F_{tu} ksi	F_{ty} ksi	e percent	RA percent
Rim	Radial	None					140.0	129.6	13.5	28.6
Web							143.2	130.4	13.5	32.7
Hub							140.2	125.8	18.0	42.3
Rim	Radial	800	70	75	225[a]	.149	141.1	132.8	16.0	30.1
Web				42	225[a]	.160	139.7	130.9	16.0	28.1
Hub				50	245[a]	.148	138.5	130.5	15.0	28.8
Rim	Radial	1000	35	7	39	.412	144.2	129.7	12.5	32.8
Web				8	44	.424	145.2	133.6	17.0	29.4
Hub				6	33	.498	138.5	126.4	12.5	34.1

[a] Extrapolated

TABLE 3.02128 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED COMPRESSOR HUB FORGING (12, pp. 13 and 15)

Alloy			Ti-6Al-2Sn-4Zr-2Mo			
Form			20-inch Diameter Compressor Wheel Forging[a]			
Condition			Duplex Annealed			
150-Hr Exposure at			Subsequent RT Tensile Properties			
Stress ksi	Temp F	Total 150Hr Plastic Deformation percent[b]	F_{tu} ksi	F_{ty} ksi	e percent	RA percent
1650 F, 1-Hr, AC + 1100 F, 8-Hr, AC						
None	None		153.0	139.8	16.0	37.3
None	None		147.4	136.0	17.0	44.2
65	850	0.15	141.5	129.0	19.0	42.0
55	900	0.19	141.2	128.8	18.0	43.6
45	950	0.24	142.3	129.6	20.0	42.0
35	1000	0.30	142.7	129.3	19.0	47.6
15	1100	0.54	142.0	132.2	17.0	34.1
1750 F, 1-Hr, WQ + 1100 F, 8-Hr, AC						
None	None		164.0	147.4	14.0	41.9
None	None		166.9	151.2	14.0	37.8
65	850	0.26	164.8	155.2	13.0	40.8
55	900	0.39	165.2	149.4	13.0	34.0
45	950	0.49	164.6	146.3	14.0	38.3
35	1000	0.81	164.4	149.7	11.0	31.5
15	1100	1.04	161.0	148.6	11.0	23.2

[a] All tests in radial direction
[b] Measured at RT after exposure

TABLE 3.02129 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED COMPRESSOR WHEEL FORGINGS (2, p. 10)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

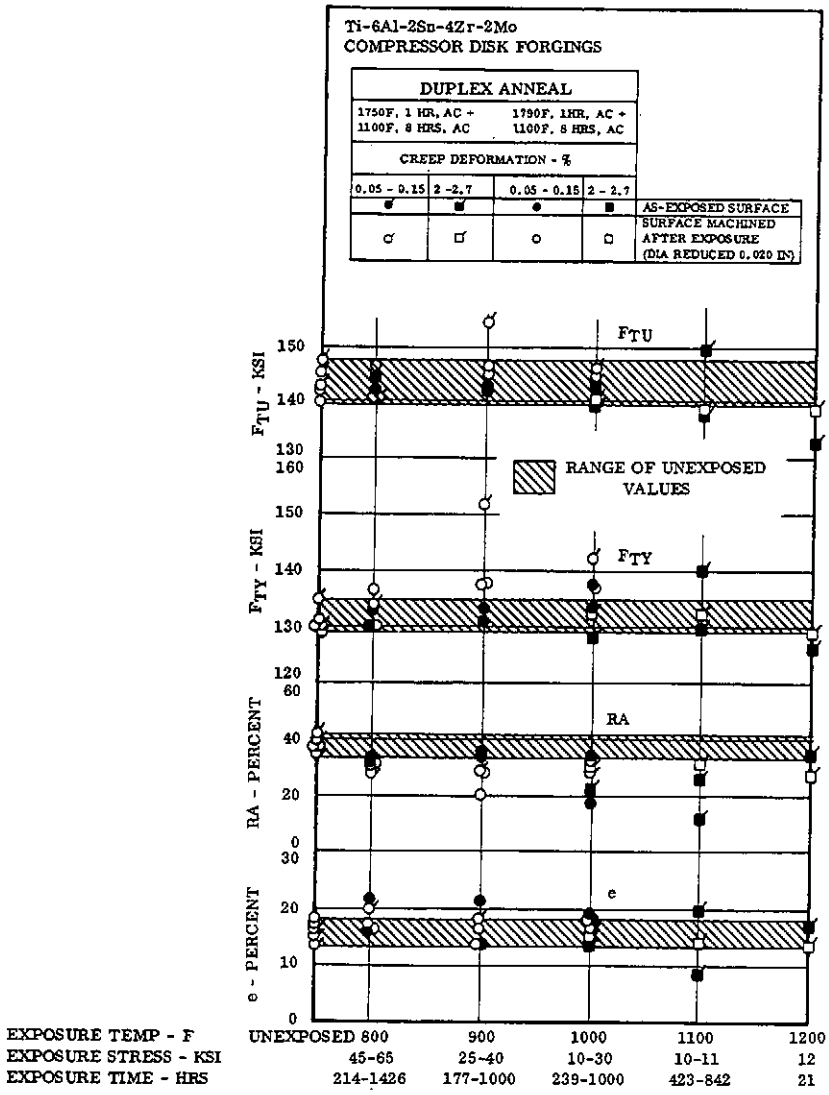


FIG. 3.02130 EFFECT OF SOLUTION ANNEAL TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED COMPRESSOR DISK FORGINGS SUBSEQUENT TO LONG TIME EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD. (68)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy			Ti-6Al-2Sn-4Zr-2Mo					
Form			Pancake Forgings					
Condition			1750F, 1 hr, AC + 1100F, 8 hrs, AC					
Heat	Exposure Conditions				Subsequent RT Tensile Properties			
	Temp F	Stress ksi	Time hrs	Plastic Deformation percent	F_{tu} ksi	F_{ty} ksi	e percent	RA percent
A	Unexposed				144-150(a)	131-140(a)	14-17(a)	42-51(a)
B	Unexposed				139-145(b)	126-133(b)	11-17(b)	33-52(b)
A	700	100	1500	1.681	155	154	14	44
B	700	80	1500	0.221	147	142	18	39
B	700	60	1500	0.221	144	130	17	39
A	800	90	1500	1.444	154	152	14	28
A	800	85	1000	0.713	154	150	8	10
A	800	80	1000	0.433	150	147	15	44
A	800	75	500	0.256	150	142	8	15
B	800	50	1500	0.158	143	132	16	39
B	900	50	1500	0.592	140	133	17	39
B	900	30	1500	0.173	146	140	9	19
B	1000	30	1500	7.706	135	128	9	19
B	1000	20	1500	2.051	147	134	14	21

(a) Range of values from 6 tests on 2 forgings.
(b) Range of values from 12 tests on 6 forgings.

TABLE 3.02131 EFFECT OF LONG TIME EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED PANCAKE FORGINGS, (83).

Alloy			Ti-6Al-2Sn-4Zr-2Mo			
Form			15 in Diameter Forged Disc			
Condition			Duplex Annealed			
	950F, 35 - ksi 150 Hr Exposure		Post Exposure RT Tensile Properties			
Direction	Time(a) Hour	150-Hr(b) percent	F_{ty} ksi	F_{tu} ksi	e percent	RA percent
	1750F, 1-Hr, AC + 1100F, 8-Hr, AC					
Chordal	44	0.280	144.4	152.2	17.0	39.5
Radial	17	0.240	144.3	150.4	15.0	42.0
	1790F, 1-Hr, AC + 1100F, 8-Hr, AC					
Chordal	43	0.110	144.3	152.8	15.0	22.5
Radial	37	0.131	142.1	150.6	13.0	27.9

(a) To 0.1% Plastic Deformation
(b) Total Plastic Deformation

TABLE 3.02132 EFFECT OF HIGH SOLUTION ANNEALING TEMPERATURE (BETA TRANSUS - 25F) ON EXPOSURE STABILITY PROPERTIES OF DUPLEX ANNEALED FORGED DISC, (14, p. 17).

Alloy	Ti-6Al-2Sn-4Zr-2Mo
Form	20 in Dia Compressor Wheel Forging
Condition	1750F, 1 Hr, AC + 1100F, 8 Hr, AC

Location	Direction	Standard Charpy-V Impact-Energy ft-lb
Web (Center Punch - Out)	Radial	21

TABLE 3.0231. STANDARD CHARPY-V IMPACT ENERGY OF DUPLEX ANNEALED COMPRESSOR WHEEL FORGING, (11, p. 17).

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

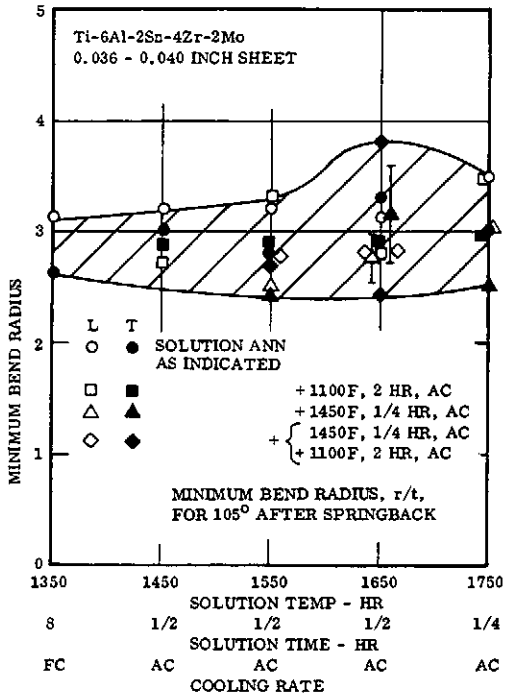


FIG. 3.0241 EFFECT OF SOLUTION ANNEAL TEMPERATURE ON ROOM TEMPERATURE MINIMUM BEND RADIUS OF SOLUTION ANNEALED, DUPLEX ANNEALED AND TRIPLEX ANNEALED SHEET. (7, p. 71)

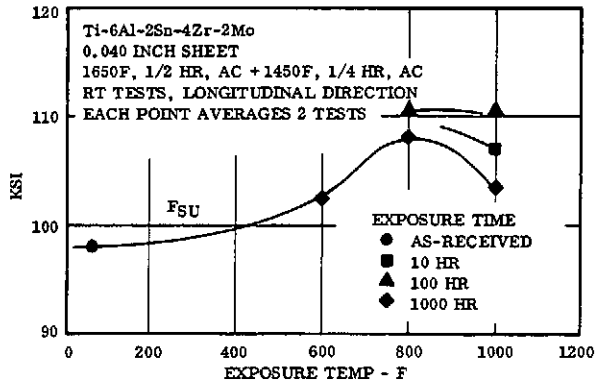


FIG. 3.0251 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ROOM TEMPERATURE ULTIMATE SHEAR STRENGTH OF DUPLEX ANNEALED SHEET. (1, p. 267)

Alloy		Ti-6Al-2Sn-4Zr-2Mo	
Form		Sheet	
Sheet Thickness Inch	Test Direction	Minimum Bend Radius (1) 1650F, 1/2 Hr, AC + 1450F, 1/4 Hr, AC	1650F, 1/2 Hr, AC + 1450F, 1/4 Hr, AC + 1100F, 2 Hr, AC
0.040	L	3.0	3.0
	T	3.0	3.0
0.080	L	3.0	3.1
	T	2.8	3.2
0.125	L	3.3	3.4
	T	3.5	3.4

(1) Minimum bend radius, r/t, for 105° after Springback

TABLE 3.0242. EFFECT OF SHEET THICKNESS ON MINIMUM BEND RADIUS OF DUPLEX AND TRIPLEX ANNEALED SHEET, (13, p. 22).

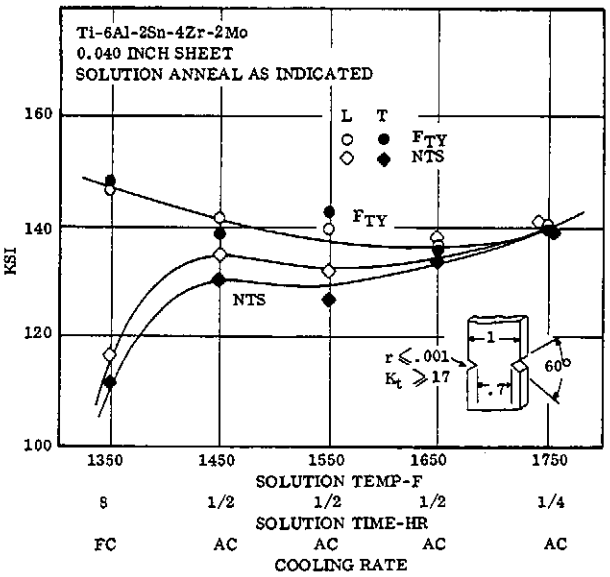


FIG. 3.02711 EFFECT OF SOLUTION ANNEAL TEMPERATURE ON ROOM TEMPERATURE SHARP NOTCH PROPERTIES OF SOLUTION ANNEALED SHEET (7, p 63)(10, pp 8 AND 9)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

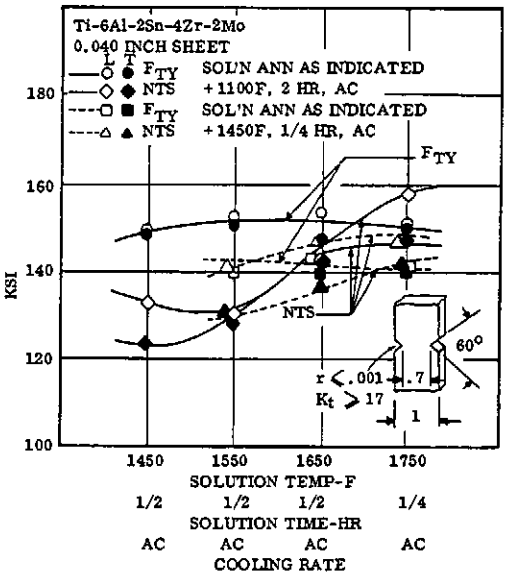


FIG. 3.02712 EFFECT OF SOLUTION ANNEAL TEMPERATURE ON ROOM TEMPERATURE SHARP NOTCH PROPERTIES OF DUPLEX ANNEALED SHEET (7, p. 63)

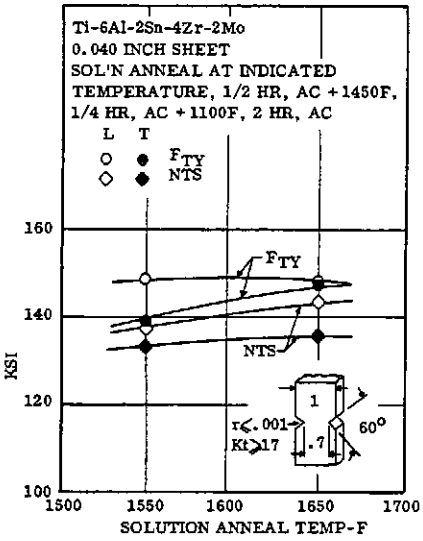


FIG. 3.02713 EFFECT OF SOLUTION ANNEAL TEMPERATURE ON ROOM TEMPERATURE SHARP NOTCH PROPERTIES OF TRIPLEX ANNEALED SHEET (7, pp. 63 - 64)

Alloy	Ti-6Al-2Sn-4Zr-2Mo			
Form	0.040 in Sheet			
Condition	Duplex and Triplex Annealed			
Heat Treatment	F_{tu} ksi	F_{ty} ksi	e(2-in) percent	NTS ksi
1650 F, 1/4-Hr, AC + 1450 F, 1/4-Hr, AC	146.7	138.0	12.3	134.5
1650 F, 1/2-Hr, AC + 1450 F, 1/4 -Hr, AC	147.5	139.2	12.0	137.0
1650 F, 1/4-Hr, AC + 1450 F, 1/4-Hr, AC + 1100 F, 2-Hr, AC	148.3	141.4	13.0	136.5
1650 F, 1/4-Hr, AC + 1450 F, 1/4-Hr, AC + 1100 F, 8-Hr, AC	146.1	137.7	12.8	138.1
1650 F, 1/2-Hr, AC + 1450 F, 1/4-Hr, AC + 1100 F, 2-Hr, AC	154.7	146.9	11.0	135.1
1650 F, 1/2-Hr, AC + 1450 F, 1/4-Hr, AC + 1100 F, 8-Hr, AC	155.3	146.7	13.0	——
Values averages of duplicate tests				

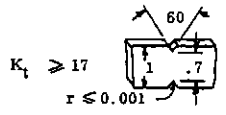


TABLE 3.02714 EFFECT OF ANNEALING TIME ON SMOOTH AND SHARP NOTCH TENSILE PROPERTIES OF DUPLEX AND TRIPLEX ANNEALED SHEET (13, p. 7)

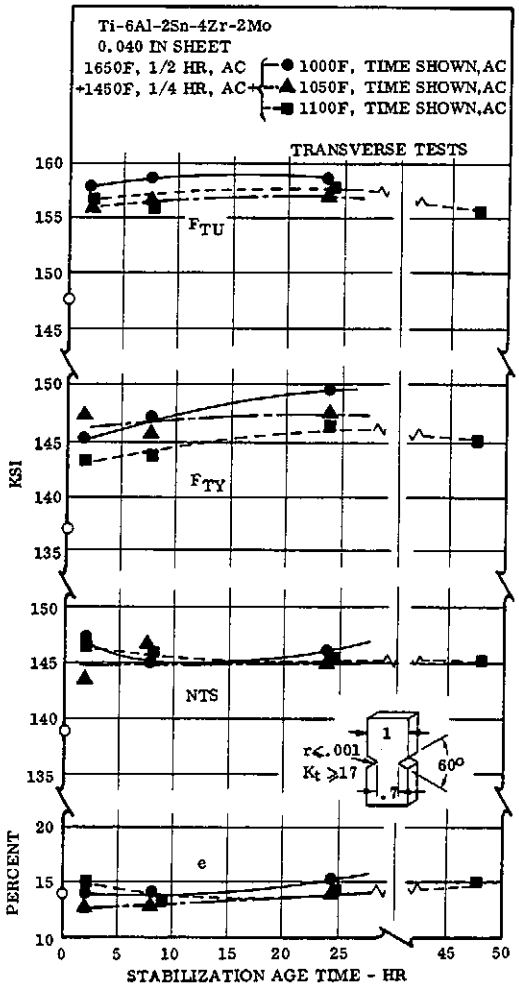


FIG. 3.02715 EFFECT OF STABILIZATION AGE TIME AND TEMPERATURE ON ROOM TEMPERATURE SMOOTH AND SHARP NOTCH TENSILE PROPERTIES OF TRIPLEX ANNEALED SHEET (13, p.20)

Alloy		Ti-6Al-2Sn-4Zr-2Mo			
Form		Sheet			
Condition		Duplex and Triplex Annealed			
Sheet Thickness in	Test Direction	F_{tu}(1) ksi	F_{ty}(1) ksi	e(2-in)(1) percent	NTS(1) ksi
1650 F, 1/2-Hr, AC + 1450 F, 1/4-Hr, AC					
0.040	L	147.7	133.7	10.8	146.4
"	T	145.1	132.6	11.8	144.6
0.080	L	154.7	142.2	12.0	144.7
"	T	139.9	126.3	11.0	132.7
0.125	L	139.3	125.1	14.0	139.0
"	T	143.0	129.0	15.0	136.3
1650F, 1/2-Hr, AC + 1450 F, 1/4-Hr, AC + 1100 F, 2-Hr, AC					
0.040	L	157.8	145.0	10.7	155.1
"	T	156.4	145.6	9.8	145.1
0.080	L	160.2	145.9	12.3	145.8
"	T	147.6	135.3	11.8	137.1
0.125	L	145.6	133.5	14.8	135.3
"	T	149.4	135.4	15.2	122.7

(1) Avg. of duplicate tests

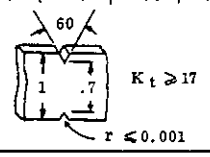


TABLE 3.02716 EFFECT OF THICKNESS ON ROOM TEMPERATURE SMOOTH AND SHARP NOTCH TENSILE PROPERTIES OF DUPLEX AND TRIPLEX ANNEALED SHEET (13, p.22)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti·6·2·4·2

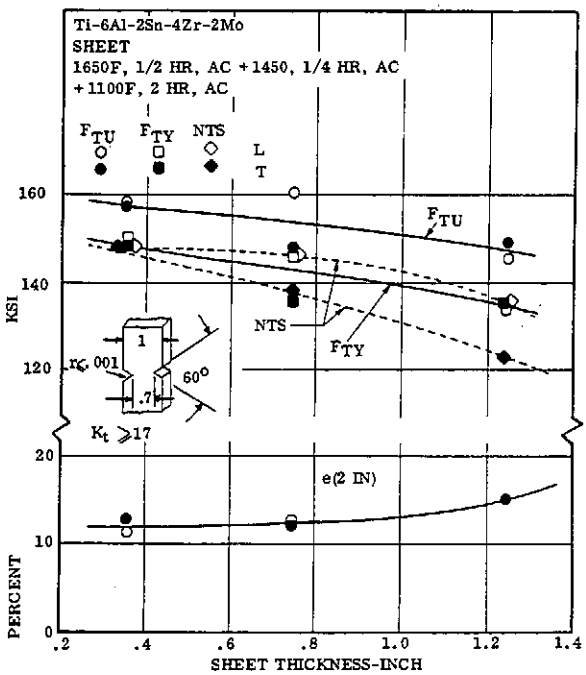


FIG. 3.02717 EFFECT OF THICKNESS ON ROOM TEMPERATURE SMOOTH AND SHARP NOTCH TENSILE PROPERTIES OF TRIPLEX ANNEALED SHEET (10, p.8)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

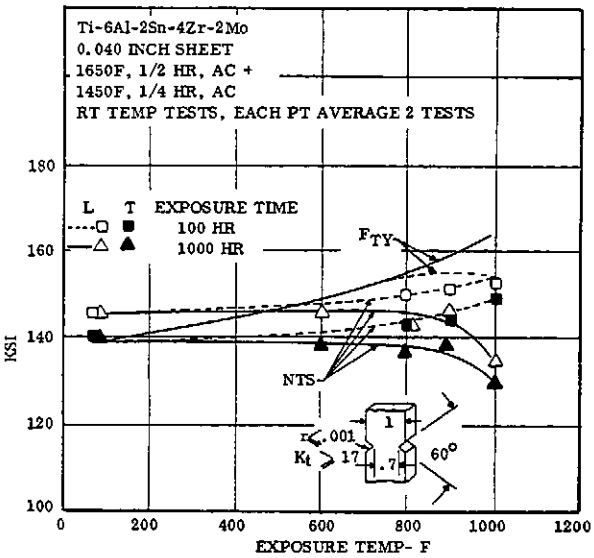


FIG. 3.02718 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ROOM TEMPERATURE SHARP NOTCH STRENGTH OF DUPLEX ANNEALED SHEET (13,p.29)

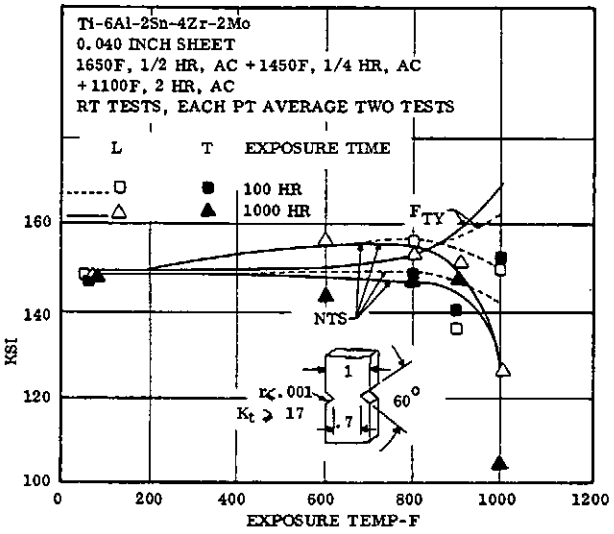


FIG. 3.027110 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ROOM TEMPERATURE SHARP NOTCH STRENGTH OF TRIPLEX ANNEALED SHEET (13,pp.29-30)

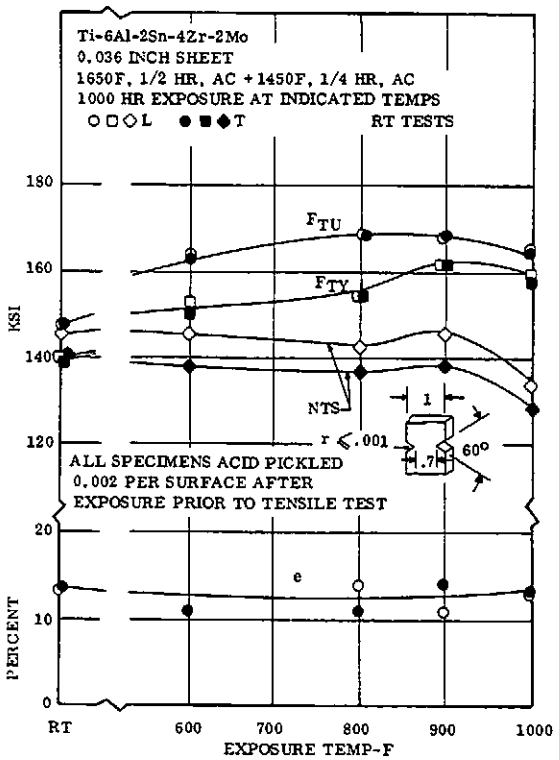


FIG. 3.02719 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ROOM TEMPERATURE SMOOTH AND SHARP NOTCH TENSILE PROPERTIES OF DUPLEX ANNEALED SHEET (10,p.9)

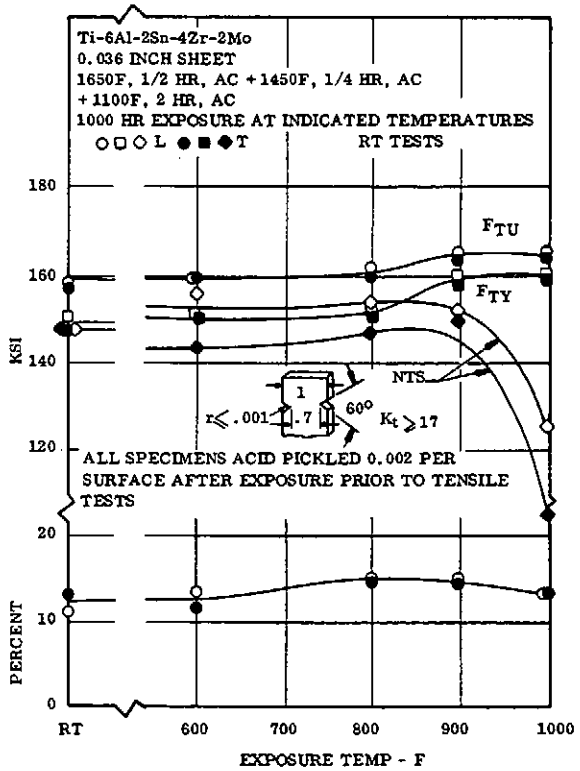


FIG. 3.027111 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ROOM TEMPERATURE SMOOTH AND SHARP NOTCH TENSILE PROPERTIES OF TRIPLEX ANNEALED SHEET (10,p.9)

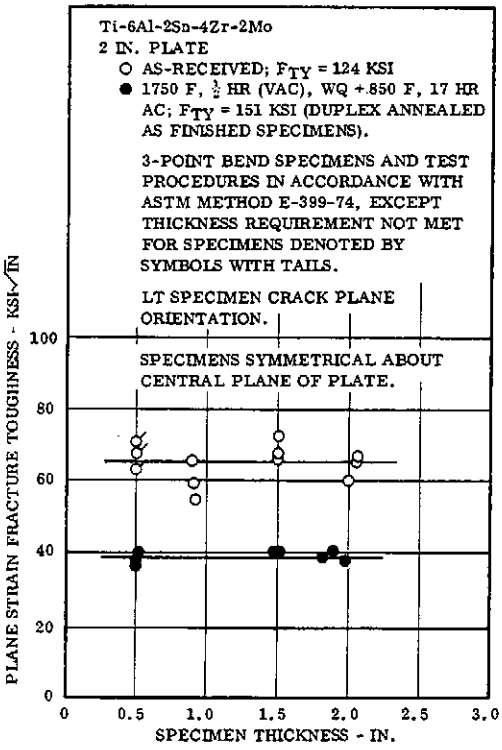


FIG. 3.02722. EFFECT OF SPECIMEN THICKNESS ON PLANE STRAIN FRACTURE TOUGHNESS OF AS-RECEIVED AND DUPLEX ANNEALED PLATE. (25), (26)

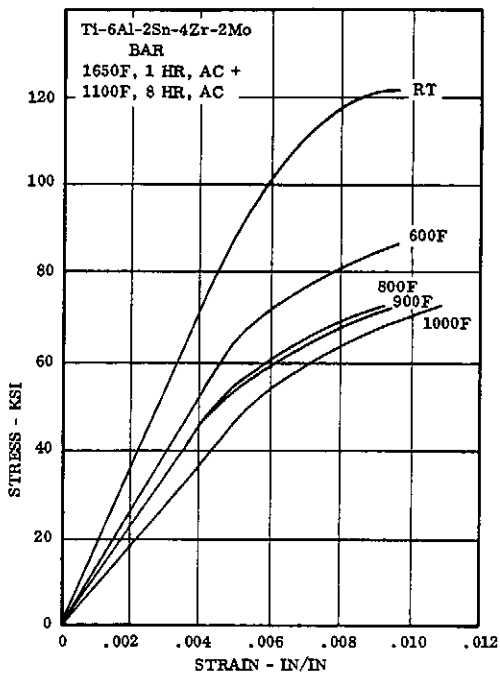


FIG. 3.0311 TYPICAL STRESS - STRAIN CURVES AT ELEVATED TEMPERATURES FOR DUPLEX ANNEALED BAR (10, p. 6)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Form	2-in x 4½-in bar					
Alloy Condition	F_{ty} ksi	3-Point Bend Specimen crack plane orientation	thickness in	width in	crack length in	K_Q ksi√in
1650F, 1 hr, AC + 1100F, 8 hrs, AC	124	LT	0.503	1.003	0.524	62 (a)(b)
			0.504	1.001	0.494	63 (a)(b)
			0.506	1.004	0.527	64 (b)
	123	TL	0.504	1.004	0.507	51 (a)
			0.502	1.001	0.523	68 (b)
			0.505	1.001	0.511	56 (b)
	123	TS	0.501	0.971	0.489	55 (a)
			0.501	1.010	0.511	59 (a)(b)
			0.502	1.010	0.521	52 (c)
1790F, 1 hr, AC + 1100F, 8 hrs, AC	119	LT	0.504	1.001	0.498	71 (a)(b)
			0.504	1.001	0.569	81 (b)
			0.504	1.001	0.587	64 (b)
	123	TL	0.506	1.002	0.533	75 (a)(b)
			0.506	1.001	0.555	70 (b)
			0.505	1.001	0.523	67 (a)(b)
	123	TS	0.502	0.982	0.501	61 (a)(b)
			0.502	0.971	0.538	65 (a)(b)

(a) Excessive crack front curvature according to ASTM E-399-74
(b) Insufficient specimen thickness according to ASTM E-399-74
(c) Valid K_{IC}

TABLE 3.02723 PLANE STRAIN FRACTURE TOUGHNESS OF DUPLEX ANNEALED BAR, (80).

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

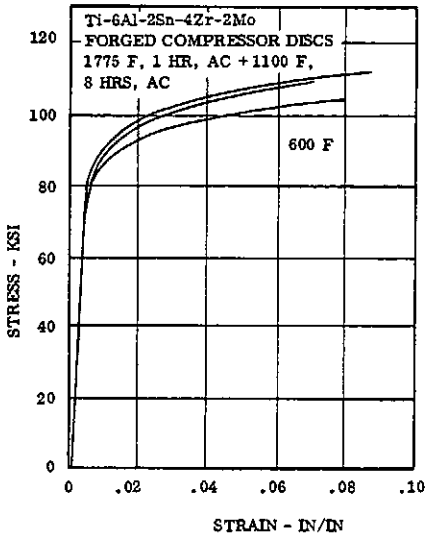


FIG. 3.0312 STRESS-STRAIN CURVES IN TENSION FOR DUPLEX ANNEALED FORGED COMPRESSOR DISCS AT 600 F. (82)

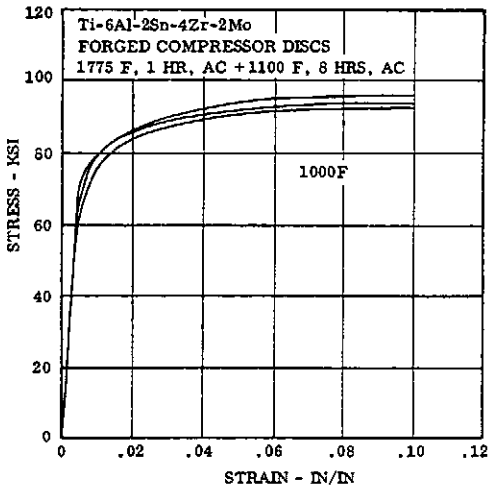


FIG. 3.0314 STRESS-STRAIN CURVES IN TENSION FOR DUPLEX ANNEALED FORGED COMPRESSOR DISCS AT 1000 F. (82)

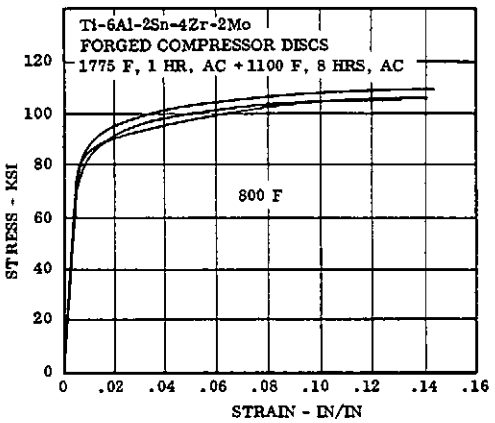


FIG. 3.0313 STRESS - STRAIN CURVES IN TENSION FOR DUPLEX ANNEALED FORGED COMPRESSOR DISCS AT 800 F. (82)

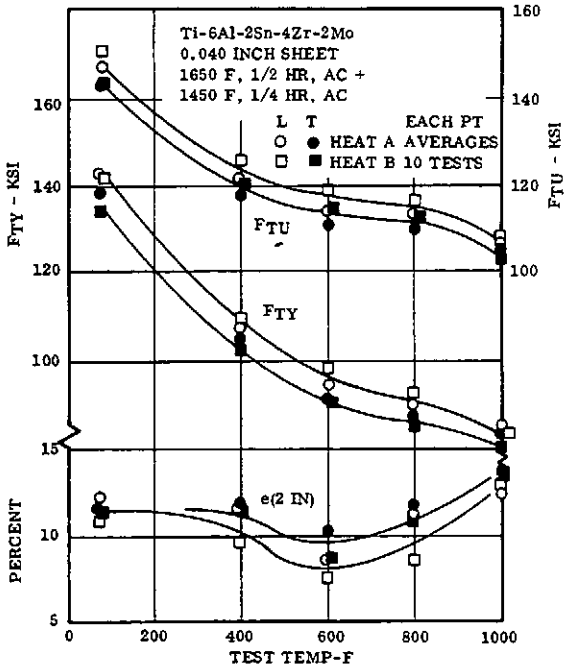


FIG. 3.0315 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF DUPLEX ANNEALED SHEET (1, p. 51)(3, p. 5)

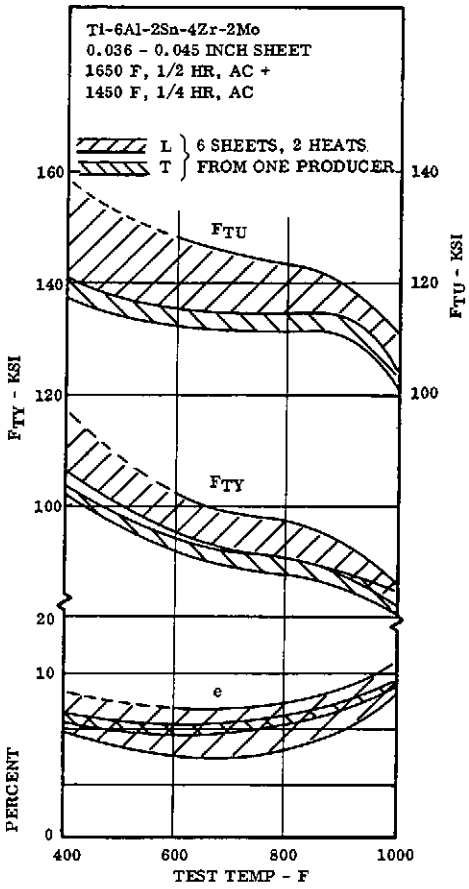


FIG. 3.0316 SPREAD OF TENSILE PROPERTIES AT ELEVATED TEMPERATURES FOR SIX DUPLEX ANNEALED SHEETS FROM FROM TWO HEATS (7, p. 44-45)

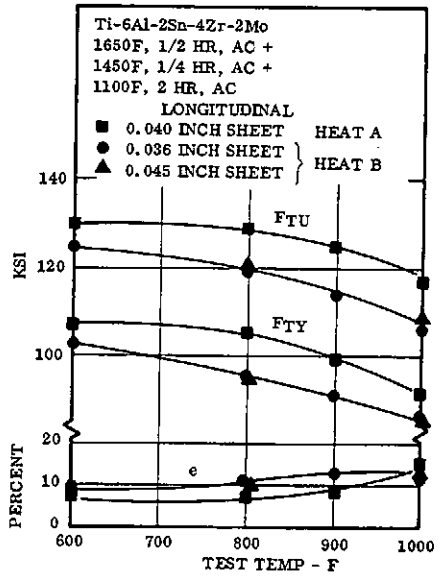


FIG. 3.0317 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF TRIPLEX ANNEALED SHEET (7, p. 44-45)

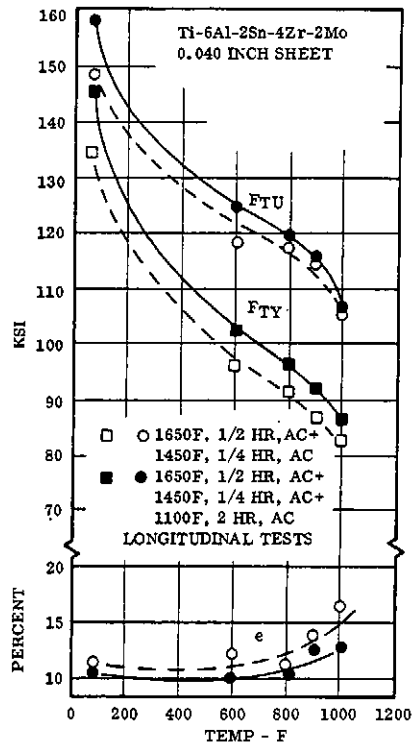


FIG. 3.0318 SMOOTH TENSILE PROPERTIES AT ROOM AND ELEVATED TEMPERATURES FOR DUPLEX AND TRIPLEX ANNEALED SHEET (13, p. 23)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

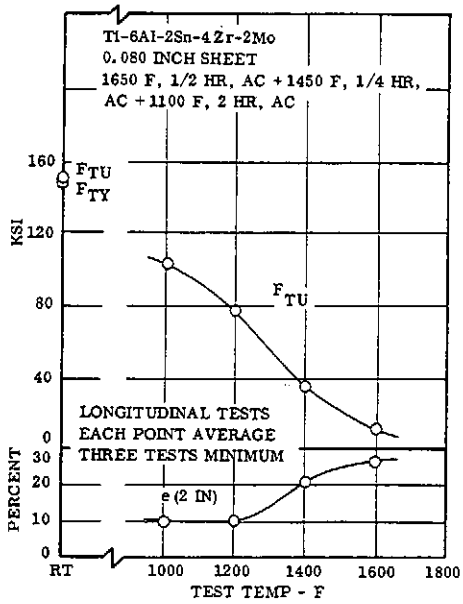


FIG. 3.0319 TENSILE PROPERTIES AT VERY HIGH TEMPERATURES FOR TRIPLEX ANNEALED SHEET. (28)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

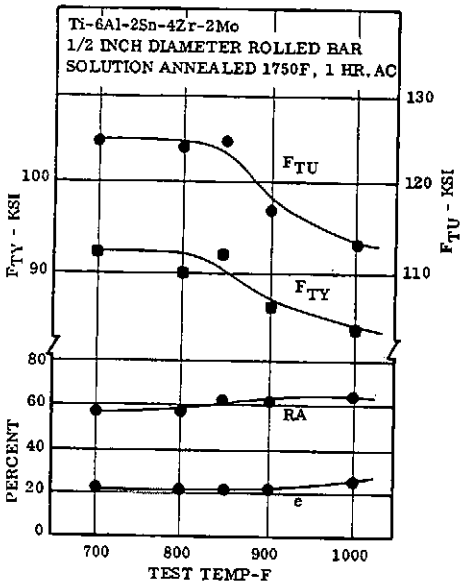


FIG. 3.03110 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION ANNEALED BAR (7, p. 43)

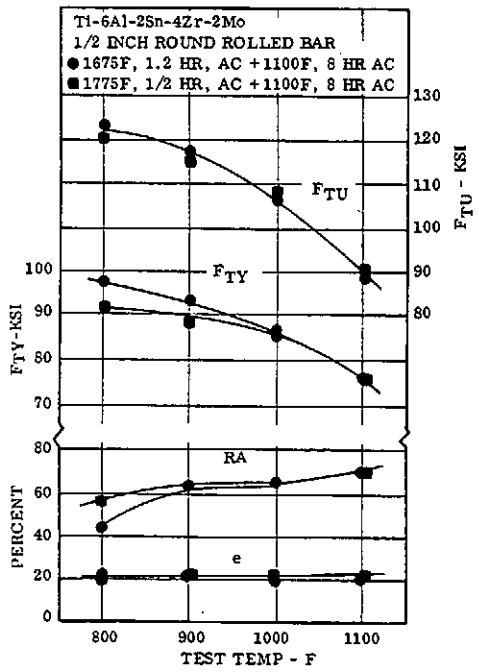


FIG. 3.03111 EFFECT OF TEST TEMP ON TENSILE PROPERTIES OF DUPLEX ANNEALED BAR (7, p. 43)

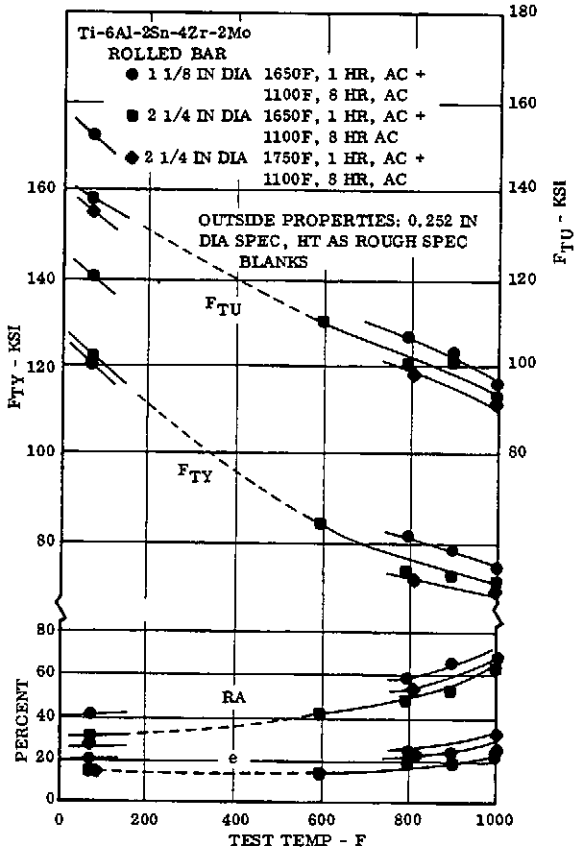


FIG. 3.03112 EFFECT OF SECTION SIZE ON ELEVATED TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED BAR (2, p. 15)

Ti	
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Alloy	Ti-6Al-2Sn-4Zr-2Mo				
Form	3/4 inch Diameter Bar				
Condition	1750F, 1 hr, AC + 1100F, 8 hrs, AC				
Test Temp F	Loading Rate[a]	F_{tu} ksi	e percent	RA percent	E 10^3 ksi
RT	Slow	152.0	17.0	44.0	16.0
	Dynamic	229.5	15.1	40.3	16.7[b]
900	Slow	106.0	21.0	60.3	11.6
	Dynamic	166.8	20.7	57.2	12.0[b]

(a) Slow loading was at conventional rate for tensile testing (strain rate $< 10^{-1}$ in/in/sec). Dynamic loading was at a strain rate $\sim 10^{3}$ in/in/sec from tests on split Hopkinson pressure-bar equipment.
(b) Dynamic modulus values were obtained from high-frequency fatigue experiments (strain rate $\sim 10^{2}$ in/in/sec).

TABLE 3.03113 EFFECT OF LOADING RATE ON ROOM TEMPERATURE AND 900F TENSILE PROPERTIES OF DUPLEX ANNEALED BAR, (24).

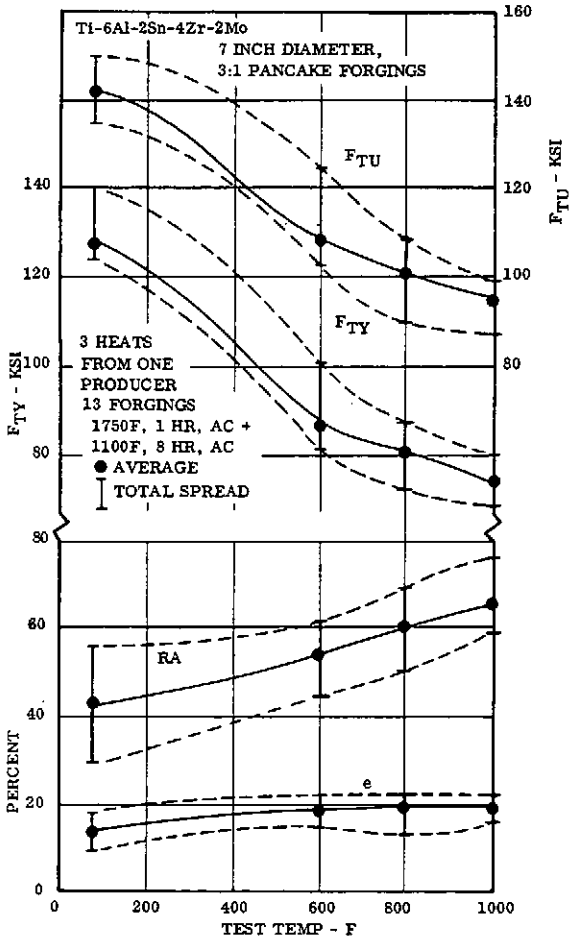


FIG. 3.03114 SPREAD OF TENSILE PROPERTIES AT ROOM AND ELEVATED TEMPERATURE FOR THIRTEEN DUPLEX ANNEALED PANCAKE FORGINGS FROM THREE HEATS (16)

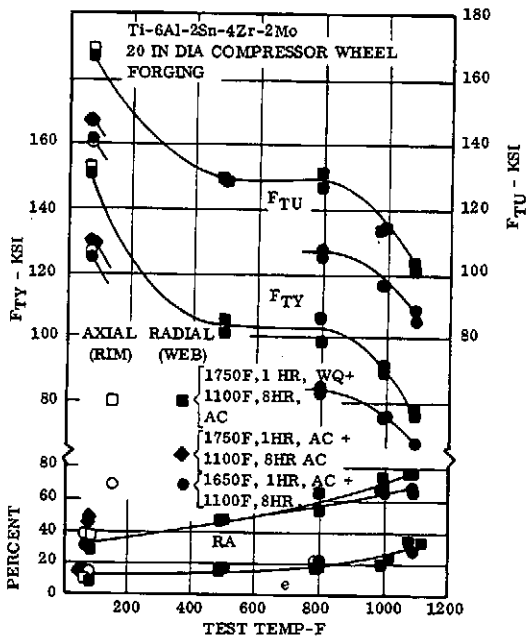


FIG. 3.03115 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF DUPLEX ANNEALED COMPRESSOR WHEEL FORGING (11,p.10)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy	Ti-6Al-2Sn-4Zr-2Mo
Form	18.5 in Dia Compressor Hub Forging
Condition	1750F, 1 Hr, AC + 1100F, 8 Hr, AC

Test Temp F	Total Variation in Tensile Properties (all locations and directions) F_{tu} ksi	F_{ty} ksi	e percent	RA percent
70	136.4-146.8	124.4-135.6	8.0-18.0	15.2-42.3
400	113.4-119.0	95.8- 98.6	16.0-19.5	36.1-45.9
900	96.6-106.0	76.0- 81.8	15.0-21.0	30.0-57.6

TABLE 3.03116 TOTAL VARIATION IN TENSILE PROPERTIES FOR DUPLEX ANNEALED COMPRESSOR HUB (12, p. 13)

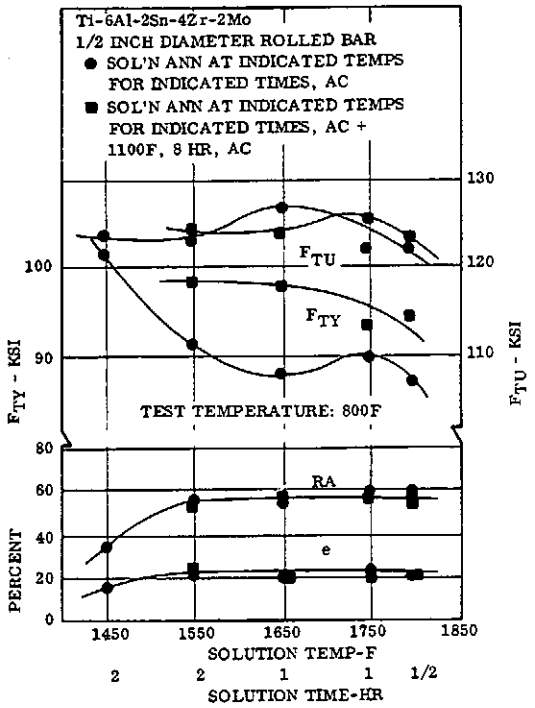


FIG. 3.3119 EFFECT OF SOLUTION ANNEAL TEMPERATURE ON 800F TENSILE PROPERTIES OF SOLUTION ANNEALED AND DUPLEX ANNEALED BAR (7,p 43)

Alloy	Ti-6Al-2Sn-4Zr-2Mo			
Form	Forged Jet Engine Compressor Discs			
Condition	Alpha-Beta Forged + Beta Transus - 25F, 1 hr, AC or faster + 1100F, 8 hrs, AC (a)		Beta Preforged + Alpha-Beta Forged + Beta Transus - 25F, 1 hr, AC or faster + 1100F, 8 hrs, AC (b)	
Value / Property	$\bar{X}$(c)	s(d)	$\bar{X}$(c)	s(d)
F_{tu} - ksi	100.6	1.5	100.4	1.9
F_{ty} - ksi	76.6	1.6	76.3	2.0
e(1-in) - percent	19.8	0.8	16.1	1.2
RA - percent	52.5	2.6	34.1	3.4

(a) 50 tests.
(b) 214 tests.
(c) Arithmetic mean.
(d) One standard deviation.
See Table 3.02113 for companion room temperature tensile properties.

TABLE 3.03117 TYPICAL 900F TENSILE PROPERTIES OF FORGED JET ENGINE COMPRESSOR DISCS, (77).

Alloy	Ti-6Al-2Sn-4Zr-2Mo
Form	Upset Forging
Condition	Beta Forged From 1910F (β + 100 F) + 1750F, 1 HR, AC + 1100F, 8 Hr, AC

Test Temp F	F_{tu} ksi	F_{ty} ksi	e percent	RA percent
70	144.9	126.9	11.8	29.2
400	119.2	94.0	16.5	42.5
900	102.6	76.6	16.5	54.5

TABLE 3.03118 ROOM AND ELEVATED TEMPERATURE TENSILE PROPERTIES OF BETA-FORGED UPSET (12,p.17)

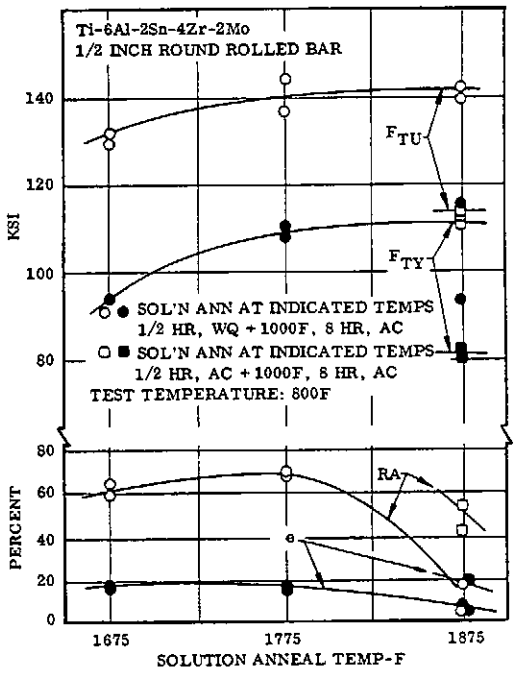


FIG. 3.03120 EFFECT OF QUENCH RATE FROM SOLUTION ANNEAL ON 800 F TENSILE PROPERTIES OF DUPLEX ANNEALED BAR (7,p.43)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

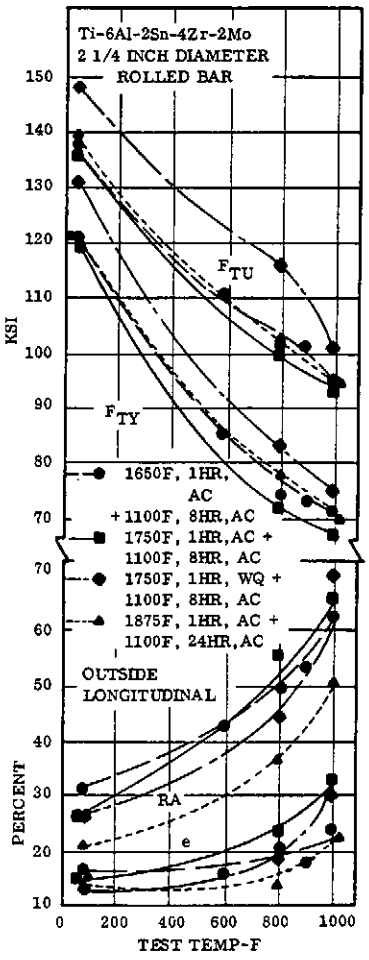


FIG. 3.03121 EFFECT OF HEAT TREATMENT ON ELEVATED TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED ROLLED BAR (13)p.64

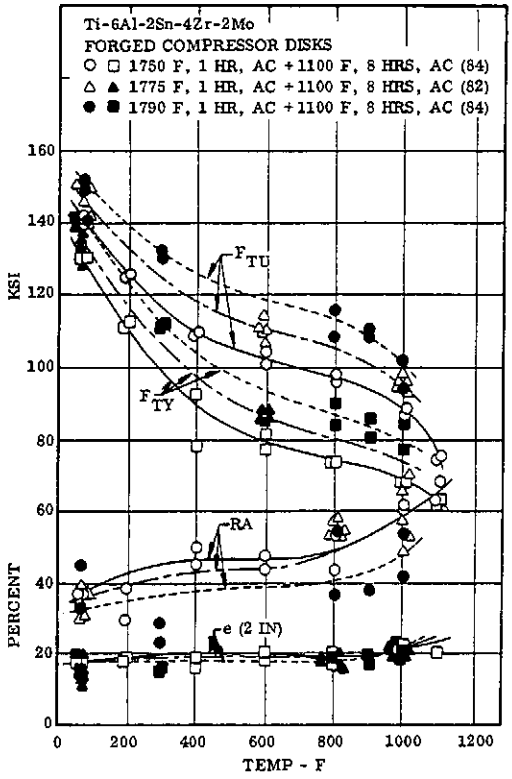


FIG. 3.03122 EFFECT OF SOLUTION ANNEALING TEMPERATURE ON ELEVATED TEMPERATURE TENSILE PROPERTIES OF FORGED COMPRESSOR DISKS. (82)(84)

Alloy				Ti-6Al-2Sn-4Zr-2Mo			
Form				20 in Dia Compressor Wheel			
Condition				Beta Forge + Duplex Annealed			
Location	Direction	Wheel No	Test Temp F	F_{tu} ksi	F_{ty} ksi	e percent	RA percent
1650F, 1 Hr, AC + 1100F, 8 Hr, AC							
Rim	Axial	1	70	138.2	124.8	11.5	31.1
Web	Radial	1	70	139.8	122.4	14.0	25.1
1750F, 1 Hr, WQ + 1100F, 8 Hr, AC							
Rim	Axial	2	70	153.4	135.4	6.5	17.4
Web	Radial	2	70	162.6	142.4	7.0	15.2
1775F, 1 Hr, AC + 1100F, 8 Hr, AC							
Rim	Axial	2	70	144.0	125.6	13.5	40.8
Web	Radial	2	70	144.6	126.5	12.3	34.2
Web	Radial	2	1000	93.4	71.7	22.0	61.4
1775F, 1 Hr, WQ + 1100F, 8 Hr, AC							
Web	Radial	1	70	175.6	154.4	8.8	25.5
Web	Radial	2	70	173.3	154.9	9.2	29.6
Web	Radial	1	1000	124.0	96.9	21.2	68.2
Web	Radial	2	1000	124.0	95.1	20.8	66.9

TABLE 3.03123 EFFECT OF SOLUTION ANNEAL TREATMENT ON ROOM TEMPERATURE AND 1000F TENSILE PROPERTIES OF BETA-FORGED, DUPLEX ANNEALED COMPRESSOR WHEEL (11, p. 11)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy	Ti-6Al-2Sn-4Zr-2Mo			
Form	3-in Square,(a)Finish Forged from Beta Field (1875F)			
Condition	Duplex Annealed			
Test Temp F	F_{tu} ksi	F_{ty} ksi	RA percent	e percent
	1750F, 1 Hr, WQ + 1100F, 8 Hr, AC			
800	118	92	50	21
1000	105	82	61	24
	1750F, 1 Hr, AC + 1100F, 8 Hr, AC			
800	102	79	44	22
1000	90	73	55	26

(a) Outside longitudinal properties

TABLE 3.03124, EFFECT OF QUENCH RATE FROM SOLUTION ANNEAL ON ELEVATED TEMPERATURE TENSILE PROPERTIES OF DUPLEX ANNEALED FORGING, (7, p. 46)

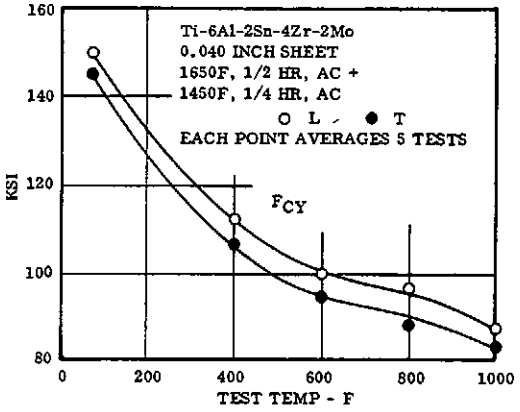


FIG. 3.0321 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF DUPLEX ANNEALED SHEET (1, p. 67)

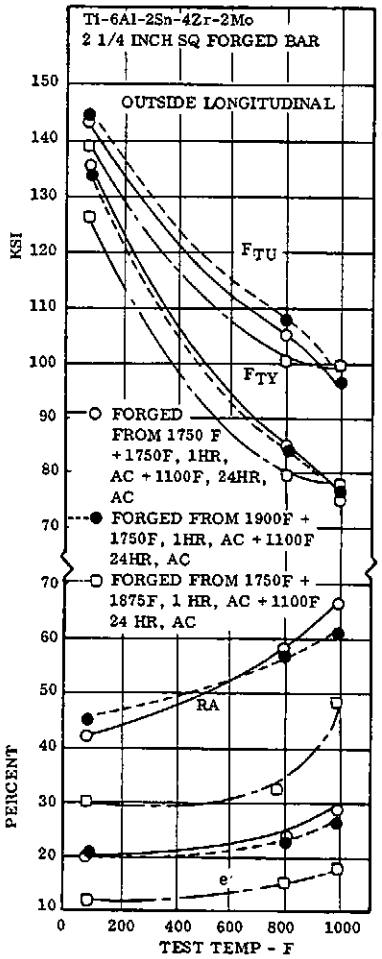


FIG. 3.03125 EFFECT OF FORGING AND ANNEALING TEMPERATURES ON THE ELEVATED TEMPERATURE TENSILE PROPERTIES OF FORGED BAR (13, p. 65)

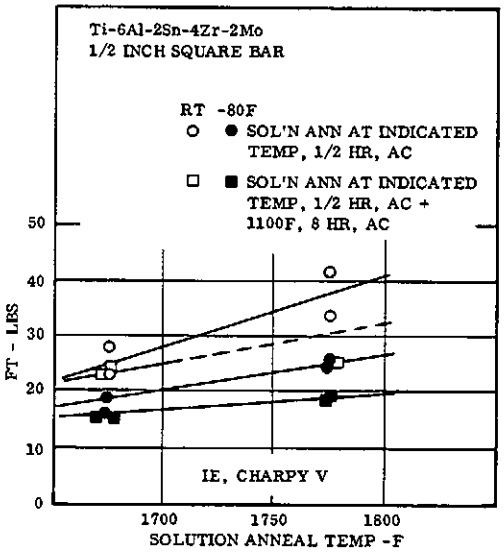


FIG. 3.0331 EFFECT OF SOLUTION ANNEAL TEMPERATURE ON STANDARD CHARPY-V IMPACT ENERGY FOR SOLUTION ANNEALED AND DUPLEX ANNEALED BAR AT ROOM TEMPERATURE AND -80F (7, p. 65)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

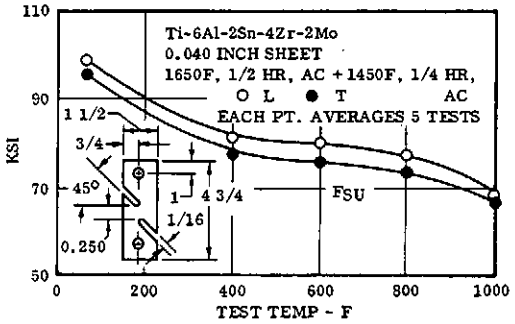


FIG. 3.0351 EFFECT OF TEST TEMPERATURE ON ULTIMATE SHEAR STRENGTH OF DUPLEX ANNEALED SHEET (1, p. 86)(3, p. 10)

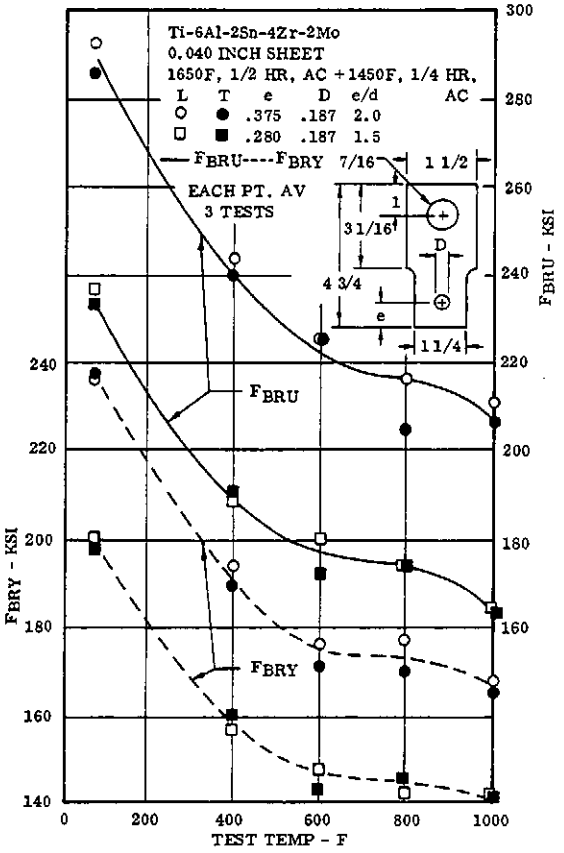


FIG. 3.0361 EFFECT OF TEST TEMPERATURE ON BEARING PROPERTIES OF DUPLEX ANNEALED SHEET (1, p. 77)

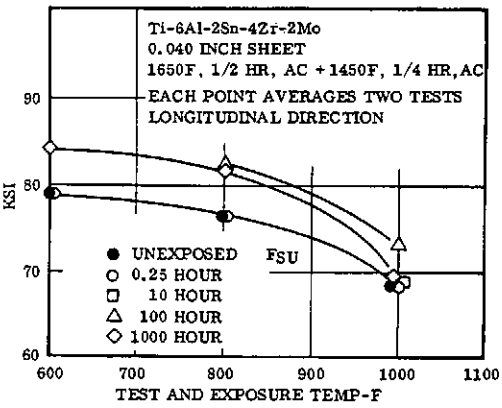


FIG. 3.0352 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ULTIMATE SHEAR STRENGTH OF DUPLEX ANNEALED SHEET AT THE EXPOSURE TEMPERATURE (1, p. 267)

Alloy	Ti-6Al-2Sn-4Zr-2Mo		
Form	0.040 - in Sheet		
Condition	1650 F, 1/2 - Hr, AC + 1450 F, 1/4 - Hr, AC		
	45° 0.375 0.5 R=0.025 K_t = 3 Long. Dir.		
Test Temp-F	70	400	800
Notch Strength - ksi	170	138	133
F_{ty} - ksi	142	107	92

TABLE 3.03711 MILD-NOTCH STRENGTH OF DUPLEX ANNEALED SHEET AT ROOM AND ELEVATED TEMPERATURES (1, pp. 51, 62)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

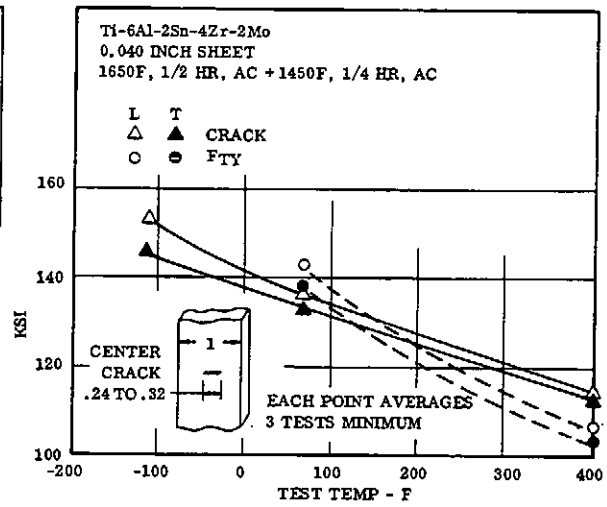


FIG. 3.03712 EFFECT OF TEST TEMPERATURE ON CENTER CRACK TENSILE AND YIELD STRENGTHS OF DUPLEX ANNEALED SHEET (1, pp. 51 AND 285)

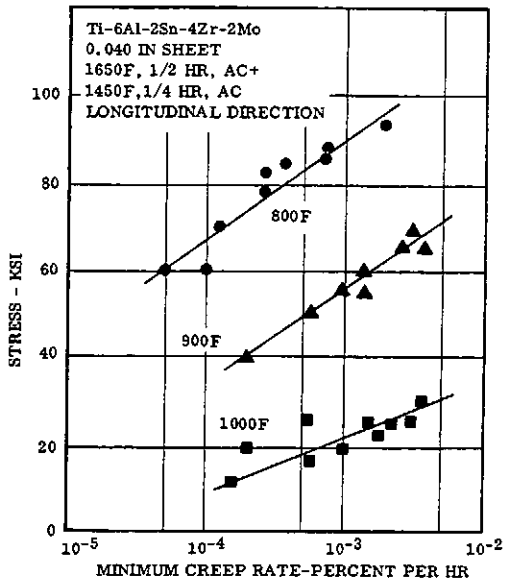


FIG. 3.0411 MINIMUM CREEP RATE CURVES AT 800, 900, AND 1000F, FOR DUPLEX ANNEALED SHEET (1, P. 271)

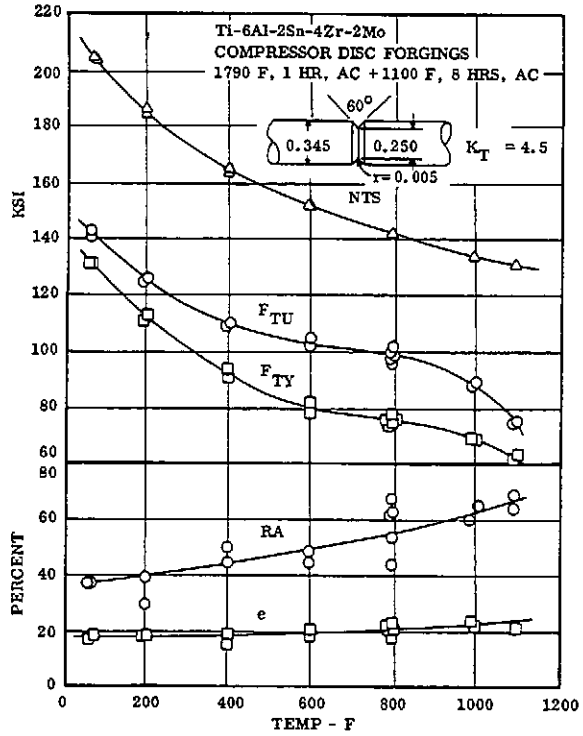


FIG. 3.03713 SMOOTH AND MILD-NOTCH TENSILE PROPERTIES OF DUPLEX ANNEALED COMPRESSOR DISC FORGINGS AT ROOM AND ELEVATED TEMPERATURES. (68)

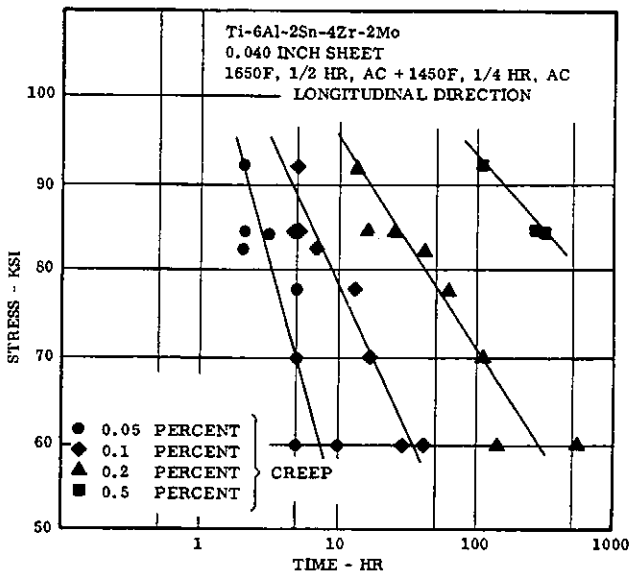


FIG. 3.0421 CREEP DEFORMATION CURVES AT 800F FOR DUPLEX ANNEALED SHEET (1, p. 271)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

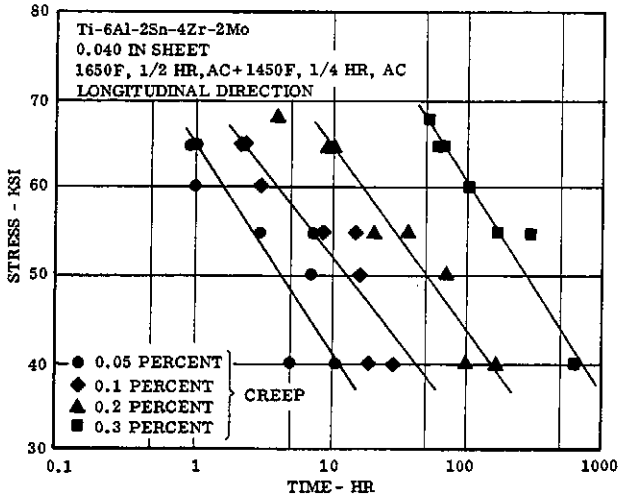


FIG. 3.0422 CREEP DEFORMATION CURVES AT 900F FOR DUPLEX ANNEALED SHEET (1, P. 271)

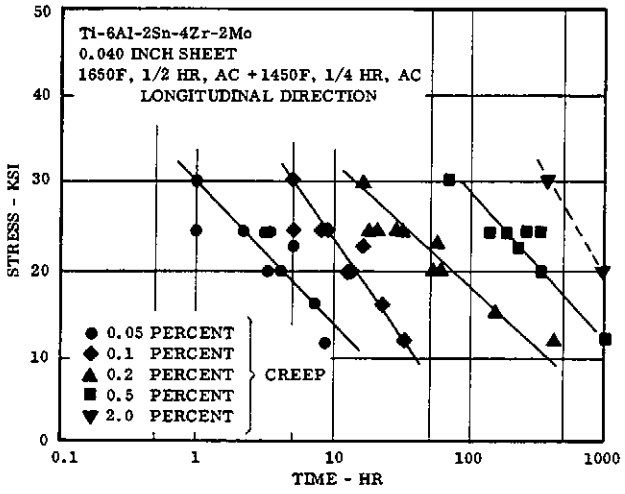


FIG. 3.0423 CREEP DEFORMATION CURVES AT 1000 F FOR DUPLEX ANNEALED SHEET (1, p. 271)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy			Ti-6Al-2Sn-4Zr-2Mo		
Form			Sheet		
Condition			Duplex and Triplex Annealed		
150-Hr Exposure at			Creep Deformation, percent		
Temp F	Stress ksi	Direction	0.040-in Gage	0.080-in Gage	0.125-in Gage
1650 F, 1/2 Hr, AC + 1450 F, 1/4-Hr, AC					
800	65	L	0.18	0.16	0.42(1)
		T	0.22	0.10	0.22
900	45	L	0.23		0.16
		T	0.22	0.22	0.19
1000	25	L	0.33	0.27	0.30
		T	0.39	0.27	0.28
1650 F, 1/2-Hr, AC + 1450 F, 1/4-Hr, AC + 1100 F, 2-Hr, AC					
800	65	L	0.07	0.05	0.06(2)
		T	0.07	0.10	0.06
900	45	L	0.15	0.12	0.19
		T	0.18	0.14	0.14
1000	25	L	0.26	0.24	0.22
		T	0.29		0.19

(1) Creep exposure time was 162.7 Hrs
(2) Creep exposure time was 126 Hrs

TABLE 3.0424 EFFECT OF SHEET THICKNESS ON 150-HOUR CREEP DEFORMATION OF DUPLEX AND TRIPLEX ANNEALED SHEET (13, p. 25)

Alloy				Ti-6Al-2Sn-4Zr-2Mo	
Form				Sheet	
Condition				Triplex Annealed	
				Creep Deformation percent	
Sheet Thickness in	Creep Exposure Temp F	Stress ksi	Time Hr	1650F, 1/2Hr, AC + 1450F, 1/4Hr, AC + 1000F, 8-Hr, AC	1650F, 1/2Hr, AC + 1450F, 1/4Hr, AC + 1100F, 2-Hr, AC
0.040	800	65	150	0.07	0.07
	900	45	150	0.19	0.15
	1000	25	150	0.40	0.26
	900	20	1000	0.11	0.09
	950	15	1000	0.14	0.15
	1000	10	1000	0.33	0.19
0.080	800	65	150	0.10	0.05
	900	45	150	0.14	0.12
	1000	25	150	0.24	0.24
0.125	800	65	150	0.07	0.06
	900	45	150	0.12	0.19
	1000	25	150	0.25	0.22

Results of single longitudinal tests

TABLE 3.0425 EFFECT OF STABILIZATION AGING TEMPERATURE ON CREEP DEFORMATION OF TRIPLEX ANNEALED SHEET OF VARIOUS THICKNESSES (13, p. 18)

Alloy	Ti-6Al-2Sn-4Zr-2Mo		
Form	2 1/4 in Diameter Rolled Bar		
Heat Treatment (1)	150 Hr Exposure at Temp F	Stress ksi	(2) percent
1700F, 1 Hr, WQ + 1100F, 8 Hr, AC	800	65	0.09
	900	45	0.21
	1000	25	0.27
	1100	10	0.31
1750F, 1 Hr, WQ + 1100F, 8 Hr, AC	800	65	0.12
	900	45	0.22
	1000	25	0.29
	1100	10	0.20

(1) Duplex annealed as full sections
(2) Creep Deformation, outside longitudinal tests

TABLE 3.0426 EFFECT OF SOLUTION ANNEAL TEMPERATURE ON 150-HOUR CREEP OF DUPLEX ANNEALED ROLLED BAR (13, p. 46)

Alloy	Ti-6Al-2Sn-4Zr-2Mo		
Form	2 1/4-in Diameter Rolled Bar		
Condition	Duplex Annealed (1)		
Heat Treatment	150-Hr Exposure at Temp F	Stress ksi	(2) percent
1750F, 1 Hr, AC + 1000F, 8 Hr, AC	800	65	0.23
	900	45	0.19
	1000	25	0.18
	1100	10	0.13
1750F, 1 Hr, AC + 1100F, 8 Hr, AC	800	65	0.12
	900	45	0.12
	1000	25	0.11
	1100	10	0.11

(1) Duplex annealed as full sections
(2) Creep Deformation, outside longitudinal tests

TABLE 3.0427 EFFECT OF STABILIZATION ANNEAL TEMPERATURE ON 150-HOUR CREEP OF DUPLEX ANNEALED ROLLED BAR (13, p. 46)

Alloy	Ti-6Al-2Sn-4Zr-2Mo			
Form	1 1/8 in Diameter Bar			
Condition	1650F, 1 Hr, AC + 1100F, 8 Hr, AC			
Creep Exposure Temp F	Creep Exposure Stress ksi	Time to 0.1 percent Creep Hr	Time to 0.5 percent Creep Hr	
600	50	0.044 percent after 3065 Hr		
600	80	0.023 percent after 3045 Hr		
800	59	83.0		
800	69	78.5		
900	55	14.6		
900	55	23.0		
800	75		3220	
800	75		3295	

TABLE 3.0429 CREEP PROPERTIES OF DUPLEX ANNEALED BAR (15)

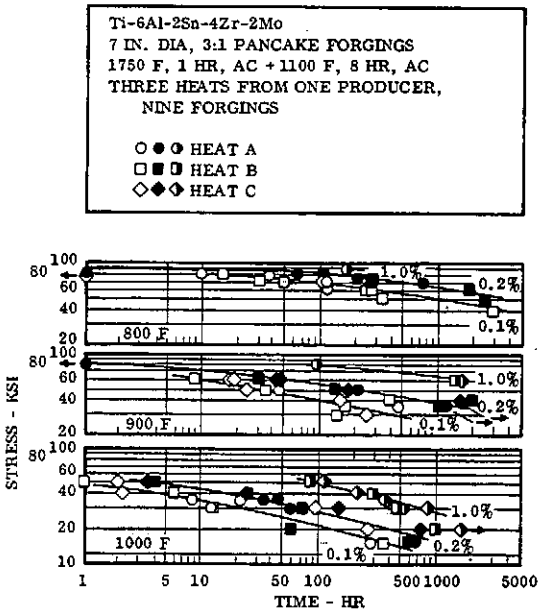


FIG. 3.04212. CREEP DEFORMATION CURVES AT 800 F TO 1000 F FOR DUPLEX ANNEALED PANCAKE FORGINGS. (83)

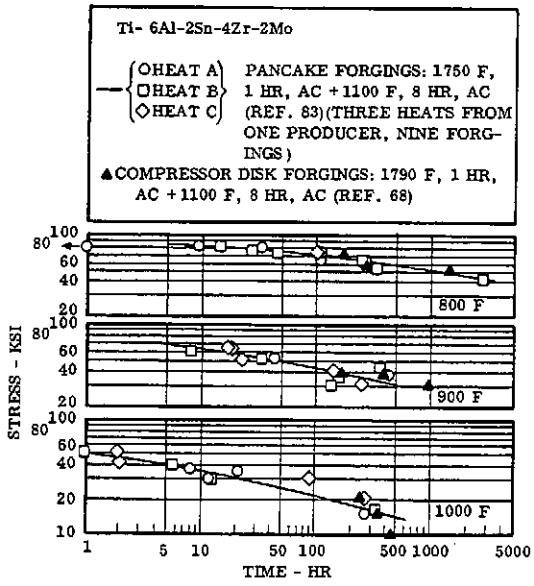


FIG. 3.04214. EFFECT OF SOLUTION ANNEALING TEMPERATURE ON TIME TO 0.1 PERCENT CREEP DEFORMATION AT 800 F, 900 F, AND 1000 F FOR DUPLEX ANNEALED FORGINGS. (83)(68)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy	Ti-6Al-2Sn-4Zr-2Mo		
Form	20-Inch Diameter Compressor Wheel Forging[a]		
Condition	Duplex Annealed		
Stress ksi	Temp F	Hrs to Creep 0.1%	Hrs to Creep 0.2%	150-Hr Creep Deformation %
	1650F, 1 hr, AC + 1100F, 8 hrs, AC			
50	900	27	102	0.261
55	900	38	>150	0.2
45	950	59	>150	0.2
35	1000	15	56	0.368
15	1100	28	56	
	1750F, 1 hr, AC + 1100F, 8 hrs, AC			
50	900	73	Not Reached	0.168
55	900	25	>150	0.2
45	950	60	>150	0.2
35	1000	15	80	0.301
35	1000	47	117	
15	1100	6	37	
	1750F, 1 hr, WQ + 1100F, 8 hrs, AC			
50	900	17	61	0.301
35	1000	2.5	8	1.03

[a]All tests in axial direction.

TABLE 3.04213 EFFECT OF SOLUTION ANNEAL TEMPERATURE AND QUENCH RATE ON CREEP PROPERTIES AT 900F TO 1100F FOR DUPLEX ANNEALED COMPRESSOR WHEEL FORGING (2, p. 11)

Source	(83)	(68)
Alloy	Ti-6Al-2Sn-4Zr-2Mo	
Form	Pancake Forging	Compressor Disk Forging
Condition	1750F, 1 hr, AC + 1100F, 8 hrs, AC	1790F, 1 hr, AC + 1100F, 8 hrs, AC
Time to 2.0% Creep at 1000F, 30 ksi	695 1244	780 679

TABLE 3.04215 EFFECTS OF SOLUTION ANNEAL TEMPERATURE ON TIME TO 2.0 PERCENT CREEP AT 1000F, 30 KSI FOR DUPLEX ANNEALED FORGINGS (83)(68)

Alloy	Ti-6Al-2Sn-4Zr-2Mo	
Form	15 in Diameter Forged Disc	
Condition	Duplex Annealed	
Direction	950F - 35 ksi Exposure: Time to 0.1 percent Plastic Deformation Hr	950F - 35 ksi Exposure: 150-Hr Total Plastic Deformation percent
	1750F, 1-Hr, AC + 1100F, 8 Hr, AC	
Chordal	44	0.280
Radial	17	0.240
	1790F (B-25F), 1-Hr, AC + 1100F, 8-Hr, AC	
Chordal	43	0.110
Radial	37	0.131

TALBE 3.04216 EFFECT OF SOLUTION ANNEALING AT HIGH TEMPERATURE (BETA - 25F) ON CREEP DEFORMATION FOR DUPLEX ANNEALED FORGING (14, p. 17)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

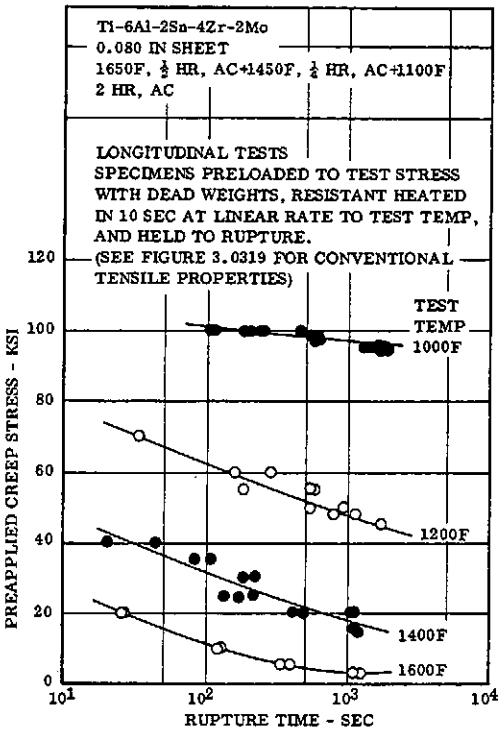


FIG. 3.0431 SHORT-TIME CREEP RUPTURE STRENGTH OF TRIPLEX ANNEALED SHEET SPECIMENS PRELOADED AND RAPIDLY HEATED TO TEST TEMP. (28)

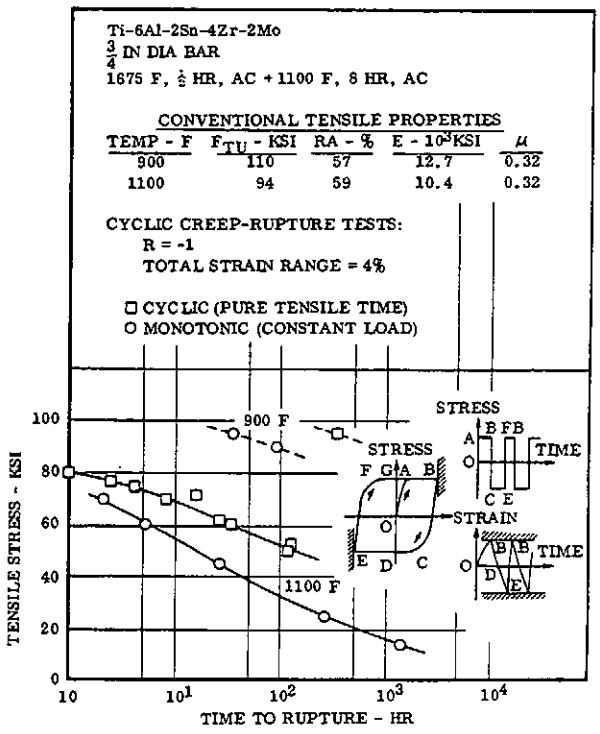


FIG. 3.0433. MONOTONIC CREEP-RUPTURE AND STRAIN-LIMITED CYCLIC CREEP-RUPTURE CURVES AT 900F AND 1100 F FOR DUPLEX ANNEALED BAR, (29) (29)

Alloy		Ti-6Al-2Sn-4Zr-2Mo		
Form		1 1/8 in Diameter Bar		
Condition		1650F, 1 HR, AC + 1100F, 8 Hr, AC		
Creep Exposure Temp F	Stress ksi	Stress Rupture Life-Hr	e percent	RA percent
1000	57.5	347.6	60.0	67.2
		307.5	50.7	63.0
		343.0	45.6	64.3
1000	70.0	94.2	48.1	63.9
		105.0	46.3	67.0
		105.5	48.7	62.5
		113.5	43.3	65.1

TABLE 3.0432 1000 F STRESS RUPTURE PROPERTIES OF DUPLEX ANNEALED BAR (15)

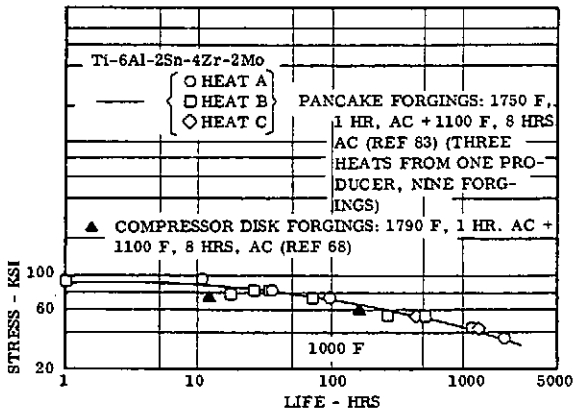


FIG. 3.0434 EFFECT OF SOLUTION ANNEAL TREATMENT ON 1000 F STRESS RUPTURE PROPERTIES OF DUPLEX ANNEALED FORGINGS. (83)(68)

Alloy		Ti-6Al-2Sn-4Zr-2Mo
Form		20-in Diameter Compressor Wheel Forging
Condition		Duplex Annealed
		RT Notch Stress Rupture, K_t=3.8
Location	Direction	Stress at Failure ksi / Time to Failure Hr
1650 F, 1-Hr, AC + 1100 F, 8-Hr, AC		
Rim	Axial	190 / 3.3
Web	Radial	190 / 2.0
1750 F, 1-Hr, AC + 1100 F, 8-Hr, AC		
Web (Center punch-out)	Radial	200 / 2.5
		200 / 1.0
1750 F, 1-Hr, WQ + 1100 F, 8-Hr, AC		
Rim	Axial	200 / >5.0
Web	Radial	200 / >5.0
1775 F, 1-Hr, AC + 1100 F, 8-Hr, AC		
Web (Center punch out)	Radial	200 / 1.5
		200 / 1.4

Note: Stress increased from 150-ksi in 10-Ksi increments every 5-Hrs

TABLE 3.0435 EFFECT OF SOLUTION ANNEAL TEMPERATURE ON ROOM TEMPERATURE MILD-NOTCH STRESS RUPTURE PROPERTIES OF DUPLEX ANNEALED COMPRESSOR WHEEL FORGING, (11, p. 12).

Alloy			Ti-6Al-2Sn-4Zr-2Mo
Form			20-in Diameter Compressor Wheel Forging
Condition			Beta Forged + Duplex Annealed
			RT Notch Stress Rupture, K_t=3.8
Location	Direction	Wheel No.	Stress at Failure ksi / Time to Failure Hr
1650 F, 1-Hr, AC + 1100 F, 8-Hr, AC			
Rim	Axial	1	200 / 3.25
Web	Radial	1	190 / 1.5
1750 F, 1-Hr, WQ + 1100 F, 8-Hr, AC			
Web	Radial	2	200 / >5.0
1775 F, 1-Hr, WQ + 1100 F, 8-Hr, AC			
Web	Radial	1	200 / 1.0
Web	Radial	1	200 / >5.0
Web	Radial	2	200 / >5.0
Web	Radial	2	200 / >5.0

Note: Stress increased from 150-ksi in 10-ksi increments every 5-Hrs

TABLE 3.0436 EFFECT OF SOLUTION ANNEAL TEMPERATURE ON ROOM TEMPERATURE MILD-NOTCH STRESS RUPTURE PROPERTIES OF DUPLEX ANNEALED, BETA FORGED COMPRESSOR WHEEL FORGING, (11, p. 12).

Alloy			Ti-6Al-2Sn-4Zr-2Mo					
Form			18.5 in Diameter Compressor Hub Forging					
Condition			1750F, 1 Hr, AC + 1100F, 8 Hr, AC + Re-Heat Treated as Noted					
			RT Tensile Properties				(1) - *	
Re-Treatment	Location	Direction	F_{tu} ksi	F_{ty} ksi	e percent	RA percent	(a)	(b)
(c)	Rim	Tang.	144.6	134.8	14.0	40.1		
	Web	Rad.	148.6	135.8	16.0	38.2		
	Rim	Axial					170	2.2
	Web	Axial					180	2.0
(d)	Rim	Tang.	153.0	137.0	16.5	34.4		
	Web	Rad.	147.4	134.0	15.0	33.8		
	Rim	Axial					190	.25
	Web	Axial					180	.75

(1) R T notch stress rupture, K_t =3.8
* Stress increased from 150-ksi in 10-ksi increments every 5 hours.
(a) Stress at failure - ksi
(b) Time to failure-hr
(c) 1750F, 1-Hr, AC +1100F, 8-Hr, AC
(d) 1790F (Beta-25F), 1 Hr, AC + 1100F, 8 Hr, AC

TABLE 3.0437 EFFECT OF SOLUTION ANNEALING AT HIGH TEMPERATURE (BETA - 25 F) ON ROOM TEMPERATURE TENSILE AND MILD-NOTCH STRESS RUPTURE PROPERTIES OF DUPLEX ANNEALED COMPRESSOR HUB FORGING (12, p. 16)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

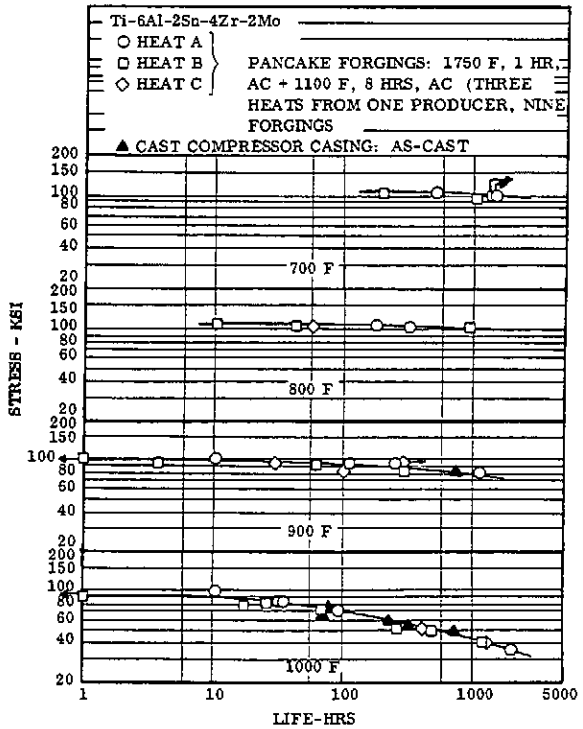


FIG. 3.0439 STRESS RUPTURE PROPERTIES AT 700 F TO 1000 F FOR DUPLEX ANNEALED PANCAKE FORGINGS AND AS - CAST COMPRESSOR CASING. (83)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

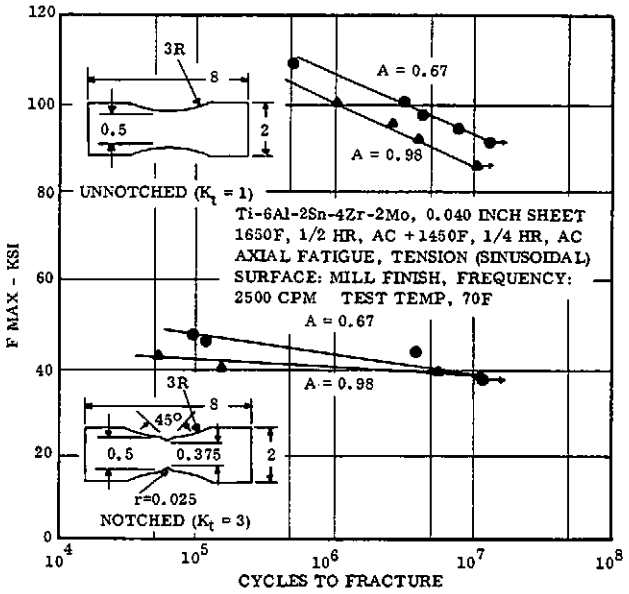


FIG. 3.051 AXIAL LOAD SMOOTH AND NOTCH FATIGUE PROPERTIES AT 70F FOR DUPLEX ANNEALED SHEET (1, pp. 277-278)

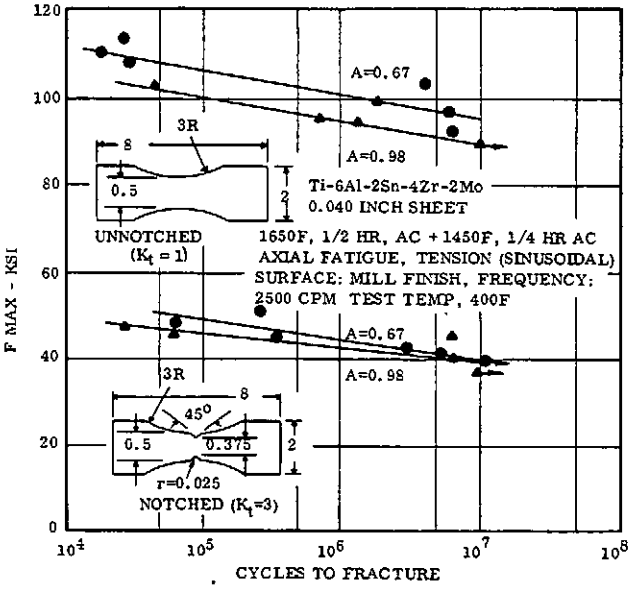


FIG. 3.052 AXIAL LOAD SMOOTH AND NOTCH FATIGUE PROPERTIES AT 400F FOR DUPLEX ANNEALED SHEET (1, pp. 277-278)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

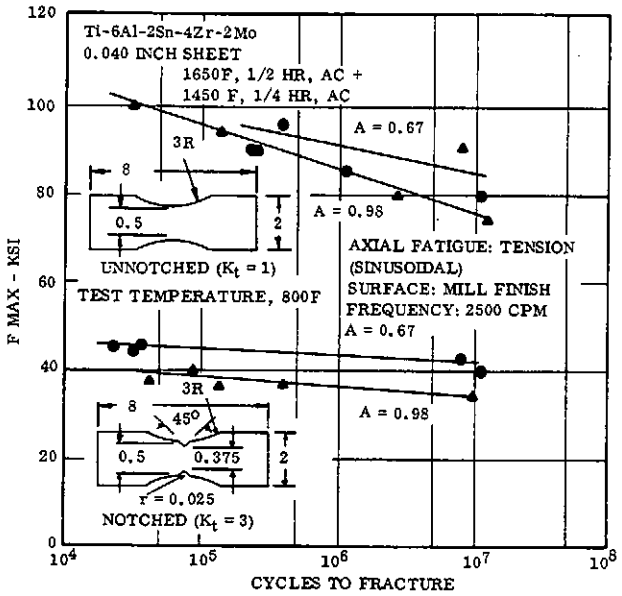


FIG. 3.053 AXIAL LOAD SMOOTH AND NOTCH FATIGUE PROPERTIES AT 800 F FOR DUPLEX ANNEALED SHEET (1,pp. 276-279)

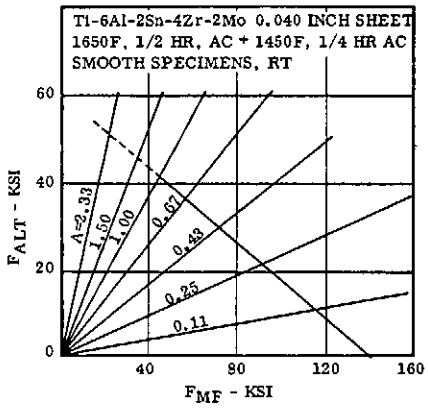


FIG. 3.054 ROOM TEMPERATURE STRESS RANGE DIAGRAM AT 10^7 CYCLES FOR SMOOTH SPECIMENS OF DUPLEX ANNEALED SHEET (10,p.13)

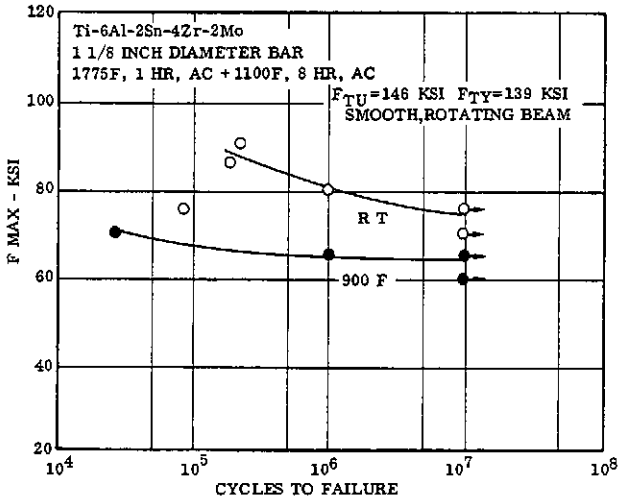


FIG. 3.055 ROOM TEMPERATURE AND 900 F SMOOTH FATIGUE PROPERTIES FOR DUPLEX ANNEALED BAR (15)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

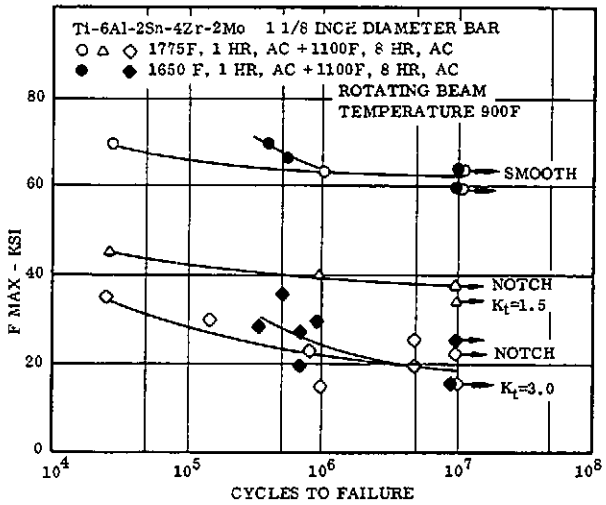


FIG. 3.056 900 F SMOOTH AND NOTCH FATIGUE PROPERTIES FOR DUPLEX ANNEALED BAR (15)

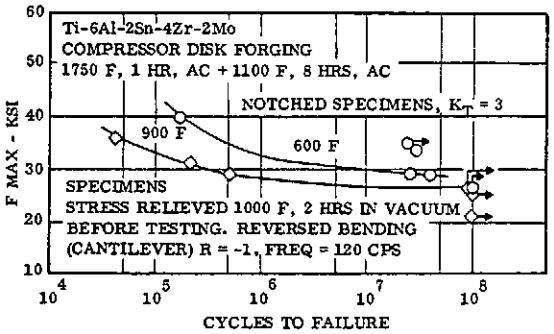


FIG. 3.058 NOTCH FATIUGE STRENGTH AT 600 F AND 900 F FOR DUPLEX ANNEALED COMPRESSOR DISK FORGING. (68)

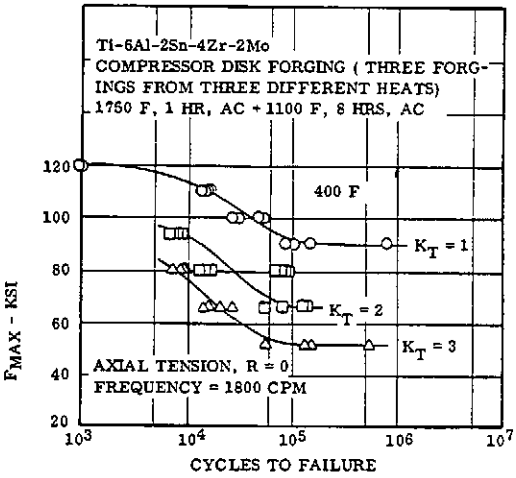


FIG. 3.059 400 F SMOOTH AND NOTCH FATIGUE PROPERTIES FOR DUPLEX ANNEALED COMPRESSOR DISK FORGINGS. (68)

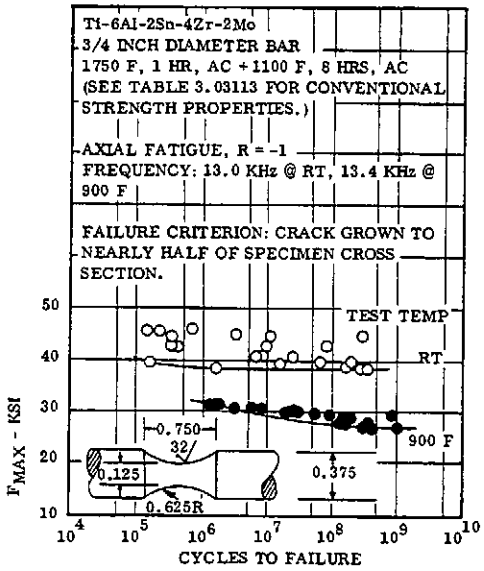


FIG. 3.057 HIGH-FREQUENCY AXIAL-LOAD FATIGUE PROPERTIES AT ROOM TEMPERATURE AND 900 F FOR DUPLEX ANNEALED BAR. (24)

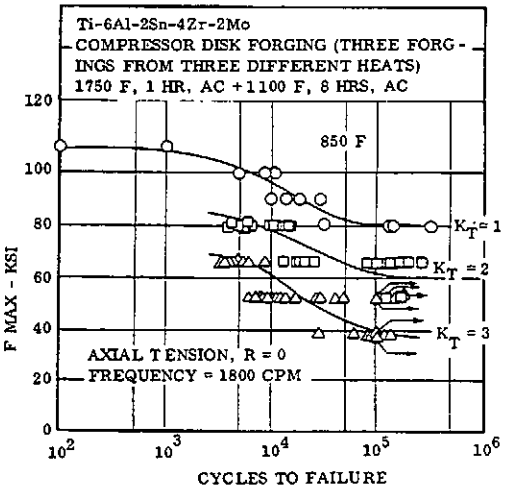


FIG. 3.0510 850 F SMOOTH AND NOTCH FATIGUE PROPERTIES FOR DUPLEX ANNEALED COMPRESSOR DISK FORGINGS. (68)

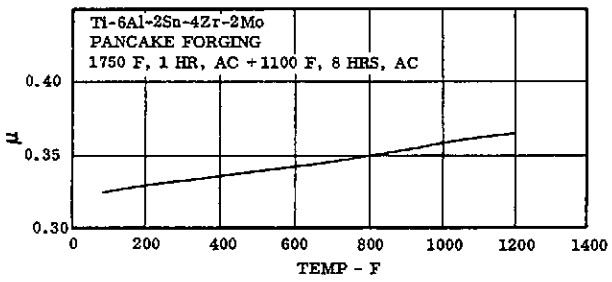
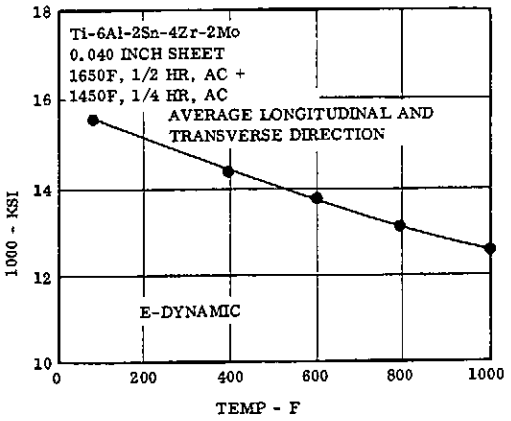


FIG. 3.0611 POISSON'S RATIO FOR DUPLEX ANNEALED PANCAKE FORGING. (83)



	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

FIG. 3.0623 DYNAMIC TENSILE MODULUS OF ELASTICITY OF DUPLEX ANNEALED SHEET AT ROOM AND ELEVATED TEMPERATURE (1, p. 143)

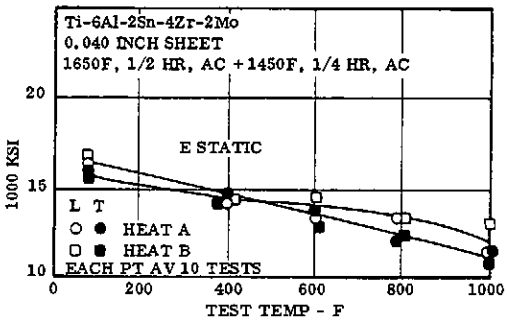


FIG. 3.0621 STATIC TENSILE MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES FOR DUPLEX ANNEALED SHEET (1, p. 51)

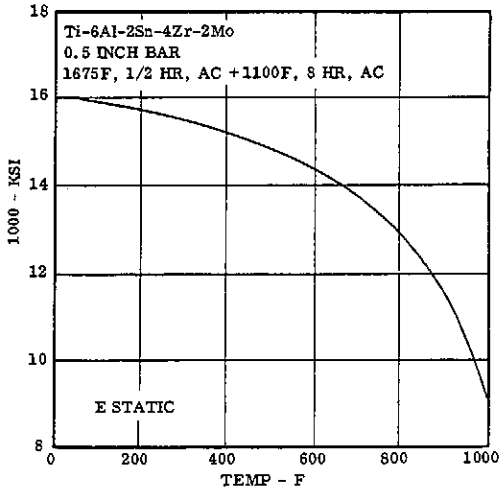


FIG. 3.0624 STATIC TENSILE MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES FOR DUPLEX ANNEALED BAR (2, p. 12)

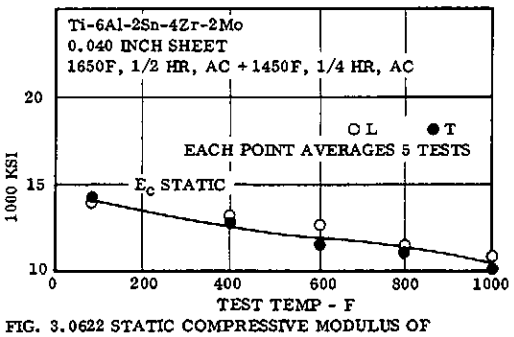


FIG. 3.0622 STATIC COMPRESSIVE MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES FOR DUPLEX ANNEALED SHEET (1, p. 67)

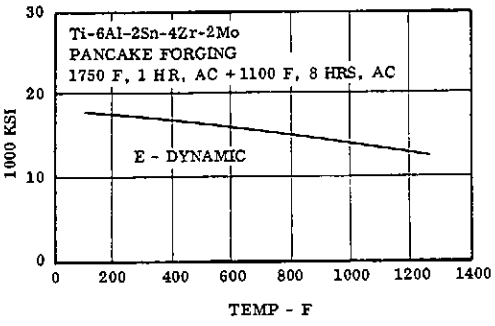


FIG. 3.0626 DYNAMIC TENSILE MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES FOR DUPLEX ANNEALED PANCAKE FORGING. (83)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Alloy			Ti-6Al-2Sn-4Zr-2Mo			
Form			2 1/4 in Square Forged Bar			
Condition			Beta or Alpha-Beta Forged + Duplex Annealed			
150-Hr Exposure at			Subsequent RT Tensile Properties (outside longitudinal)[a]			
Temp F	Stress ksi	Deformation percent	F_{tu} ksi	F_{ty} ksi	e (1-in) percent	RA percent
Alpha-Beta Forged +1750F, 1-Hr, AC + 1100F, 24-Hr, AC						
None			113.3	135.3	20.0	41.5
850	70	0.25	143.4	134.2	20.0	45.1
900	55	0.28	146.0	134.5	19.0	39.8
950	45	0.29	143.7	132.2	18.0	36.0
1050	30	2.43	147.6	136.0	18.0	33.9
Beta Forged +1750F, 1-Hr, AC +1100F, 24-Hr, AC						
None			144.0	134.8	20.5	45.5
850	70	0.13	147.3	135.2	15.5	34.2
900	55	0.18	144.8	133.0	16.5	35.1
950	45	0.21	145.6	133.8	16.5	36.7
1050	30	0.52	144.0	133.1	17.5	33.8
Alpha-Beta Forged +1875F (in Beta Field), 1-Hr, AC +1100F, 24-Hr, AC						
None			139.0	126.4	11.5	29.9
850	70	0.16	138.9	130.4	14.5	26.7
900	55	0.17	146.1	134.6	14.0	23.3
950	45	0.16	146.1	135.2	13.0	23.3
(a) 1050	30	0.25	145.5	136.9	12.5	26.7

Tested after exposure without surface conditioning

TABLE 4.0121 EFFECT OF BETA FORGING AND BETA ANNEALING ON ELEVATED TEMPERATURE STABILITY OF DUPLEX ANNEALED FORGED BAR, (13, pp. 69-70).

Alloy				Ti-6Al-2Sn-4Zr-2Mo			
Form				Forging			
Condition				1750F, 1 Hr, AC + 1100F, 8 Hr, AC			
	1000-Hr Exposure at			Subsequent RT Tensile Properties			
Specimen Grain Structure	Temp F	Stress ksi	Deformation percent	F_{tu} ksi	F_{ty} ksi	e percent	RA percent
Equiaxed (1)	None			143.5	131.9	17.0	43.4
Transformed (2)	None			141.1	129.0	13.5	43.0
Equiaxed	800	65	0.195	142.4	131.4	20.0	40.6
Transformed	800	65	0.113	141.3	130.4	17.0	39.8
Equiaxed	900	50	0.250	148.9	134.1	17.0	36.2
Transformed	900	50	0.168	149.4	136.9	18.0	28.1

(1) Sub-transus processed
(2) Beta processed

TABLE 4.0122 EFFECT OF PROCESSED STRUCTURE ON ELEVATED TEMPERATURE STABILITY OF DUPLEX ANNEALED FORGING, (10, p. 12).

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy		Ti-6Al-2Sn-4Zr-2Mo		
Forge		Anneal Treatment	Beta Recrystallization percent	Average Grain Diameter[2] inch
Temp	Reduction			
2300F	One 50%	None	5	
2300F	One 50%	2300F, 1/2 hr	75	
2300F	One 50%	2300F, 1 hr	75	
2300F	Two 50%[1]	None	50	
2300F	Two 50%	1900F, 1 hr	95	
2300F	Two 50%	2300F, 1 hr	100	0.55
2200F	One 50%	None	3	
2200F	One 50%	2200F, 1/2 hr	75	
2200F	One 50%	2200F, 1 hr	75	
2200F	Two 50%	None	40	
2200F	Two 50%	1900F, 1 hr	95	
2200F	Two 50%	2200F, 1 hr	100	0.049
2100F	One 50%	None	1	
2100F	One 50%	2100F, 1/2 hr	75	
2100F	One 50%	2100F, 1 hr	75	
2100F	Two 50%	None	30	
2100F	Two 50%	1900F, 1 hr	95	
2100F	Two 50%	2100F, 1 hr	100	0.049
2000F	One 50%	None	0	
2000F	One 50%	2000F, 1/2 hr	75	
2000F	One 50%	2000F, 1 hr	75	
2000F	Two 50%	None	10	
2000F	Two 50%	1900F, 1 hr	95	
2000F	Two 50%	2000F, 1 hr	100	0.047

(1) Reheated 1/2-hr at forging temperature between successive 50% forging reductions.
(2) Determined by counting the number of grain boundaries intersecting a line 3-inches in length. Initial, as-cast grain diameter of ingot was 0.27 inch.

TABLE 4.0123 HIGH TEMPERATURE FORGING AND RECRYSTALLIZATION RESULTS, (86).

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy		Ti-6Al-2Sn-4Zr-2Mo	
Forge		Anneal Treatment	Beta Recrystallization percent
Temp	Reduction		
1950F	30%	None	0
1950F	30%	1900F, 1 hr	5
1950F	30%	1950F, 1 hr	70
1950F	30%	2000F, 1 hr	80
1950F	50%	None	0
1950F	50%	1900F, 1 hr	5
1950F	50%	1950F, 1 hr	90
1950F	50%	2000F, 1 hr	95
1900F	30%	None	0
1900F	30%	1900F, 1 hr	5
1900F	30%	1950F, 1 hr	90
1900F	30%	2000F, 1 hr	90
1900F	50%	None	0
1900F	50%	1900F, 1 hr	10
1900F	50%	1950F, 1 hr	95
1900F	50%	2000F, 1 hr	95
1850F	30%	None	0
1850F	30%	1900F, 1 hr	5
1850F	30%	1950F, 1 hr	90
1850F	30%	2000F, 1 hr	90
1850F	50%	None	0
1850F	50%	1900F, 1 hr	20
1850F	50%	1950F, 1 hr	95
1850F	50%	2000F, 1 hr	95
1800F	30%	None	0
1800F	30%	1900F, 1 hr	95
1800F	30%	1950F, 1 hr	95
1800F	30%	2000F, 1 hr	95
1800F	50%	None	0
1800F	50%	1900F, 1 hr	95
1800F	50%	1950F, 1 hr	95
1800F	50%	2000F, 1 hr	95

TABLE 4.0124 LOWER TEMPERATURE FORGING AND RECRYSTALLIZATION RESULTS, (86).

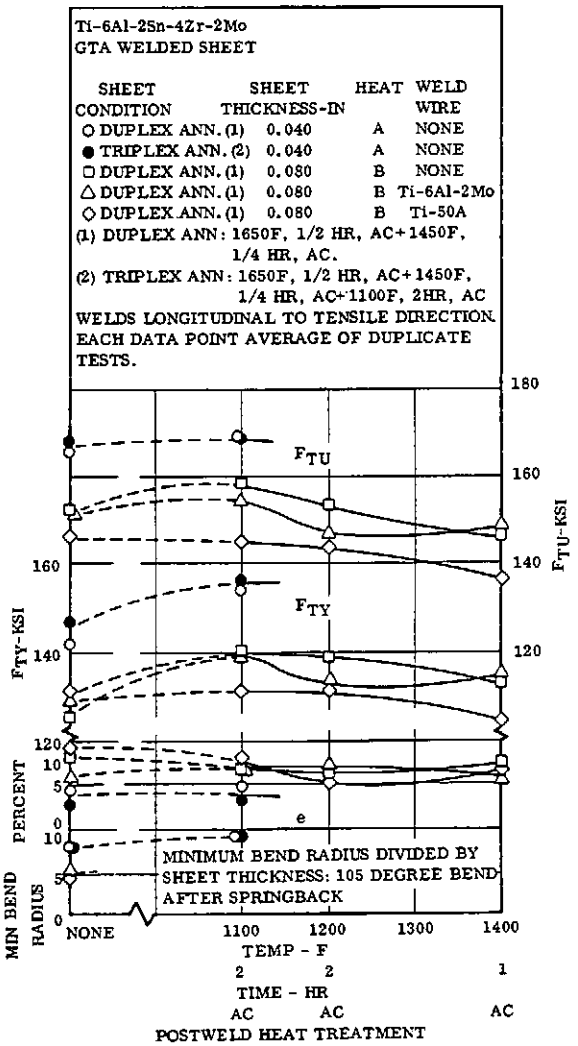


FIG. 4.036 EFFECT OF HEAT TREATMENT AND FILLER WIRE COMPOSITION ON ROOM TEMPERATURE TENSILE AND BEND PROPERTIES OF WELDED SHEET. (13, P.34)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti·6·2·4·2

Alloy	Ti-6Al-2Sn-4Zr-2Mo						
Form	GTA Welded Sheet						
Sheet Condition	Sheet Thickness Inch	Heat	Weld Wire	Postweld Heat Treatment	F_{ty} ksi (1)	Weld NTS ksi (2)	HAZ NTS ksi (2)
Duplex Ann (3)	0.040	A	None	None	142	116	116
Triplex Ann (4)	0.040	A	None	None	146	122	121
Duplex Ann (3)	0.040	A	None	1100F, 2 hr, AC	154	112	106
Triplex Ann (4)	0.040	A	None	1100F, 2 hr, AC	155	104	118
Duplex Ann (3)	0.080	B	None	None	125	134	---
Duplex Ann (3)	0.080	B	None	1200F, 2 hr, AC	138	128	---
Duplex Ann (3)	0.080	B	None	1400F, 1 hr, AC	132	122	---
Duplex Ann (3)	0.080	B	Ti-6Al-2Mo	None	128	134	---
Duplex Ann (3)	0.080	B	Ti-50A	None	129	146	---

(1) Welds longitudinal to tensile direction.
(2) Welds transverse to tensile direction (see illustration below).
(3) Duplex Ann: 1650F, ½ hr, AC + 1450F, ¼ hr, AC.
(4) Triplex Ann: 1650F, ½ hr, AC + 1450F, ½ hr, AC + 1100F, 2 hr, AC.
All values average duplicate tests.

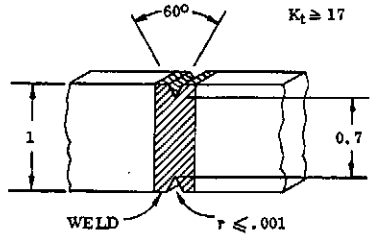


TABLE 4.037 EFFECT OF HEAT TREATMENT ON ROOM TEMPERATURE SHARP NOTCH TENSILE PROPERTIES OF WELDED SHEET. (13, pp.34,35)

Alloy	Ti-6Al-2Sn-4Zr-2Mo						
Form	GTA Welded 0.040 inch Sheet						
Sheet Condition	Postweld Heat Treatment	150 hour Exposure at: Temp F	Stress ksi	Deformation percent	Subsequent RT Tensile Properties F_{tu} ksi	F_{ty} ksi	e (1-in) percent
Duplex Ann (1)	None	None			166	142	4.5
Triplex Ann (2)	None	None			168	146	3.0
Duplex Ann (1)	1100F, 2 hr, AC	None			170	154	5.0
Triplex Ann (2)	1100F, 2 hr, AC	None			170	155	3.0
Duplex Ann (1)	None	800	65	0.209	182	163	3.5
Triplex Ann (2)	None	800	65	0.185	172	155	2.5
Duplex Ann (1)	1100F, 2 hr, AC	800	65	0.088	168	156	3.5
Triplex Ann (2)	1100F, 2 hr, AC	800	65	0.092	174	160	4.0
Duplex Ann (1)	None	900	45	0.452	180	164	4.0
Triplex Ann (2)	None	900	45	0.510 (3)	173	160	1.5
Duplex Ann (1)	1100F, 2 hr, AC	900	45	0.177	173	160	2.5
Triplex Ann (2)	1100F, 2 hr, AC	900	45	0.199	177	163	3.0
Duplex Ann (1)	None	1000	25	0.706 (3)	181	168	3.0
Triplex Ann (2)	None	1000	25	0.610	174	164	2.0
Duplex Ann (1)	1100F, 2 hr, AC	1000	25	0.407	172	162	2.0
Triplex Ann (2)	1100F, 2 hr, AC	1000	25	0.356	174	163	2.0

(1) Duplex Ann: 1650F, ½ hr, AC + 1450F, ¼ hr, AC.
(2) Triplex Ann: 1650F, ½ hr, AC + 1450F, ¼ hr, AC + 1100F, 2 hr, AC.
(3) Single values: all others average of duplicate tests.
Welds longitudinal to tensile direction, tested in as-exposed condition.

TABLE 4.038 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF WELDED SHEET GIVEN VARIOUS HEAT TREATMENTS. (13, p. 36)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Alloy		Ti-6Al-2Sn-4Zr-2Mo			
Form		GTA Welded 0.040 inch Sheet			
Sheet Condition	Postweld Heat Treatment	Test Temp F	F_{tu} ksi	F_{ty} ksi	e (2-in) percent
Duplex Ann (1)	None	RT (3)	166	142	4.5
Triplex Ann (2)	None	RT (3)	168	146	3.0
Duplex Ann (1)	1100F, 2 hr, AC	RT (3)	170	154	5.0
Triplex Ann (2)	1100F, 2 hr, AC	RT (3)	170	155	3.0
Duplex Ann (1)	None	600 (4)	110	87	7.0
Triplex Ann (2)	None	600 (4)	118	92	7.0
Duplex Ann (1)	1100F, 2 hr, AC	600 (4)	120	96	7.5
Triplex Ann (2)	1100F, 2 hr, AC	600 (4)	117	91	7.5
Duplex Ann (1)	None	800 (4)	114	85	8.5
Triplex Ann (2)	None	800 (4)	111	87	8.0
Duplex Ann (1)	1100F, 2 hr, AC	800 (4)	120	95	7.5
Triplex Ann (2)	1100F, 2 hr, AC	800 (4)	112	89	7.5

(1) Duplex Ann: 1650F, ½ hr, AC + 1450F, ¼ hr, AC.
(2) Triplex Ann: 1650F, ½ hr, AC + 1450F, ¼ hr, AC + 1100F, 2 hr, AC.
(3) Welds longitudinal to tensile direction.
(4) Welds transverse to tensile direction.
All values average duplicate tests.

TABLE 4.039 ELEVATED TEMPERATURE TENSILE PROPERTIES OF WELDED SHEET. (30, pp. 7,5)

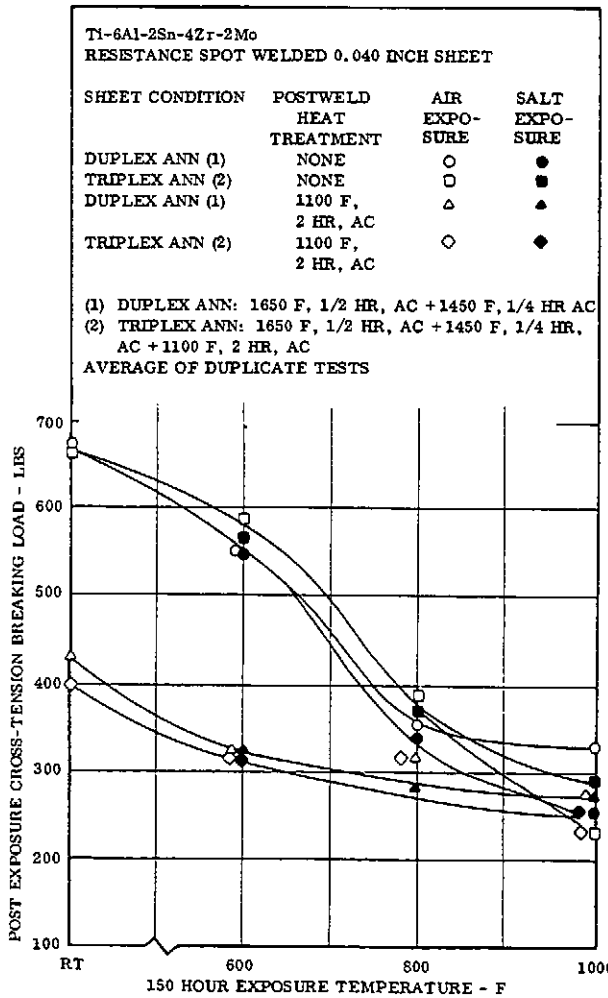


FIG. 4.0310 EFFECT OF HEAT TREATMENT AND THERMAL EXPOSURE, WITH AND WITHOUT A SALT ENVIRONMENT, ON ROOM TEMPERATURE CROSS-TENSION STRENGTH OF SINGLE RESISTANCE SPOT WELDS (30, p. 13)

Alloy	Ti-6Al-2Sn-4Zr-2Mo		
Form	Resistance Spot Welded 0.040 inch Sheet		
		Breaking Load - Lbs (3)	
Sheet Condition	Postweld Heat Treatment	Shear-Tension	Cross-Tension
Duplex Ann (1)	None	2190	670
Triplex Ann (2)	None	2080	660
Duplex Ann (1)	1100F, 2 hr, AC	1660	440
Triplex Ann (2)	1100F, 2 hr, AC	1650	400

(1) Duplex Ann: 1650F, ½ hr, AC + 1450F, ½ hr, AC.
(2) Triplex Ann: 1650F, ½ hr, AC + 1450F, ½ hr, AC + 1100F, 2 hr, AC
(3) Average of triplicate tests.

TABLE 4.0311 ROOM TEMPERATURE SHEAR-TENSION AND CROSS-TENSION STRENGTHS OF SINGLE RESISTANCE SPOT WELDS GIVEN VARIOUS HEAT TREATMENTS. (13, p. 38)

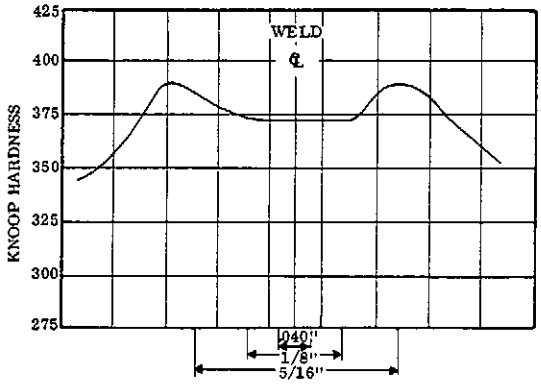


FIG. 4:0314 MICROHARDNESS OF WELD CROSS SECTION IN 0.025 INCH THICK Ti-6Al-2Sn-4Zr-2Mo SHEET. (27 p 33)

Ti
6 Al
2 Sn
4 Zr
2 Mo

Ti-6-2-4-2

Alloy	Ti-6Al-2Sn-4Zr-2Mo			
Form	GTA Welded Sheet			
			Ratio: Minimum Bend Radius to Sheet Thickness (1)	
			Weld Cooling Rate	
Sheet Condition	Sheet Thickness inch	Heat	Slow	Fast (2)
Triplex Ann (3)	0.038	A	10.0	10.0
Duplex Ann (4)	0.080	A	7.8	9.4
Duplex Ann (4)	0.125	A	7.0	> 8.0
Triplex Ann (3)	0.050	B	10.0	12.5
Duplex Ann (4)	0.025	C	7.5	10.0
Duplex Ann (4)	0.025	D	10.0	11.0
Triplex Ann (3)	0.025	D	7.5	10.0
Triplex Ann (3)	0.040	D	10.9	>12.5
Duplex Ann (4)	0.060	D	10.0	12.5
Duplex Ann (4)	0.080	D	9.4	10.2
Triplex Ann (3)	0.080	D	10.9	>12.5

(1) Weld transverse to bend axis.
(2) Copper chill fixtures employed.
(3) Triplex Ann: 1650F, ½ hr, AC + 1450F, ½ hr, AC + 1100F, 2 hr, AC
(4) Duplex Ann: 1650F, ½ hr, AC + 1450F, ½ hr, AC.

TABLE 4.0312 MINIMUM BEND RADII OF DUPLEX AND TRIPLEX ANNEALED SHEET OF VARIOUS THICKNESSES FROM SEVERAL HEATS, WELDED AND COOLED AT TWO DIFFERENT RATES FROM THE WELD CYCLE. (30, p. 20)

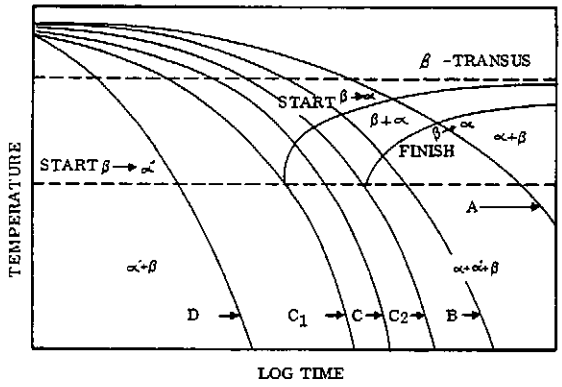


FIG. 4.0313 HYPOTHETICAL COOLING CURVES A, B, C_2, C C_1 AND D, SUPERIMPOSED ON SCHEMATIC CONTINUOUS-COOLING-TRANSFORMATION (CCT) DIAGRAM FOR AN ALPHA-LEAN BETA TITANIUM ALLOY. (27, p 21)

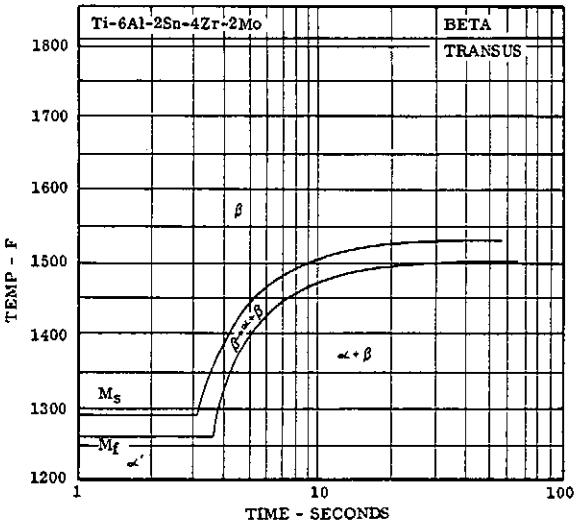
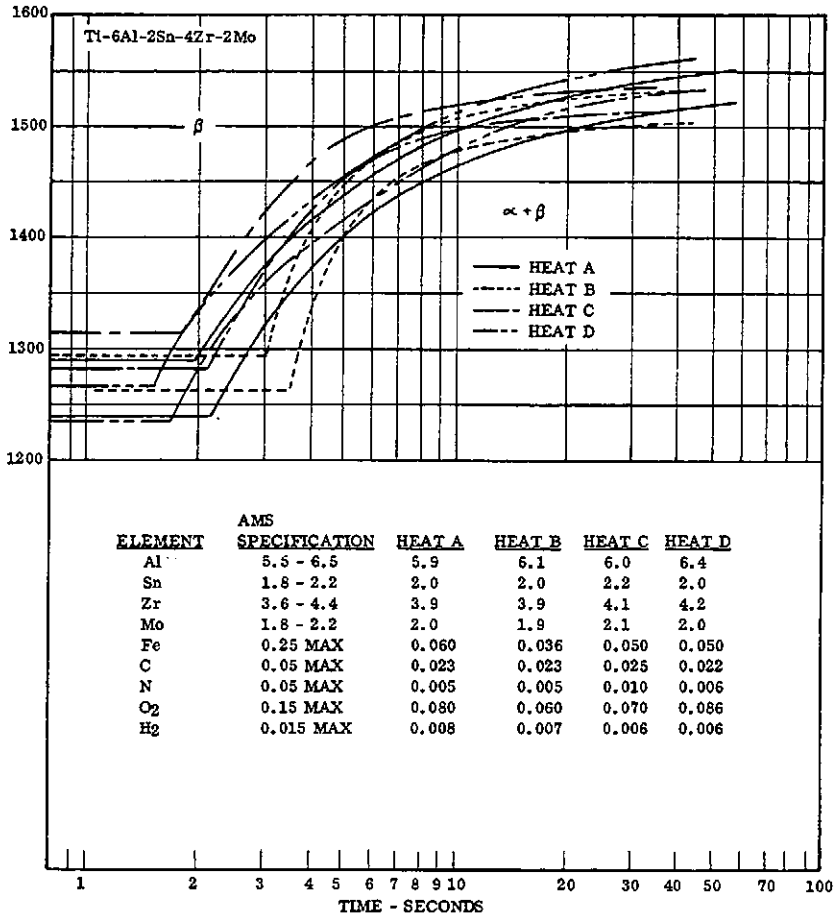


FIG. 4.0315 CONTINUOUS-COOLING-TRANSFORMATION (CCT) DIAGRAM FOR Ti-6Al-2Sn-4Zr-2Mo. (27, p 28)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti·6·2·4·2



ELEMENT	AMS SPECIFICATION	HEAT A	HEAT B	HEAT C	HEAT D
Al	5.5 - 6.5	5.9	6.1	6.0	6.4
Sn	1.8 - 2.2	2.0	2.0	2.2	2.0
Zr	3.6 - 4.4	3.9	3.9	4.1	4.2
Mo	1.8 - 2.2	2.0	1.9	2.1	2.0
Fe	0.25 MAX	0.060	0.036	0.050	0.050
C	0.05 MAX	0.023	0.023	0.025	0.022
N	0.05 MAX	0.005	0.005	0.010	0.006
O_2	0.15 MAX	0.080	0.060	0.070	0.086
H_2	0.015 MAX	0.008	0.007	0.006	0.006

FIGURE 4.0316 EFFECT OF COMPOSITIONAL VARIATIONS WITHIN SPECIFICATION ON CONTINUOUS-COOLING-TRANSFORMATION (CCT) DIAGRAM FOR Ti-6Al-2Sn-4Zr-2Mo (27, pp. 24, 25, 26 and 27)

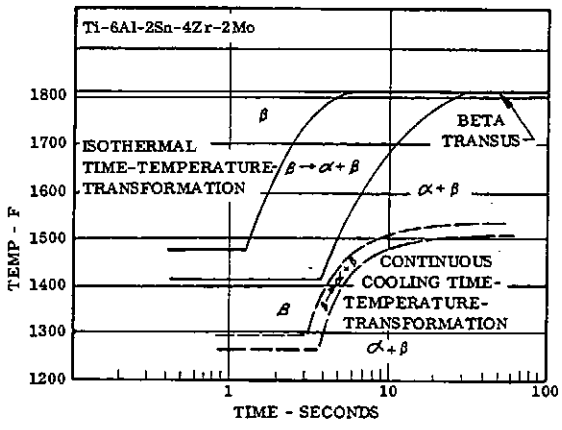


FIG. 4.0317 COMPARISON OF CONTINUOUS-COOLING-TRANSFORMATION (CCT) DIAGRAM AND ISOTHERMAL-TRANSFORMATION (TTT) DIAGRAM FOR Ti-6Al-2Sn-4Zr-2Mo ALLOY. (27, p. 28)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

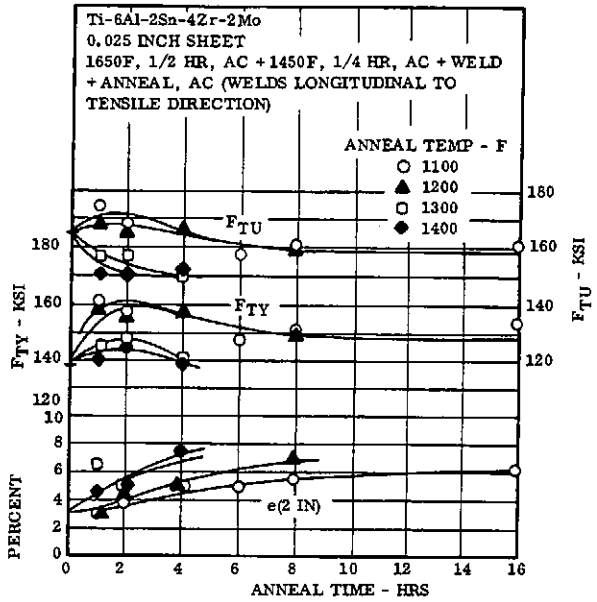


FIG. 4.0318 EFFECT OF POSTWELD ANNEAL TEMPERATURE AND TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF WELDED DUPLEX ANNEALED 0.025 INCH SHEET (30, p.25)

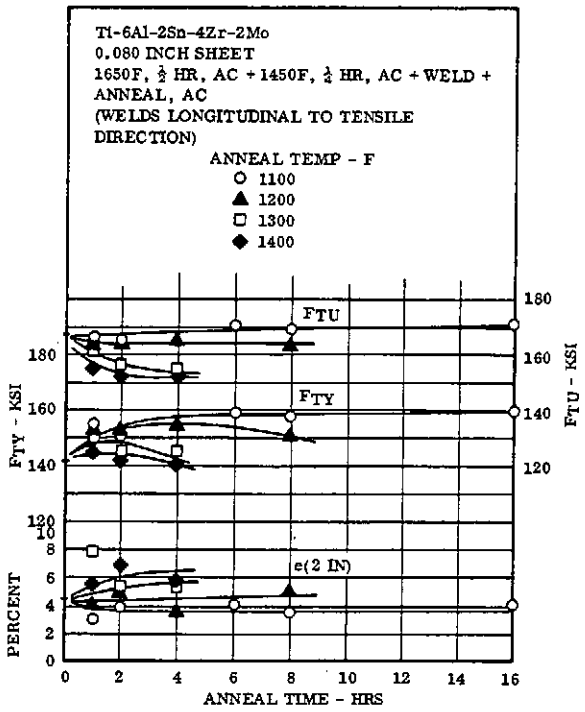


FIG. 4.0319 EFFECT OF POSTWELD ANNEAL TEMPERATURE AND TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF WELDED DUPLEX ANNEALED 0.080 INCH SHEET (30, p. 25)

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

Alloy	Ti-6Al-2Sn-4Zr-2Mo					
Form	Welded Sheet					
Condition	1650F, ½ Hr, AC + 1450F, ½ Hr, AC + Weld + Anneal, 2 Hr, AC					
Postweld Anneal Temp - F	RT Tensile Properties (1)					
	Unexposed			Exposed 150 Hr at 1000F		
	F_{tu} - ksi	F_{ty} - ksi	e (2-in) - %	F_{tu} - ksi	F_{ty} - ksi	e (2-in) - %
0.025 inch Sheet						
As Welded	164.3	138.8	3.0	167.1	157.9	2.8
1100	168.5	157.2	3.8	167.8	160.9	2.5
1200	165.1	155.3	4.5	165.8	158.8	3.0
1300	157.1	147.5	5.0	159.0	151.4	4.0
1400	150.0	144.8	5.0	155.4	150.6	4.0
0.080 inch Sheet						
As Welded	165.6	141.6	4.3	175.3	153.4	3.0
1100	164.5	150.2	3.8	173.6	165.1	2.3
1200	163.0	152.8	4.8	170.2	160.9	2.3
1300	155.6	145.0	5.3	165.6	156.0	5.5
1400	152.0	141.5	6.8	162.4	152.8	3.8

(1) Welds longitudinal to tensile direction.

TABLE 4.0320 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF WELDED DUPLEX ANNEALED SHEET POSTWELD ANNEALED FOR TWO HOURS AT VARIOUS TEMPERATURES. (30, p.25)

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86. W.W. Wuerfel, "Beta Recrystallization Characteristics of Ti-6Al-2Sn-4Zr-2Mo", TMCA Project 99-5, Progress Report No. 25, January 5, 1967.

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti-6-2-4-2

	Ti
6	Al
2	Sn
4	Zr
2	Mo

Ti·6·2·4·2

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3. H. R. Gray and J. R. Johnston, "Hot-Salt Stress Corrosion of a Titanium Alloy in a Dynamic Air Environment," Metallurgical Transactions, Volume 1, November 1970.

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AUTHOR: J. R. KATTUS

NONFERROUS ALLOYS

	Ti
6	Al
2	Sn
4	Zr
6	Mo

Ti-6-2-4-6

1. GENERAL

This heat-treatable alpha-beta alloy was designed to combine the long-time, elevated-temperature strength characteristics of Ti-6Al-2Sn-4Zr-2Mo with markedly improved short-time strength properties at both room and elevated temperatures. It is intended for use as forgings in intermediate-temperature-range sections of gas turbine engines, particularly in disc and fan blade components of the compressor. The alloy is available in the form of billets and bars for forging stock. It has also been successfully produced and evaluated in the form of sheet and plate. It should be considered for long-time load-carrying applications at temperatures up to 750F and short-time load-carrying applications at temperatures up to 1000F. (1)(2)(3)

1.01 Commercial Designation

Ti-6Al-2Sn-4Zr-6Mo

1.02 Alternate Designations

Ti-6246

1.03 Specifications

1.031 No government, AMS or ASTM specifications have been published for this alloy. Titanium Metals Corp. of America provides information on guaranteed minimum mechanical properties for two heat-treated conditions (1).

1.04 Composition

Table 1.04

1.05 Heat Treatment

1.051 General. Although this alloy requires heat treatment to attain optimum properties, the important variables-temperature, time, and cooling rate - have not been thoroughly and systematically studied; therefore, specific conditions for heat treatment have not been standardized. Generally, optimum properties are attained through a solution treatment at temperatures in the range 1500 to 1700F followed by aging in the range 1000 to 1350F, variations within these ranges having significant effects upon properties as illustrated by Figures 3.021004 through 3.021007. Cooling rate from the solution temperature is also an important heat-treating variable, faster cooling rates generally resulting in higher strength and reduced ductility. For a given section size, cooling rates after solution treatment are controlled by the following techniques, from the slowest to the fastest: air cool (AC), forced air cool (FAC), oil quench (OQ), and water quench (WQ). Because of its influence on cooling rate, section size is also a significant variable in the heat treatment of this alloy, larger sections, of course, tending to cool more slowly than thin sections for a given cooling technique. The effects of these variables - cooling technique after solution treatment and section size - are illustrated in a number of Figures and Tables in this text. The effects of time at temperature are probably less clearly established than those of the other heat-treating variables. Reported solution treatment times range from a few minutes to one hour, the shorter times being used for sheet and the longer times for forgings. Aging times range from a one-quarter hour to eight hours, the shorter times usually being applied at the higher temperatures and for thin (sheet) sections.

1.052 Nomenclature. The following terminology is usually used to describe, in a general way, the heat treatments applied to this alloy:

Solution Treat (ST): Treat at a temperature between 1500 and 1700F and quench in water or oil.

Solution anneal (SA): Treat at a temperature between 1500 and 1700F and cool in still air or forced air.

Solution treat and age (STA): Solution treat and age at a temperature between 1000 and 1350F.

Duplex anneal (DA): Solution anneal and age at a temperature between 1000 and 1350F.

Triplex anneal (TA): Solution anneal and age twice at temperatures between 1000 and 1350F, the first aging treatment being at a higher temperature than the second.

1.053 Because of the sensitivity of the properties of this alloy to variations in heat treatment and other processing variables, efforts are being made to correlate properties with microstructure (9)(10). One such study shows that, at a yield-strength level of 170 to 180 ksi, optimum fracture toughness and ductility are obtained with a microstructure of 10 percent equiaxed (primary) alpha with relatively coarse alpha prime (secondary, martensitic alpha) and aged beta, regardless of the processing and heat-treatments used to obtain the structure (9).

1.06 Hardness

Table 1.06

1.07 Forms and Conditions Available

Available in the form of billets and bars for forging stock and in the form of forgings. Also can be made available as plate and sheet.

1.08 Melting and Casting Practice

Double consumable-electrode vacuum melted (2).

1.09 Special Considerations

1.091 The alloy has excellent strength stability when exposed to elevated temperatures up to 1000F, both when stressed and when free of stress. At the higher combinations of temperature and stress, however, somewhat erratic and inconsistent losses in ductility tend to occur. These effects are illustrated in Tables 3.021010 through 3.021012.

1.092 Considerable study has been devoted to the relative merits of forging the alloy at temperatures below the beta transus (alpha-beta forging) and at temperatures above the beta transus (beta forging). In general, the alpha-beta forging tends to result in slightly better strength and ductility. The effects on fracture toughness in air were inconsistent and inconclusive, but beta processing appears to be beneficial to salt-water crack-propagation resistance. Based upon limited data, alpha-beta forged material appears to be more resistant to the effects of creep-exposure surface contamination than beta-forged material (3).

1.093 Good through hardenability has been demonstrated for this alloy in sections up to 3 inches, but deep hardenability decreases in thicker sections (1)(2).

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range. Approximately 3000F.

2.012 Phase changes.

2.0121 Alpha-beta to beta transition temperature, 1720F (2).

2.0122 The strengthening of the solution-treated alloy during aging is in part due to tempering of the alpha prime (martensite). Further strengthening is due to a dispersion of fine alpha produced by decomposition of retained beta (7).

2.013 Thermal conductivity, Figure 2.013.

2.014 Thermal expansion, Figure 2.014.

2.015 Specific heat.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density. 0.169 lb per cu in (1).

2.022 Electrical properties.

2.023 Magnetic properties. Nonmagnetic.

2.024 Emittance.

2.025 Damping capabity.

2.03 Chemical Properties

2.031 The resistance to crack propagation of this alloy in salt water has been reported to be better after beta forging than after alpha-beta forging (3). No further studies of its corrosion resistance and other chemical properties have been reported. It is believed that

	Ti
6	Al
2	Sn
4	Zr
6	Mo

Ti-6-2-4-6

these characteristics are similar to those of other titanium alloys, particularly Ti-6Al-2Sn-4Zr-2Mo (See Code 3718, Sections 2.03 through 2.0333).

2.04 Nuclear Properties

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 Producers guaranteed tensile properties, Table 3.011.

3.02 Mechanical Properties at Room Temperature

3.021 Tension.

3.021001 Tensile properties of square die-press forgings of various section sizes, Table 3.021001.

3.021002 Tensile properties at various locations in disc forging, Table 3.021002.

3.021003 Tensile properties of upset forgings with variations in forge temperature, solution temperature, cooling rate from solution temperature, and aging temperature, Table 3.021003.

3.021004 Effect of solution temperature on tensile properties of 1-1/2" and 3" square bars forged at two different temperatures, Figure 3.021004.

3.021005 Effect of aging temperature on tensile properties of α-β forged upsets after two different solution treatments, Figure 3.021005.

3.021006 Effect of aging temperature on tensile properties of 1.25-in thick discs forged at two different temperatures and subjected to three different solution treatments, Figure 3.021006.

3.021007 Effect of aging temperature and time on the tensile properties of 0.500-in thick plate. Figure 3.021007.

3.021008 Effect of thickness on tensile properties of sheet in three heat-treated conditions, Figure 3.021008.

3.021009 Effect of cooling rate on tensile properties of solution-annealed sheet. Table 3.021009.

3.021010 Effect of creep exposures at temperatures from 750 to 1000F on tensile properties of forgings in the solution-treated and aged condition, Table 3.021010.

3.021011 Effect of creep exposures at 800F on tensile properties of forgings from 1 to 3 in thick in both the duplex-annealed and the solution-treated and aged conditions, Table 3.021011.

3.021012 Effect of creep exposures at 600 and 750F on tensile properties of forgings in two duplex-annealed conditions, Table 3.021012 .

3.021013 Effect of exposures of 500 hours at 600F on tensile properties of sheet in the duplex-annealed and triplex-annealed conditions, Table 3.021013 .

3.0211 Stress-strain diagrams.

3.02111 Duplicate stress-strain curves for forgings subjected to two different duplex annealing treatments, Figure 3.02111.

3.022 Compression.

3.0221 Stress-strain diagrams.

3.0222 Compressive yield strength of sheet in the duplex-annealed and triplex-annealed conditions, Table 3.0222

3.023 Impact.

3.0231 Charpy V-notch impact strength of duplex-annealed press upsets in various sizes, Table 3.0231.

3.0232 Charpy V-notch impact strength of upset forgings with variations in forging temperature and heat treatment, Table 3.0232.

3.024 Bending.

3.025 Torsion and shear.

3.026 Bearing.

3.027 Stress concentration.

3.0271 Notch properties.

3.02711 Notch tensile strength at various locations in disc forging, Table 3.02711.

3.02712 Notch time fracture properties at various locations in disc forging, Table 3.02712.

3.0272 Fracture toughness.

3.02721 Fracture toughness at various locations in solution-treated and aged disc forging, Table 3.02721.

3.02722 Variations in fracture toughness of forgings with different forging conditions, heat treatments, and section thicknesses, Table 3.02722.

3.028 Combined properties.

3.03 Mechanical Properties at Various Temperatures

3.031 Tension.

3.0311 Stress-strain diagrams.

3.0312 Effect of temperature on tensile properties of 3-in thick sections forged at two different temperatures, Figure 3.0312.

3.0313 Effect of temperature and various cooling rates after solution treatment on tensile properties of α-β forged 3-in thick sections, Figure 3.0313.

3.0314 Effect of temperature on tensile properties of sheet in the solution-annealed condition, Figure 3.0314.

3.0315 Effect of temperature on tensile properties of sheet in the duplex-annealed condition, Figure 3.0315.

3.0316 Effect of temperature on tensile properties of sheet in the triplex-annealed condition, Figure 3.0316.

3.032 Compression.

3.0321 Stress-strain diagrams.

3.0322 Effect of temperature on compressive yield strength of sheet in the triplex-annealed condition, Figure 3.0322.

3.033 Impact.

3.034 Bending.

3.035 Torsion and shear.

3.036 Bearing.

3.037 Stress concentration.

3.0371 Notch properties.

3.0372 Fracture toughness.

3.038 Combined properties.

3.04 Creep and Creep Rupture Properties

3.041 Variations in creep deformation with different creep exposures, Table 3.041.

3.05 Fatigue Properties

3.051 Low-cycle axial fatigue properties of α-β forged materials in two heat-treated conditions, Figure 3.051

3.052 Smooth and notched axial fatigue strength at 10^7 cycles of forgings in two duplex-annealed conditions, Table 3.052.

3.06 Elastic Properties

3.061 Poisson's ratio.

3.062 Modulus of elasticity

3.0621 Effect of temperature on tensile and compressive modulus of elasticity of sheet in the triplex-annealed condition, Figure 3.0621.

3.063 Modulus of rigidity.

4. FABRICATION

4.01 Formability

4.011 The alloy appears to have good forgeability in the high alpha-beta range (1600 to 1720 F) and in the low beta range (1720 to 1825 F).

4.012 Minimum bend radii of sheet in various heat-treated conditions at room temperature, Table 4.012.

4.02 Machining and Grinding

4.021 See Commercially Pure Titanium, Code 3701, Section 4.03 through 4.033.

4.022 The machinability of Ti-6246 in the as-forged condition is similar to that of annealed Ti-6Al-4V and Ti-6Al-6V-2Sn; in the solution-treated-and-aged condition it is similar to that of Ti-6Al-6V-2Sn and Ti-7Al-4Mo alloys in the same type of heat-treated condition (4).

4.03 Welding

4.031 No data on fusion-welded properties have been reported. One producer says that, in general, fusion welds have poor ductility and that the alloy should not be considered suitable for fusion welding, except that for some purposes electron-beam welding may be possible (4).

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	Ti
6	Al
2	Sn
4	Zr
6	Mo

Ti-6-2-4-6

4.032 Limited experimental work has shown that the alloy can be diffusion bonded at 1660F, but the optimum conditions of time, pressure, deformation, surface finish, and temperature have not been established.(7) (8).

4.04 Surface Treatment

4.041 See Commercially Pure Titanium, Code 3701, Section 4.05 through 4.055.

Alloy	Ti-6246	
Source	(1) (2)	
	Percent	
Element	Minimum	Maximum
Aluminum	5.5	6.5
Tin	1.8	2.2
Zirconium	3.6	4.4
Molybdenum	5.5	6.5
Iron	--	0.15
Oxygen	--	0.15
Carbon	--	0.04
Nitrogen	--	0.02
Hydrogen	--	0.15
Titanium	Balance	

TABLE 1.04 COMPOSITION.

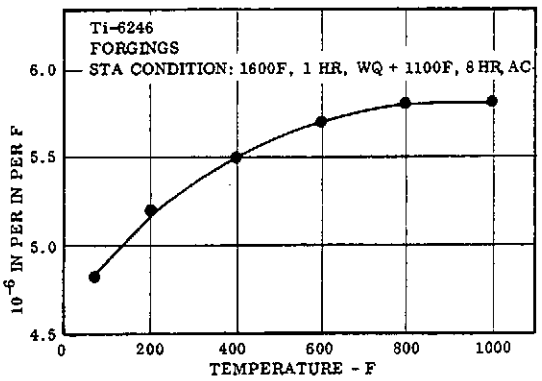


FIG. 2.014 THERMAL EXPANSION. (1)

Alloy	Ti-6246	
Source	(4)	
	Hardness	
Condition	Brinnell	Rockwell C
As Forged	310-370	33-38
STA	350-450	36-42

TABLE 1.06 HARDNESS.

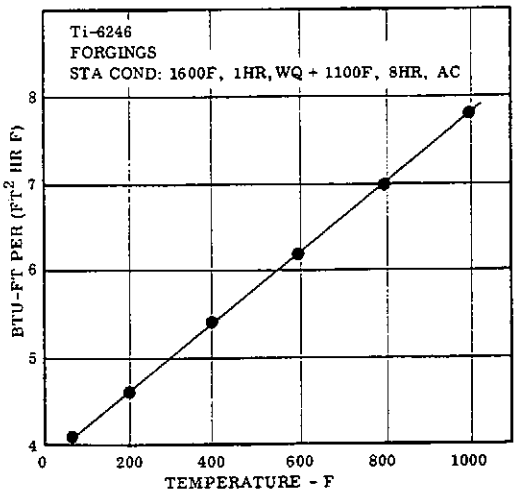


FIG. 2.013 THERMAL CONDUCTIVITY. (1)

Alloy	Ti-6246			
Source	(1)			
Form	Forgings			
Condition	STA (a)		DA (b)	
Thickness	up to 3 in	3-4 in	up to 2 in	2-3 in
F_{tu}-ksi, min	170	160	160	150
F_{ty}-ksi, min	160	150	150	140
e(1 in) percent, min				
Longitudinal	8	8	10	10
Transverse	6	6	10	8
RA, percent, min				
Longitudinal	20	20	20	20
Transverse	12	12	20	20
(a) STA: 1600F, 1hr, WQ+1100F, 8hr, AC				
(b) DA: 1600F, 1hr, AC+1000F, 8hr, AC				

TABLE 3.011 PRODUCERS GUARANTEED TENSILE PROPERTIES.

	Ti
6	Al
2	Sn
4	Zr
6	Mo

Ti-6-2-4-6

Alloy	Ti-6246				
Condition	STA: 1600F, 1 hr, WQ +1100F, 8 hr, AC				
Source	(1)				
Form	Square Die-Press Forgings*				
Square Section size, in	Specimen Location	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
1	Ctr long	184.9	165.2	12	27.9
	Ctr long	177.3	165.7	12	41.5
3	Out trans	188.1	174.9	10	32.7
	Out trans	187.4	173.5	9	29.7
	Ctr trans	177.6	164.9	13	42.8
	Out long	195.3	183.9	13	24.9
	Out long	191.4	178.4	12	25.4
	Ctr long	181.1	172.2	15	46.4
6	Out trans	177.8	164.9	8	28.9
	Out trans	184.9	171.3	11	37.1
	Mid rad trans	172.3	161.4	10	32.6
	Mid rad trans	169.6	160.3	9	38.0
	Ctr trans	160.4	144.5	12	33.4
	Out long	189.4	175.3	9	20.9
	Out long	186.4	174.3	11	36.0
	Mid rad long	173.9	162.7	15	28.9
	Mid rad long	165.8	153.8	14	39.7
	Ctr long	167.7	153.7	15	30.9
* α-β forged at 1620F					

TABLE 3.021001 TENSILE PROPERTIES OF SQUARE DIE-PRESS FORGINGS OF VARIOUS SECTION SIZES.

Alloy	Ti-6246							
Condition	STA: 1600 F, 1 hr, WQ+1100 F, 8 hr, AC							
Source	(3)							
Form	Disc Forging							
Forge Temperature-F	$\alpha-\beta$ forged at 1620 F				β forged at 1850 F			
Specimen Location	F_{tu}, ksi	F_{ty}, ksi	e(1 in) percent	RA percent	F_{tu}, ksi	F_{ty}, ksi	e(1 in) percent	RA percent
Outside Tangential	197.0	180.4	8.0	23.6	179.5	163.0	2.0	4.0
Outside Tangential	191.8	176.2	13.0	30.6	174.3	157.6	6.5	10.9
Center Tangential	190.4	174.6	11.5	37.8	180.5	162.0	6.0	16.5
Center Tangential	184.6	172.4	8.5	32.8				
Center Axial	192.0	174.2	9.0	24.2	175.0	162.9	8.0	11.2
Center Axial	184.6	172.3	7.0	19.7	178.9	167.5	6.5	9.2
Outside Radial	189.1	173.3	11.0	26.9	181.5	169.2	10.0	17.9
Outside Radial	186.4	175.2	10.5	41.6	185.4	168.0	6.5	8.8
Center Radial	187.9	171.6	10.5	31.8	184.0	168.4	9.0	14.3
Center Radial	184.4	170.0	8.0	20.2	179.7	164.8	9.5	14.3
Center Diametral	196.1	180.0	6.5	11.1	190.4	185.3	10.0	22.7

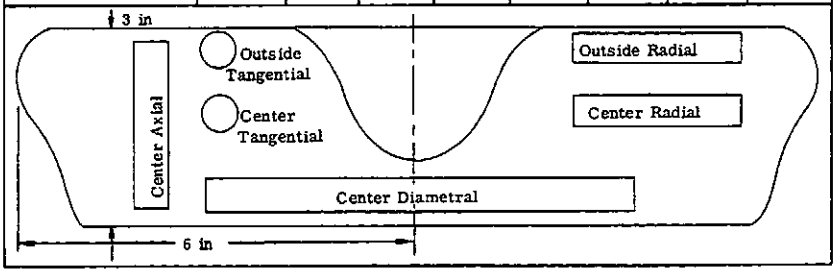


TABLE 3.021002 TENSILE PROPERTIES AT VARIOUS LOCATIONS IN DISC FORGING.

Ti
6 Al
2 Sn
4 Zr
6 Mo

Ti-6-2-4-6

Alloy	Ti-6246						
Source	(6)						
Form	1 3/4 inch Thick Upset Forgings						
Forge Temp, F	Solution Temp, F (a)	Cooling from Solution	Age Temp, F (b)	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
1625	1525	air cool	1000	180	163	13	26.0
			1100	182	167	10	27.5
		oil quench	1000	188	168	9	17.0
			1100	184	170	12	28.0
	1600	air cool	1000	190	169	12	41.0
			1100	181	166	13	28.0
		oil quench	1000	216	184	4	10.0
			1100	192	170	8	12.0
1675	1525	air cool	1000	173	161	12	40.5
			1100	169	160	12	24.0
		oil quench	1000	194	173	8	16.0
			1100	180	170	12	37.5
	1600	air cool	1000	182	167	14	34.0
			1100	185	173	10	24.0
		oil quench	1000	212	185	6	8.0
			1100	197	183	8	20.0
(a) 1 hr at temp (b) 8 hr at temp							

TABLE 3.021003 TENSILE PROPERTIES OF UPSET FORGINGS WITH VARIATIONS IN FORGE TEMPERATURE, SOLUTION TEMPERATURE, COOLING RATE FROM SOLUTION TEMPERATURE, AND AGING TEMPERATURE.

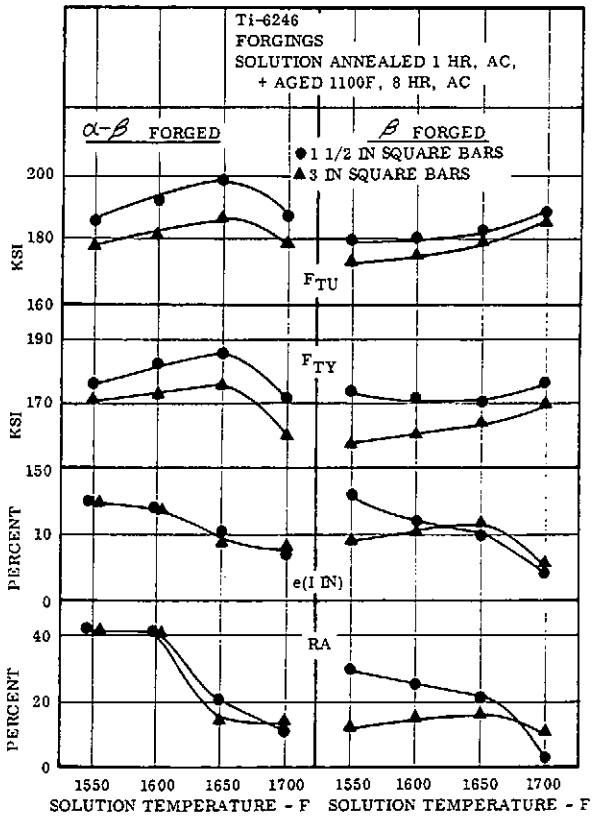


FIG. 3.021004 EFFECT OF SOLUTION TEMPERATURE ON TENSILE PROPERTIES OF 1 1/2 IN AND 3 IN SQUARE BARS FORGED AT TWO DIFFERENT TEMPERATURES. (5)

	Ti
6	Al
2	Sn
4	Zr
6	Mo

Ti-6-2-4-6

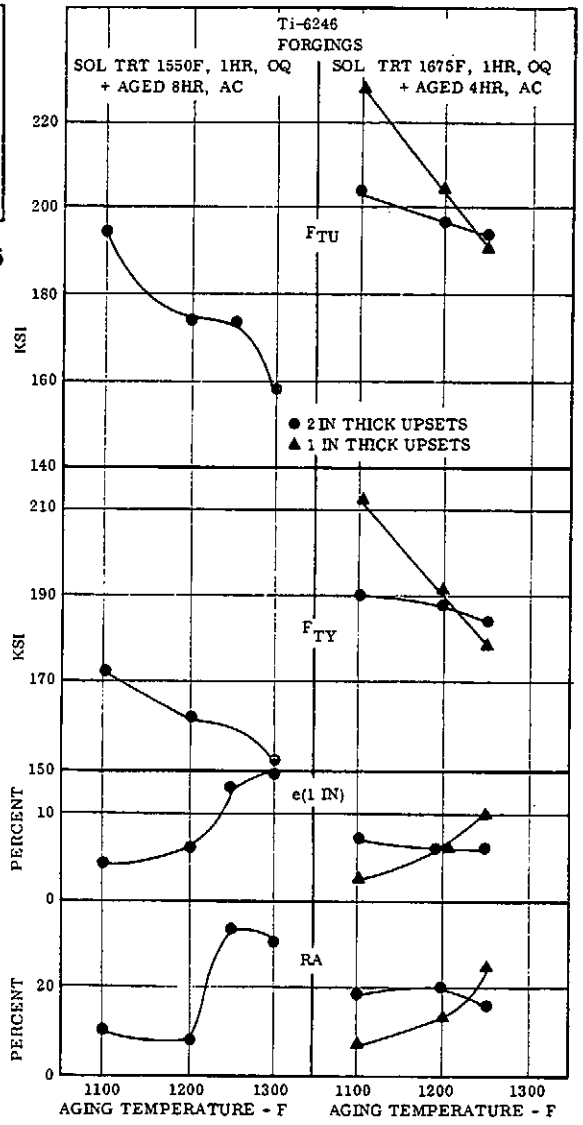


FIG. 3.021005 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF α-β FORGED UPSETS AFTER TWO DIFFERENT SOLUTION TREATMENTS. (5)

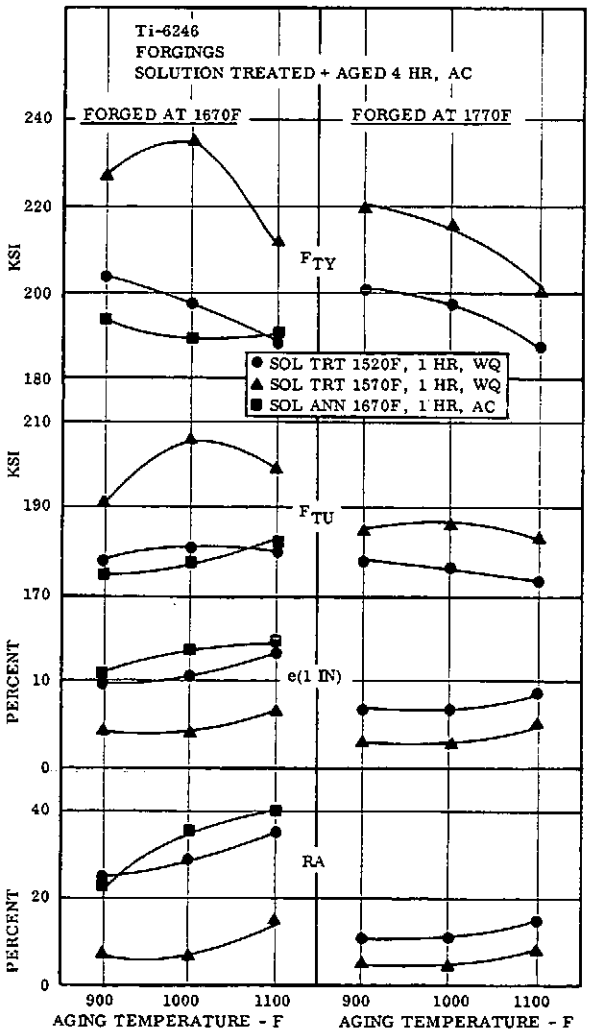


FIG. 3.021006 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF 1.25-IN THICK DISCS FORGED AT TWO DIFFERENT TEMPERATURES AND SUBJECTED TO THREE DIFFERENT SOLUTION TREATMENTS. (2)

	Ti
6	Al
2	Sn
4	Zr
6	Mo

Ti-6-2-4-6

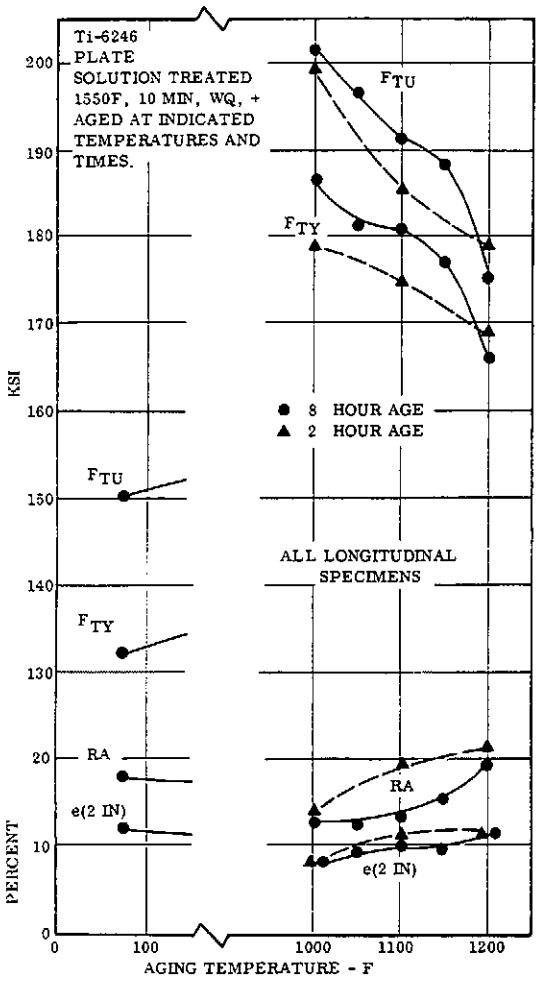


FIG. 3.021007 EFFECT OF AGING TEMPERATURE AND TIME ON THE TENSILE PROPERTIES OF 0.500 - INCH THICK PLATE. (5)

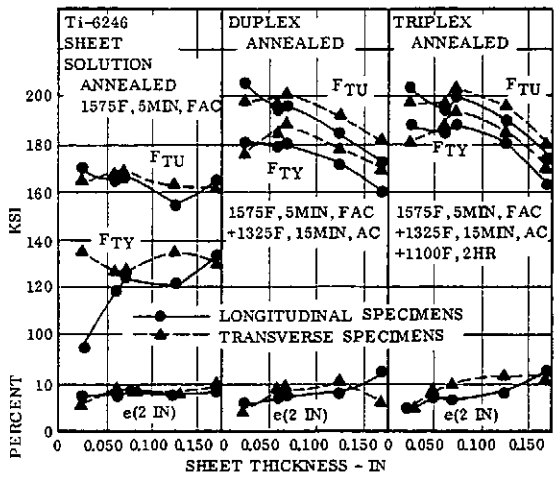


FIG. 3.021008 EFFECT OF THICKNESS ON TENSILE PROPERTIES OF SHEET IN THREE HEAT-TREATED CONDITIONS. (5)

Alloy	Ti-6246				
Source	(5)				
Form	Sheet				
Condition	Orientation	F_{tu}, ksi	F_{ty}, ksi	e(2 in) percent	
SA: 1575F, 5 min, FAC	L	163	120	7.5	
	T	165	132	7.5	
SA: 1600F, 15 min, AC	L	159	58	9.5	
	T	160	64	8.0	

TABLE 3.021009 EFFECT OF COOLING RATE ON TENSILE PROPERTIES OF SOLUTION-ANNEALED SHEET.

Alloy	Ti-6246					
Condition	STA: 1600F, 1 hr, WQ+1100F 8 hr, AC					
Source	(3)					
Form	Disc Forging, 3 in thick x 11 in dia					
Creep Exposure			F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
Temp, F	Stress, ksi	Time, hr	α - β forged at 1620F			
unexposed			186.9	172.5	10.0	30.1
750	90	1228	198.7	175.8	6.0	22.8
750	89	150	184.7	170.2	6.0	16.2
800	75	504	197.6	174.6	--	--
800	85	241	199.0	175.8	7.0	26.9
800	85	150	188.3	168.6	6.0	16.8
1000	20	51	185.0	167.1	12.0	32.3
1000	30	72	185.0	169.1	--	25.9
1000	30	150	184.1	167.5	5.0	15.7
			β forged at 1850F			
unexposed			182.6	167.6	8.8	13.8
750	90	336	177.9	162.8	5.0	21.0
750	89	150	185.8	167.2	4.0	13.0
800	75	290	180.6	161.5	--	--
800	85	313	183.6	166.1	4.0	12.7
1000	20	120	174.6	161.2	8.0	16.2
1000	30	72	181.7	162.8	5.0	10.4
Note: Specimens had gage sections 0.250 inches in diameter and 1 in long.						

TABLE 3.021010 EFFECT OF CREEP EXPOSURES AT TEMPERATURES FROM 750 TO 1000F ON TENSILE PROPERTIES OF FORGINGS IN THE SOLUTION TREATED AND AGED CONDITION.

	Ti
6	Al
2	Sn
4	Zr
6	Mo

Ti-6-2-4-6

Alloy	Ti-6246							
Source	(5)							
Form	α-β Forged Discs, 6 in diameter x Various Thicknesses							
Condition	DA: 1675F, 1 hr, AC+1100F, 4 hr, AC							
Thickness, inches	Creep Exposure			Creep Def. Percent	F_{tu} ksi	F_{ty} ksi	e(1 in) Percent	RA Percent
	Temp F	Stress, ksi	Time, hr					
3	---	---	---	---	172.6	156.6	16.5	43.3
	800	85	50	0.102	167.8	154.2	14.0	40.5
2	---	---	---	---	168.8	154.7	14.0	41.9
	800	85	50	0.136	162.7	148.4	17.0	41.8
1	---	---	---	---	174.1	157.7	14.0	39.4
	800	85	50	0.098	176.2	160.5	14.0	35.0
Condition	STA: 1675F, 1hr, OQ+1100F, 4 hr, AC							
3	---	---	---	---	200.9	189.3	7.0	27.5
	800	85	50	0.071	195.6	186.3	7.0	20.4
2	---	---	---	---	202.1	190.3	7.0	18.3
	800	85	50	0.106	198.9	186.4	5.0	17.5
1	---	---	---	---	228.6	212.9	2.5	8.2
	800	85	50	0.165	227.8	212.0	3.5	10.1

TABLE 3.021011 EFFECT OF CREEP EXPOSURES AT 800F ON TENSILE PROPERTIES OF FORGINGS FROM 1 TO 3 IN THICK IN BOTH THE DUPLEX-ANNEALED AND THE SOLUTION-TREATED AND AGED CONDITIONS.

Alloy	Ti-6246							
Source	(5)							
Form	α-β Forged 1 in Rounds							
Condition	DA: 1600F, 1 hr, AC + 1100F, 8 hr, AC							
Creep Exposure				Creep Def	F_{tu}	F_{ty}	e(1 in)	RA
Temp F	Stress ksi	Time hr		percent	ksi	ksi	percent	percent
--	--	--		--	195.6	182.9	11.5	24.3
600	100	100		0.020	185.5	175.0	10.0	24.8
750	89	100		0.063	195.2	181.3	9.5	18.0
Condition	DA: 1675F, 1 hr, AC + 1100F, 8 hr, AC							
---	--	--		--	192.9	177.7	13.0	22.1
600	100	100		0.024	191.9	172.6	8.0	14.0
750	89	100		0.057	190.2	172.2	8.5	15.4

TABLE 3.021012 EFFECT OF CREEP EXPOSURES AT 600 AND 750F ON TENSILE PROPERTIES OF FORGINGS IN TWO DUPLEX-ANNEALED CONDITIONS.

Alloy	Ti-6246				
Source	(5)				
Form	Sheet				
Condition	DA: 1600F, 15 min, AC+1300F, 15 min, AC				
Exposure			F_{tu}	F_{ty}	e(1 in)
Temperature, F	Time, hr		ksi	ksi	percent
--	--		184.5	170.2	8.3
600	500		188.6	169.1	8.8
Condition	TA: 1600F, 15 min, AC+1350, 15 min, AC+1100F, 2 hr AC				
--	--		182.1	171.7	9.0
600	500		185.1	170.0	9.5

TABLE 3.021013 EFFECT OF EXPOSURES OF 500 HOURS AT 600F ON TENSILE PROPERTIES OF SHEET IN THE DUPLEX-ANNEALED AND TRIPLEX-ANNEALED CONDITIONS.

	Ti
6	Al
2	Sn
4	Zr
6	Mo

Ti-6-2-4-6

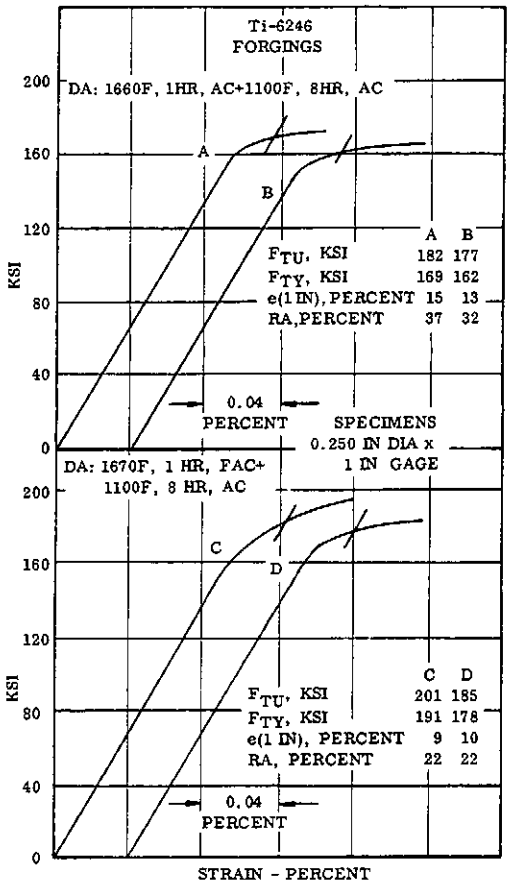


FIG. 3.02111 DUPLICATE STRESS-STRAIN CURVES FOR FORGINGS SUBJECTED TO TWO DIFFERENT DUPLEX-ANNEALING TREATMENTS. (4)

Alloy	Ti- 6246	
Condition	DA: 1600F, 1 hr, AC+1100F, 8 hr, AC	
Source	(5)	
Form	Press Upsets	
Forge Temp, F	α-β forged at 1625 F	
Product size, in	Charpy V-notch impact, ft-lb	F_{tu}
6 round x 3/4	7	192.9
8 round x 3/4	10	183.7
9 round x 3/4	11	180.7
4 x 7 x 3/4	7	188.9

TABLE 3.0231 CHARPY V-NOTCH IMPACT STRENGTH OF DUPLEX-ANNEALED PRESS UPSETS IN VARIOUS SIZES.

Alloy	Ti-6246	
Source	(2)	
Form	0.060 in sheet	
Condition		F_{cy}, ksi
DA: 1600F, 15 min, AC + 1300F, 15 min, AC		184
TA: 1600F, 15 min, AC + 1300F, 15 min, AC +1100F, 2 hr, AC		182

TABLE 3.0222 COMPRESSIVE YIELD STRENGTH OF SHEET IN THE DUPLEX-ANNEALED AND TRIPLEX-ANNEALED CONDITIONS.

Alloy	Ti-6246				
Source	(6)				
Form	1 3/4 in thick Upset Forgings				
Forge Temp, F	Solution Temp, F(a)	Cooling from Solution	Age Temp, F(b)	Charpy V-notch impact, ft-lb	F_{tu} ksi
1625	1525	air cool	1000	9	180
			1100	10	182
		oil quench	1000	7.5	188
			1100	11	184
	1600	air cool	1000	8.5	190
			1100	7	181
		oil quench	1000	6	216
			1100	6	192
1675	1525	air cool	1000	8	173
			1100	8	169
		oil quench	1000	8	194
			1100	9.5	180
	1600	air cool	1000	9	182
			1100	9.5	185
		oil quench	1000	7	212
			1100	6.5	197

(a) 1 hr at temperature
(b) 8 hr at temperature

TABLE 3.0232 CHARPY V-NOTCH IMPACT STRENGTH OF UPSET FORGINGS WITH VARIATIONS IN FORGING TEMPERATURE AND HEAT TREATMENT.

Ti
6 Al
2 Sn
4 Zr
6 Mo

Ti-6-2-4-6

Alloy	Ti-6246			
Condition	STA: 1600F, 1hr, WQ+1100F, 8hr, AC			
Source	(3)			
Form	Disc Forging			
Forge Temperature, F	α-β forged at 1620F		β forged at 1850F	
Specimen location (a)	NTS (b), ksi	NTS/F_{ty}	NTS(b), ksi	NTS/F_{ty}
Outside Tangential	217.9	1.21	226.3	1.41
Outside Tangential			213.0	1.33
Center Tangential	218.1	1.25	223.6	1.38
Center Axial	227.9	1.31	167.7	1.01
Center Diametral	235.6	1.31	228.2	1.23
Center Radial	218.8	1.28		

(a) See diagram on Table 3.021002

(b) K_t=3.8 60° Notch tip radius 0.005 in

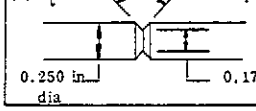


TABLE 3.02711 NOTCH TENSILE STRENGTH AT VARIOUS LOCATIONS IN DISC FORGING.

Alloy	Ti-6246			
Source	(5)			
Form	Forgings			
Forging Conditions	Heat Treat Conditions	Section Thickness, in	F_{tu} ksi	K_{Ic} ksi$\sqrt{in}$
1625F, AC	1600F, 2hr, AC+1100F, 8hr, AC	2	166	33.4
				30.5
1650F, AC	1650F, 1hr, WQ+1200F, 8hr, AC	3	189	19.1
	1650F, 1hr, AC+1200F, 8hr, AC	3	170	24.2
1625F, AC	1675F, 1hr, AC+1100F, 8hr, AC	2	168	45.9
1800F, WQ		2	168	59.9
1625F, AC	1675F, 1hr, AC+975F, 8hr, AC	1	177	29.7
1800F, WQ	1675F, 1hr, AC+975F, 8hr, AC	1	177	41.9
1800F, WQ	1675F, 1hr, AC+1100F, 8hr, AC	1	172	43.3
1650F, AC	1675F, 1hr, AC+1550F, 8hr, OQ	3	177	35.5
	+ 1100F, 8hr, AC	2 1/8	182	33.1
1800F, AC	1550F, 1hr, OQ+1100F, 8hr, AC	3	172	33.9
		2 1/8	184	32.2
		1 1/2	188	25.2
1625F, AC	1675F, 1hr, AC+1100F, 4hr, AC	3	172	30.7
		2	169	30.3
		1	179	27.3

TABLE 3.02722 VARIATIONS IN FRACTURE TOUGHNESS OF FORGINGS WITH DIFFERENT FORGING CONDITIONS, HEAT TREATMENTS, AND SECTION THICKNESSES.

Alloy	Ti-6246			
Condition	STA: 1600F, 1hr, WQ+1100F, 8hr, AC			
Source	(3)			
Form	Disc Forging			
Forge Temp, F	α-β forged at 1620F		β forged at 1850F	
Specimen Location(a)	Notch(b) time fracture Stress, ksi	Time, hr	Notch(b) time fracture Stress	Time, hr
Outside Tangential	170	4.92	190	2.75
Outside Tangential			190	0.16
Center Tangential	200	3.75	200	0.33
Center Axial	180	4.92	170	5.00+
Center Radial	220	0.00		
Center Radial	210	5.00+		

(a) See diagram on Table 3.021002

(b) K_t=3.8 60° Notch tip radius 0.005 in

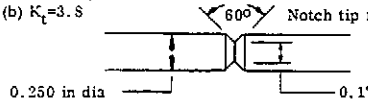


TABLE 3.02712 NOTCH TIME FRACTURE PROPERTIES AT VARIOUS LOCATIONS IN DISC FORGING.

Alloy	Ti-6246	
Condition	STA: 1600F, 1 hr, WQ + 1100F, 8 hr, AC	
Source	(3)	
Form	Disc Forging*	
Forge Temp, F	α-β forged at 1620F	β forged at 1850F
Specimen Location*	K_{Ic}, ksi $\sqrt{in}$	K_{Ic}, ksi $\sqrt{in}$
Center tangential	25.74	
Outside tangential	22.27	19.85
Outside tangential	24.11	
Center diametral		19.52

Note: K_{Ic} values determined with precracked three-point notched bend specimens.

* See diagram on Table 3.021002

TABLE: 3.02721 FRACTURE TOUGHNESS AT VARIOUS LOCATIONS IN SOLUTION-TREATED AND AGED DISC FORGING.

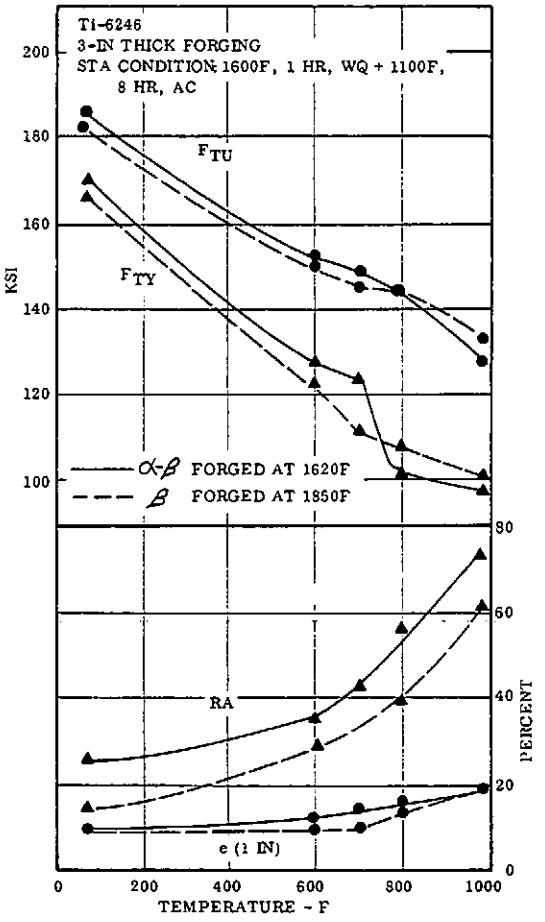


FIG. 3.0312 EFFECT OF TEMPERATURE ON TENSILE PROPERTIES OF 3-INCH-THICK SECTIONS FORGED AT TWO DIFFERENT TEMPERATURES. (3)

	Ti
6	Al
2	Sn
4	Zr
6	Mo

Ti-6-2-4-6

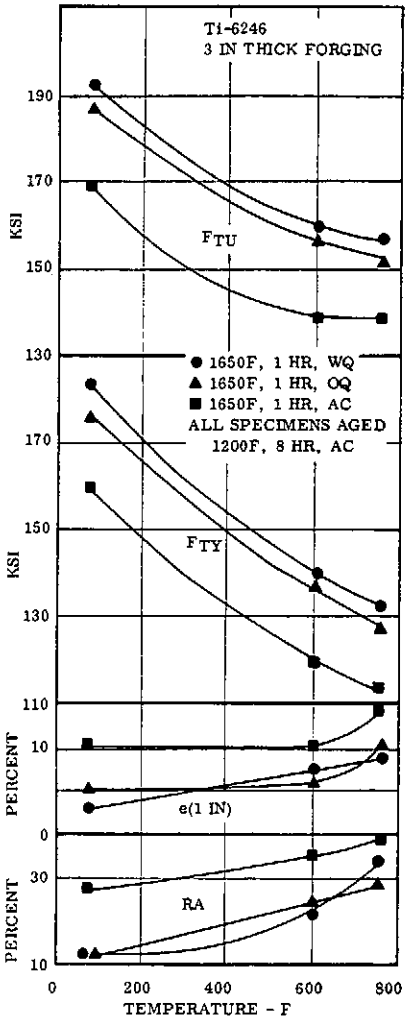


FIG. 3.0313 EFFECT OF TEMPERATURE AND VARIOUS COOLING RATES AFTER SOLUTION TREATMENT ON TENSILE PROPERTIES OF α-β FORGED 3 IN THICK SECTIONS. (5)

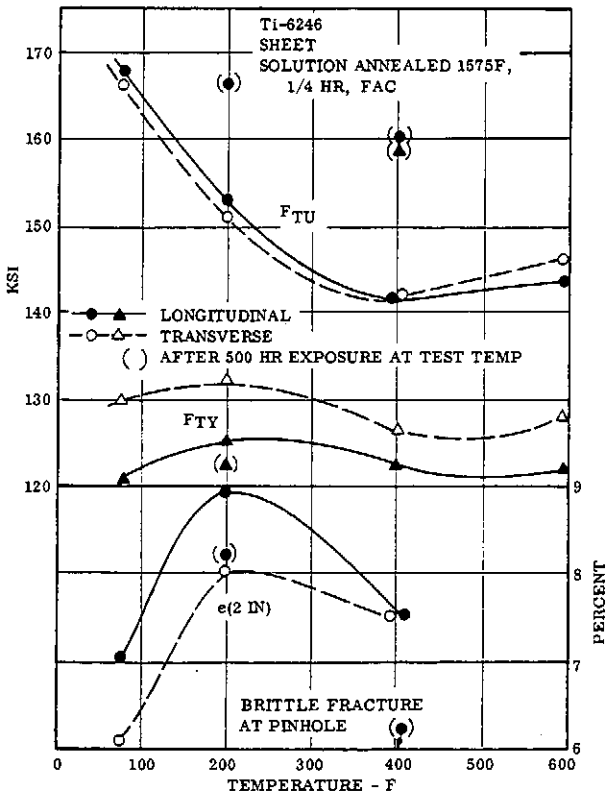


FIG. 3.0314 EFFECT OF TEMPERATURE ON TENSILE PROPERTIES OF SHEET IN THE SOLUTION-ANNEALED CONDITION. (5)

	Ti
6	Al
2	Sn
4	Zr
6	Mo

Ti-6-2-4-6

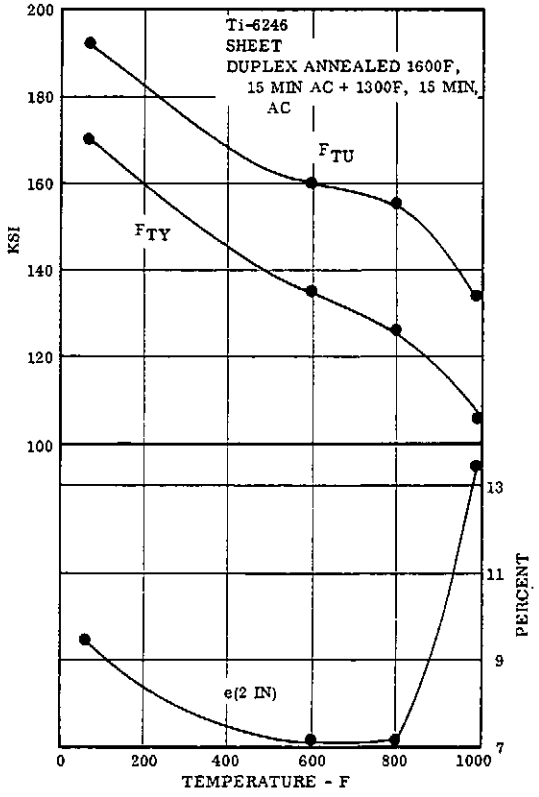


FIG. 3.0315 EFFECT OF TEMPERATURE ON TENSILE PROPERTIES OF SHEET IN THE DUPLEX-ANNEALED CONDITION. (5)

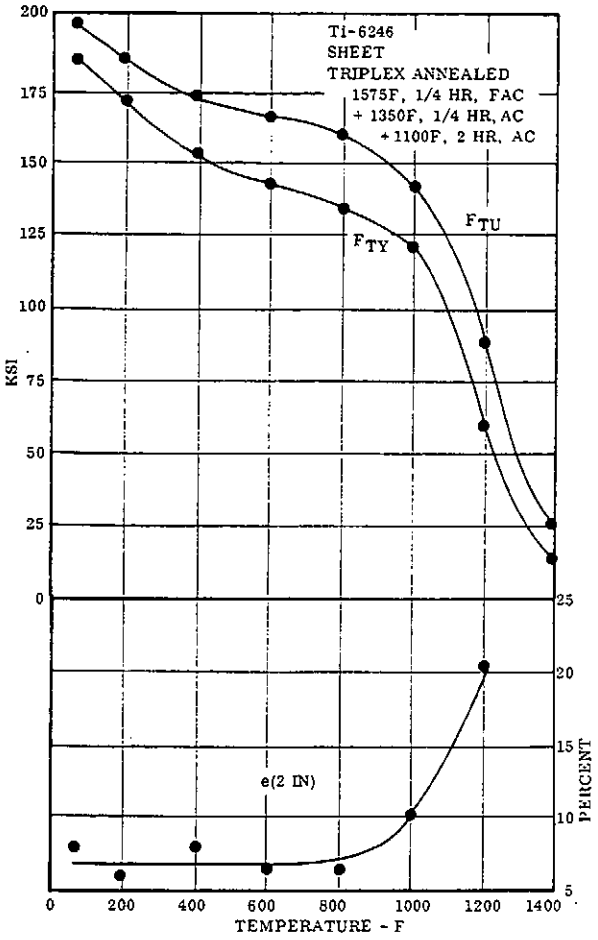


FIG. 3.0316 EFFECT OF TEMPERATURE ON TENSILE PROPERTIES OF SHEET IN THE TRIPLEX-ANNEALED CONDITION. (5)

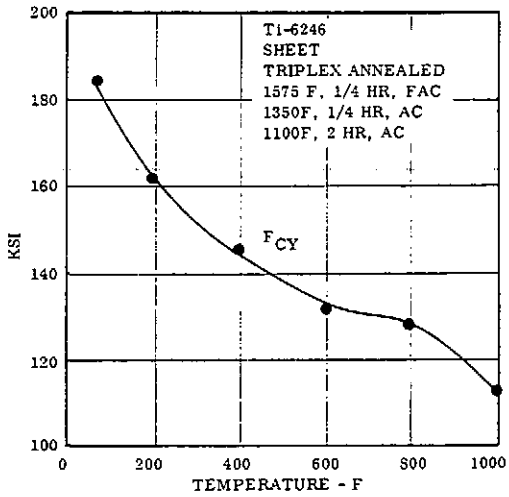


FIG. 3.0322 EFFECT OF TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF SHEET IN THE TRIPLEX-ANNEALED CONDITION. (5)

Ti
6 Al
2 Sn
4 Zr
6 Mo

Ti-6-2-4-6

Alloy	Ti-6246				
Condition	STA: 1600F, 1 hr, WQ + 1100F, 8 hr, AC				
Source	(3)				
Form	Disc Forging, 3 in thick x 11 in dia				
Creep Exposures			Time to 0.1 percent creep, hr	Time to 0.2 percent creep, hr	Total Plastic Def, percent
Temp, F	Stress, ksi	Time, hr	α-β forged at 1620F		
750	90	1228	270	840	0.251
750	89	150	--	--	0.101
800	75	504	105	420	0.217
800	85	241	40	210	0.234
800	85	150	--	--	0.180
1000	20	51	6	27	0.246
1000	30	72	2	8	0.760
1000	30	150	--	--	0.820
			β forged at 1850F		
750	90	336	75	264	0.203
750	89	150	--	--	0.091
800	75	290	35	250	0.223
800	85	313	25	165	0.252
1000	20	120	4	22	0.427
1000	30	72	1	6	0.613

TABLE 3.041 VARIATIONS IN CREEP DEFORMATION WITH DIFFERENT CREEP EXPOSURES.

Alloy	Ti-6246			
Source	(5)			
Form	1-in-round forgings			
			Axial Fatigue Str ksi at 10^7 cycles	
Heat Treatment	R	A	K_t=1	K_t=3.8*
1600F, 1hr, AC+1100F, 8hr, AC	0.1	0.82	115	55
1675F, 1hr, AC+1100F, 8hr, AC	0.1	0.82	120	50

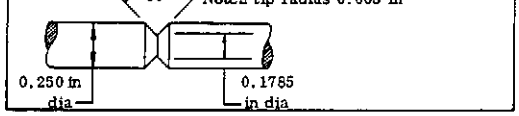


TABLE 3.052 SMOOTH AND NOTCHED AXIAL FATIGUE STRENGTH AT 10^7 CYCLES OF FORGINGS IN TWO DUPLEX-ANNEALED CONDITIONS.

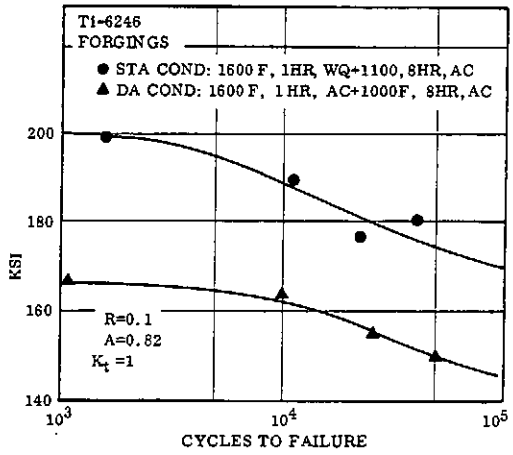


FIG. 3.051 LOW-CYCLE AXIAL FATIGUE PROPERTIES OF α-β FORGED MATERIAL IN TWO HEAT-TREATED CONDITIONS. (1)

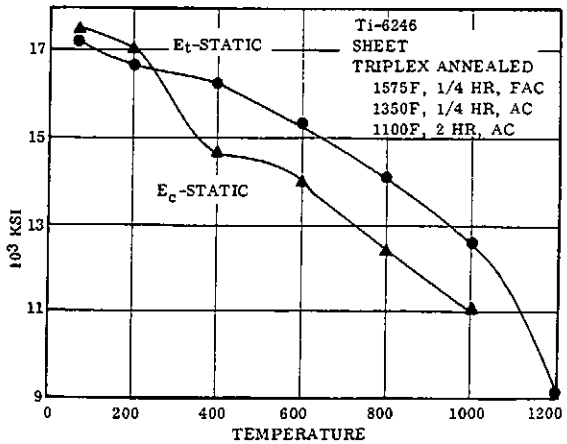


FIG. 3.0621 EFFECT OF TEMPERATURE ON TENSILE AND COMPRESSIVE MODULUS OF ELASTICITY OF SHEET IN THE TRIPLEX-ANNEALED CONDITION. (5)

Ti
6 Al
2 Sn
4 Zr
6 Mo

Ti-6-2-4-6

Alloy	Ti-6246	
Source	(5)	
Form	Sheet	
Condition	SA: 1575F, 5min, FAC	
Sheet Thickness, in	Specimen Orientation	Minimum Bend Radius to Thickness Ratio
0.025	L	4.25
	T	4.0
0.063	L	4.6
	T	5.0
0.070	L	4.25
	T	4.25
0.125	L	4.0
	T	4.0
0.170	L	4.5
	T	4.5
Condition	SA: 1600F, 15 min, AC	
--	L	3.7
--	T	3.8
Condition	DA: 1600F, 15 min, AC + 1300F, 15 min, AC	
--	L	5.0
--	T	5.3

TABLE 4.012 MINIMUM BEND RADII OF SHEET IN VARIOUS HEAT-TREATED CONDITIONS AT ROOM TEMPERATURE.

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10. Ruckle, D. L., "Development of Computerized Microstructure Control Procedure for Ti-6Al-2Sn-4Zr-6Mo Alloy Production Compressor Discs", First Interim Technical Report (December 1971), AFML Contract F33615-71-C-1569.

REVISED: DECEMBER 1975
AUTHOR: W. F. BROWN, JR.

NONFERROUS ALLOYS

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

1. GENERAL

This is a heat treatable alpha + beta alloy that in many respects is similar to Ti-6Al-4V but containing increased content of beta stabilizing elements which provide higher strength potential at a sacrifice in toughness and weldability. In forged sections and plate up to one inch thick solution treated and aged material has a guaranteed minimum F_{tu} = 170 ksi. For forged sections between 3 and 4 inches the corresponding F_{tu}=150ksi. The response to heat treatment may vary from heat to heat and the correct aging temperature is best determined by tests on the heat in question. As is characteristic of other titanium alloys exposure to stress at elevated temperature produces changes in the retained mechanical properties. The stress and temperature limits below which these changes will not occur have not yet been established for this alloy. Structural applications should be based on a knowledge of the low toughness characterizing the higher strength conditions of this alloy and the limited toughness of welds. Particular attention should be given to the influence of aggressive environments in the presence of cracks. Such environments include aqueous solutions of chlorides and possibly certain organic solvents such as methanol.

1.01 Commercial Designation

6Al-6V-2Sn-Ti alloy.

1.02 Alternate Designations

None

1.03 Specifications

1.031 AMS Specifications, Table 1.031.

1.04 Composition

1.041 Producers and AMS specified composition, Table 1.041.

1.05 Heat Treatment

1.051 General. Heat treatment has an important effect on the mechanical properties of this alloy through its control of the microstructure. Details concerning the influence of heat treatment on microstructure may be found in (42). The tensile strength increases with solution temperature in the alpha + beta range but the tensile ductility and the sharp notch strength decrease (Figures 3.0215, 3.0216, 3.02122 and 3.02713). At solution temperatures above the beta transus, the tensile strength decreases somewhat and the ductility drops rapidly (Figure 3.02125). An aging temperature of about 800F produces a full aged condition of the solution treated material with a tensile strength of about 240 ksi (Figure 3.02128). This fully aged condition is relatively brittle (Figure 3.02715) and overaging in the temperature range between 1000 and 1150F is generally employed. In this range the tensile strength decreases relatively slowly with increasing aging temperature and the tensile ductility and the plane strain fracture toughness increase (Figures 3.02114, 3.02117, 3.02123, 3.02126 and 3.02723). Several so called duplex annealing treatments have been investigated (Tables 3.02724 and 3.02725). In some cases these appeared to increase the plane strain fracture toughness as compared with the mill annealed material but resulted in some loss in tensile yield strength. However, a toughness improvement was not noted for all product forms.

1.052 AMS specified heat treatments, Table 1.052.

1.053 Producers recommended heat treatments, Table 1.053.

1.06 Hardness

1.061 Jominy hardenability curve and hardness distribution after aging, Figure 1.061.

1.062 Effect of solution temperature on the hardness, Figure 1.062.

1.063 Hardness as a function of aging time and temperature for two solution temperatures, Figure 1.063.

1.064 Hardness as a function of aging temperature and time, Figure 1.064.

1.07 Forms and Conditions Available

Sheet and plate in annealed, solution treated and solution treated and aged condition. Bar stock and forging billet in as-rolled or annealed conditions. Extruded shapes up to a size that can be circumscribed by a 5-1/4 inch diameter circle in annealed or heat treated condition.

1.08 Melting and Casting Practice

1.081 For melting practice see Ti-6Al-4V (Code 3707). The alloy is not normally used in the cast form, however, a limited amount of information on precision casting can be found in (31).

1.09 Special Considerations

1.091 Notch tensile strength of annealed sheet at room temperature as influenced by hydrogen content, Figure 1.091.

1.0911 Hardenability. An attempt has been made to improve the hardenability of this alloy as compared with Ti-6Al-4V by increasing the amount of beta stabilizing alloy additions. These modifications have increased the maximum strength potential. However, the available evidence indicates that percentagewise the strength loss produced by increasing the solution treated section size is about the same for this alloy and for Ti-6Al-4V. This is illustrated in Figure 1.0911 which shows the reduction in F_{ty} as the solution treated section size is increased for forgings, bar and plate. All but one set of data indicates the hardenability for this alloy is essentially the same as for Ti-6Al-4V. If the amount of hot working is the same for each heat treated section size, then ductility as measured by reduction in area may be essentially unchanged or increase as the heat treated section size increases (see Figures 3.02112 and 3.02113). If the heat treated size variation represents a variation in the degree of working, the ductility may decrease with increasing section size (see Figures 3.02112 and 3.02121).

1.0912 Hardenability of various forms of alloy, Figure 1.0912.

1.092 Stability. Long time exposure to elevated temperature with or without stress produces the so called creep instability characteristic of the higher aluminum titanium alloys. This instability is probably due to a combination of structural change and interstitial embrittlement. It is evidenced by an increase in the tensile and yield strength and a decrease in the elongation and reduction in area (Tables 3.02119 and 3.02120 and Figures 3.02130 and 3.02131). Tests on cracked specimens (55) indicate that the fracture toughness is also reduced by elevated temperature exposure. However, these tests did not yield valid (ASTM E-399) K_{Ic} values. The magnitude of the instability depends on both time and temperature of exposure (Figure 3.02130) with shorter times shifting the effects to higher temperatures. The data is not sufficient to define the role of stress on the exposure effect. However, apparently substantial instability can occur in the annealed alloy due to temperature alone (Figure 3.02130). Instability may be noticed at temperatures as low as 250F for extended exposure times, however, large effects are not noticed below about 600F (Figures 3.02130 and 3.02131). The solution treated and aged condition appears to be somewhat less susceptible to instability perhaps because exposure effects are reduced by concurrent overaging. A special heat treatment has been suggested to reduce the instability. This treatment appears to increase the unexposed tensile and yield strength and to decrease the exposure effect on these properties but the ductility is still adversely affected (Figure 3.02130). On the basis of the data available it is evident that exposure instability effects should be given careful consideration in elevated temperature applications of this alloy.

1.093 Segregation. The relatively high beta stabilizing element content of this alloy makes it particularly prone to effects associated with microsegregation of the beta stabilizing elements iron and copper. These segregated regions will have a reduced transus temperature and may transform to beta on heating during fabrication processes. After solution quenching these regions

Ti
6 Al
6 V
2 Sn

Ti-6-6-2

will be softer than the matrix and will consist of stable beta and martensite with the prior beta grain boundaries being outlined in alpha. Aging will transform the martensite to acicular alpha and the regions will then be harder than the matrix. These areas of transformed beta have been called "beta flecks" although they sometimes appear as bands. The possibility of segregation will increase as the ingot size increases and beta flecks are most likely to be encountered at the center of heavy sections. Their significance is not understood as yet. It has been reported (63) that they reduce the tensile ductility and it is possible that other properties such as fracture toughness and fatigue strength may be affected.

1.094 Interstitials. Reduction in the oxygen level improves the Charpy impact strength of the annealed and of the solution treated and aged conditions (Table 3.02115). It should be noted that substantial improvement in these properties can be obtained with relatively small loss in smooth tensile or yield strength. The notch fatigue strength is also improved by a reduction in the oxygen content (Table 3.0519).

1.095 Environmental Effects. See 2.03 and 3.052.

1.096 Fracture toughness. See 3.02721.

1.097 Hydrogen embrittlement. This alloy is subject to hydrogen embrittlement. One investigation (62) indicated that hot forming of annealed sheet between 1225 and 1425F followed by air cooling resulted in a significant strength reduction and an increase in the susceptibility to hydrogen pickup during chem milling. A stabilization treatment, 1100F, 1 hr, AC + 900F, 1 hr, AC, following hot forming significantly reduced the hydrogen pick up during chem milling and gave acceptable tensile properties.

2. PHYSICAL PROPERTIES AND ENVIRONMENTAL EFFECTS.

2.01 Thermal Properties

2.011 Melting range.

2.012 Phase changes. Beta transus approximately 1700F varying with the composition.

2.013 Thermal conductivity, Figure 2.013.

2.014 Thermal expansion, Figure 2.014.

2.015 Specific heat, Figure 2.015.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density. 0.164 lb per cu in. 4.58 gr per cu cm (1).

2.022 Electrical properties.

2.0221 Electrical resistivity, Figure 2.0221.

2.024 Emissivity

2.025 Damping capacity.

2.03 Chemical Environments

See also 3.052.

2.031 General. This alloy is susceptible to stress corrosion in the presence of solid NaCl at elevated temperatures and exhibits delayed failure of cracked specimens in aqueous solutions of chlorides. Smooth specimens exposed to stress in solutions simulating human body fluids show increasingly positive electropotential with time indicating film repair (see Figure 2.038) but cracked specimens do exhibit accelerated crack growth under cyclic loads when subjected to these solutions (see Figure 3.0522).

2.032 Delayed failure. A short cut procedure was used (21) to determine a stress intensity level below which delayed failure in 3-1/2 percent salt solution did not occur in some specified time period. Pre-cracked notch bend specimens were immersed in salt water and subject to stresses below those causing failure when rapidly applied in air. Specimens were held under load until failure occured or until "one to three hours" elapsed with no indication of crack propagation after which the load was increased. The maximum stress intensity sustained without failure was called "ksi held". The lowest sustained stress intensity that produced failure was also reported. It is doubtful whether such types of tests can establish a stress intensity threshold below which failure would never occur in the corrosion media, however, they do establish stress ksi levels above which rapid failure can be expected. A large number of heat treatments were investigated for both extrusions and forgings. The data is too limited and unsystematic to define preferred heat treatments for maximum resistance to stress corrosion, however, there does appear to be a trend of decreasing susceptibility with decreasing strength level (see Figure 2.034). The susceptibility of high strength conditions of this alloy is also indicated by tests on plate run at NRL (20). For the annealed and the solution treated and aged conditions, crack growth has been observed under sustained load when specimens were subjected to stress intensities as low as 30 ksi-$in^{1/2}$ for 100 hours in air having a relative humidity of 10 percent. The same type of tests in air with a 100 percent relative humidity did not give different results. The data available are not of sufficient duration to establish a threshold below which no crack growth would occur nor was the test time long enough to rule out transient phenomena (see Figure 2.036).

2.033 Solid salt corrosion. Smooth tensile specimens 1/8 inch thick in either the annealed (1350F, 1/4 hr FC) or solution treated and aged condition (1550F, 5 minutes WQ + 1100F, FC) were coated with 0.002 inch of NaCl and loaded at 550 or 650F, to various fractions of their yield strength for different lengths of time (16). An attempt was made to establish the nucleation time for stress corrosion by examination of the surface for cracks (after cleaning) at 500X. In addition, cyclic exposure was investigated using a heating time of 10 to 15 minutes, a hold time of 3 hours and a cooling time of 45 to 50 minutes. Preliminary tests showed the transverse direction to be more sensitive than the longitudinal direction and all tests were run in the transverse direction. The data are too limited to define stress limits below which stress corrosion would not occur or to accurately establish stress vs. time to cracking curves. The essential feature of the results are summarized in Table 2.035. As might be expected stress corrosion occurs at lower fractions of the yield strength at 650F, than at 550F. At 550F, cracking was observed at less than 0.6 F_{ty} for the aged condition and at less than 0.5 F_{ty} for the annealed condition. At 650F, cracking was observed at less than 0.3 F_{ty} for both conditions with the aged condition being more sensitive than the annealed condition. There is an indication that cyclic stressing may be less severe than continuous loading although more data is needed to definitely establish such an effect.

Tests on smooth specimens exposed to solid NaCl for 1000 hours at elevated temperatures show a rapid loss in retained room temperature tensile strength at exposure temperatures above 500F (see Figure 2.037).

2.034 Effect of yield strength level on delayed failure characteristics in salt water, Figure 2.034.

2.035 Results of elevated temperature solid salt stress corrosion test of sheet, Table 2.035.

2.036 Sustained load crack extension in air, Figure 2.036.

2.037 Residual tensile strength at room temperature following elevated temperature stress exposure to solid salt, Figure 2.037.

2.038 Potential time curves for stressed wire in simulated human body environment, Figure 2.038.

2.04 Nuclear Properties

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 AMS specified minimum mechanical properties for bars forgings and rings in the solution treated and aged condition, Table 3.011.

3.012 AMS specified mechanical properties for annealed extrusions and for bars, forgings and rings. Table 3.012.

3.013	AMS specified mechanical properties for sheet strip and plate, Table 3.013.
3.014	Producers guaranteed tensile properties of solution treated and aged bar and forging stock, Table 3.014.
3.015	Producers guaranteed tensile properties of annealed bar, Table 3.015.
3.016	Producers guaranteed tensile properties of annealed and of solution treated and aged extrusion, Table 3.016.
3.017	Producers guaranteed tensile properties of annealed solution treated and solution treated and aged plate, Table 3.017.
3.018	Producers guaranteed tensile properties of annealed solution treated and solution treated and aged sheet, Table 3.018.
3.02	Mechanical Properties at Room Temperature
3.021	Tension. Stress strain diagrams and tension properties.
3.0211	Stress strain curve in tension for forging (specimens heat treated), Figure 3.0211.
3.0212	Stress strain curves for plate in several conditions of heat treatment, Figure 3.0212.
3.0213	Tensile properties of investment cast specimens given several heat treatments, Table 3.0213.
3.0214	Effect of solution temperature on the as quenched tensile properties of extrusion, Figure 3.0214.
3.0215	Effect of solution temperature on tensile properties of 1000F aged extrusion, Figure 3.0215.
3.0216	Effect of solution temperature on tensile properties of 1100F aged extrusion, Figure 3.0216.
3.0217	Tensile properties for extruded cylinders from three heats aged at two temperatures and tested at various crossectional locations, Table 3.0217.
3.0218	Tensile properties of solution treated and aged extruded bar at various crossectional locations, Table 3.0218.
3.0219	Tensile properties in various locations in a forged section, Table 3.0219.
3.02110	Variation of tensile properties of center section of test forging with heavy ribs and thin webs, Table 3.02110.
3.02111	Effect of solution treated section size and age time on tensile properties of forging (forged to solution treated size), Figure 3.02111.
3.02112	Effect of heat treated section size on tensile properties of specimens removed from center of solution treated and aged bar sections, Figure 3.02112.
3.02113	Effect of heat treated section size on tensile properties of square sections removed from center of 4 inch square press forging, Figure 3.02113.
3.02114	Effect of aging temperature on tensile properties of specimens cut from forging and solution treated at two temperatures, Figure 3.02114.
3.02115	Tensile properties of forged bar at two interstitial levels, Table 3.02115.
3.02116	Effect of forging and quench temperature on tensile properties of hammer forged disks, Table 3.02116.
3.02117	Effect of age temperature on tensile properties of a beta forging solution treated at various temperatures, Figure 3.02117.
3.02118	Tensile properties of annealed and of solution treated and aged specimens from forged bar, Table 3.02118.
3.02119	Effect of elevated temperature exposure on tensile properties of annealed and solution treated and aged bar, Table 3.02119.
3.02120	Effect of 150 hour exposure to stress and elevated temperature on tensile properties of forged bar, Table 3.02120.
3.02121	Effect of thickness on tensile properties of solution treated and aged plate, Figure 3.02121.
3.02122	Effect of solution treating and aging temperature on the tensile properties of plate, Figure 3.02122.
3.02123	Effect of aging and solution treating temperature on the tensile properties of plate, Figure 3.02123.
3.02124	Effect of exposure to stress and temperature on retained tensile properties of plate, Table 3.02124.
3.02125	Effect of solution temperature on tensile properties of aged sheet, Figure 3.02125.
3.02126	Effect of aging temperature on the tensile properties of sheet, Figure 3.02126.
3.02127	Effect of aging time on tensile properties of sheet, Figure 3.02127.
3.02128	Effect of aging temperature on tensile properties of sheet, Figure 3.02128.
3.02129	Tensile properties of plate, bar and forging annealed or solution treated and aged, Table 3.02129.
3.02130	Effect of stressed and unstressed elevated temperature exposure on the tensile properties of annealed plate, Figure 3.02130.
3.02131	Effect of stressed exposure at elevated temperature on tensile properties of solution treated and aged plate, Figure 3.02131.
3.02132	Effect of as quenched section size on tensile properties of beta forged bars, Table 3.02132.
3.022	Compression - stress strain diagrams - compression properties, (see 3.032)
3.023	Impact, (see also 3.033).
3.0231	Impact strength of investment cast specimens, Table 3.0231.
3.0232	Effect of heat treated section size on impact strength of specimens removed from center of solution treated and aged bar sections, Figure 3.0232.
3.024	Bending.
3.025	Torsion and shear (see 3.0325)
3.026	Bearing (see 3.0326)
3.027	Stress concentration (see also 3.037)
3.0271	Notch properties.
3.02711	Effect of notch diameter on sharp notch properties of annealed billet, Figure 3.02711.
3.02712	Notch strength of forging at various locations, Table 3.02712.
3.02713	Effect of solution treating and aging temperatures on the sharp notch tensile properties of plate, Figure 3.02713.
3.02714	Notch strength as a function of root radius for annealed sheet, Figure 3.02714.
3.02715	Effect of aging temperature on strength of double edge crack sheet specimens, Figure 3.02715.
3.02716	Effect of surface cracks on the strength of solution treated and aged sheet, Figure 3.02716.
3.0272	Fracture toughness.
3.02721	General. The plane strain fracture toughness is strongly dependent on the yield strength and can be expected to decrease with factors that increase the yield strength such as heat treatment, low temperatures and elevated temperature exposure. The general effects of yield strength on toughness are shown in Figure 3.03724 for plate and forging. The substantial differences in toughness between these two product forms is probably due to processing differences which can influence the microstructure and should not be taken as typical. On the basis of the limited data available it appears that the optimum combination of toughness and yield strength is associated with solution treated and substantially overaged conditions (Table 3.02722) and with duplex annealed treatments (Table 3.02724 and Table 3.02725 Condition B). It should be noted that the smooth fatigue properties of this latter condition are reported to be poorer than annealed material of about the same yield strength. Beta annealing does not appear to benefit the toughness as compared with the above treatments (Table 3.02724). Low interstitial material appears to have superior toughness to normal interstitial material at the same yield strength level (Figure 3.03724).
3.02722	Plane strain fracture toughness of extrusions given several heat treatments, Table 3.02722.
3.02723	Effect of aging temperature on the plane strain fracture toughness of plate, Figure 3.02723.
3.02724	Plane strain fracture toughness of two heats of plate given several heat treatments, Table 3.02724.
3.02725	Plane strain fracture toughness of plate, bar and forging given several heat treatments, Table 3.02725.
3.028	Combined properties.
3.03	Mechanical Properties at Various Temperatures
3.031	Tension-stress strain diagrams-tension properties.
3.0311	Elevated temperature tension stress-strain curves for aged bar, Figure 3.0311.
3.0312	Elevated temperature tension stress strain curves for

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Ti-6-6-2

	Ti
6	Al
6	V
2	Sn

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annealed sheet, Figure 3.0312.

3.0313 Stress strain curves for mill annealed plate at various temperatures, Figure 3.0313.

3.0314 Average and spread of room temperature and 800F tensile properties of solution treated and aged extrusion, Table 3.0314.

3.0315 Effect of test temperature on tensile properties of annealed extrusions of various shapes (14), Table 17 (39) Table 6, Figure 3.0315.

3.0316 Effect of test temperature on tensile properties of a hammer forged disk, Figure 3.0316.

3.0317 Effect of test temperature and specimen location on tensile properties of forgings at two interstitial levels, (specimens heat treated), Figure 3.0317.

3.0318 Effect of test temperature on the tensile properties of Forging, Figure 3.0318.

3.0319 Effect of test temperature on the tensile properties of low interstitial forging (forging, heat treated), Figure 3.0319.

3.03110 Effect of low test temperatures on tensile properties of annealed and aged bar, Figure 3.03110.

3.03111 Effect of test temperature on tensile properties of solution treated and aged plate, Figure 3.03111.

3.03112 Effect of test temperature on tensile properties of annealed plate from two heats, Figure 3.03112.

3.03113 Effect of low test temperatures on tensile properties of low interstitial plate, Figure 3.03113.

3.03114 Effect of thickness on the tensile properties of solution treated and aged plate at 600F, Figure 3.03114.

3.03115 Effect of test temperature on tensile properties of sheet, Figure 3.03115.

3.032 Compression.

3.0321 Effect of temperature on compressive yield strength of annealed extrusion, Figure 3.0321.

3.0322 Effect of test temperature and specimen location on compressive yield strength of solution treated and aged forging (specimens heat treated), Figure 3.0322.

3.0323 Effect of temperature on compressive yield strength of annealed forgings, Figure 3.0323.

3.033 Impact.

3.0331 Effect of temperature on impact strength of aged bar, Figure 3.0331.

3.0332 Effect of test temperature on impact strength of annealed extrusion, Figure 3.0332.

3.0333 Effect of low test temperature on impact strength of annealed and solution treated and aged low interstitial plate, Figure 3.0333.

3.034 Bending.

3.035 Torsion and shear.

3.0351 Shear ultimate strength at room and elevated temperature for several forms and conditions of alloy, Table 3.0351.

3.0352 Effect of test temperature on double shear strength of annealed extrusion, Figure 3.0352.

3.036 Bearing.

3.0361 Bearing strength at room and elevated temperature for several forms and conditions of alloy, Table 3.0361.

3.0362 Effect of test temperature on bearing strength of annealed extrusion, Figure 3.0362.

3.037 Stress concentration.

3.0371 Notch properties (see also 3.0271).

3.03711 Effect of test temperature on strength of center cracked specimens of two thicknesses cut from forging (specimens heat treated), Figure 3.03711.

3.03712 Effect of test temperature on strength of fatigue cracked notch rounds from annealed forgings (specimens re-annealed), Figure 3.03712.

3.03713 Effect of test temperature on strength of fatigue cracked notch rounds cut from forging, (specimens solution treated and aged), Figure 3.03713.

3.03714 Strength of fatigue cracked notch rounds cut from two locations in a solution treated and aged forging, Table 3.03714.

3.03715 Effect of low test temperatures on sharp notch strength of annealed and solution treated and of aged bar, Figure 3.03715.

3.03716 Effect of low test temperatures on sharp notch strength of low interstitial plate, Figure 3.03716.

3.0372 Fracture toughness.

3.03721 Effect of test temperature on strength of double edge crack specimens and plane strain fracture toughness of low interstitial forging (K_{Ic} by technique of ASTM E 399-70T), Figure 3.03721.

3.03722 Effect of specimen orientation on the -110F plane strain fracture toughness of low interstitial forging, Figure 3.03722.

3.03723 Effect of specimen orientation on the -110F plane strain fracture toughness of plate, Table 3.03723.

3.03724 Effect of strength level on the plane strain fracture toughness of various forms and conditions of alloy, Figure 3.03724.

3.03725 Plane strain fracture toughness of forged bar in annealed and in solution treated and aged condition, Figure 3.03725.

3.038 Combined properties.

3.04 Creep and Creep Rupture Properties

3.041 Creep strength for annealed extrusion, Table 3.041.

3.042 Stress for 0.2 percent creep strain at several temperatures for aged bar, Figure 3.042.

3.043 Total creep strain for aged sheet at several temperatures and stresses, Table 3.043.

3.05 Fatigue Properties

3.051 Conventional properties.

3.0511 Smooth and notched fatigue strength of annealed extrusions at room temperature, Table 3.0511.

3.0512 Smooth and notch fatigue strength of solution treated and aged extrusion, Table 3.0512.

3.0513 Stress range diagram at 400F and 600F for smooth and notched specimens from annealed extrusion, Figure 3.0513.

3.0514 Stress range diagrams at room temperature for smooth and notched specimens from annealed extrusion, Figure 3.0514.

3.0515 Smooth and notched fatigue strength at room temperature for alpha + beta and for beta processed forgings, Figure 3.0515.

3.0516 Smooth and notch fatigue strength of solution treated and aged forging at room and elevated temperature, Table 3.0516.

3.0517 Smooth and notch fatigue strength of annealed bar, Table 3.0517.

3.0518 Strain cycling results for annealed bar at room and elevated temperature, Figure 3.0518.

3.0519 Notched fatigue strength at room temperature for plate at two interstitial levels in annealed and solution treated and aged conditions, Table 3.0519.

3.05110 Stress range diagram for notched specimens of mill annealed plate tested at room temperature, Figure 3.05110.

3.05111 Stress range diagram for specimens of solution treated and aged plate tested at room temperature, Figure 3.05111.

3.05112 Stress range diagram for notched specimens of solution treated and aged plate tested at room temperature, Figure 3.05112.

3.05113 Stress range diagram for smooth specimens of solution treated and aged plate tested at room temperature, Figure 3.05113.

3.05114 Smooth and notch fatigue strength of annealed and of solution treated and aged plate, Table 3.05114.

3.05115 Smooth and notched fatigue strength of annealed plate and solution treated and aged plate and sheet at room temperature, Table 3.05115.

3.05116 Smooth and notch fatigue strength of annealed and of solution treated and aged sheet tested at room temperature and 450F, Table 3.05116.

3.05117 Smooth and notch fatigue strength of annealed sheet tested at room temperature, Table 3.05117.

3.05118 Rotating beam fatigue life curve for three heat treated conditions of bar tested in simulated human body environments. Figure 3.05118.

3.052 Fatigue crack growth rates.

3.0521 General. The lack of standardization in this field of testing often makes meaningful comparison among the results from different investigators essentially impossible. However, the published fatigue crack growth data

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

for this alloy are derived from reasonably consistent experimental techniques so that certain general observations are possible.

Results from one investigation on forged bar (30) show that the fatigue growth rates in air for mill annealed and for solution treated and aged material are essentially the same at low and intermediate ΔK levels. However, as might be expected from its lower K_{Ic} the rate is more rapid for the solution treated and aged condition at high ΔK levels (compare Figures 3.0523 and 3.0524) In contrast, data from another investigation (36) do not clearly reveal substantial differences between a variety of heat treatments applied to plate, including mill annealing and solution treating and aging (Figure 3.05213).

The available information does not indicate any significant effect of relative humidity (Figures 3.0523 and 3.0524) or distilled water (Figures 3.0528 and 3.0529) on the crack growth rates for either the mill annealed or the solution treated and aged conditions. Sodium chloride solutions including those intended to simulate human body environments increase the crack propagation rates for both mill annealed and solution treated and aged conditions (Figures 3.0528, 3.0529 and 3.0522). It should be noted that similar environments have no effect on the smooth fatigue strength (see Figure 3.05118). Beta annealed material appears to behave the same in 3.5 NaCl as in air (Figure 3.05210).

The crack propagation rate for annealed material appears to be essentially the same at -65F, R.T. and 300F (compare Figures 3.0524, 3.0525 and 3.0527). On the other hand, the crack propagation rate of the solution treated and aged condition decreases with increasing temperature in the same range (compare Figures 3.0523, 3.0525 and 3.0526).

3.0522 Effect of simulated human body environments on fatigue crack propagation rates for annealed sheet, Figure 3.0522.

3.0523 Fatigue crack growth rates in humid air for solution treated and aged specimens from a forging, Figure 3.0523.

3.0524 Fatigue crack growth rates in humid air for annealed forging, Figure 3.0524.

3.0525 Fatigue crack growth rates at 300F for annealed forging and solution treated and aged specimens from forging, Figure 3.0525.

3.0526 Fatigue crack growth rates at -65F for solution treated and aged specimens from forging, Figure 3.0526.

3.0527 Fatigue crack growth rates at -65F for annealed forging, Figure 3.0527.

3.0528 Fatigue crack growth rates for annealed plate in air and in salt water, Figure 3.0528.

3.0529 Fatigue crack growth rates for beta processed solution treated and aged plate tested in air, distilled water and salt water, Figure 3.0529.

3.05210 Fatigue crack growth rates for beta annealed plate in air and salt water, Figure 3.05210.

3.05211 Fatigue crack growth rates at various temperatures for annealed plate, Figure 3.05211.

3.05212 Fatigue crack growth rates for specimens cut from plate and given two annealing treatments, Figure 3.05212.

3.05213 Average fatigue crack growth rates for plate given several heat treatments and tested in laboratory air, Figure 3.05213.

3.05214 Fatigue crack growth rates for annealed plate at several R ratios tested in laboratory air, Figure 3.05214.

3.06 Elastic Properties

3.061 Poisson's ratio.

3.062 Modulus of elasticity at room and elevated temperatures, Figure 3.062.

4. FABRICATION

4.01 Forming

4.011 General. Cold working operations are difficult because of the high loads required and the large amounts of springback encountered. However, cold forming is capable of producing satisfactory parts. Hot forming may be carried out at temperatures up to 1500F, however, above 1100F surface oxidation and interstitial contamination are problems and parts will require surface removal by machining or etching. Hot sizing may be used to creep form parts in metal dies at temperatures between 1000 and 1300F for times between 5 and 20 minutes. When using this process attention should be given to the possibility of interstitial contamination. Hot sizing of solution treated parts may be combined with aging which will start at temperatures above about 500F. More detailed information on forming may be obtained from (42) (57).

4.012 Forging.

4.0121 General. Generally, the alloy is forged in the alpha + beta field at temperatures between 1550 and 1700F. The lower limit is set by workability and the upper limit by the beta transus which varies somewhat with the composition. Increasing amounts of work in the alpha + beta field tend to increase the strength of solution treated and aged material and consequently reduce fracture toughness.

Working primarily within the beta field reduces the energy requirements but results in a transformed beta structure that is frequently associated with reduced tensile elongation and reduction in area. However, it has been reported (58) that beta worked material has improved resistance to hot salt corrosion and improved fracture toughness. Claims for increased fracture toughness are based on a small amount of data from a mixture of fracture toughness tests. None of the available toughness data conforms to the ASTM E 399 K_{Ic} specification. Results from precracked Charpy tests, (Table 4.0122) do not indicate any substantial toughness improvement except for material solution treated at 1525F and aged at 1100F. If insufficient work in the beta field is provided, the tensile properties may be relatively low. It is sometimes difficult to provide sufficient deformation in certain sections of some forgings (e.g. the wall in Table 4.0124) and the design should provide for removal of such "dead" areas during finish machining. Excessive dwell in the beta field in the absence of work will cause rapid grain growth and avoidance of this effect can complicate the forging operation. A detailed discussion of beta forging and precautions is given in (58).

If press speeds are sufficiently reduced and heated dies are employed, advantage may be taken of creep during the forging process (Figure 4.0125) which greatly reduces the press forces and permits better shape definition and dimensional control. This process is called isothermal creep forging. It has the disadvantage that die temperatures in the order of 1700F are required and the dies themselves are subject to creep. To minimize this creep very expensive high temperature alloy dies are used (35)(59). Insufficient forging experience has been gained to assess the life of these dies and the economic feasibility of the process (60).

4.0122 Tensile properties and precracked Charpy values for alpha + beta and for beta forged disks, Table 4.0122.

4.0123 Effect of upset deformation for beta forging on room temperature tensile properties, Table 4.0123.

4.0124 Effect of forging temperatures on room temperature tensile properties of landing gear wheel forging, Table 4.0124.

4.0125 Effect of upset temperature and press speed on flow stress, Figure 4.0125.

4.0126 Tensile properties at room temperature of isothermally forged and heat treated nose wheel, Table 4.0126.

4.02 Machining and Grinding

Refer to Machinability Data Center, Metcut Research Associates, 390 Rosslyn Drive, Cincinnati, Ohio 45209.

4.03 Joining

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

4.031 Welding.

4.0311 General. Welding of this alloy required careful attention to ensure adequate fracture toughness in the weldment. Generally, an experimental program tailored to the specific application is desirable as an aid to establishing the proper welding procedures.

The beta stabilization of this alloy is sufficient that transformation hardening will occur during the cooling of weldments and consequently the ductility and fracture toughness of the weld metal and heat affected zone may be below that of the parent metal. Solution treating and aging of welds leads to brittle behavior and should be avoided. GTA, GMA, plasma arc, and EB welding processes have been investigated and all are capable of producing weld metal having tensile strength somewhat higher than annealed parent metal (e.g. Table 4.0312). Inert gas protection is essential to avoid interstitial contamination. Alpha filler metal will produce weld metal of higher toughness than matching filler (Table 4.0313). A postweld heat treatment of from 1200 to 1400F reduces the yield strength and appears to improve the fracture toughness of the weld metal (Table 4.0313). The plane strain fracture toughness data available related only to the fusion zone. Older data on center cracked panels indicate that the crack strength of the heat affected zone is low even when alpha filler is used in conjunction with a postweld heat treatment (Table 4.0314). Results from an investigation of electron beam welds indicate lower toughness in the heat affected zone than in the parent metal (Table 4.0315). A postweld heat treatment did not raise the heat affected zone toughness.

Conventional fatigue tests on weld metal produced with different fillers and by different processes indicate that those welding conditions yielding the highest yield strength (matching filler and no postweld heat treatment) produce the highest fatigue strength. None of the postweld heat treatments produce fatigue strengths as high as mill annealed plate (compare Figures 4.0316 and 4.0317 with Figure 3.0511 and Table 3.05115).

4.0312 Tensile properties at room temperature for welds made by several processes with matching filler, Table 4.0312

4.0313 Tensile properties and plane strain fracture toughness for GTA weld metal from several fillers, Table 4.0313.

4.0314 Crack strength of TIG welded sheet using several filler wires, Table 4.0314.

4.0315 Plane strain fracture toughness of the heat affected zone of electron beam welds, Table 4.0315.

4.0316 Charpy impact energy for sheet weldments made with two fillers and given different heat treatments, Table 4.0316.

4.0317 Fatigue strength of auto GTA welds with matching filler given postweld heat treatments, Figure 4.0316.

4.0318 Fatigue strength for auto GTA welds made with different fillers, Figure 4.0317.

4.0319 Fatigue strength for several different welds made in annealed plate with matching filler, Figure 4.0318.

4.04 Surface Treatment

4.041 General. Resistance to wear and abrasion can be improved by coatings of Ni or Cr. Electroplating is difficult probably because of the tightly adherent oxide film. Electroless Ni has been successfully applied to the alloy using diffusion hardening treatments which substantially increase the plate depth (Figure 4.042) and increase the wear resistance as measured with a modified McMillan wear tester (Figure 4.043). However, the room temperature tensile strength of solution treated and aged material decreases rapidly with diffusion bond temperature above about 1200F. A recommended best compromise between wear characteristics and loss of tensile strength in the solution treated and aged condition is bonding at 1350F (27). The electroless Ni plate does appear to reduce the smooth specimen fatigue life of annealed material (Figure 4.045).

4.042 Effect of diffusion bonding temperature on electroless Ni plate depth, Figure 4.042.

4.043 Effect of diffusion bond temperature applied to electroless Ni plate on the failure time in a modified McMillan wear tester, Figure 4.043.

4.044 Effect of diffusion bonding temperature on room temperature tensile and impact properties of electroless nickel plated stock heat treated to two strength levels, Figure 4.044.

4.045 Effect of various fretting resistant coatings on fatigue life of annealed bar, Figure 4.045.

AMS	Heat Treatment	Ref.	Form
4971A	Annealed or solution treat and age	49	Bars, forgings, wire flash welded rings and stock for forgings or for flash welded rings.
4978A	Annealed	50	As above
4979	Solution treat and age	51	As above
4936	Annealed	52	Extruded bars, tubes, shapes and stock for flash welded rings.
4918C	Annealed	53	Sheet strip and plate.

TABLE 1.031 AMS SPECIFICATIONS

Source	(1) (49 thru 53)	
Alloy	6Al-6V-2Sn	
	Percent	
	Min.	Max.
Aluminum	5.0	6.0
Vanadium	5.0	6.0
Tin	1.5	2.5
Iron	0.35	1.0
Copper	0.35	1.0
Oxygen	-	0.20
Carbon	-	0.05
Nitrogen	-	0.04
Hydrogen	-	0.015
Titanium	Balance	

TABLE 1.041 PRODUCERS AND AMS SPECIFIED COMPOSITION

Source	AMS Specifications (49 thru 53)			
Condition	Anneal		Solution Treat and Age	
Heat Treat	1275-1325F 2 hr., cool as required	1300-1500(2) 2 hr., cool as required	1625-1675F, 1 hr., WQ + 1035-1065F, 4 hr., AC	1575-1650F (2) 1 hr., WQ + >1000F, 4 hr., AC
Specification	AMS 4971A	AMS 4978A AMS 4936 AMS 4918C (1)	AMS 4971A	AMS 4979
(1) Hold at temperature 20 min. per inch of thickness but not less than 10 min. (2) Hold at a temperature within this range to ± 25F.				

TABLE 1.052 AMS SPECIFIED HEAT TREATMENTS

Ti
6 Al
6 V
2 Sn

Ti-6-6-2

Source	(1, Table III)		
Alloy	Ti-6Al-6V-2Sn		
Form	Flat Rolled <0.125 in	Flat Rolled >0.125 in	Bar, Forgings & Extrusions
Stress Relief	1000 to 1200F, 1 to 4 hr., A.C.	1000 to 1200F, 1 to 4 hr., A.C.	1000 to 1200F, 1 to 4 hr., A.C.
Anneal	1400F, 4 hr, F.C. to 1100F, A.C.	1400F, 4 hr, F.C. to 1100F, A.C.	1400F, 4 hr, A.C.
Solution Treat	1500 to 1600F, 5 to 15 min. W.Q.	1550 to 1625F, 1/2 hr., W.Q.	1550 to 1650F, 1 hr. W.Q.
Age	1050 to 1150F 4 hr., A.C.	1050 to 1150F 4 hr., A.C.	950 to 1100F 4 to 12 hr., A.C.

TABLE 1.053 PRODUCERS RECOMMENDED HEAT TREATMENTS.

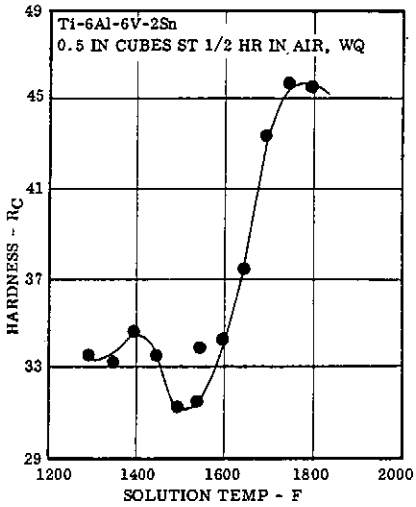


FIG. 1.062 EFFECT OF SOLUTION TEMPERATURE ON HARDNESS. (29, Fig. 1)

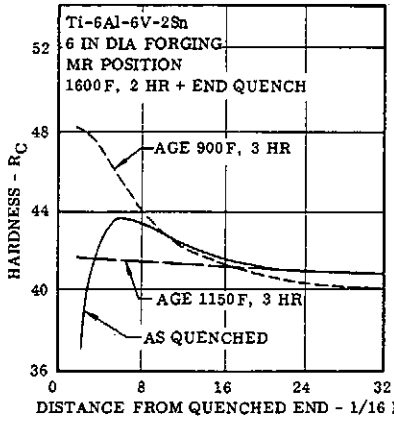


FIG. 1.061 JOMINY HARDENABILITY CURVE AND HARDNESS DISTRIBUTION AFTER AGING. (54, Fig. 1)

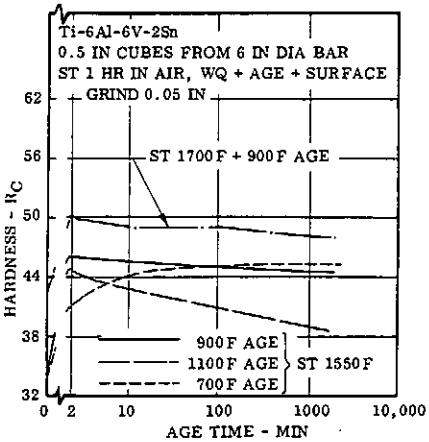


FIG. 1.063 HARDNESS AS FUNCTION OF AGING TIME AND TEMPERATURE FOR TWO SOLUTION TEMPERATURES. (28, Fig. 2)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

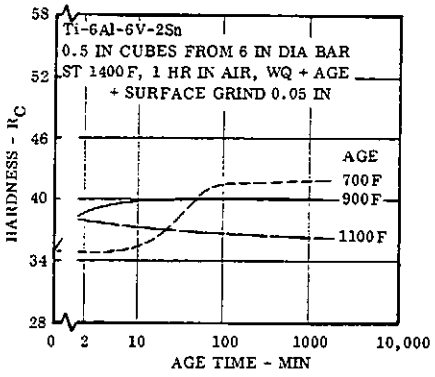


FIG. 1.064 HARDNESS AS FUNCTION OF AGING TEMPERATURE AND TIME.
(28, Fig. 2)

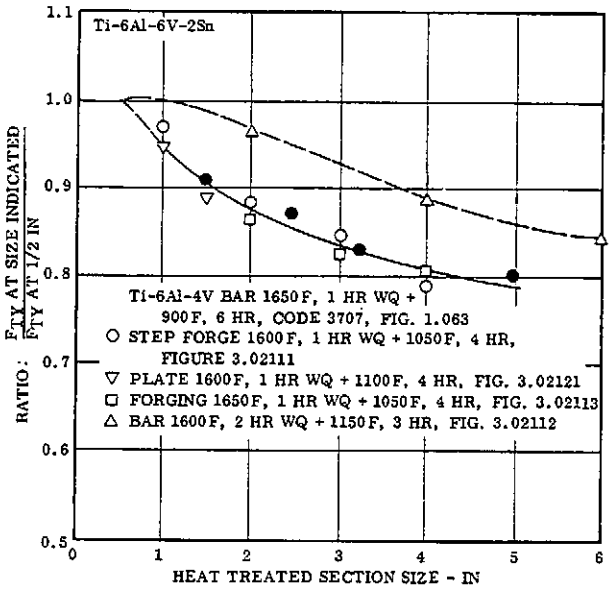


FIG. 1.0912 HARDENABILITY OF VARIOUS FORMS OF ALLOY.

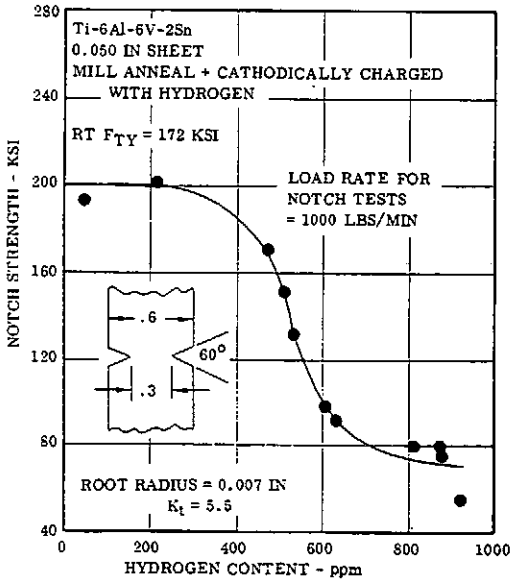


FIG. 1.091 NOTCH TENSILE STRENGTH OF ANNEALED SHEET AT ROOM TEMPERATURE AS INFLUENCED BY HYDROGEN CONTENT. (41, Fig. 3)

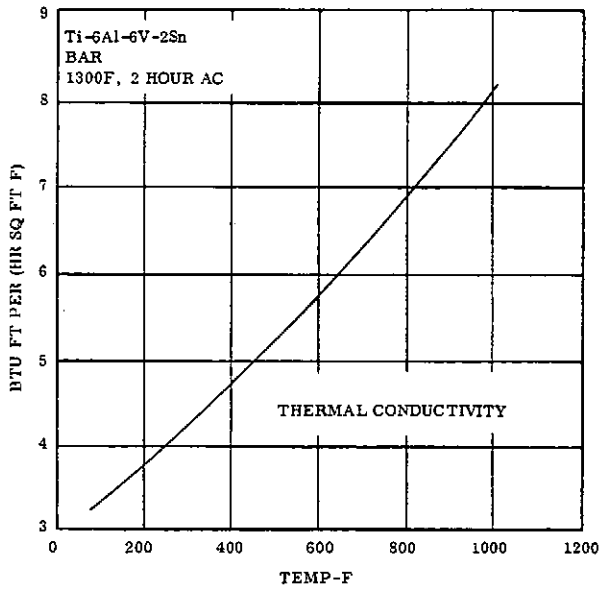


FIG. 2.013 THERMAL CONDUCTIVITY (1)

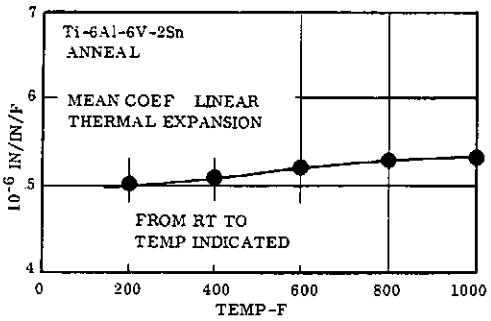


FIG. 2.014 THERMAL EXPANSION (1)

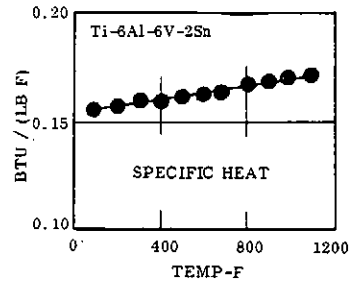


FIG. 2.015 SPECIFIC HEAT (1)

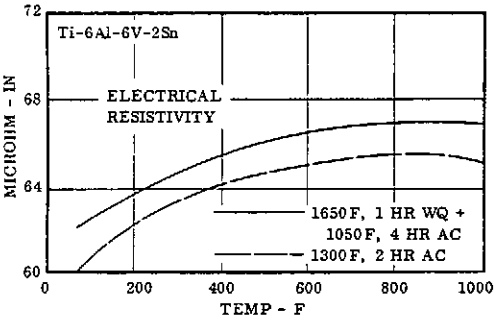


FIG. 2.0221 ELECTRICAL RESISTIVITY. (1)

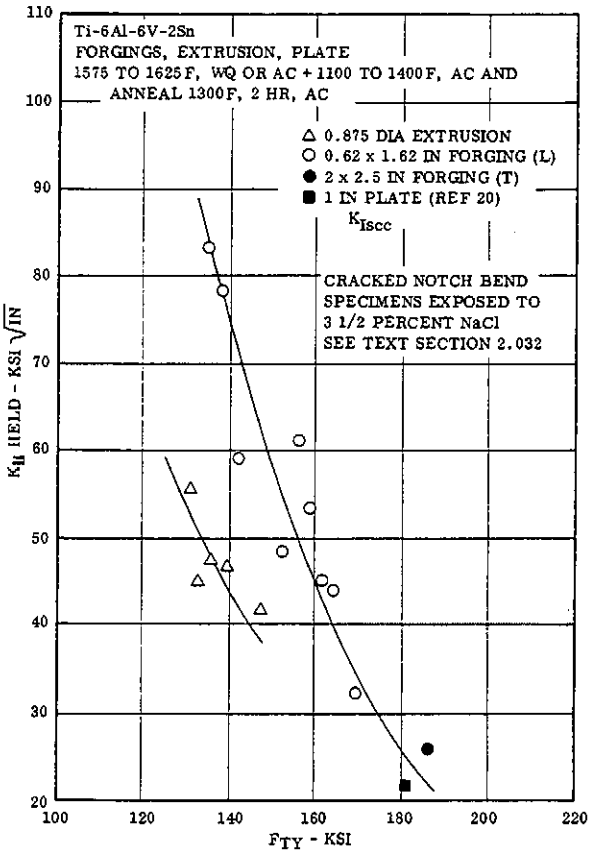


FIG. 2.034 EFFECT OF YIELD STRENGTH LEVEL ON DELAYED FAILURE CHARACTERISTICS IN SALT WATER. (20)(21)

Ti
6 Al
6 V
2 Sn

Ti-6-6-2

Source	(16)				
Alloy	Ti-6Al-6V-2Sn				
Form	0.120 inch sheet				
Condition	Expose Temp-F	Cracks Observed (1) σ_a/F_{ty}	Cracks Observed Time at Load-hr.	No Cracks Observed σ_a/F_{ty}	No Cracks Observed Time at Load-hr.
1350F, 1/4 hr FC - F_{ty} = 122 Ksi	650	0.30	50	0.30	18
1550F, 5 min WQ + 1100F, 4 Hr AC					
F_{ty} = 134 Ksi	650	0.22	10	0.16	10
1350F, 1/4 hr FC - F_{ty} = 125 Ksi	550	0.47	18	0.33	65
1550F, 5 min WQ + 1100F, 4 Hr AC				(0.48)(2)	(350)
F_{ty} = 137 Ksi	550	0.58	180	<0.58	180

(1) 0.120 Smooth specimen exposed at stress σ_a
(2) Cyclic exposure: heat in 10 to 15 min; hold 3 hrs; cool in 45 to 60 min.

TABLE 2.035 RESULTS OF ELEVATED TEMPERATURE SOLID SALT STRESS CORROSION TEST OF SHEET

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

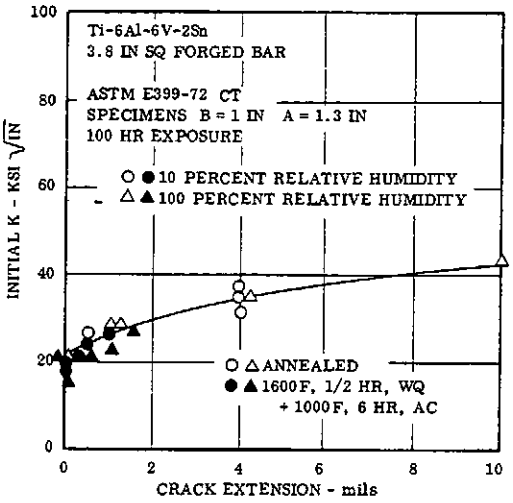


FIG. 2.036 SUSTAINED LOAD CRACK EXTENSION IN AIR. (30, Tables 7, 8)

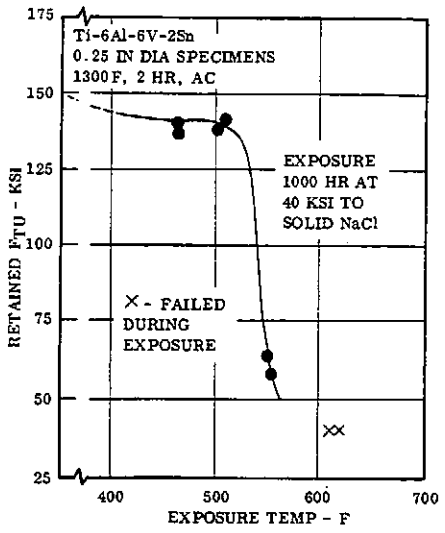


FIG. 2.037 RESIDUAL TENSILE STRENGTH AT ROOM TEMPERATURE FOLLOWING ELEVATED TEMPERATURE STRESS EXPOSURE TO SOLID SALT. (45, Fig. 5)

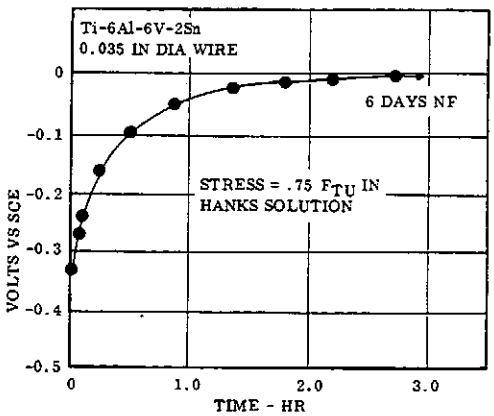


FIG. 2.038 POTENTIAL TIME CURVES FOR STRESSED WIRE IN SIMULATED HUMAN BODY ENVIRONMENT. (26, Fig. 3)

Alloy	Ti-6Al-6V-2Sn						
Form	Bars, forgings and rings						
Condition	Solution treated and aged						
AMS	4979 and 4971A						
As Received Size - in.(1)	Heat Treated Size - in.(2)	F_{tu} - ksi	F_{ty} - ksi	e-percent(4)		RA-percent	
				L	T (3)	L	T(3)
≤2	≤1	175	160	8	6	20	15
	>1 thru 2	170	155	8	6	20	15
>2 thru 3	≤1	170	160	8	6	20	15
	>1 thru 2	165	155	8	6	20	15
	>2 thru 3	155	145	8	6	20	15
>3 thru 4	≤1	165	155	8	6	20	15
	>1 thru 2	160	150	8	6	20	15
	>2 thru 3	155	145	8	6	20	15
	>3 thru 4	150	140	8	6	20	15

(1) Nominal diameter or distance between parallel sides.
(2) AMS 4979 gives As Received Size same as Heat Treated Size. Values underlined apply to both AMS 4979 and 4971A. Other values apply only to AMS 4971A.
(3) Transverse requirements do not apply if a specimen ≥2-1/2 in long cannot be abstracted.
(4) In 4D or 2 inches.

TABLE 3.011 AMS SPECIFIED MINIMUM MECHANICAL PROPERTIES FOR BARS, FORGINGS AND RINGS IN SOLUTION TREATED AND AGED CONDITION

Alloy	Ti-6Al-6V-2Sn				
Condition	Annealed				
Form	Extrusions AMS 4936			Bars, Forgings and Rings (AMS 4978A)	
Size - in (1)	≤1.5	>1.5 thru 3	>3 thru 4	≤2	>2 thru 4
F_{tu} (min) - ksi	150	145	140	150	145
F_{ty} - ksi	140 to 165	135 to 160	130 to 155	140 to 165	135 to 160
e - L (min)-percent (2)	10	10	10	10	10
e - T (min)-percent	8	8	8	8	8
RA - L (min)-percent	20	20	20	20	15
RA - T (min)-percent	15	15	15	15	15

(1) Nominal diameter or distance between parallel sides.
(2) In 4D or 2 inches

TABLE 3.012 AMS SPECIFIED MECHANICAL PROPERTIES FOR ANNEALED EXTRUSIONS AND BARS, FORGINGS AND RINGS

Alloy	Ti-6Al-6V-2Sn			
Condition	Annealed			
Form	AMS 4918C Sheet, strip and plate			
Size - in.	<0.025	≥0.025 but <0.1875	≥0.1875 thru 2.000	≥2.000 thru 4.000
F_{tu} (min) - ksi	155	150	150	145
F_{ty} - ksi	145-170	145-170	140-165	135-160
e (4D) - percent				
L (min)	8	10	10	8
T (min)	6	8	8	6

TABLE 3.013 AMS SPECIFIED MECHANICAL PROPERTIES FOR ANNEALED SHEET, STRIP AND PLATE

Source	(1)									
Alloy	Ti-6Al-6V-2Sn									
Form	Bar and Forging Stock (STA)									
Condition	1550F, to 1650F, 1 Hr, WQ + 950 to 1100F, AC									
Original Thickness - Inch	≤1	>1 to 2		>2 to 3			>3 to 4			
Heat Treated Thickness - In	≤1	≤1	>1 to 2	≤1	>1 to 2	>2 to 3	≤1	>1 to 2	>2 to 3	>3 to 4
F_{tu} (min) - ksi	175	175	170	170	165	160	165	160	155	150
F_{ty} (min) - ksi	160	160	155	160	155	150	155	150	145	140
e (4D) - percent										
L	8	8	8	8	8	8	8	8	8	8
T	6	6	6	6	6	6	6	6	6	6
RA - percent										
L	20	20	20	20	20	20	20	20	20	20
T	15	15	15	15	15	15	15	15	15	15

TABLE 3.014 PRODUCERS GUARANTEED TENSILE PROPERTIES OF SOLUTION TREATED AND AGED BAR AND FORGING STOCK

Ti
6 Al
6 V
2 Sn

Ti-6-6-2

Source	(1)		
Alloy	Ti-6Al-6V-2Sn		
Form	Bar		
Condition	Annealed (see Table 1.053)		
Thickness	≤2 inch	>2 to 4	>4 to 6
F_{tu} (min) - ksi	150	140	135
F_{ty} (min) - ksi	140	130	125
e (4D) min percent			
L	10	8	8
T	8	6	6
RA - min percent			
L	20	15	15
T	15	12	12

TABLE 3.015 PRODUCERS GUARANTEED TENSILE PROPERTIES OF ANNEALED BAR

Source	(1)		
Alloy	Ti-6Al-6V-2Sn		
Form	0.187 inch Sheet		
Condition (1)	Anneal	Solution Treated	Sol Treat + Age
F_{tu} (min) - ksi	155	-	170
F_{ty} (min) - ksi	145	130 (max)	160
e (2 in) min percent			
<0.015 inch	6	6	-
0.015 to 0.020 in	8	8	-
>0.020 inch	10	10	-
>0.020 inch	-	-	3
0.020 to 0.032 in	-	-	4
>0.032 to 0.049 in	-	-	5
>0.049 inch	-	-	6
(1) For recommended heat treatments, see Table 1.052			

TABLE 3.018 PRODUCERS GUARANTEED TENSILE PROPERTIES OF ANNEALED SOLUTION TREATED AND SOLUTION TREATED AND AGED SHEET

Source	(1)		
Alloy	Ti-6Al-6V-2Sn		
Form	Extrusions		
Condition (1)	Annealed	Solution Treat + Age	
Size (2)	All	≤1/2	>1/2 thru 3/4
F_{tu} (min) - ksi	145	170	165
F_{ty} (min) - ksi	135	160	155
e (4D) min percent	8	6	6
RA - min percent	12	12	12
(1) See Table 1.053			
(2) Maximum inscribed circle diameter			

TABLE 3.016 PRODUCERS GUARANTEED TENSILE PROPERTIES OF SOLUTION TREATED AND AGED EXTRUSION

Source	(1)					
Alloy	Ti-6Al-6V-2Sn					
Form	Plate					
Condition (2)	Annealed		Solution Treated	Solution Treat + Age		
Thickness	>0.187 to 2 in	>2 <4 in	Any	>0.187 to 1.5 in	>1.5 to 2.5 in	>2.5 to 4 in
F_{tu} (min) - ksi	150	135	150	170	160	150
F_{ty} (min) - ksi	140	145	130(1)	160	150	140
e (2 in)-percent						
L	10	8	10	8	6	6
T	8	6	10	8	6	6
RA - percent						
L	20	20	20	15	15	15
T	15	15	15	15	15	15
(1) Guaranteed Maximum	(2) See Table 1.053					

TABLE 3.017 PRODUCERS GUARANTEED TENSILE PROPERTIES OF ANNEALED SOLUTION TREATED AND SOLUTION TREATED AND AGED PLATE

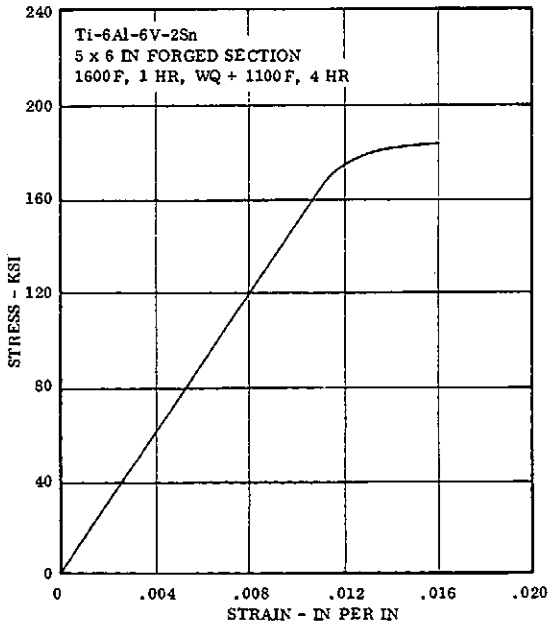


FIG. 3.0211 STRESS-STRAIN CURVE IN TENSION FOR FORGING (SPECIMENS HEAT TREATED). (2)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

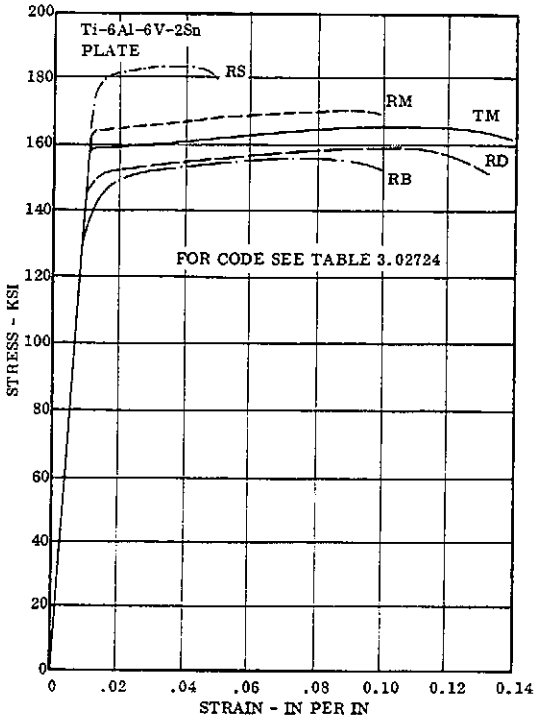


FIG. 3.0212 STRESS STRAIN CURVES FOR PLATE IN SEVERAL CONDITIONS OF HEAT TREATMENT.

(36, p. 85)

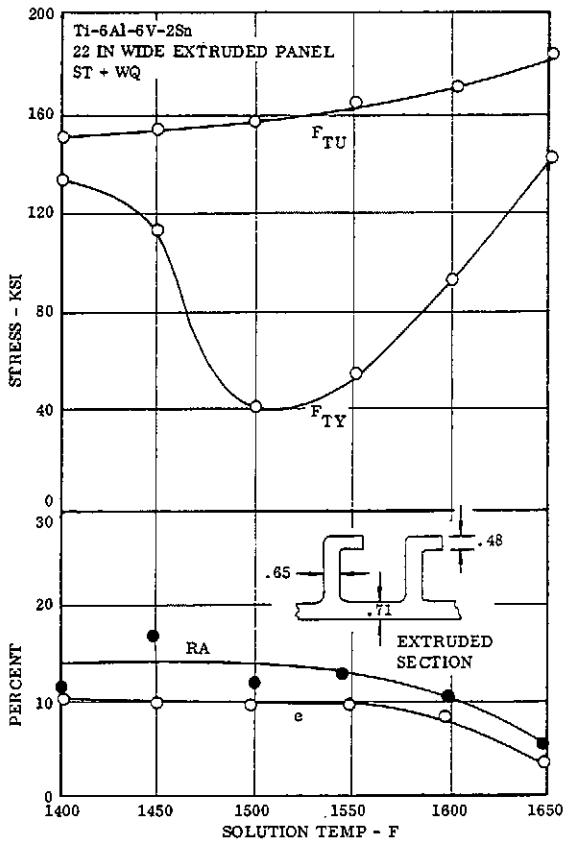


FIG. 3.0214 EFFECT OF SOLUTION TEMPERATURE ON AS QUENCHED TENSILE PROPERTIES OF EXTRUSION.

(46, Fig. 22)

Source	(31, Table III)		
Alloy	Ti-6Al-6V-2Sn		
Form	Investment Cast Specimens		
Condition	As Cast + 1100F, 1 hr AC	1600F, 1 hr WQ + 1200F, 1 hr AC	1800F, 1 hr WQ + 1100F, 4 hr AC
F_{tu} - ksi	154	167	189
F_{ty} - ksi	141	158	(1)
e - percent	8	4	1.2
RA - percent	18	10	3
(1) Broke before 0.2 percent yield			

TABLE 3.0213 TENSILE PROPERTIES OF INVESTMENT CAST SPECIMENS GIVEN SEVERAL HEAT TREATMENTS

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

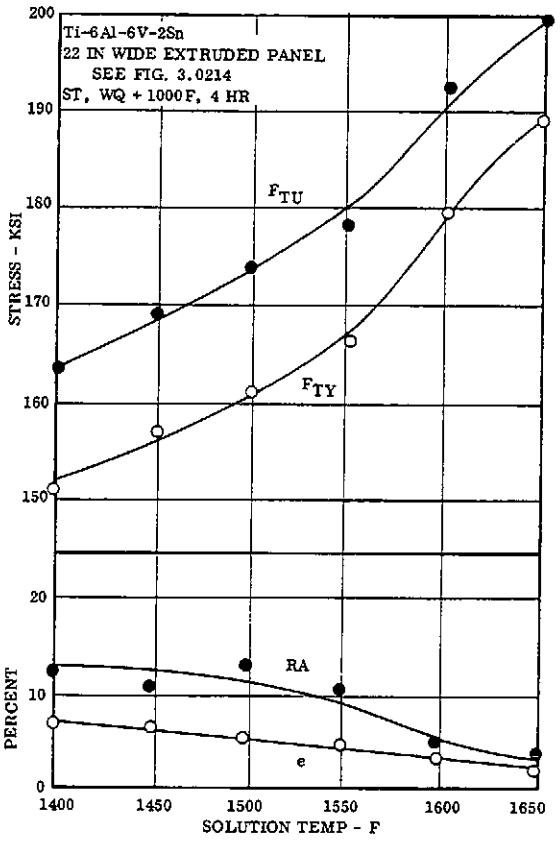


FIG. 3.0215 EFFECT OF SOLUTION TEMPERATURE ON TENSILE PROPERTIES OF 1000F AGED EXTRUSION.
(46, Fig. 23)

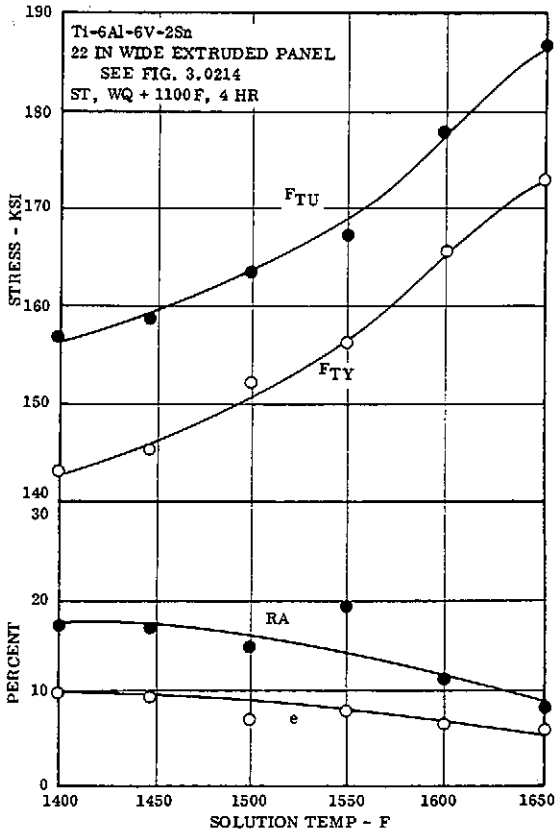


FIG. 3.0216 EFFECT OF SOLUTION TEMPERATURE ON TENSILE PROPERTIES OF 1100F AGED EXTRUSION. (46, p. 24)

Ti
6 Al
6 V
2 Sn

Ti-6-6-2

Source	(25, Table III)								
Alloy	Ti-6Al-6V-2Sn								
Form	Extrusion at 1675F to 8-3/4 in OD x 11-3/4 in ID Cylinders								
Condition	St. 1600F, 3 hr WQ								
Age	1300F, 6 hr			1000F, 4 hr					
Heat (1)	A			B			C		
Position (2)	OD	MW	ID	OD	MW	ID	OD	MW	ID
F_{tu} - ksi (L)	154	152	155	209	186	200	176	162	177
F_{tu} - ksi (T)	-	153	154	198	192	202	179	171	177
F_{ty} - ksi (L)	143	143	145	202	181	195	166	149	165
F_{ty} - ksi (T)	143	144	144	193	187	198	161	158	163
e - percent(L)	15	15	17	2	4	4	6	10	8
e - percent(T)	17	17	16	3	2	1	4	8	7
RA - percent(L)	34	37	44	6	9	8	13	21	15
RA - percent(T)	30	36	42	5	4	4	8	15	12

(1) For compositions see Table 3.02722
(2) OD - outside, MW - midwall, ID - inside

TABLE 3.0217 TENSILE PROPERTIES FOR EXTRUDED CYLINDERS FROM THREE HEATS AGED AT TWO TEMPERATURES AND TESTED AT VARIOUS CROSSECTIONAL LOCATIONS

Source	(3)		
Alloy	Ti-6Al-6V-2Sn		
Form	2-3/4 x 4 inch center section of test forging with heavy ribs and thin webs		
Condition	1650F, 2 hr, WQ + 1100F, 4 hr, AC		
Direction	L	T	ST
F_{tu} - ksi	166-185	174-194	175-192
F_{ty} - ksi	153-175	161-181	161-181
e (4D) - percent	10-12	6-8	6-10
RA - percent	20-29	17-25	14-20

TABLE 3.02110 VARIATION OF TENSILE PROPERTIES OF CENTER SECTION OF TEST FORGING WITH HEAVY RIBS AND THIN WEBS

Source	(24, Table 4)		
Alloy	Ti-6Al-6V-2Sn		
Form (2)	Extrusion at 1735F 85 percent red. to 3 in diameter bar		
Condition	ST 1600F, 1-1/2 hr WQ + age		
Direction (1)	L,O	L,MR	T
F_{tu} - ksi	166	166	158
F_{ty} - ksi	152	142	143
e - percent	26	20	19
RA - percent	45	39	38

(1) L,O - long outside, L,MR - long mid radius, T - trans.
(2) For composition see Table 3.02722

TABLE 3.0218 TENSILE PROPERTIES OF SOLUTION TREATED AND AGED EXTRUDED BAR AT VARIOUS CROSSECTIONAL LOCATIONS

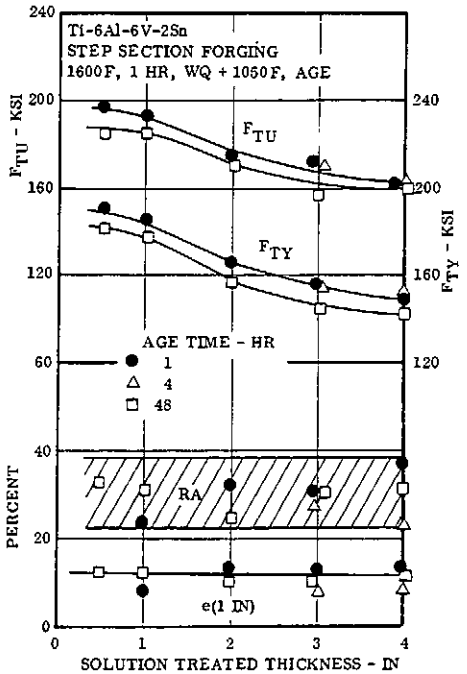


FIG. 3.02111 EFFECT OF SOLUTION TREATED SECTION SIZE AND AGE TIME ON TENSILE PROPERTIES OF FORGING (FORGED TO SOLUTION TREATED SIZE). (4)

Source	(2)								
Alloy	Ti-6Al-6V-2Sn								
Form	5 x 6 inch forged section								
Condition	1600F, 1 hr WQ + 1100F, 4 hr (specimens heat treated)								
Direction	Edge			Mid Radius			Center		
Direction	L	LT	ST	L	LT	ST	L	LT	ST
F_{tu} - ksi	175	179	178	168	174	174	159	162	164
F_{ty} - ksi	167	170	170	160	165	166	150	150	155
e (1 in) percent	9	10	10	12	10	10	15	13	11
RA - percent	24	28	28	32	27	34	43	42	40

TABLE 3.0219 TENSILE PROPERTIES IN VARIOUS LOCATIONS IN A FORGED SECTION

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

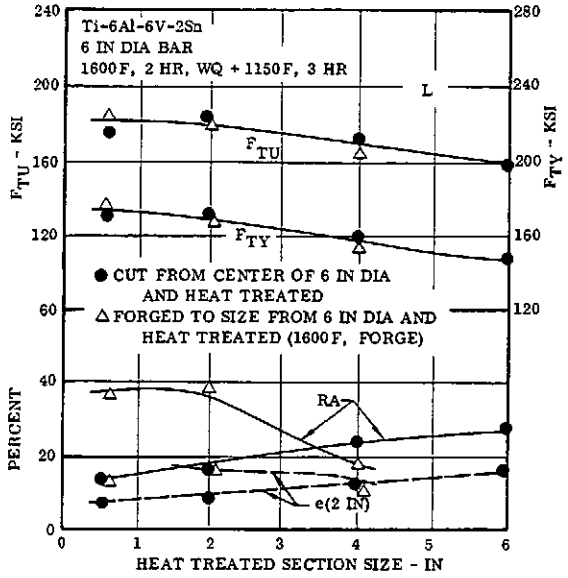


FIG. 3.02112 EFFECT OF HEAT TREATED SECTION SIZE ON TENSILE PROPERTIES OF SPECIMENS REMOVED FROM CENTER OF SOLUTION TREATED AND AGED BAR SECTIONS. (5)

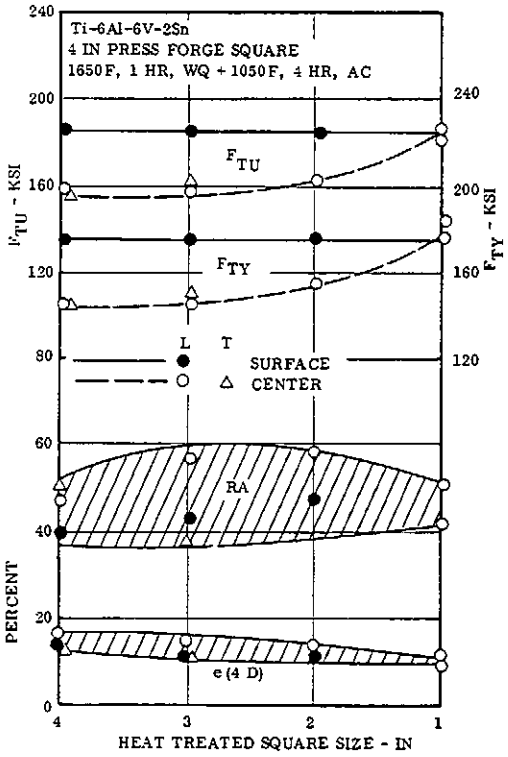


FIG. 3.02113 EFFECT OF HEAT TREATED SECTION SIZE ON TENSILE PROPERTIES OF SQUARE SECTIONS REMOVED FROM CENTER OF 4 INCH SQUARE PRESS FORGING. (1)

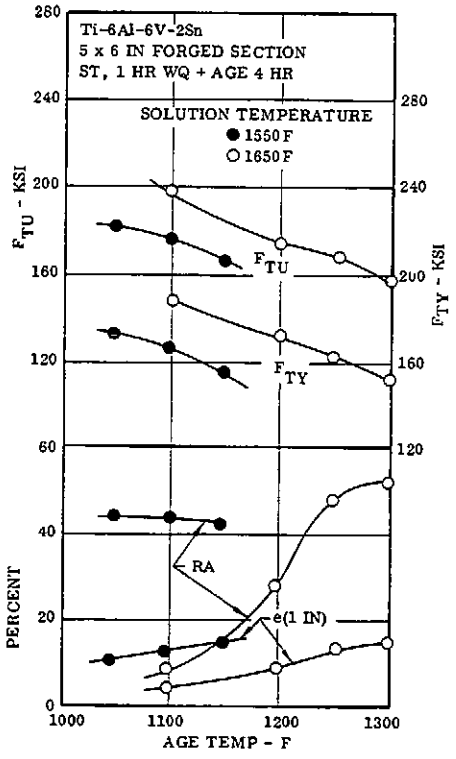


FIG. 3.02114 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF SPECIMENS CUT FROM FORGING AND SOLUTION TREATED AT TWO TEMPERATURES. (2)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

Source	(4)											
Alloy	Ti-6Al-6V-2Sn											
Form	4 Inch Square Forged Bar (Specimens Heat Treated)											
Composition	0.11 O_2, 0.025C, 0.75 Fe						0.16 O_2, 0.023C, 0.73Fe					
Heat Treatment	1450F, 2 hr FC		1600F, 1 hr AC +1100F, 8 hr AC		1600F, 1 hr WQ + 1350F, 2 hr AC		1450F, 2 hr FC		1600F, 1 hr AC +1100F, 8 hr AC		1650F, 1 hr WQ +1350F, 2 hr AC	
Direction (1)	L	T	L	T	L	T	L	T	L	T	L	T
F_{tu} - ksi	147	147	143	141	142	151	150	150	150	150	152	153
F_{ty} - ksi	137	136	135	133	130	138	140	142	139	141	141	142
e (1 in)	20	20	20	14	18	14	20	16	19	14	17	17
RA percent	34	33	41	36	29	23	38	32	34	24	33	26
IE Charpy V ft-lbs	18	12	22	15	29	19	12	10	14	9	15	11
(1) Specimens removed from center of forging												

TABLE 3.02115 TENSILE PROPERTIES OF FORGED BAR AT TWO INTERSTITIAL LEVELS

Source	(47, Table 4)						
Alloy	Ti-6Al-6V-2Sn						
Form	13 in dia. x 1.25 in thick hammer forged disk						
Forging temp-F	1665			1725			
Solution temp-F 1 hr. WQ + 1100F, 4 hr	1525	1650	Forge→WQ	1525	1650	1725	Forge→WQ
F_{tu} - ksi (1)	178	193	188	176	195	200	195
F_{ty} - ksi	170	184	180	166	183	190	190
e - percent	13	8	10	14	9	5	7
RA - percent	39	20	27	36	25	8	25
(1) Specimens taken in tangential direction.							

TABLE 3.02116 EFFECT OF FORGING AND QUENCH TEMPERATURE ON TENSILE PROPERTIES OF HAMMER FORGED DISKS

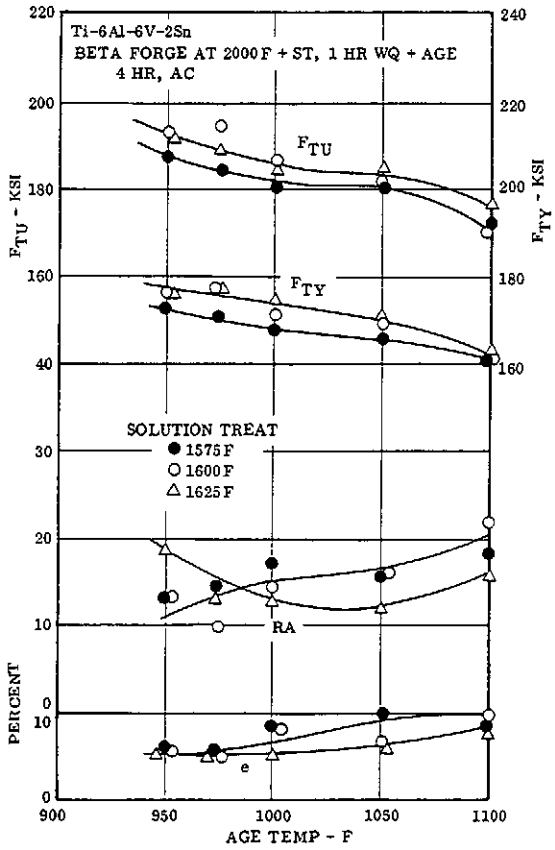


FIG. 3.02117 EFFECT OF AGE TEMPERATURE ON TENSILE PROPERTIES OF BETA FORGING SOLUTION TREATED AT VARIOUS TEMPERATURES. (23, Table 2)

Ti
6 Al
6 V
2 Sn

Ti-6-6-2

Source	(30, Table 3)	
Alloy	Ti-6Al-6V-2Sn	
Form	Forged bar 3.8 in sq.	
Condition	Annealed (as received)	1600F, 1/2 hr WQ + 1000F, 6 hr AC (1)
F_{tu} - ksi (2)	155	192
F_{ty} - ksi	149	184
e - percent	16	16
RA - percent	43	18
(1) Specimens heat treated		
(2) Longitudinal tests		

TABLE 3.02118 TENSILE PROPERTIES OF ANNEALED AND OF SOLUTION TREATED AND AGED SPECIMENS FROM FORGED BAR

Source	(1)							
Alloy	Ti-6Al-6V-2Sn							
Form	Bar							
Condition	Annealed				1650F, 1/2 hr WQ + 1050F, 1 hr AC			
140 to 150 hour exposure	None	600F 88 ksi	700F 40 ksi	800F 15 ksi	None	600F 125 ksi	700F 65 ksi	800F 45 ksi
Total creep deformation percent	-	0.45	0.32	0.30	-	0.75	0.48	0.76
F_{tu} - ksi	161	193	193	183	187	194	200	194
F_{ty} - ksi	153	161	168	175	182	192	184	181
e (1 in) percent	17	14	11	12	11	9	8	6
RA - percent	51	32	23	30	31	24	15	10

TABLE 3.02119 EFFECT OF ELEVATED TEMPERATURE EXPOSURE ON TENSILE PROPERTIES OF ANNEALED AND SOLUTION TREATED AND AGED BAR

Source	(1)			
Alloy	Ti-6Al-6V-2Sn			
Form	1 inch forged bar			
Condition	1650F, 1/2 hr, WQ + 1050F, 1 hr			
150 hour creep exposure	None	750F 65 ksi	800F 55 ksi	850F 55 ksi
Plastic creep deformation percent	-	0.72	1.0	3.63
F_{tu} - ksi	194	196	205	202
F_{ty} - ksi	185	185	195	191
e (4D) - percent	9	8.5	7	8
RA - percent	39	37	21	24

TABLE 3.02120 EFFECT OF 150 HOUR EXPOSURE TO STRESS AND ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF FORGED BAR

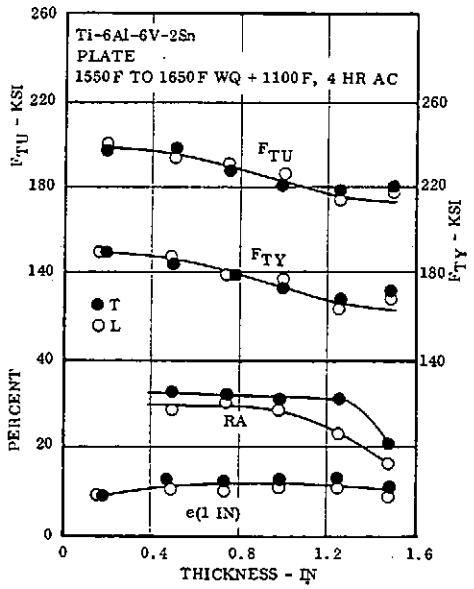


FIG. 3.02121 EFFECT OF THICKNESS ON THE TENSILE PROPERTIES OF SOLUTION TREATED AND AGED PLATE. (1)

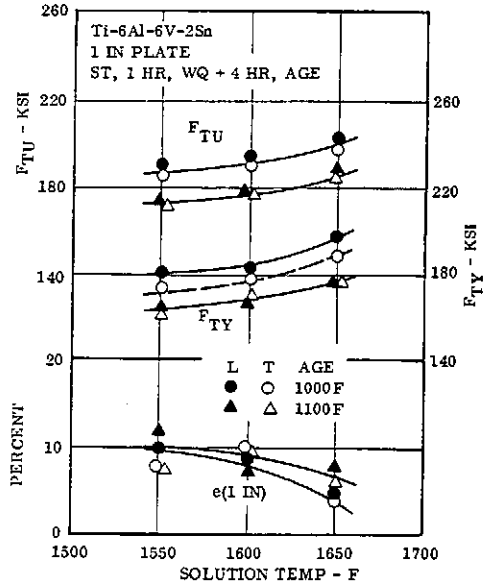


FIG. 3.02122 EFFECT OF SOLUTION TREATING AND AGING TEMPERATURES ON THE TENSILE PROPERTIES OF PLATE. (6)

Source	(42, Table 1-5:7)			
Alloy	6Al-6V-2Sn			
Form	3/4 in plate			
Exposure conditions at 25 ksi	Retained properties (T)			
Heat treat	Anneal 1300F, 2 hr			
Temp - F Time - hr	F_{tu} - ksi	F_{ty} - ksi	e (in) percent	RA percent
No exposure	158	151	14	32
250 5000	160	154	17	32
350 5000	162	155	16	32
450 2500	166	159	14	35
650 1000	190	163	11	22
Heat treat 1800F, 1/2 hr AC + 1625F, 4 hr WQ + 1200F, AC				
No exposure	166	153	9	18
250 5000	178	166	7	7
350 2500	169	160	9	14
350 5000	170	161	7	9
450 2500	171	162	9	16
650 1000	185	165	7	11

TABLE 3.02124 EFFECT OF EXPOSURE TO STRESS AND TEMPERATURE ON RETAINED TENSILE PROPERTIES OF PLATE

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

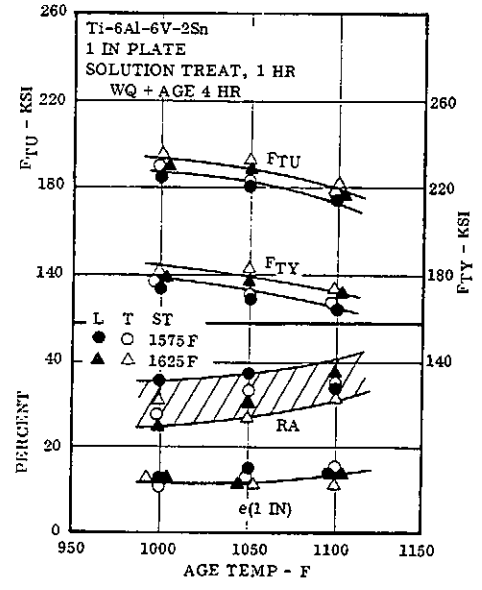


FIG. 3.02123 EFFECT OF AGING AND SOLUTION TREATING TEMPERATURE ON THE TENSILE PROPERTIES OF PLATE. (7)

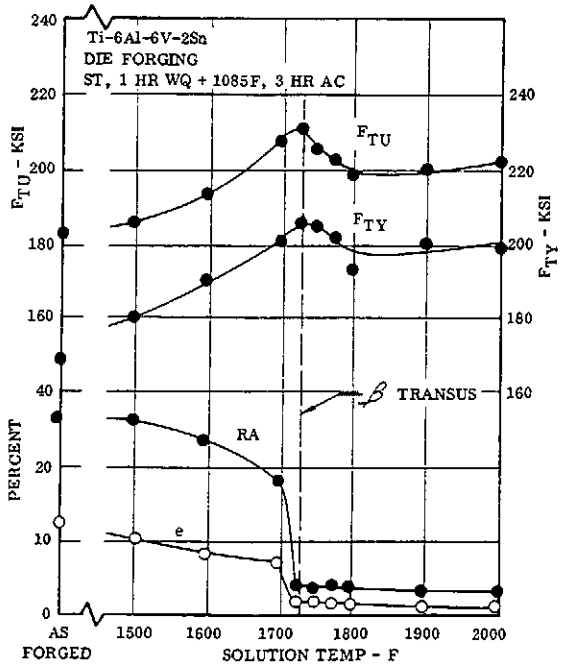


FIG. 3.02125 EFFECT OF SOLUTION TEMPERATURE ON TENSILE PROPERTIES OF AGED SHEET. (42, Fig. 1-5:15)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

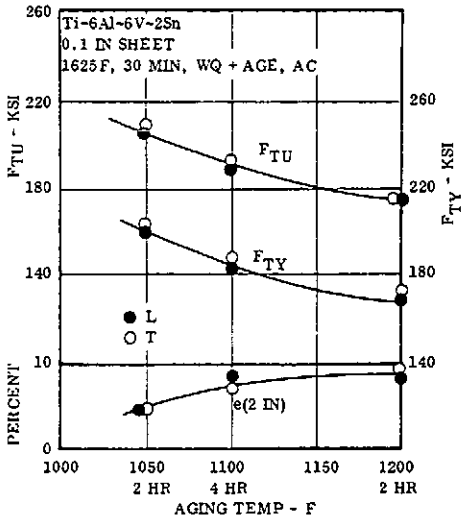


FIG. 3.02126 EFFECT OF AGING TEMPERATURE ON THE TENSILE PROPERTIES OF SHEET. (8)

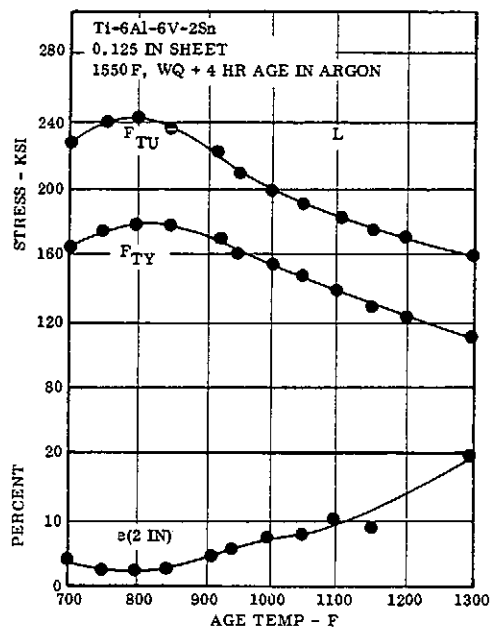


FIG. 3.02128 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF SHEET. (9)

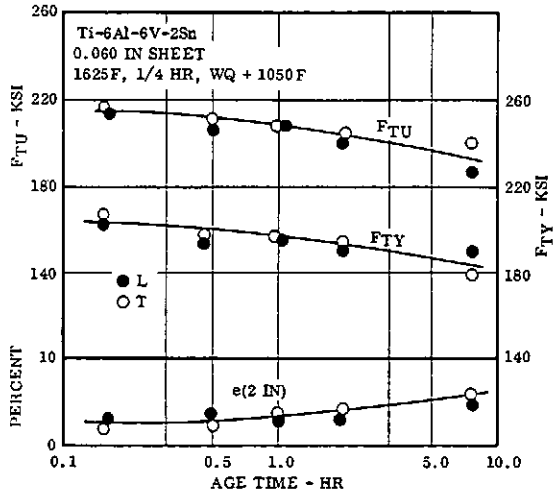
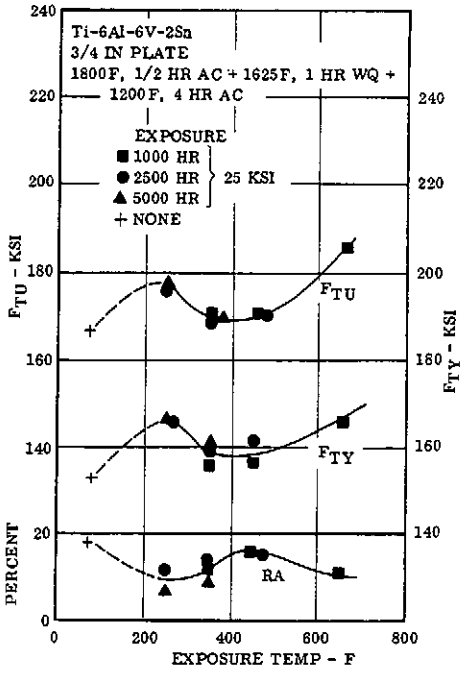


FIG. 3.02127 EFFECT OF AGING TIME ON TENSILE PROPERTIES OF SHEET. (1)

Source	(37, p. 3-10 and 3-8)						
Alloy	Ti-6Al-6V-2Sn						
Form	2 in Plate			1-1/2 in dia. bar		Large die forging	
Condition (1)(2)	A	B	C	A	B	A	B
F_{tu} - ksi	161	158	149	157	-	151	145
F_{ty} - ksi	157	150	139	153	-	144	138
e (1 in) percent	10	13	15	14	-	18	19
RA - percent	22	26	28	44	-	44	45

(1) A - mill anneal; B - 1675, 2 hr. AC, + 1600F, 1 hr. FC
C - 1700F, 4 hr. AC + 1400F, 1 hr AC
(2) Specimen blanks heat treated

TABLE 3.02129 TENSILE PROPERTIES OF PLATE, BAR AND FORGINGS ANNEALED OR SOLUTION TREATED AND AGED



Ti
6 Al
6 V
2 Sn
Ti-6-6-2

FIG. 3.02131 EFFECT OF STRESSED EXPOSURE AT ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION TREATED AND AGED PLATE. (55, Table 4)

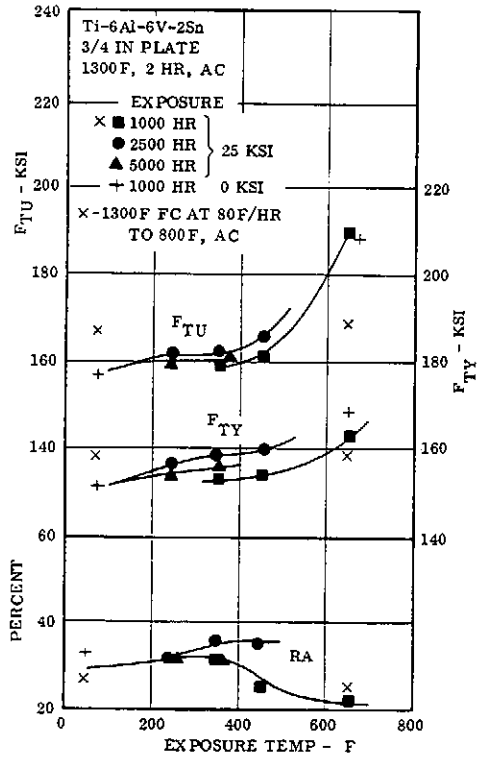


FIG. 3.02130 EFFECT OF STRESSED AND UNSTRESSED ELEVATED TEMPERATURE EXPOSURE ON TENSILE PROPERTIES OF ANNEALED PLATE. (55, Table 4)

Source	(47, Table 15)		
Alloy	Ti-6Al-6V-2Sn		
Form	Beta forged at 1725F		
Condition	1525F 1 hr WQ + 1000F, 4 hr AC		
Quenched section size - in	1.25	2	4
F_{tu} - ksi	187	184	163
F_{ty} - ksi	176	171	149
e (2 in) - percent	11	10	11
RA - percent	25	26	33

TABLE 3.02132 EFFECT OF AS QUENCHED SECTION SIZE ON TENSILE PROPERTIES OF BETA FORGED BARS

Ti
6 Al
6 V
2 Sn

Ti-6-6-2

Source	(31, Table III)		
Alloy	Ti-6Al-6V-2Sn		
Form	Investment cast specimens		
Condition	As cast + 1100F, 1 hr AC	1600F, 1 hr WQ + 1200F, 1 hr AC	1800F, 1 hr WQ + 1100F, 4 hr AC
F_{ty} - ksi	141	158	(1)
IE Charpy V ft-lb	13.3	12.5	6.25

(1) Broke before 0.2 percent yield, F_{tu} = 189 ksi

TABLE 3.0231 IMPACT STRENGTH OF INVESTMENT CAST SPECIMENS

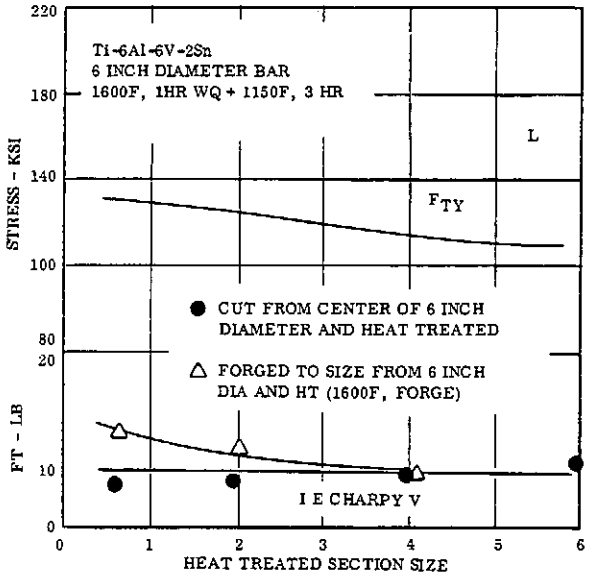


FIG. 3.0232 EFFECT OF HEAT TREATED SECTION SIZE ON IMPACT STRENGTH OF SPECIMENS REMOVED FROM CENTER OF SOLUTION TREATED AND AGED BAR SECTIONS
(5)

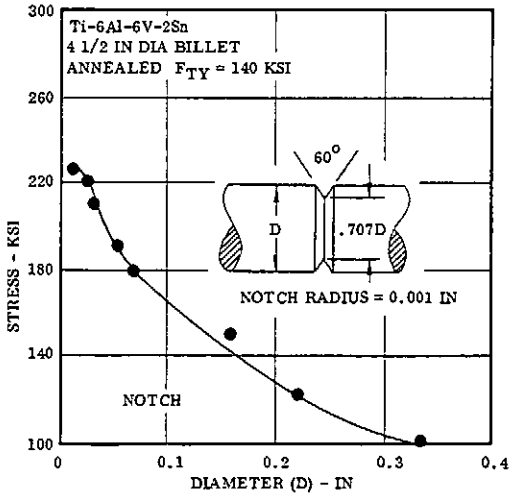


FIG. 3.02711 EFFECT OF NOTCH DIAMETER ON THE SHARP NOTCH PROPERTIES OF ANNEALED BILLET.
(13)

Source	(2)					
Alloy	Ti-6Al-6V-2Sn					
Form	5 x 6 inch forged section					
Condition	1600F, 1 hr WQ + 1100F, 4 hr (Specimens heat treated)					
Location	Edge			Mid radius		Center
Direction	L	LT	ST	LT	ST	L
F_{tu} - ksi	183	180	190	176	178	185
N.S./F_{tu} (1)	0.96	0.95	0.97	0.99	0.96	1.07

(1) Notch strength

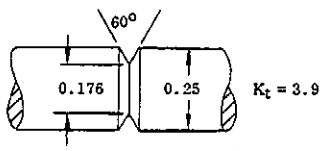


TABLE 3.02712 NOTCH STRENGTH OF FORGING AT VARIOUS LOCATIONS

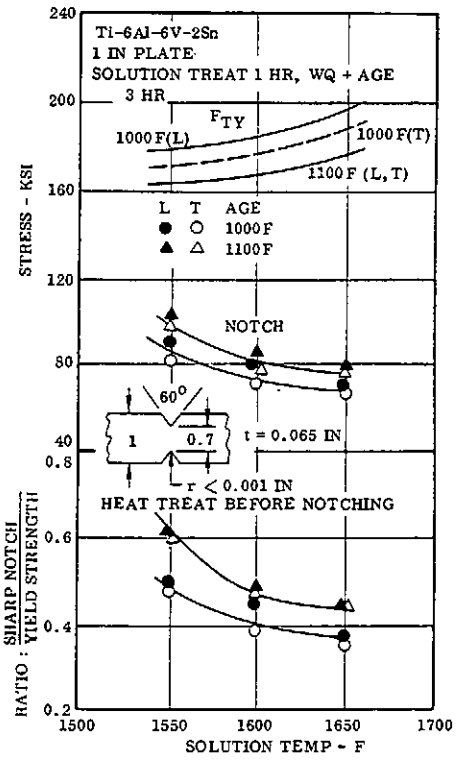


FIG. 3.02713 EFFECT OF SOLUTION TREATING AND AGING TEMPERATURE ON THE SHARP NOTCH TENSILE PROPERTIES OF PLATE.
(6)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

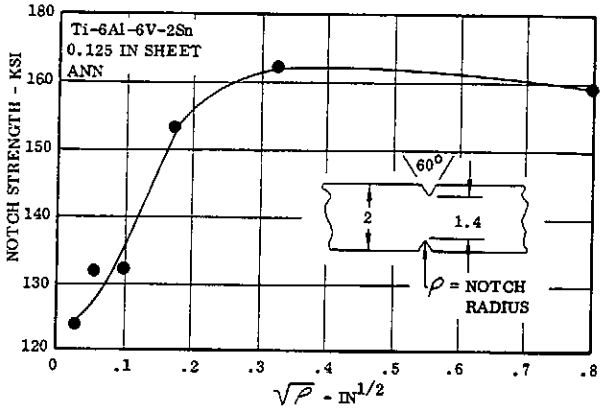


FIG. 3.02714 NOTCH STRENGTH AS FUNCTION OF ROOT RADIUS FOR ANNEALED SHEET.

(32, Table 9)

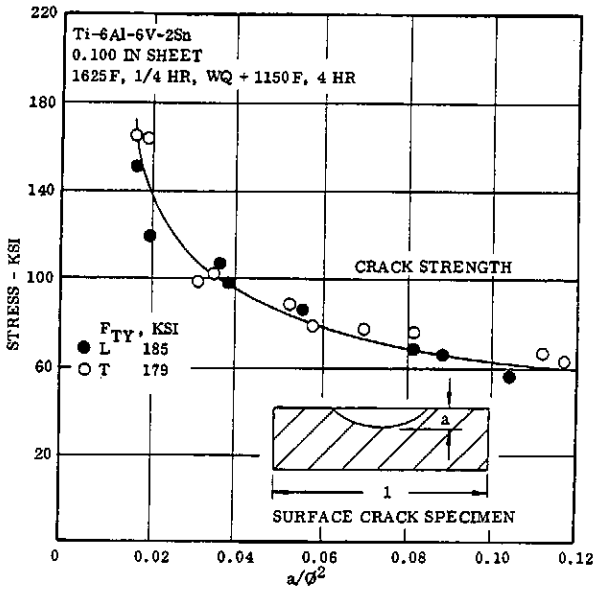


FIG. 3.02716 EFFECT OF SURFACE CRACKS ON STRENGTH OF SOLUTION TREATED AND AGED SHEET. (17)

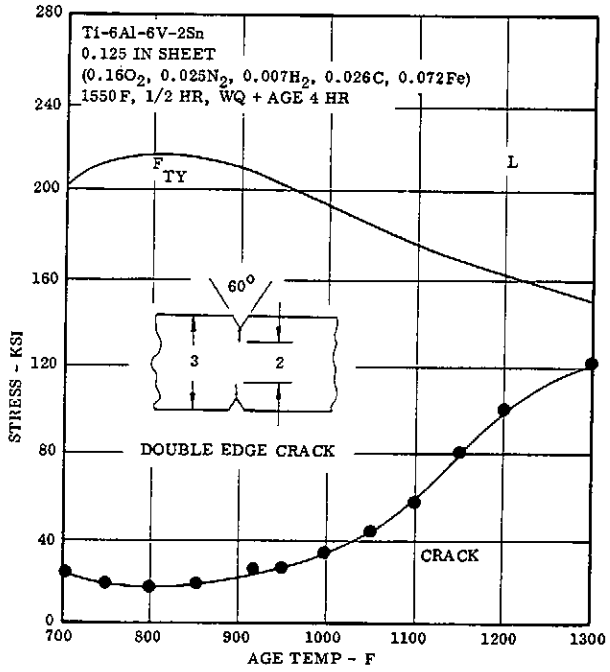


FIG. 3.02715 EFFECT OF AGING TEMPERATURE ON STRENGTH OF DOUBLE EDGE CRACK SHEET SPECIMENS. (9)

Ti
6 Al
6 V
2 Sn

Ti-6-6-2

Source	(25, Table 324) (24)			
Alloy	Ti-6Al-6V-2Sn			
Form	Extrusion at 1675F to 8-3/4 in O.D. x 11-3/4 in I.D.			Extrusion at 1735F, 85 percent reduction to 3 inch diameter bar
Condition (3)	ST. 1600F, 3 hr WQ + age			St. 1600F, 1-1/2 hr WQ + age
Age	1300F, 6 hr	1000F, 4 hr		1250F, 6 hr
Heat (4)	A	B	C	C
F_{tu} - ksi (1)	153	192	171	158
F_{ty} - ksi	144	187	156	143
K_{Ic} - ksi$\sqrt{in}$ (2)	69	32	39	54

(1) Transverse tensile: midwall of tube or center of bar
(2) ASTM E-399-72 orientation CR with crack tip at midwall or at bar center
(3) Extrusions heat treated
(4) A - 0.020C, 0.16 O_2, 0.005 H_2 and 0.015 N_2; B - 0.12C, 0.07 O_2, 0.004 H_2, 0.010 N_2 and 2.0 Zr; C-0.022C, 0.13 O_2, 0.010 H_2 and 0.017 N_2.

TABLE 3.02722 PLANE STRAIN FRACTURE TOUGHNESS OF EXTRUSIONS GIVEN SEVERAL HEAT TREATMENTS

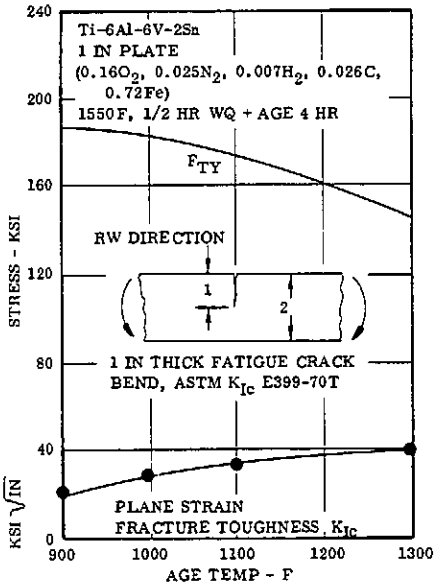


FIG. 3.02723 EFFECT OF AGE TEMPERATURE ON PLANE STRAIN FRACTURE TOUGHNESS OF PLATE. (11)

Source	(36, Tables 6 and 7)				
Alloy	Ti-6Al-6V-2Sn				
Form	1/2 in plate				1-1/4 in plate
Processing	Alpha + beta				Beta
Heat	T-1	R-2	R-2	R-2	R-1
Code	TM	RM	RB	RD	RS
Condition	Mill ann.	Mill ann.	Beta ann. 1850F, 1 hr in vac. Argon cool	Duplex ann. 1700F, 1 hr in vac. Argon cool + 1400F, 1 hr, Argon cool	STA 1675F, 1/4 hr WQ + 1100F 4 hr
F_{ty} - ksi (T)	159	163	140	151	173
K_{Ic} - ksi$\sqrt{in}$	-	32	54	65	34
W/B	-	2	2	4	4
ASTM E399-70T C.T. specimens B = 1/2 in					

TABLE 3.02724 PLANE STRAIN FRACTURE TOUGHNESS OF TWO HEATS OF PLATE GIVEN SEVERAL HEAT TREATMENTS

Ti
6 Al
6 V
2 Sn

Ti-6-6-2

Source	(37, p. 3-8 and 3-10)						
Alloy	Ti-6Al-6V-2Sn						
Form	2 in plate			1-1/2 in dia bar		Large die forging	
Condition (1)(2)	A	B	C	A	B	A	B
F_{ty} - ksi	157	150	139	153	–	144	138
K_{Ic} - ksi$\sqrt{in}$	42	54	84	43	60	56	56

(1) A - mill anneal; B - 1675F, 2 hr AC + 1600F, 1 hr, FC
C - 1700F, 4 hr AC + 1400F, 1 hr AC
(2) Specimen blanks heat treated

TABLE 3.02725 PLANE STRAIN FRACTURE TOUGHNESS OF PLATE, BAR AND FORGING GIVEN SEVERAL HEAT TREATMENTS

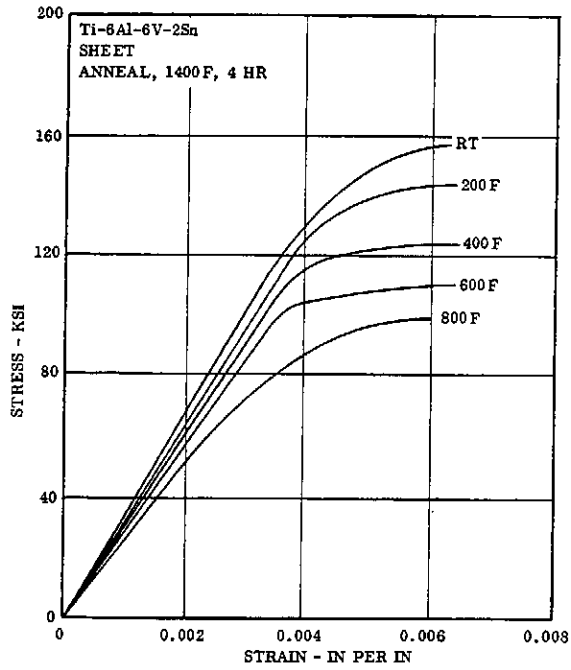


FIG. 3.0312 ELEVATED TEMPERATURE TENSION STRESS-STRAIN CURVES FOR ANNEALED SHEET. (1)

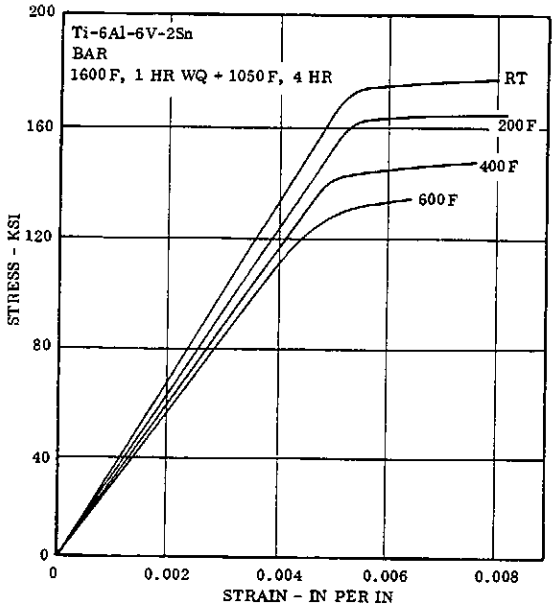


FIG. 3.0311 ELEVATED TEMPERATURE TENSION STRESS-STRAIN CURVES FOR AGED BAR. (1)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

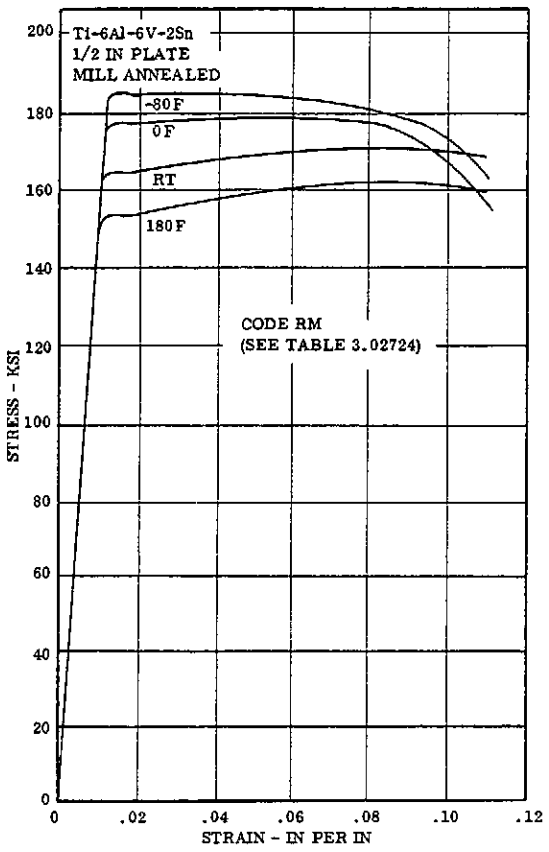


FIG. 3.0313 STRESS STRAIN CURVES FOR MILL ANNEALED PLATE AT VARIOUS TEMPERATURES.

(36, Fig. 16)

Source	(46, Appendix 8)					
Alloy	Ti-6Al-6V-2Sn					
Form	16 in wide extrusion (see Figure 3.0214)					
Condition	1625F, 1 hr, WQ + 1100F, 4 hr AC					
Test Temp. -F	R.T.				800	
Location (1)	Skin		Riser		Skin	Riser
	1	2	1	2	1	2
F_{tu} (avg) - ksi	167	170	165	168	124	121
Spread	156-179	157-180	151-175	152-180	116-130	112-128
F_{ty} (avg) - ksi	157	157	151	154	98	95
Spread	145-166	140-165	138-161	138-161	94-103	92-99
e (2 in) avg. percent	9	10	10	10	13	13
Spread	5-12	7-13	5-13	7-12	11-17	11-16

(1) Locations 1 and 2 are at opposite end of extrusion designated bottom and top respectively

TABLE 3.0314 AVERAGE AND SPREAD OF R.T. AND 800F TENSILE PROPERTIES IN LARGE SOLUTION TREATED AND AGED EXTRUSION

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

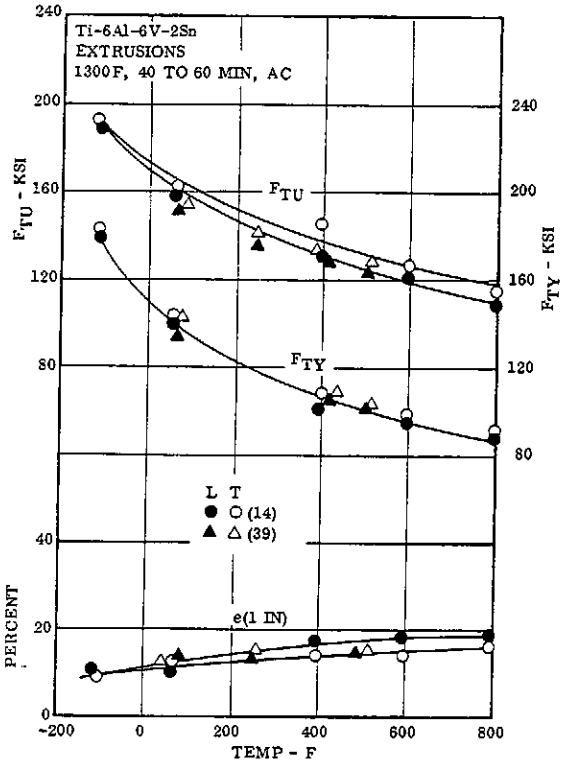


FIG. 3.0315 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED EXTRUSIONS OF VARIOUS SHAPES.
(14, Table 17)(39, Table 6)

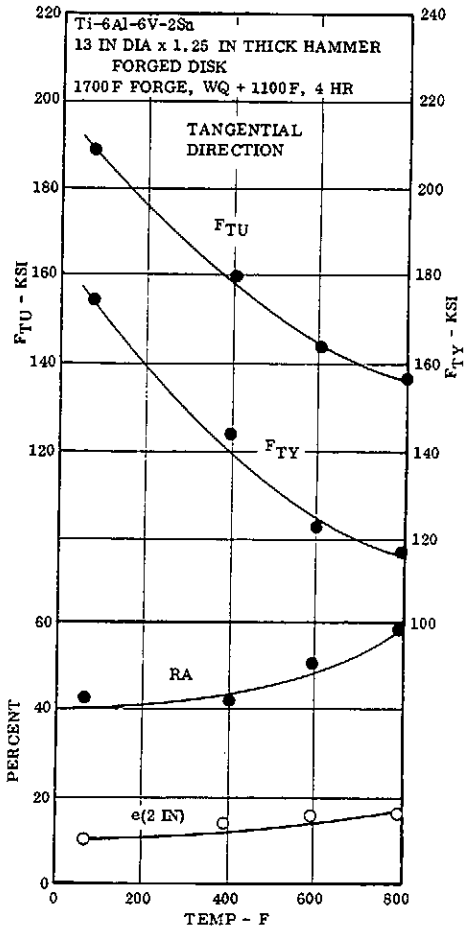


FIG. 3.0316 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF HAMMER FORGED DISK. (47, Table 14)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

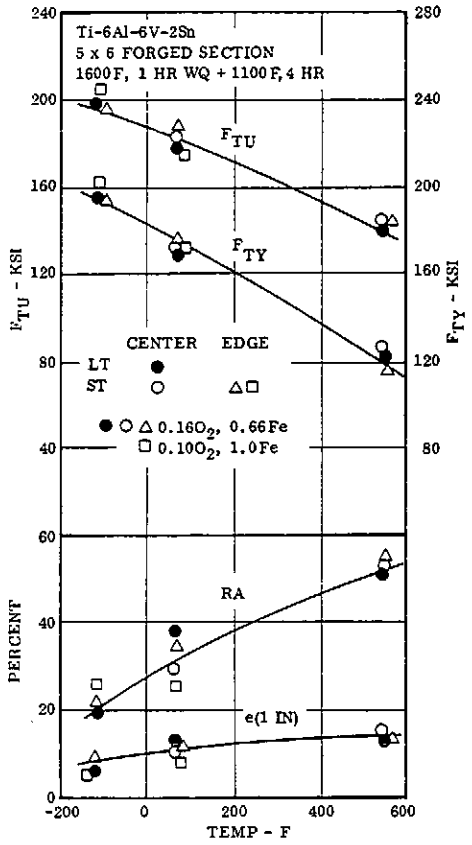


FIG. 3.0317 EFFECT OF TEST TEMPERATURE AND SPECIMEN LOCATION ON TENSILE PROPERTIES OF FORGINGS AT TWO INTERSTITIAL LEVELS (SPECIMENS HEAT TREATED). (2)

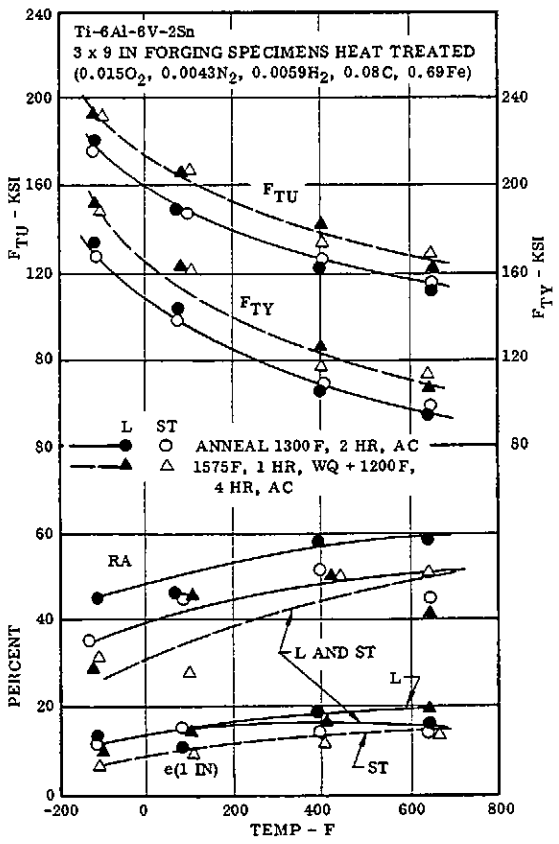


FIG. 3.0318 EFFECT OF TEST TEMPERATURE ON THE TENSILE PROPERTIES OF FORGING. (12)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

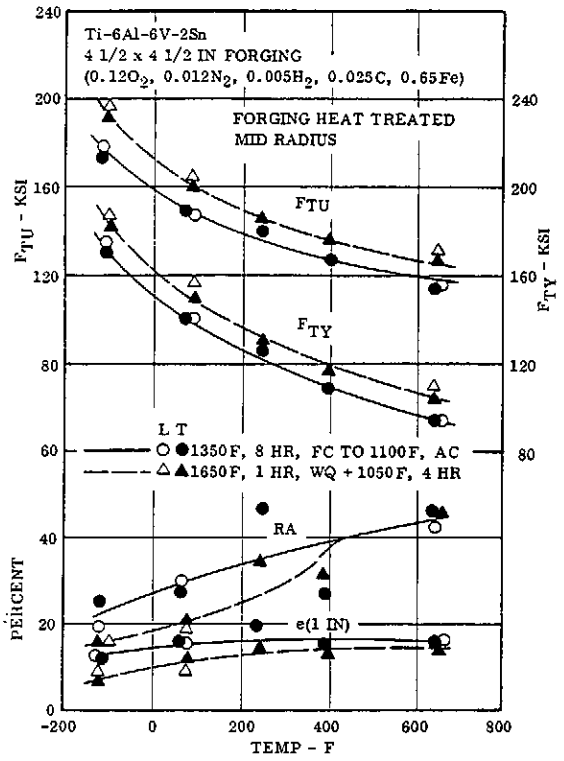


FIG. 3.0319 EFFECT OF TEST TEMPERATURE ON THE TENSILE PROPERTIES OF LOW INTERSTITIAL FORGING, (FORGING HEAT TREATED). (15)

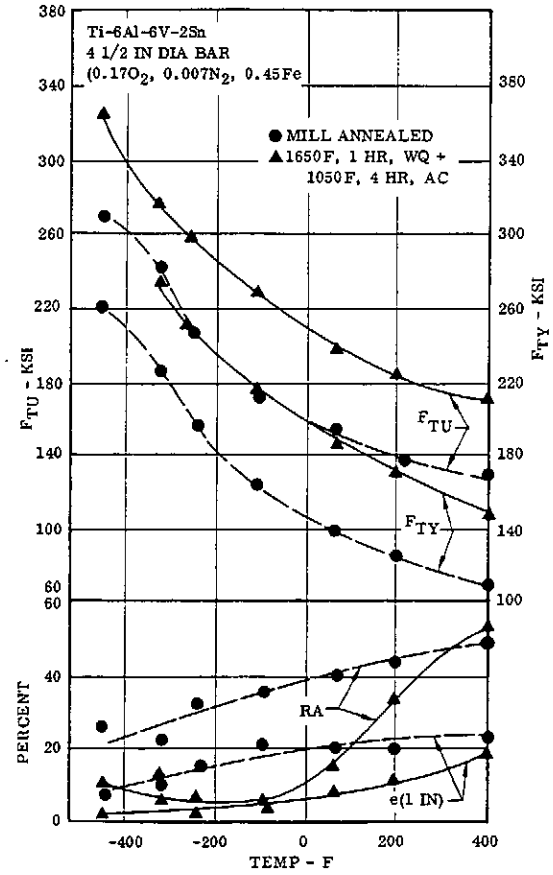


FIG. 3.03110 EFFECT OF LOW TEST TEMPERATURES ON TENSILE PROPERTIES OF ANNEALED AND AGED BAR. (10)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

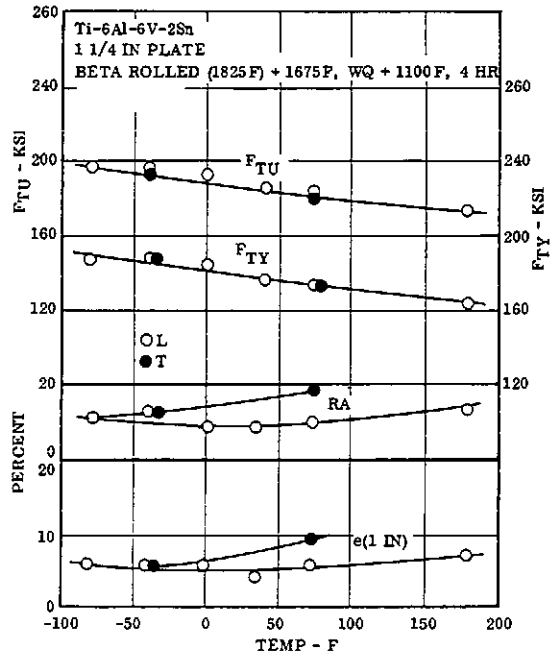


FIG. 3.03111 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION TREATED AND AGED PLATE. (36, Table 2)

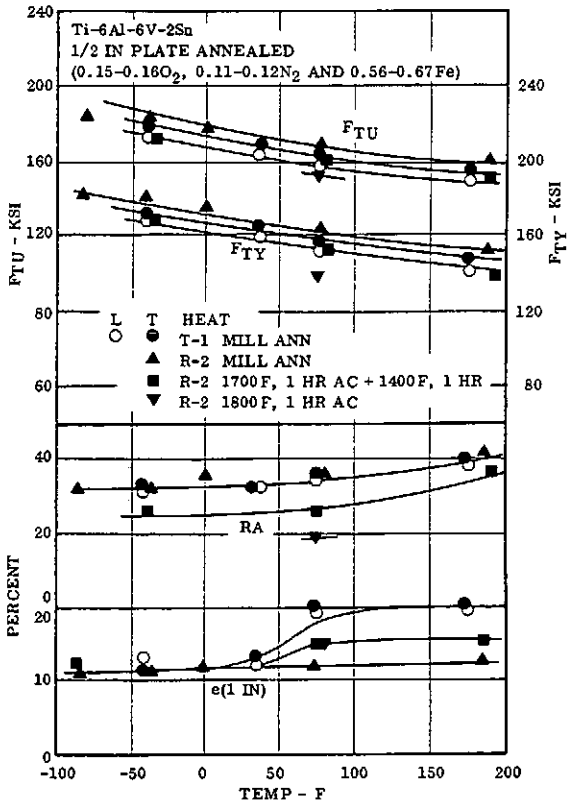


FIG. 3.03112 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED PLATE FROM TWO HEATS. (36, Table 5)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

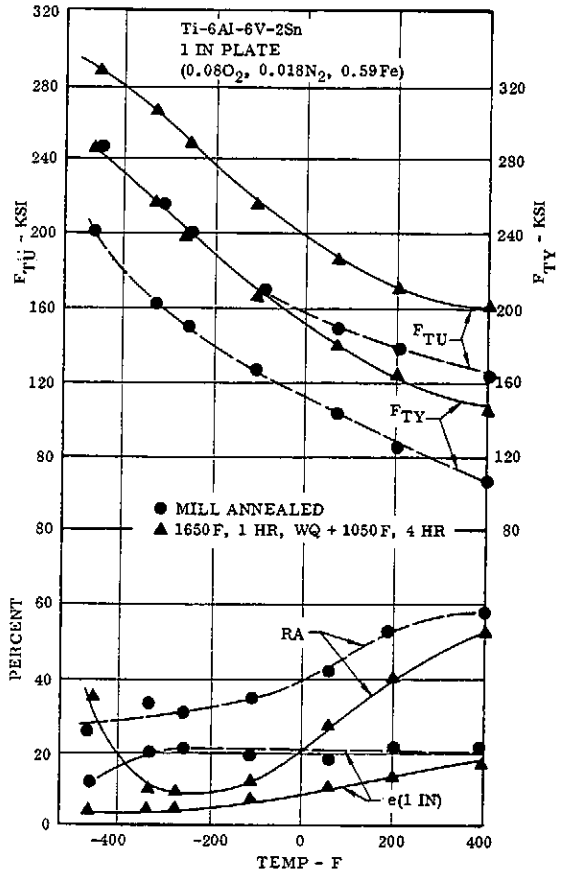


FIG. 3.03113 EFFECT OF LOW TEST TEMPERATURES ON TENSILE PROPERTIES OF LOW INTERSTITIAL PLATE. (10)

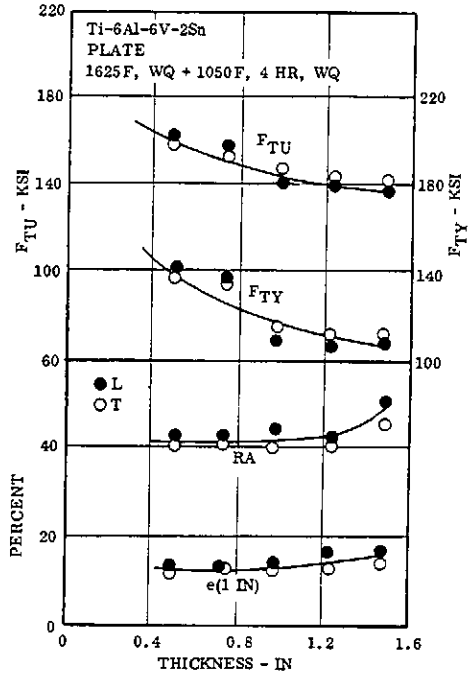


FIG. 3.03114 EFFECT OF THICKNESS ON THE TENSILE PROPERTIES OF SOLUTION TREATED AND AGED PLATE AT 600F. (7)

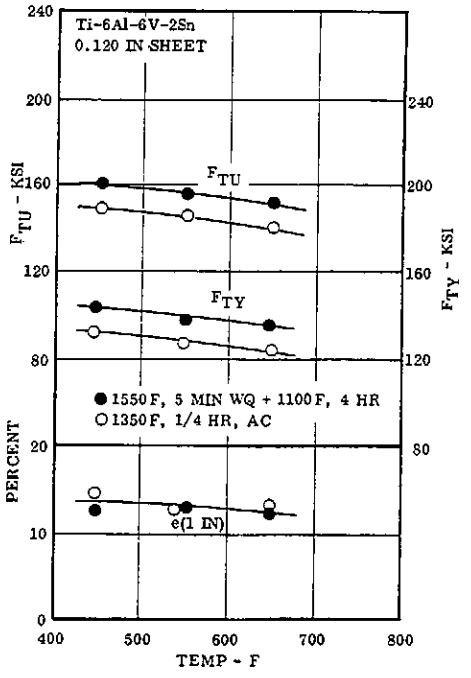


FIG. 3.03115 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SHEET. (16)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

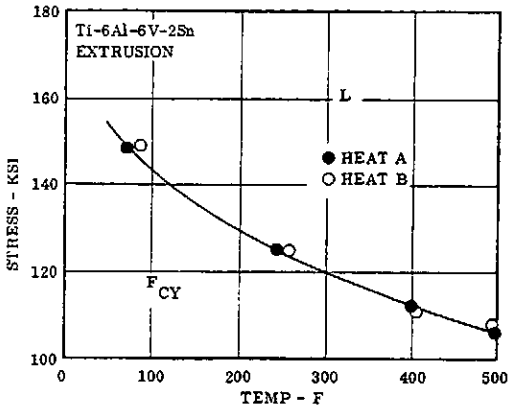


FIG. 3.0321 EFFECT OF TEMPERATURES ON COMPRESSIVE YIELD STRENGTH OF ANNEALED EXTRUSION. (39, Table 9)

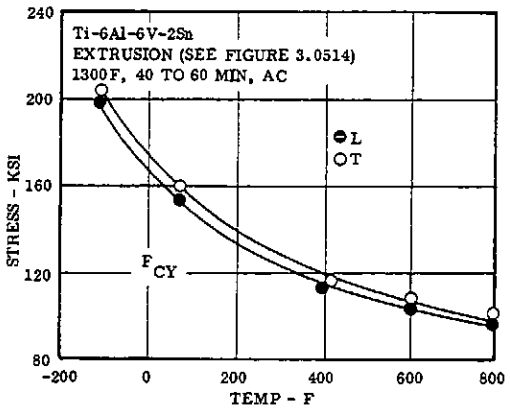


FIG. 3.0323 EFFECT OF TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF ANNEALED FORGINGS. (14)

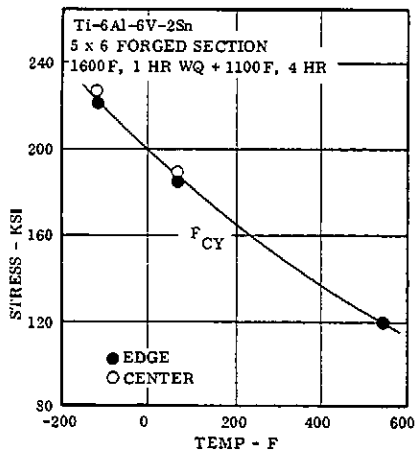


FIG. 3.0322 EFFECT OF TEST TEMPERATURE AND SPECIMEN LOCATION ON COMPRESSIVE YIELD STRENGTH OF SOLUTION TREATED AND AGED FORGING (SPECIMENS HEAT TREATED). (2)

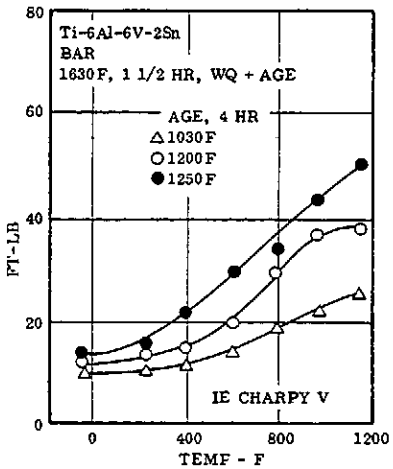


FIG. 3.0331 EFFECT OF TEMPERATURE ON IMPACT STRENGTH OF AGED BAR. (1)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

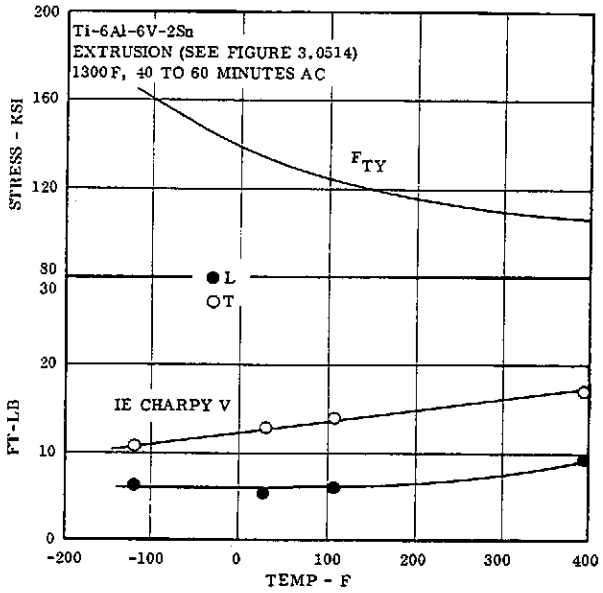


FIG. 3.0332 EFFECT OF TEST TEMPERATURE ON IMPACT STRENGTH OF ANNEALED EXTRUSION. (14)

Alloy	Ti-6Al-6V-2Sn					
Source	(2)		(1)			
Form	5 x 6 in forging		Plate		Sheet	
Condition	1600F, 1 hr, WQ + 1100F 4 hr (1)		Anneal 1350F	1600F, 1 hr, WQ + 1100F 4 hr	Anneal	Solution Treat + Age
Temperature	RT	550F	RT	RT	RT	RT
F_{SU}	105	85	97	111	103	110
(1) Specimens heat treated						

TABLE 3.0351 SHEAR ULTIMATE STRENGTH AT ROOM AND ELEVATED TEMPERATURE FOR SEVERAL FORMS AND CONDITIONS OF ALLOY

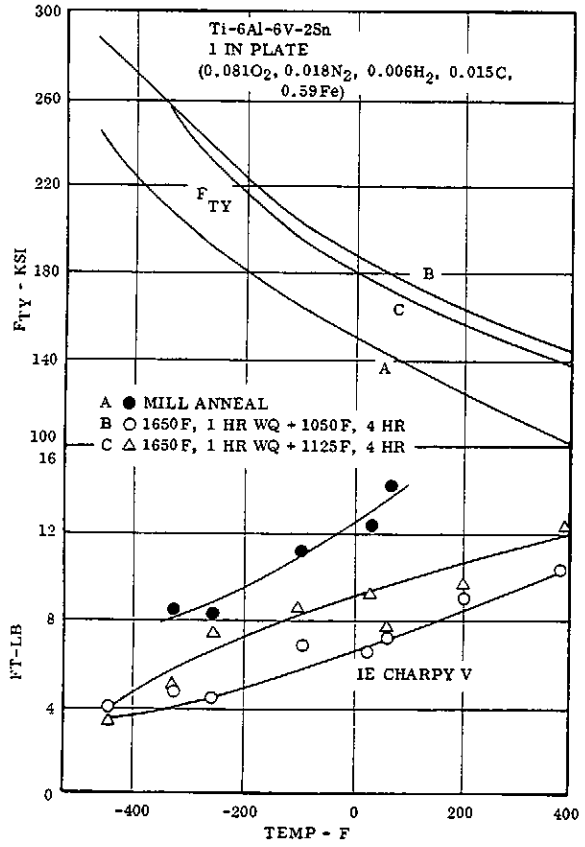


FIG. 3.0333 EFFECT OF LOW TEST TEMPERATURES ON IMPACT STRENGTH OF ANNEALED AND SOLUTION TREATED AND AGED LOW INTERSTITIAL PLATE. (10)

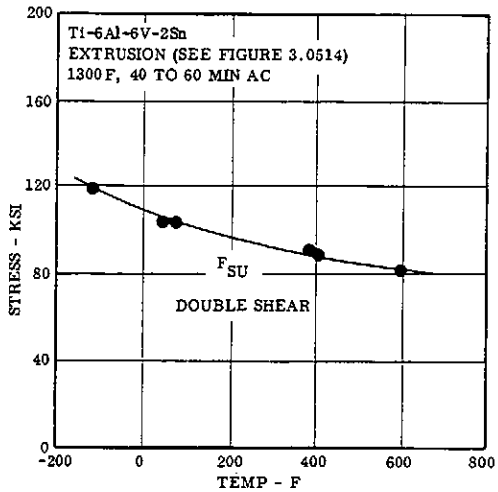


FIG. 3.0352 EFFECT OF TEST TEMPERATURE ON DOUBLE SHEAR STRENGTH OF ANNEALED EXTRUSION. (14)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

Alloy	Ti-6Al-6V-2Sn					
Source	(2)		(1)			
Form	5 x 6 in Forging		Plate		Sheet	
Condition	1600F, 1 hr WQ + 1100F, 4 hr		Anneal	Solution Treat + Age	Anneal	Solution Treat + Age
Temperature	RT	550F	RT	RT	RT	RT
$F_{bru(1)}$ - ksi	370	300	287	326	299	326
F_{bry} - ksi	338	243	229	262	239	262
(1) e/D = 2						

TABLE 3.0361 BEARING STRENGTH AT ROOM AND ELEVATED TEMPERATURE FOR SEVERAL FORMS AND CONDITIONS OF ALLOY

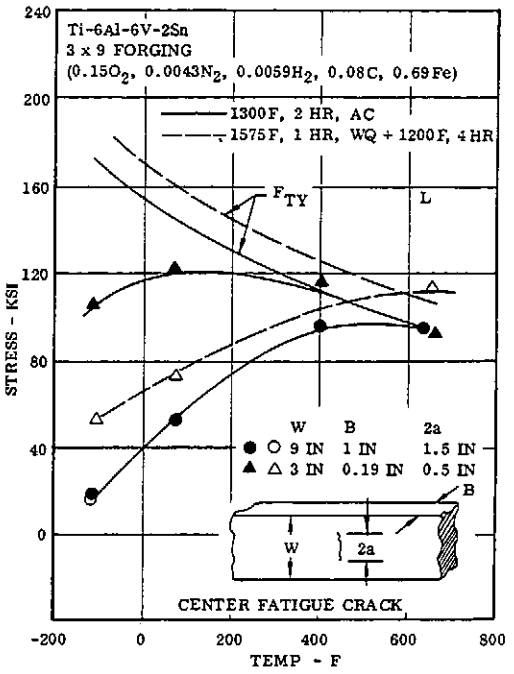


FIG. 3.03711 EFFECT OF TEST TEMPERATURE ON STRENGTH OF CENTER CRACKED SPECIMENS OF TWO THICKNESSES CUT FROM FORGING (SPECIMENS SOLUTION TREATED AND AGED). (12)

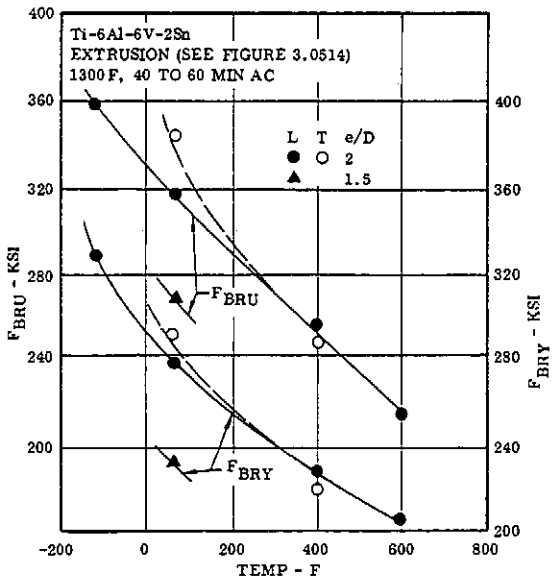


FIG. 3.0362 EFFECT OF TEST TEMPERATURE ON BEARING STRENGTH OF ANNEALED EXTRUSION. (14)

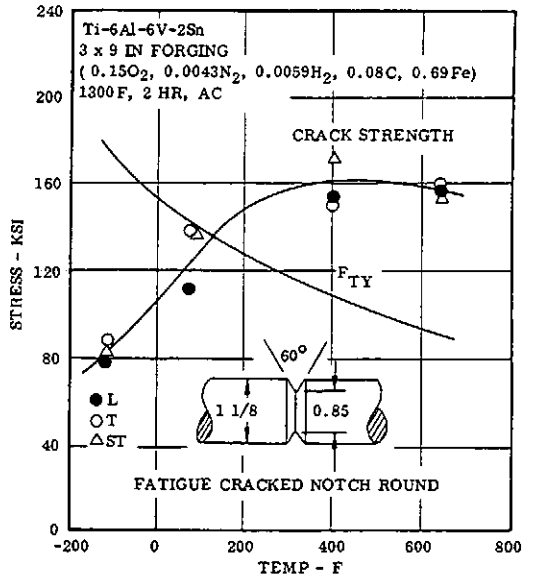


FIG. 3.03712 EFFECT OF TEST TEMPERATURE ON STRENGTH OF FATIGUE CRACKED NOTCH ROUNDS FROM ANNEALED FORGINGS. (SPECIMENS REANNEALED). (12)

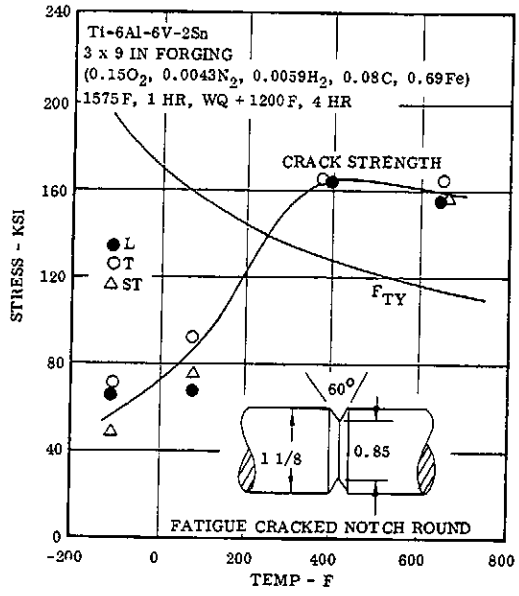
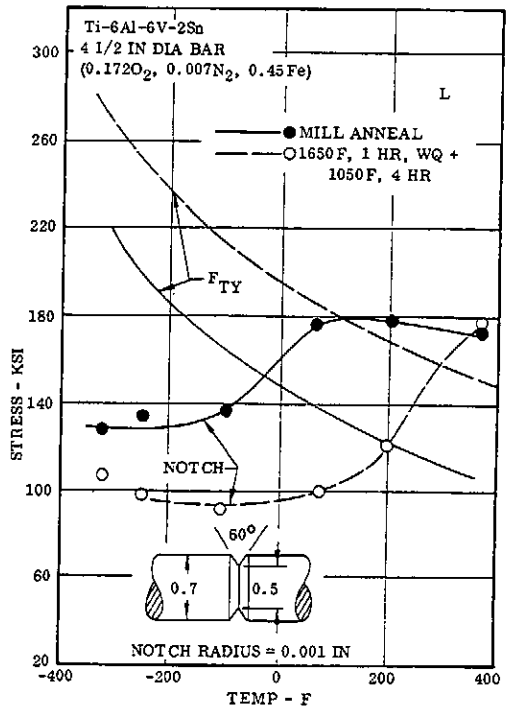


FIG. 3.03713 EFFECT OF TEST TEMPERATURE ON STRENGTH OF FATIGUE CRACKED NOTCH ROUNDS CUT FROM FORGING (SPECIMENS SOLUTION TREATED AND AGED). (12)



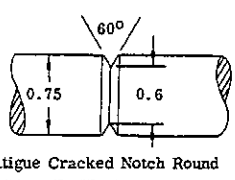
	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

FIG. 3.03715 EFFECT OF LOW TEST TEMPERATURES ON SHARP NOTCH STRENGTH OF ANNEALED AND SOLUTION TREATED AND AGED BAR. (10)

Source	(2)					
Alloy	Ti-6Al-6V-2Sn					
Form	5 x 6 inch Forged Section					
Condition	1600F, 1 hr WQ + 1100F, 4 hr (3)					
Forging	Forging A (1)		Forging B (1)		Forging C (2)	
Location	Edge	Center	Edge	Center	Edge	
Temp - F	-110	RT	RT	RT	-110	RT
F_{ty} - ksi	194	175	170	155	200	160
N.S./F_{ty}	0.51	0.71	0.47	0.41	0.53	0.46

(1) 0.16 O_2, 0.66 Fe
(2) 0.10 O_2, 1.0 Fe
(3) Specimens heat treated



Fatigue Cracked Notch Round

TABLE 3.03714 STRENGTH OF FATIGUE CRACKED NOTCH ROUNDS CUT FROM TWO LOCATIONS IN A SOLUTION TREATED AND AGED FORGING

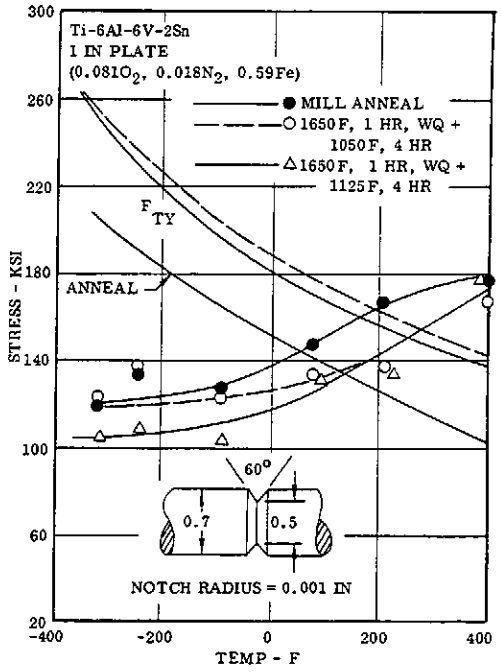


FIG. 3.03716 EFFECT OF LOW TEST TEMPERATURES ON SHARP NOTCH STRENGTH OF LOW INTERSTITIAL PLATE. (10)

Ti
6 Al
6 V
2 Sn

Ti-6-6-2

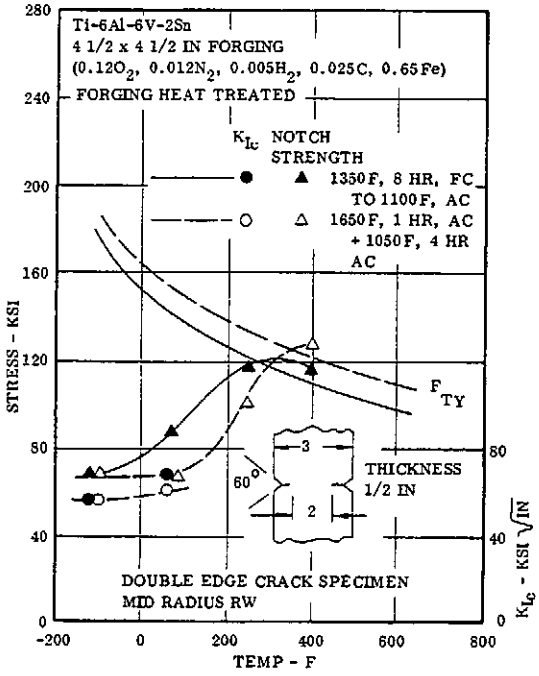


FIG. 3.03721 EFFECT OF TEST TEMPERATURE ON STRENGTH OF DOUBLE EDGE CRACK SPECIMENS AND PLANE STRAIN FRACTURE TOUGHNESS OF LOW INTERSTITIAL FORGING (K_{Ic} BY TECHNIQUE OF ASTM E 399-70T). (15)

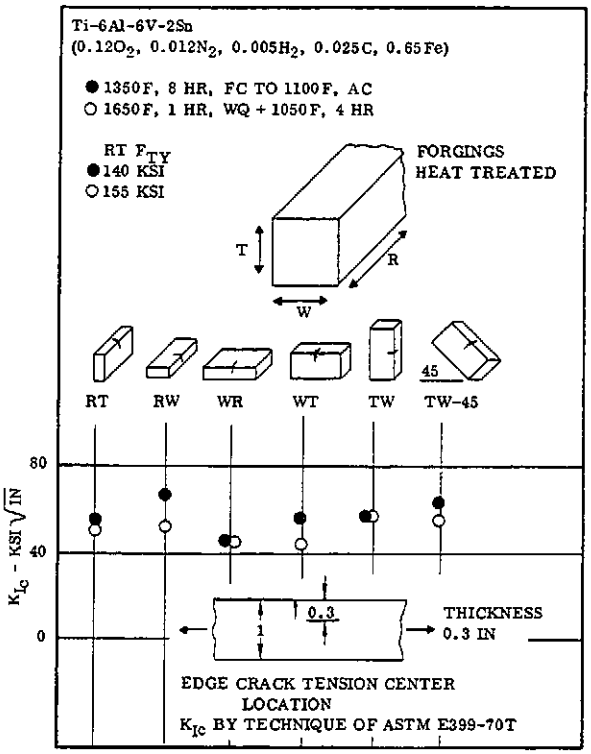


FIG. 3.03722 EFFECT OF SPECIMEN ORIENTATION ON THE -110F PLANE STRAIN FRACTURE TOUGHNESS OF LOW INTERSTITIAL FORGING. (15)

Source	(15)					
Alloy	Ti-6Al-6V-2Sn					
Form	1/2 inch Plate				1-1/2 in Plate	
Condition (3)	1350F, 8 hr, FC to 1100F, AC		1650F, 1 hr, WQ + 1050F, 4 hr		1350F, 8 hr, FC to 1100F, AC	
F_{ty} - ksi	186		208		171	
Direction (2)	RW	WR	RW	WR	RW	WR
K_{Ic} at -110F Ksi $\sqrt{in}$ (1)	33	34	34	27	39	38

(1) For specimen see Figure 3.03721
(2) For directions see Figure 3.03722
(3) Plate heat treated

TABLE 3.03723 EFFECT OF SPECIMEN ORIENTATION ON THE -110F PLANE STRAIN FRACTURE TOUGHNESS OF PLATE

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

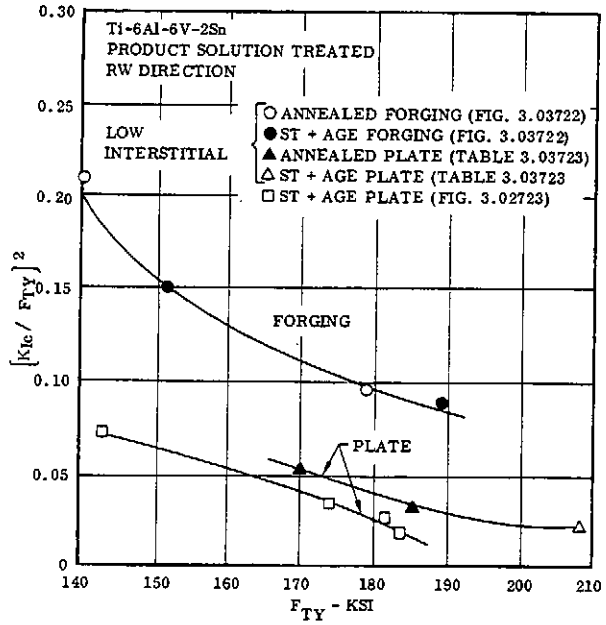


FIG. 3.03724 INFLUENCE OF YIELD STRENGTH ON PLANE STRAIN CRACK PROPAGATION RESISTANCE OF SEVERAL FORMS AND CONDITIONS.

Source	(14)						
Alloy	Ti-6Al-6V-2Sn						
Form	Extrusion (see Figure 3.0514)						
Condition	1300F, 40 to 60 minute AC						
Temp - F	600F (F_{ty} = 95 ksi)				800F (F_{ty} = 90 ksi)		
Total creep strain percent	0.5		1		2		2
Time-hours	100	500	100	500	100	500	1
Stress - ksi	116	112	119	116	122	119	98

TABLE 3.041 CREEP STRENGTH FOR ANNEALED EXTRUSION

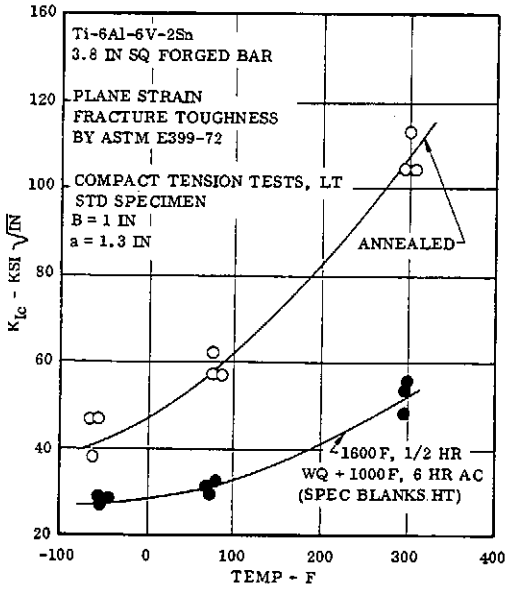


FIG. 3.03725 PLANE STRAIN FRACTURE TOUGHNESS OF FORGED BAR IN ANNEALED AND IN SOLUTION TREATED AND AGED CONDITION.
(30, Tables 4,5)

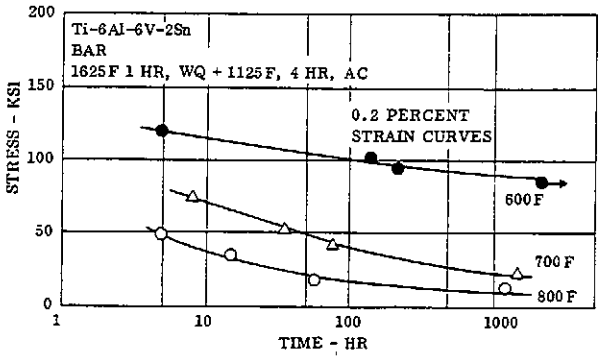


FIG. 3.042 STRESS FOR 0.2 PERCENT CREEP STRAIN AT SEVERAL TEMPERATURES FOR AGED BAR. (42)

Ti
6 Al
6 V
2 Sn

Ti-6-6-2

Source	(42, Table 1-5:6)											
Alloy	Ti-6Al-6V-2Sn											
Form	0.060 in sheet											
Condition	1625F 1/4 hr. WQ + 1050F, 4 hr AC				1675F 1/4 hr. WQ + 1100F, 4 hr AC				1550F 1/4 hr. WQ + 1100F, 4 hr AC			
Temp. - F	600			850	550	600		650	550	650	850	
Time - hr	150			47	150	150		150	150	307	22	24
Stress - ksi	60	70	100	25	120	50	80	35	110	35	30	32
Total creep-percent	.07	.08	.21	.44	.12	.08	.08	.10	.13	.11	.55	.54

TABLE 3.043 TOTAL CREEP STRAIN FOR AGED SHEET AT SEVERAL TEMPERATURES AND STRESSES

Source	(39, Figure 16)				
Alloy	Ti-6Al-6V-2Sn				
Form	Extrusions (lowest of three heats) R.T. F_{ty} = 153 ksi				
Condition	Mill annealed F_{ty} = 137 to 144 at R.T.				
Method	Stress Conc.	Fatigue strength at cycles - ksi			
		10^4	10^5	10^6	10^7
Axial load R.T. R = 0.1	Smooth K_t = 1	140	120	106	100
	Notched K_t = 4	70	42	32	32

TABLE 3.0511 SMOOTH AND NOTCHED FATIGUE STRENGTH OF ANNEALED EXTRUSIONS AT ROOM TEMPERATURE

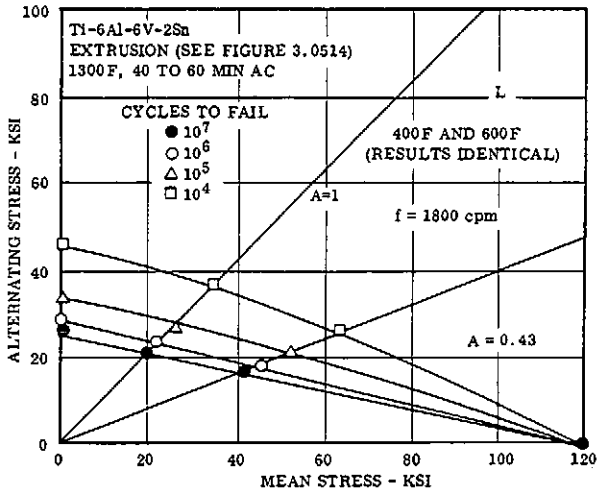


FIG. 3.0513 STRESS RANGE DIAGRAM AT 400 AND 600F FOR NOTCHED SPECIMENS FROM ANNEALED EXTRUSION. (14)

Source	(1)						
Alloy	Ti-6Al-6V-2Sn						
Form	T Extrusion						
Condition	1550F, WQ + 1050F, 4 hr. AC						
Method	Stress Ratio		Direction	Stress Conc.	Fatigue Strength ksi at Cycles		
	A	R			10^5	10^6	10^7
Axial Load	0.82	0.1	L	K_t = 1 Smooth	105	95	90
				K_t = 3.3	45	30	29

TABLE 3.0512 SMOOTH AND NOTCH FATIGUE STRENGTH OF SOLUTION TREATED AND AGED EXTRUSION

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

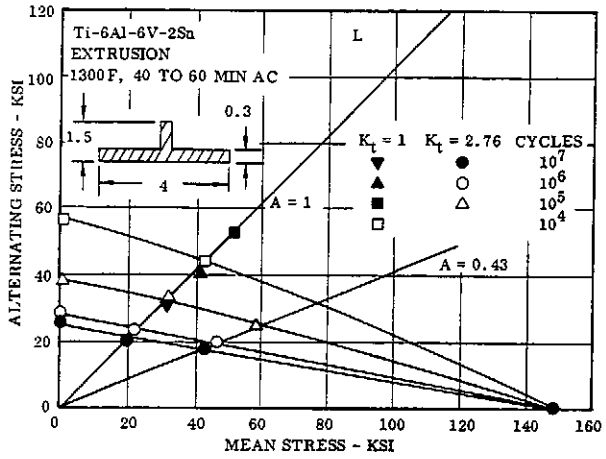


FIG. 3.0514 STRESS RANGE DIAGRAM AT ROOM TEMPERATURE FOR SMOOTH AND NOTCHED SPECIMENS FROM ANNEALED EXTRUSION. (14)

Source	(2)							
Alloy	Ti-6Al-6V-2Sn							
Form	5 x 6 inch Forged Section							
Condition	1600F, 1 hr, WQ + 1100F, 4 hr. (Specimens heat treated)							
Method	Stress Ratio		Stress Conc.	Forging	Temp F	Fatigue Strength ksi at Cycles			
	A	R				10^4	10^5	10^6	10^7
Axial Load	0.82	0.1	Smooth K_t = 1	A (1)	RT	155	130	108	
					550	120	105	93	80
				B (2)	RT	155	130	105	90
			Notched K_t=3.9	A	RT	78	42	30	25
				B	RT	78	45	35	25
(1) 0.16O_2, 0.66Fe (2) 0.10O_2, 1.0 Fe									

TABLE 3.0516 SMOOTH AND NOTCH FATIGUE STRENGTH OF SOLUTION TREATED AND AGED FORGING AT ROOM AND ELEVATED TEMPERATURE

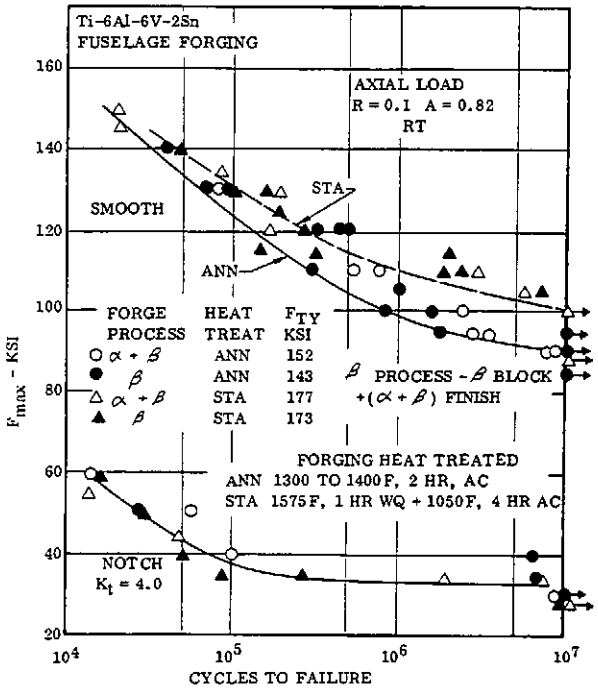


FIG. 3.0515 SMOOTH AND NOTCHED FATIGUE STRENGTH AT ROOM TEMPERATURE FOR ALPHA + BETA AND FOR BETA PROCESSED FORGING. (56)

Source	(18)						
Alloy	Ti-6Al-6V-2Sn						
Form	1 inch diameter bar						
Condition	Specimen vacuum annealed 1300F, 2 hr. FC						
	Stress Ratio		Temp - F	Stress Conc.	Fatigue Strength ksi at Cycles		
	A	R		K_t	10^5	10^6	10^7
Axial Load	0	-1	RT				
			F_{tu} = 160 ksi	3.4	27	21	20
			F_{ty} = 153 ksi	5.7	19	12	11
			RA = 35 percent	10.0	20	10	-
			600				
			F_{tu} = 127 ksi	3.4	21	20	19
			F_{ty} = 104 ksi	5.7	16	11	10
			RA = 50 percent	1.0	-	10	9
Notch radius 0.001, 0.005 and 0.015 inch							

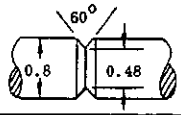


TABLE 3.0517 SMOOTH AND NOTCH FATIGUE STRENGTH OF ANNEAL BAR

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

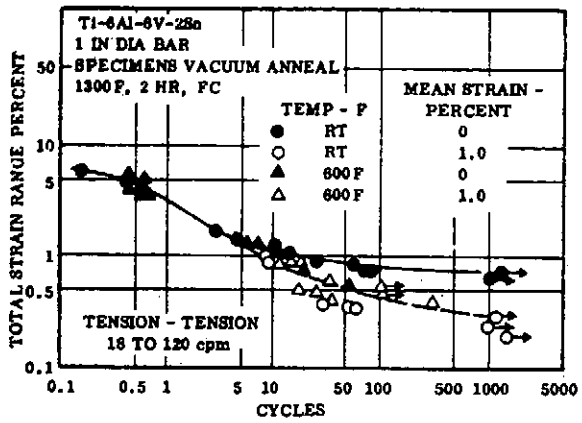


FIG. 3.0518 STRAIN CYCLING RESULTS FOR ANNEALED BAR AT ROOM AND ELEVATED TEMPERATURE. (18)

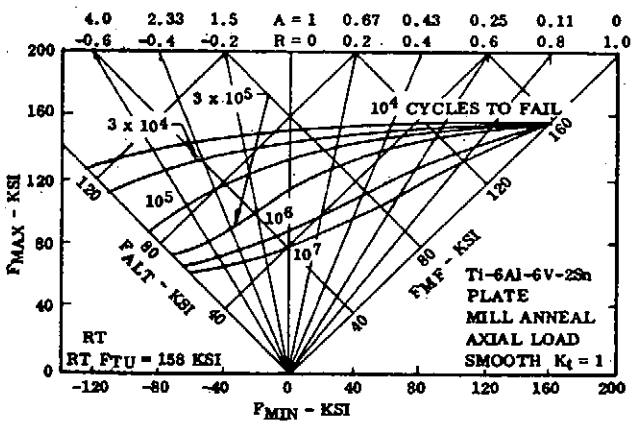


FIG. 3.0511 STRESS RANGE DIAGRAM FOR SMOOTH SPECIMENS OF MILL ANNEALED PLATE TESTED AT ROOM TEMPERATURE. (43, p. 210)

Source	(48, p. 41 and 42)			
Alloy	Ti-6Al-6V-2Sn			
Form	1 to 1-1/4 in plate			
Fatigue	Axial load (A = 0.82, R = 0.1) Notched K_t = 3.5			
Heat	A - 0.18 percent O_2		B - 0.11 percent O_2	
Condition	Annealed 1350F 8 hr. AC	1550F, 1 hr WQ + 1150F, 4 hr. AC	Annealed 1350F, 8 hr AC	1550F, 1 hr. WQ + 1150F, 4 hr. AC
Fatigue strength - ksi at cycles				
5×10^4	40	38	40	-
10^5	37	38	37	50
10^6	28	28	28	44
10^7	27	27	27	40

TABLE 3.0519 NOTCHED FATIGUE STRENGTH AT ROOM TEMPERATURE FOR PLATE AT TWO INTERSTITIAL LEVELS IN THE ANNEALED AND SOLUTION TREATED AND AGED CONDITIONS

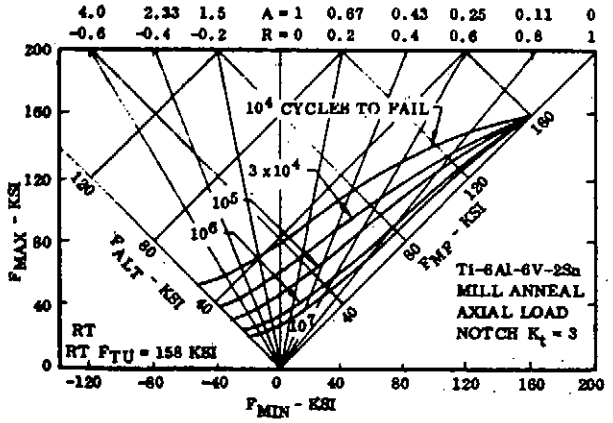


FIG. 3.05110 STRESS RANGE DIAGRAM FOR NOTCHED SPECIMENS OF MILL ANNEALED PLATE TESTED AT ROOM TEMPERATURE. (43, p. 211)

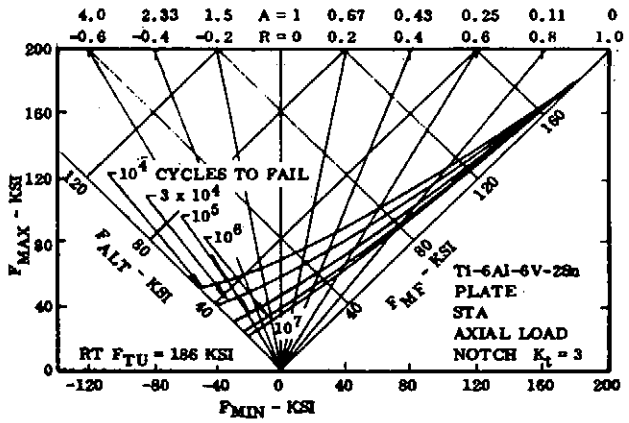


FIG. 3.05112 STRESS RANGE DIAGRAM FOR NOTCHED SPECIMENS OF SOLUTION TREATED AND AGED PLATE TESTED AT ROOM TEMPERATURE. (43, p. 233)

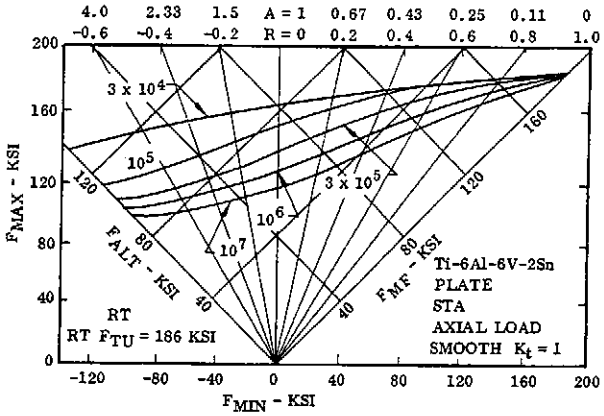


FIG. 3.05113 STRESS RANGE DIAGRAM FOR SMOOTH SPECIMENS OF SOLUTION TREATED AND AGED PLATE TESTED AT ROOM TEMPERATURE. (43, p. 232)

Source	(19)						
Alloy	Ti-6Al-6V-2Sn						
Form	Plate (center)						
Method	Thickness	Condition	Direction	Stress Conc. K_t	Fatigue Strength ksi at Cycles 10^5	10^6	10^7
Axial Load	1-1/4 in. 0.18 O_2	1350F, 8 hr. AC	L & T	1	-	110	86
				3.5	35	28	26
A = 0.82	1 inch 0.11 O_2		L & T	1	-	115	90
				3.5	40	45	30
R = 0.1	1-1/4 in 0.18 O_2	1550F, 1 hr, WQ + 1200F, 4 hr.	L	1	-	133	105
			T	1	-	120	95
			L	3.5	40	32	28
			T	3.5	30	28	25
	1 inch 0.11 O_2		L & T	1	-	-	115
				3.5	50	43	40
	2 inch 0.18 O_2	1625F, 1 hr. WQ +1050F, 4 hr.	L & T	1	-	-	95
				3.5	30	28	25

TABLE 3.05114 SMOOTH AND NOTCH FATIGUE STRENGTH OF ANNEALED AND OF SOLUTION TREATED AND AGED PLATE

Source	(40)							
Alloy	Ti-6Al-6V-2Sn							
Method	Condition	Form	Stress Ratio A	R	Stress Conc.	Fatigue Strength ksi at Cycles 10^4	10^5	10^6	10^7
Axial Load	1600F, WQ + 1050 to 1100F, 4 hr AC F_{ty} = 177 ksi	0.020, 0.100 and 0.125 in sheet	0.82	0.1	Smooth K_t = 1	-	120	114	114
					Notched K_t = 4.2	46	32	30	30
	1600F, WQ + 1050 to 1100F, 4 hr AC F_{ty} = 171 ksi	1 in plate	0.82	0.1	Smooth K_t = 1	(1) (155)	138	120	108
			∞	-1		128	90	80	56
	Mill anneal F_{ty} = 153 ksi		0.82	0.1	Smooth K_t = 1	(150)	123	100	88
			∞	-1		(110)	76	68	65

(1) Values in ( ) extrapolated

TABLE 3.05115 SMOOTH AND NOTCHED FATIGUE STRENGTH OF ANNEALED PLATE AND SOLUTION TREATED AND AGED SHEET AND PLATE AT ROOM TEMPERATURE

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

Source	(34, Figures 11, 12 and 13)					
Alloy	Ti-6Al-6V-2Sn					
Method	Axial Load R = 0.1					
Form and Condition	Stress Conc.	Test Temp. F	Fatigue Strength ksi at Cycles 10^4	10^5	10^6	10^7
0.1 in sheet annealed	Smooth	RT	160	125	110	102
F_{tu} = 164 ksi	K_t = 1	450	130	112	100	95
F_{ty} = 155 ksi	Notch	RT	50	30	28	28
	K_t = 4.2	450	53	28	24	24
0.125 in sheet solution treated and aged	Smooth K_t = 1	RT	-	120	114	114
F_{tu} = 181 ksi	Notch	RT	45	31	30	30
F_{ty} = 177 ksi	K_t = 4.2					

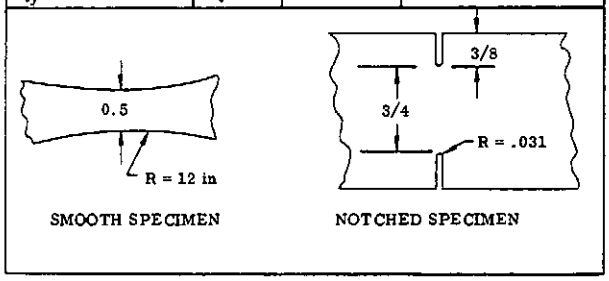


TABLE 3.05116 SMOOTH AND NOTCH FATIGUE STRENGTH OF ANNEALED AND SOLUTION TREATED AND AGED SHEET TESTED AT ROOM TEMPERATURE AND 450F

Source	(40)							
Alloy	Ti-6Al-6V-2Sn							
Form	0.020, 0.100 and 0.125 inch sheet							
Condition	Mill annealed (1300 to 1400F), R.T. F_{ty} = 158 ksi							
Method	Stress Ratio A	Stress Ratio R	Temp. (F)	Stress Conc.	Fatigue Strength, ksi At Cycles 10^4	10^5	10^6	10^7
Axial Load	0.82	0.1	RT	Smooth K_t = 1	(155)(a)	125	110	103
				Notched K_t = 4	52	32	28	28
	0.6	0.25	RT	Smooth K_t = 1	-	125	115	110
	0.82	0.1	450	Smooth K_t = 1	128	114	103	97
				Notched K_t = 4	54	28	24	24

(a) Values in ( ) are extrapolated.

TABLE 3.05117 SMOOTH AND NOTCHED FATIGUE STRENGTH OF ANNEALED SHEET TESTED AT R.T.

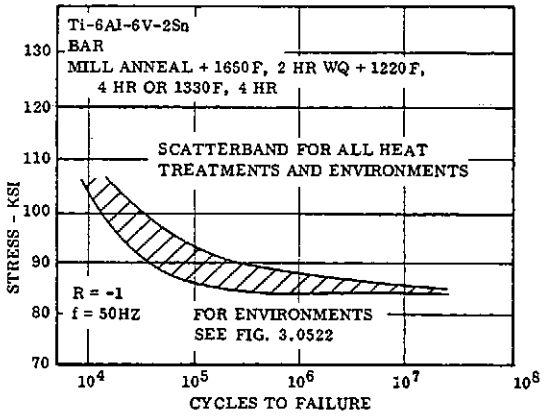


FIG. 3.05118 ROTATING BEAM FATIGUE LIFE CURVE FOR THREE HEAT TREATED CONDITIONS OF BAR TESTED IN SIMULATED HUMAN BODY ENVIRONMENTS. (26, Fig. 46)

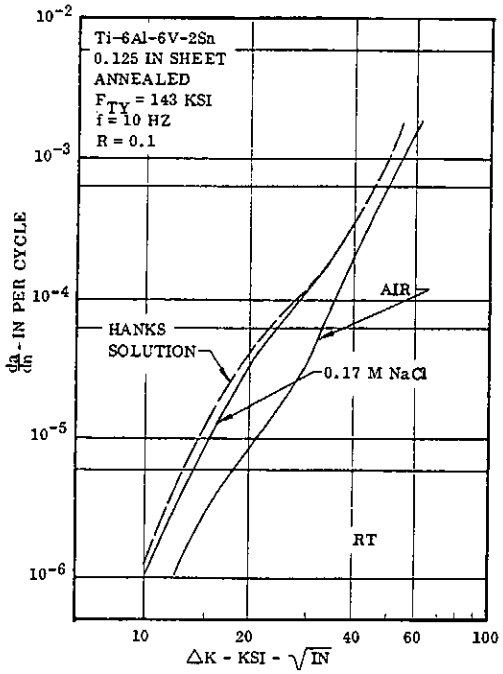
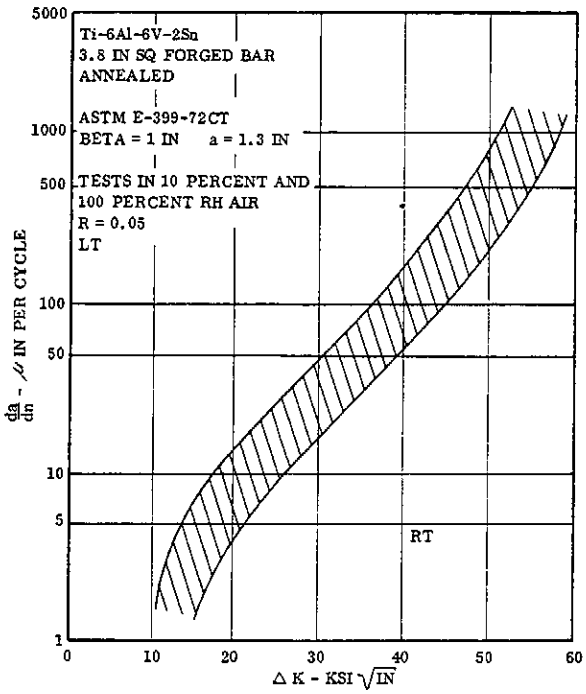


FIG. 3.0522 EFFECT OF SIMULATED HUMAN BODY ENVIRONMENTS ON FATIGUE CRACK PROPAGATION RATES OF ANNEALED SHEET.
(26, Fig. 5)



Ti
6 Al
6 V
2 Sn
Ti-6-6-2

FIG. 3.0524 FATIGUE CRACK GROWTH RATES IN HUMID AIR FOR ANNEALED FORGING.
(30, Tables B-1, 2, 3, 4 and C-1, 2, 3, 4)

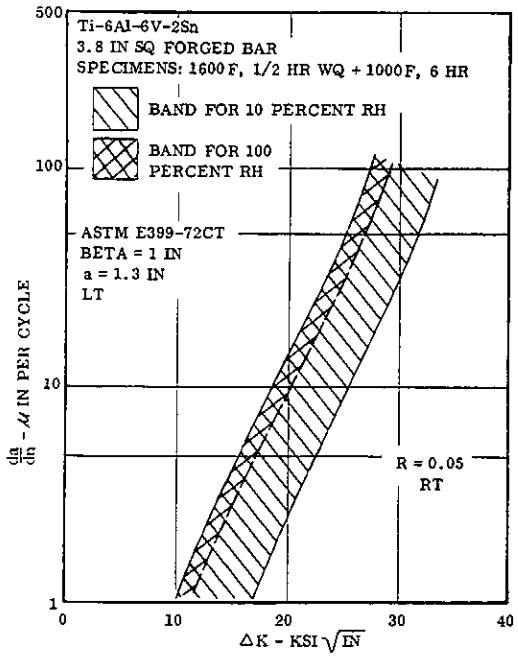


FIG. 3.0523 FATIGUE CRACK GROWTH RATES IN HUMID AIR FOR SOLUTION TREATED AND AGED SPECIMENS FROM FORGING.
(30, Tables B-1, 2, 3, 4 and C-1, 2, 3, 4)

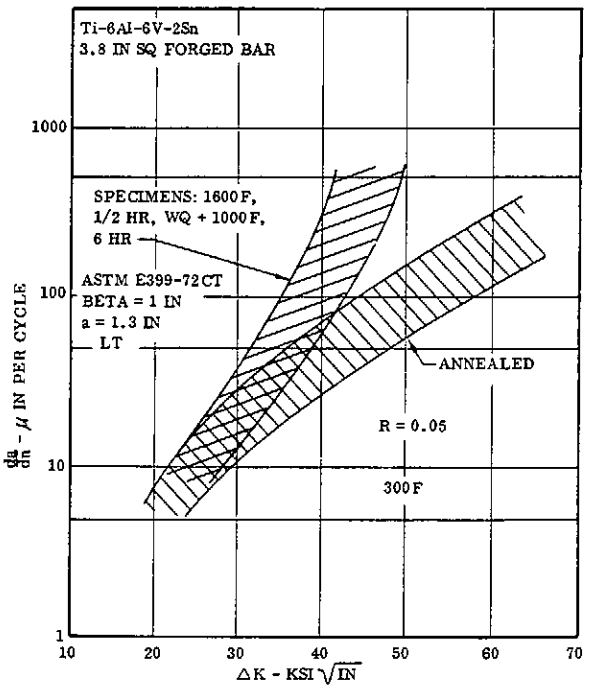


FIG. 3.0525 FATIGUE CRACK GROWTH RATES AT 300F FOR ANNEALED FORGING AND SOLUTION TREATED AND AGED SPECIMENS FROM FORGING.
(30, Tables E-1 thru E-11)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

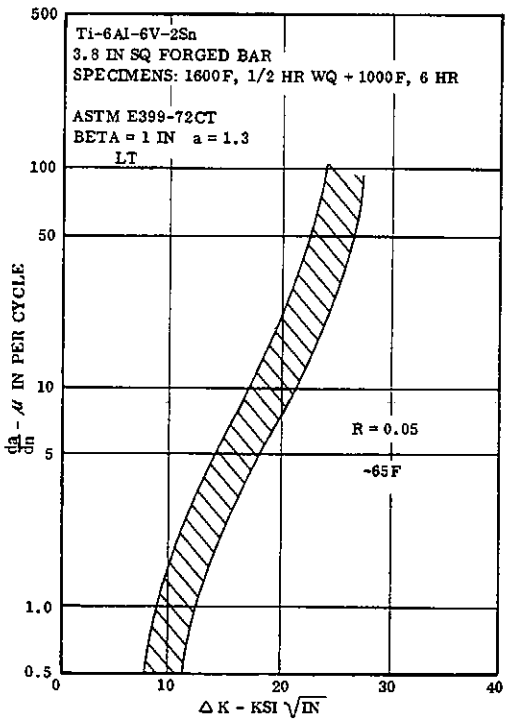


FIG. 3.0526 FATIGUE CRACK GROWTH RATES AT -65F FOR SOLUTION TREATED AND AGED SPECIMENS FROM FORGING.
(30, Tables D-6,7,8,9,10)

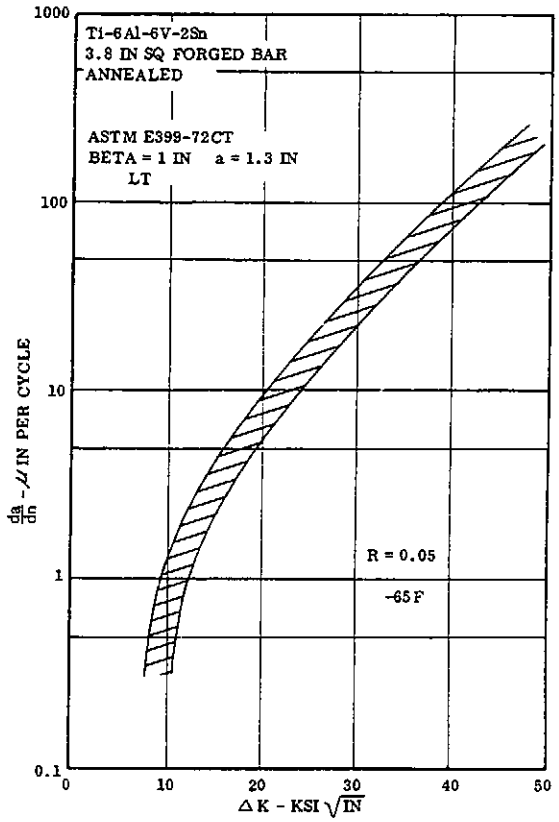


FIG. 3.0527 FATIGUE CRACK GROWTH RATES AT -65F FOR ANNEALED FORGING. (30, Tables D-1,2,3,4,5)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

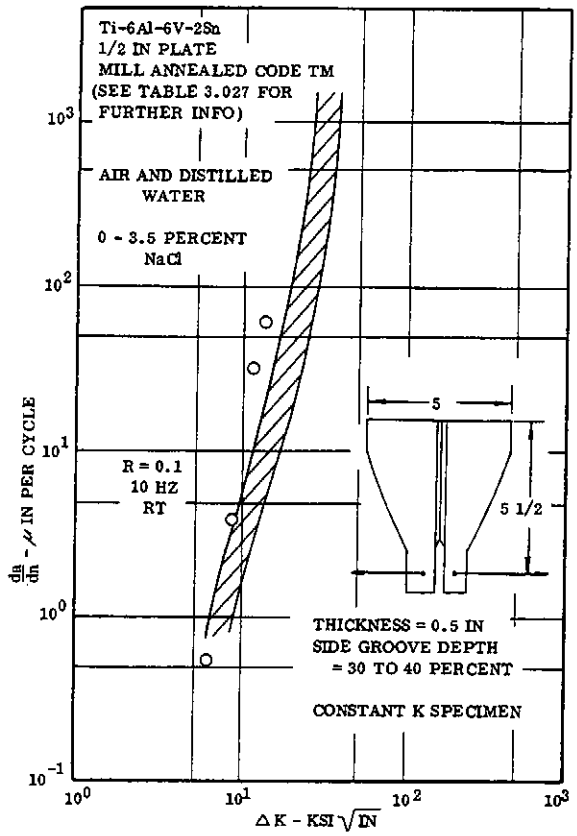


FIG. 3.0528 FATIGUE CRACK GROWTH RATES FOR ANNEALED PLATE IN AIR AND SALT WATER. (36, Fig. 86)

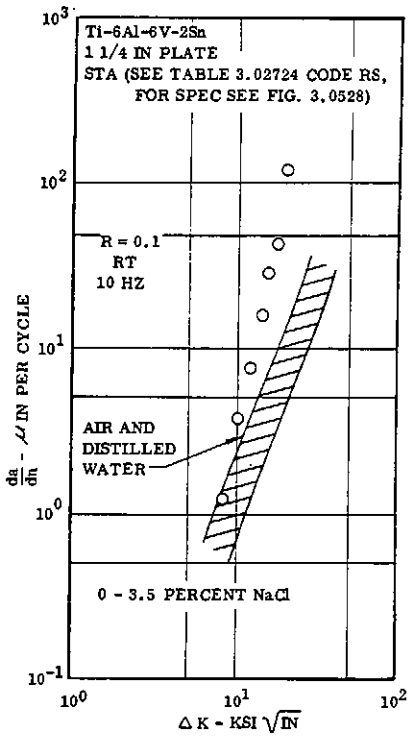


FIG. 3.0529 FATIGUE CRACK GROWTH RATES FOR BETA PROCESSED, SOLUTION TREATED AND AGED PLATE TESTED IN AIR, DISTILLED WATER AND SALT WATER. (36, Fig. 87)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

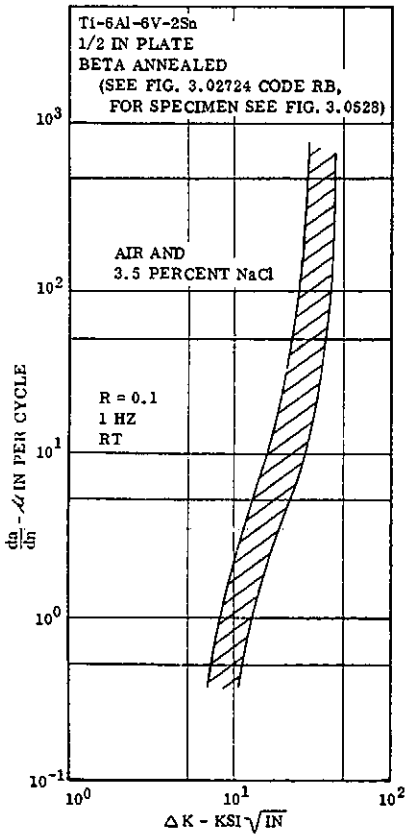


FIG. 3.05210 FATIGUE CRACK GROWTH RATES FOR BETA ANNEALED PLATE IN AIR AND SALT WATER.
(36, Fig. 89)

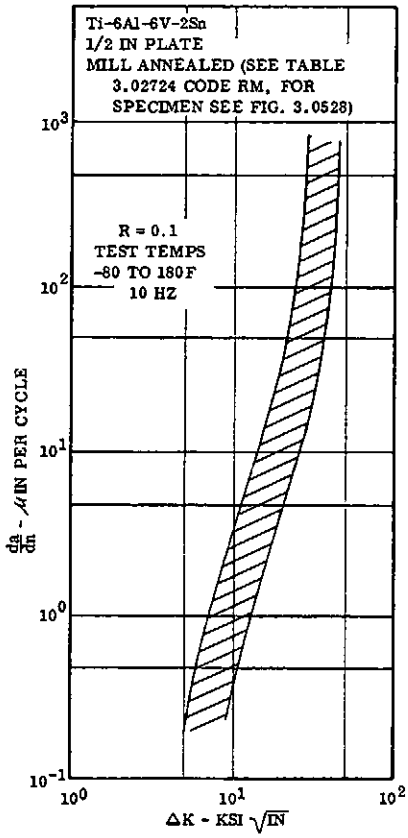


FIG. 3.05211 FATIGUE CRACK GROWTH RATES AT VARIOUS TEMPERATURES FOR ANNEALED PLATE.
(36, Fig. 93)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

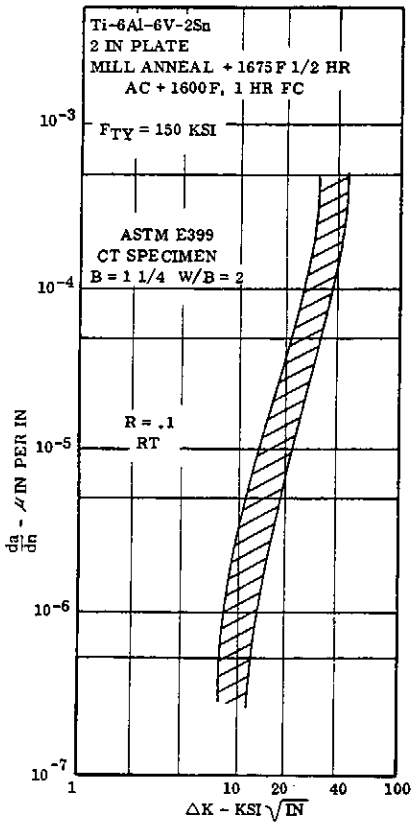


FIG. 3.05212 FATIGUE CRACK GROWTH RATES FOR SPECIMENS CUT FROM PLATE AND GIVEN TWO ANNEALING TREATMENTS. (37, Fig. A-3)

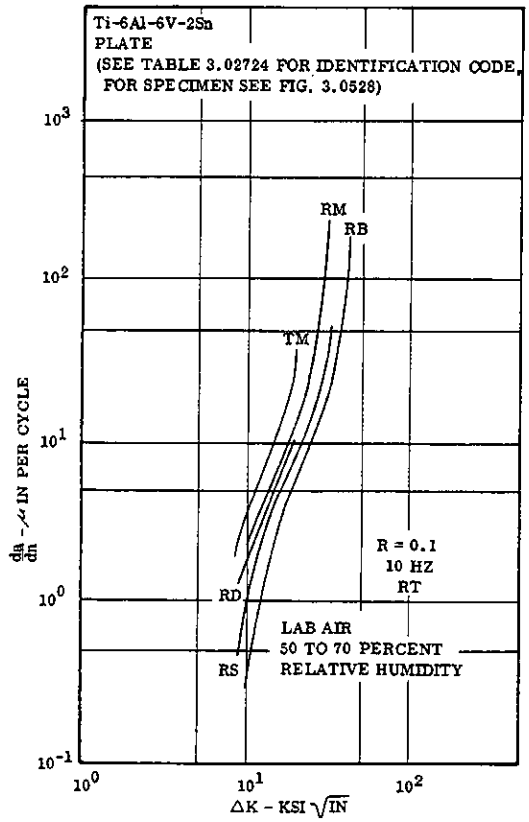


FIG. 3.05213 AVERAGE FATIGUE CRACK GROWTH RATES FOR PLATE GIVEN SEVERAL HEAT TREATMENTS AND TESTED IN LABORATORY AIR. (36, Fig. 92)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

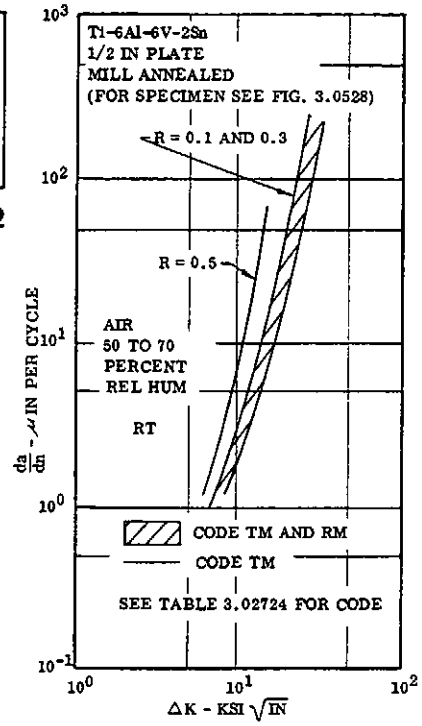


FIG. 3.05214 FATIGUE CRACK GROWTH RATES FOR ANNEALED PLATE AT SEVERAL R RATIOS TESTED IN LABORATORY AIR. (36)

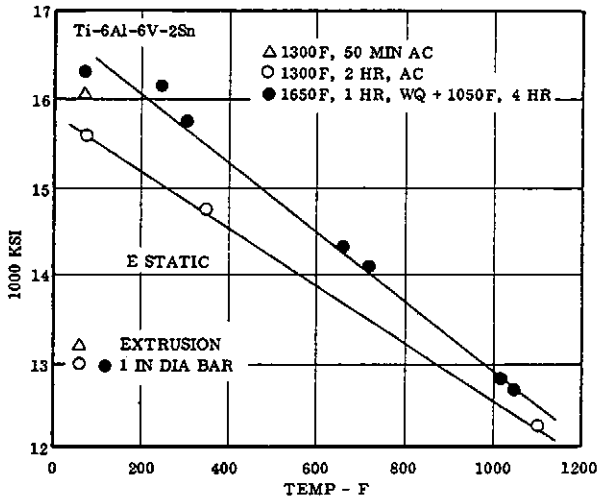


FIG. 3.062 MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES. (1)(14)

Source	(47, Table 4)											
Alloy	Ti-6Al-6V-2Sn											
Form	Start as 6 in dia. billet reduced in three steps to 1-1/4 in thick disk											
Forge Temp.	1725F (Beta forge) (1)						1665F (Alpha + beta forge)					
Solution temp. F	Direct quench		1525		1650		Direct quench		1525		1650	
Age temp - F	1000	1100	1000	1100	1000	1100	1000	1100	1000	1100	1000	1100
F_{tu} - ksi	200	195	190	176	207	195	200	187	192	178	203	193
F_{ty} - ksi	188	188	178	166	193	183	192	180	181	170	194	184
e - percent	7	8	10	14	7	9	5	10	9	13	8	8
RA - percent	20	25	21	36	16	24	11	27	25	39	20	20
W/A in-lb/in^2	74	88	108	285	72	88	68	92	80	106	49	102
(1) 1675F = Beta transus												

TABLE 4.0122 TENSILE PROPERTIES AND PRECRACKED CHARPY VALUES FOR ALPHA + BETA AND FOR BETA FORGED DISKS

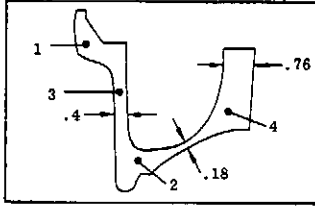
Source	(23, Table 3)			
Alloy	Ti-6Al-6V-2Sn			
Form	9 in dia. billets press upset at 2000F to reductions shown to 1 in thick pancakes			
Condition	Pancakes: S.T. 1600F WQ + 1000F, 4 hr.			
2 Stage upset red. percent	50 + 0	50 + 10	50 + 25	50 + 40
F_{tu} - ksi	181	185	184	188
F_{ty} - ksi	167	166	166	170
e - percent	3.2	4.5	4.2	5.5
RA - percent	7.4	10.4	9.6	9.6

TABLE 4.0123 EFFECT OF UPSET DEFORMATION FOR BETA FORGING ON ROOM TEMPERATURE TENSILE PROPERTIES

Source	(23, Table 13)					
Alloy	Ti-6Al-6V-2Sn					
Form	Landing gear wheel forging					
Condition	Finish forging: 1600F, 1 hr WQ + 1000F, 4 hr AC					
Forge	Pot 1675F + extrude 2000F + block and finish as indicated					
Block - F	1700		1700		1950	
Finish - F	1700		1950		1700	
Location	Wall	Rim	Wall	Rim	Wall	Rim
F_{tu} - ksi	196	188	178	178	184	164
F_{ty} - ksi	179	173	156	161	165	164
e - percent	8	9	5	7	4	6
RA-percent	15	21	10	15	8	14

TABLE 4.0124 EFFECT OF FORGING TEMPERATURES ON ROOM TEMPERATURE TENSILE PROPERTIES OF LANDING GEAR WHEEL FORGING

Source	(35, Table 14)				
Alloy	Ti-6Al-6V-2Sn				
Form	Full Scale Nose Wheel Isothermal Creep Forged. In-100 Alloy Die and Work Piece at 1650F.				
Condition	Forge + WQ + 1050F, 4 hr.	Forge + WQ + 1650F, 1/2 hr. WQ + 1050F, 24 hr			
Location	3	1	2	3	4
F_{tu} - ksi	185	200	187	190	190
F_{ty} - ksi	172	192	180	185	180
e - percent	10	4.5	5.5	7.0	5.0
RA - percent	27	8	15	21	20



Section of Nose Wheel Forging showing specimen locations and thicknesses

TABLE 4.0126 TENSILE PROPERTIES AT ROOM TEMPERATURE OF ISOTHERMALLY FORGED AND HEAT TREATED NOSE WHEEL.

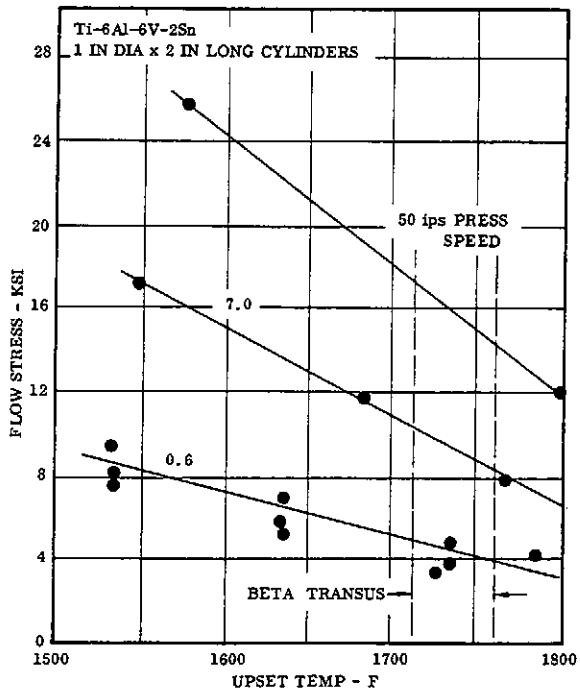
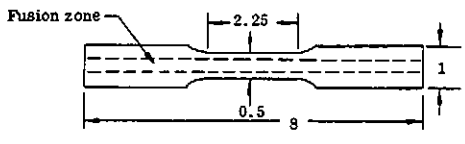


FIG. 4.0125 EFFECT OF UPSET TEMPERATURE AND PRESS SPEED ON FLOW STRESS. (35, Fig. 80)

Source	(44, Table 9)			
Alloy	Ti-6Al-6V-2Sn			
Form	0.35 inch Plate Mill Annealed			
Condition	As Welded			
Weld Type	Manual GTA Matching Filler	Plasma Arc	Auto. GTA Matching Filler	Electron Beam
F_{tu} - ksi	172	173	175	173
F_{ty} - ksi	153	156	158	156
e (2 in) percent	4	4	4	5



Weld Test Specimen

TABLE 4.0312 TENSILE PROPERTIES AT ROOM TEMPERATURE FOR WELDS MADE BY SEVERAL PROCESSES WITH MATCHING FILLER

Ti
6 Al
6 V
2 Sn

Ti-6-6-2

Source	(44)				
Alloy	Ti-6Al-6V-2Sn				
Form	0.35 in Plate, Annealed				
Condition	Auto. GTA Weld				
Filler	Ti 75A	Ti 75A + Ti-6-6-2	Ti-6-6-2	Ti-6-6-2	Ti-6-6-2
Post Weld Treatment	None	None	None	1400F, 4 hrs.	1400F, 4 hr +500F, 1000 hr
F_{tu} - ksi (1)	168	172	175	159	162
F_{ty} - ksi	146	156	158	147	147
e (2 in) percent	4	4	4	12	9
K_{Ic} -ksi$\sqrt{in}$(2)	(68)	(62)	44	(57)	54

(1) For specimen see Table 4.0312.
(2) ASTM E-399, values in ( ) not valid because of insufficient specimen thickness. Crack at weld center.

TABLE 4.0313 TENSILE PROPERTIES AND PLANE STRAIN FRACTURE TOUGHNESS FOR GTA WELD METAL FROM SEVERAL FILLERS

Source	(8)											
Alloy	Ti-6Al-6V-2Sn											
Form	0.1 inch Sheet (0.14 O_2, 0.014 N_2, 0.004 H_2, 0.02C, 0.91 Fe)											
Condition	1625F, 1/2 hr + 1200F, 2 hr AC	1625F, 1/2 hr. WQ + 1200F, 2 hr, AC + Weld				1625F, 1/2 hr, WQ + Weld + 1200F, 2 hr, AC						
Filler Wire (3)	Not Welded	6Al-6V-2Sn		6Al-4V		6Al-6V-2Sn		6Al-4V		Ti-55A		
Weld Location (1).		C	E	C	E	C	E	C	E	C	E	
F_{ty} - ksi (2)	172	192	191	174	185	192	191	189	182	159	188	
Notch (4) Strength - ksi	63	30	28	38	35	27	28	24	35	80	43	

(1) Location C - weld center, E - weld edge
(2) Weld yield strength estimated from Hardness tests
(3) Filler 6Al-6V-2Sn cut from parent sheet
Filler Ti-55A (0.11 O_2, 0.009 N_2, 0.007 H_2, 0.03C, 0.11 Fe)
(4) Center crack specimen W - 3 inch, $2a_o$ = 1 in

TABLE 4.0314 CRACK STRENGTH OF TIG WELDED SHEET USING SEVERAL FILLER WIRES

Source	(38)							
Alloy	Ti-6Al-6V-2Sn							
Form	1.5 in Plate							
Location	Parent Metal				EB Weld HAZ			
Direction	TL		LT		TL		LT	
Condition (1)	A	B	A	B	A	B	A	B
K_{Ic} -ksi$\sqrt{in}$	40	33	49	36	36	35	40	34

(1) A - as received, mill annealed
B - Stress relieved 1350F, 4 hr

TABLE 4.0315 PLANE STRAIN FRACTURE TOUGHNESS OF THE HEAT AFFECTED ZONE OF ELECTRON BEAM WELDS

Source	(65, p.17-S)											
Alloy	6Al-6V-2Sn-Ti											
Form	0.125-in-Sheet											
Condition	GTA Weld Single Pass											
Filler Metal	6Al-6V-2Sn									6Al-4V		
Location	Base Metal			HAZ (c)			FZ (b)			FZ		
Postweld(d) Heat Treat	A	B	C	A	B	C	A	B	C	A	B	C
F_{ty} - (ksi)	161	144	154	-	-	-	127	105	150	-	-	-
Charpy V(a) (ft-lbs)	229	1215	340	116	889	214	96	1020	242	181	810	196

(a) Sub thickness (0.125 in.) Charpy.
(b) Fusion Zone
(c) Heat Affected Zone
(d) A - As welded
B - 1350F, 6 hr, F.C. + 1700F, 3 hr. F.C. + 1350F, 3 hr. F.C.
C - 1500F, 1 hr + cool 250F/hr to 1200F, 2 hr. A.C. + 1000F, 2 hr., A.C.

TABLE 4.0316 CHARPY IMPACT ENERGY FOR SHEET WELDMENTS MADE WITH TWO FILLERS AND GIVEN DIFFERENT HEAT TREATMENTS.

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

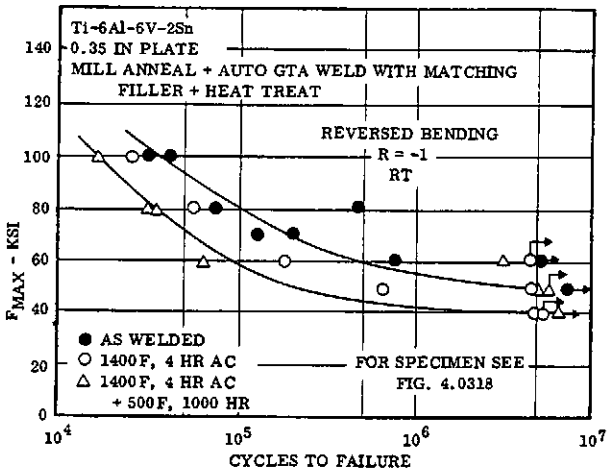


FIG. 4.0317 FATIGUE STRENGTH OF AUTO GTA WELDS WITH MATCHING FILLER GIVEN POST WELD HEAT TREATMENTS. (44, Fig. 80)

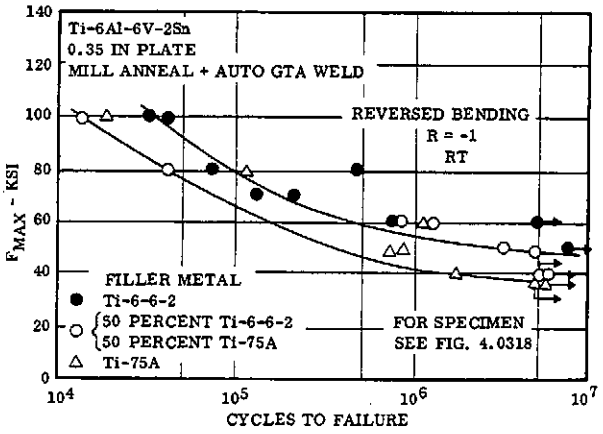


FIG. 4.0318 FATIGUE STRENGTH FOR AUTO GTA WELDS MADE WITH DIFFERENT FILLERS. (44, Fig. 76)

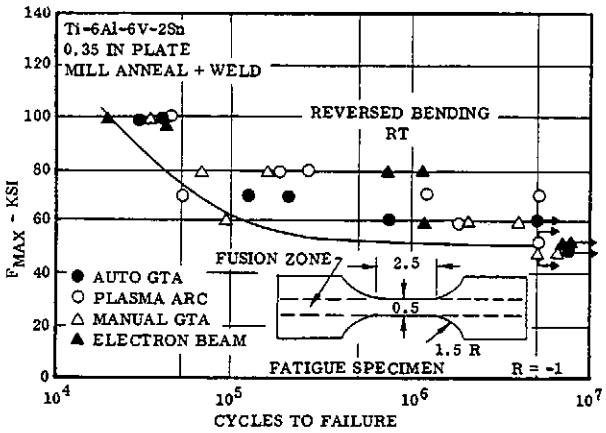


FIG. 4.0319 FATIGUE STRENGTH FOR SEVERAL DIFFERENT WELDS MADE IN ANNEALED PLATE WITH MATCHING FILLER. (44, Fig. 62)

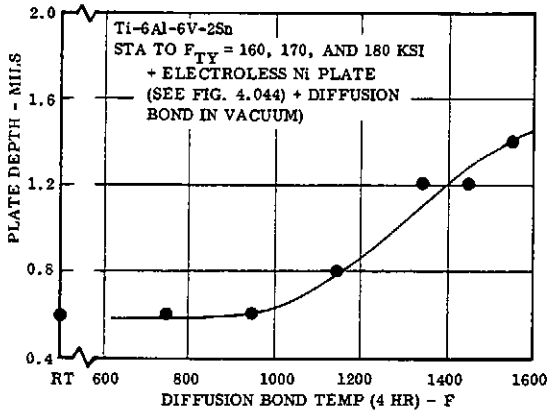


FIG. 4.042 EFFECT OF DIFFUSION BONDING TEMPERATURE ON ELECTROLESS Ni PLATE DEPTH. (27, Table 3)

	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

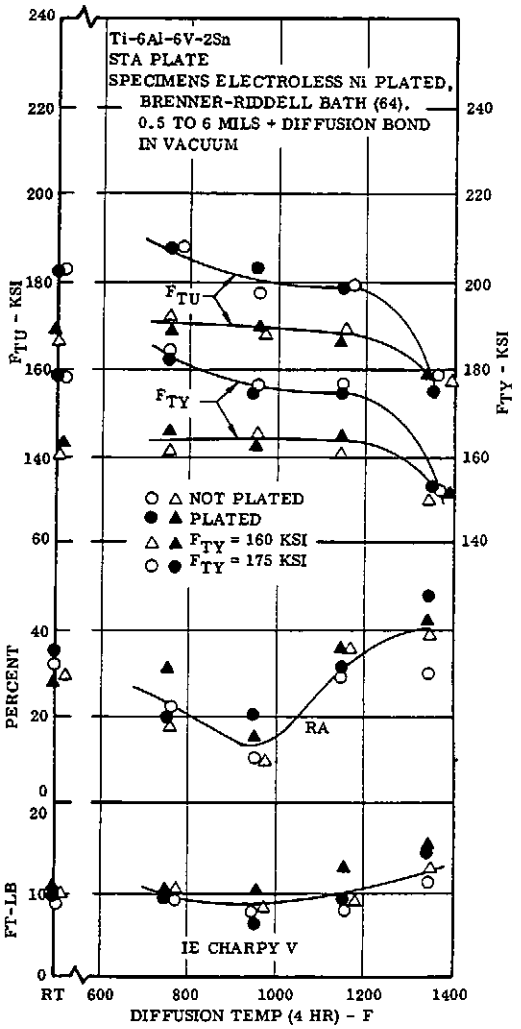


FIG. 4.044 EFFECT OF DIFFUSION BONDING TEMPERATURE ON ROOM TEMPERATURE TENSILE AND IMPACT PROPERTIES OF ELECTROLESS Ni PLATED STOCK HEAT TREATED TO TWO STRENGTH LEVELS. (27, p. 12)

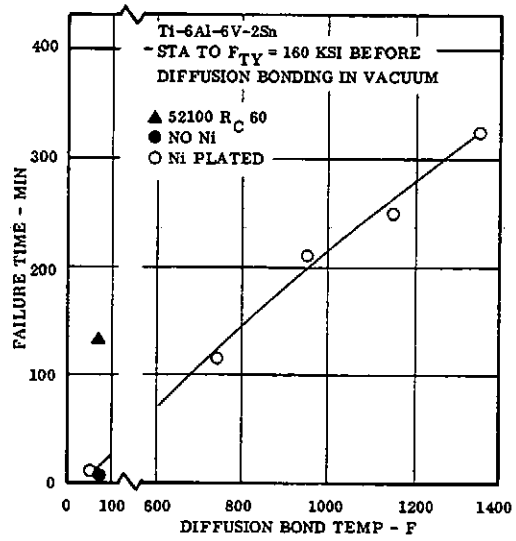
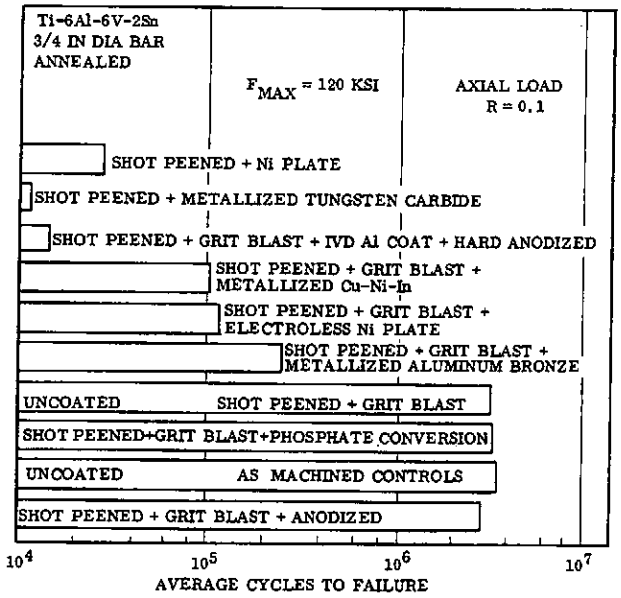


FIG. 4.043 EFFECT OF DIFFUSION BOND TEMPERATURE APPLIED TO ELECTROLESS NICKEL PLATE ON THE FAILURE TIME IN A MODIFIED McMILLAN WEAR TESTER. (22, Table 4)



	Ti
6	Al
6	V
2	Sn

Ti-6-6-2

FIG. 4.045 EFFECT OF VARIOUS FRETTING RESISTANT COATINGS ON FATIGUE LIFE OF ANNEALED BAR. (33, Fig. 18)

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Ti
6 Al
6 V
2 Sn

Ti-6-6-2

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	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb-1Ta-0.8Mo

1. GENERAL

Ti-6Al-2Cb-1Ta-0.8Mo (Ti-621/0.8) is a modification of the Ti-7Al-2Cb-1Ta (Ti-721) composition, itself a modification of the original Ti-8Al-2Cb-1Ta (Ti-821) alloy. The Ti-721 alloy was introduced specifically to avoid weld-cracking problems encountered in thick plate with the Ti-821 composition. The Ti-621/0.8 alloy was developed as a saltwater stress-corrosion resistant modification of Ti-721.

Ti-6Al-2Cb-1Ta-0.8Mo is of medium strength and, on the basis of fracture appearance, is considered seawater stress-corrosion resistant. Sustained-load tests on precracked specimens, however, indicate the load-carrying capability of the alloy is reduced in seawater although no evidence of stress-corrosion cracking has been observed on the fracture surfaces of failed specimens.

The alloy is forgeable and weldable and is intended for use as a structural alloy for marine application. It is normally processed in the beta phase region. On request, however, the alloy may be processed in the alpha-beta field with an improvement in strength at some sacrifice in toughness. All data presented in this chapter are for beta processed material, with the exception of the producer's guaranteed properties for alpha-beta processed material presented in Table 3.014.

1.01 Commercial Designation

Ti-6Al-2Cb-1Ta-0.8Mo
Ti-6Al-2Cb-1Ta-1Mo

1.02 Alternate Designations

RMI-6Al-2Cb-1Ta-0.8Mo
RMI-6Al-2Cb-1Ta-1Mo
Ti-621/0.8
Ti-621/1.0

1.03 Specifications

MIL-T-9046F (April 3, 1967), Ammendment 1 (March 15, 1968).

1.04 Composition

1.041 Producer's specified composition, Table 1.041.

TABLE 1.041

Source	RMI(1)	
	Weight Percent	
	Minimum	Maximum
Aluminum	5.50	6.50
Columbium	1.50	2.50
Tantalum	0.50	1.50
Molybdenum	0.50	1.50
Iron		0.25
Carbon		0.05
Nitrogen		0.03
Oxygen		0.10
Hydrogen		0.0125*
Other Elements (each)		0.10
Other Elements (combined)		0.40
Titanium	Balance	

*Bar and billet 0.0125 maximum; sheet and plate 0.0150 maximum.

1.042 Military's specified composition, Table 1.042.

TABLE 1.042

Source	Military (7)	
	Weight Percent	
	Minimum	Maximum
Aluminum	5.5	6.5
Columbium	1.5	2.5
Tantalum	0.5	1.5
Molybdenum	0.5	1.0
Iron		0.20
Carbon		0.05
Nitrogen		0.03
Oxygen		0.10
Hydrogen		0.0125*
Other Elements (total)		0.40
Titanium	Balance	

* Shall be determined on each lot of the product as shipped.

1.05 Heat Treatment

1.051 Stress relief anneal; 1100F, 2 hours, AC (9).

1.0511 Stress relaxation of plate at 900 and 1000F, Figure 1.0511.

1.052 Full anneal; 1650F, 1 hour, AC (9).

1.053 Solution treat and age; 1850F, 1 hour, WQ + 1100F, 2 hours, AC (9).

1.054 This alloy is generally used in the as-fabricated or fabricated-plus-annealed conditions. A small increase in strength can be obtained by solution treating and aging, but at a considerable sacrifice in ductility and toughness (compare as-rolled plate with plate solution treated and aged in Tables 3.0217 and 3.0338). Studies are continuing to establish heat treating schedules for optimum combinations of strength, toughness, weldability, and seawater stress-corrosion resistance (9).

1.055 A quench delay from the solution treating furnace to the quenching medium may be encountered in some production heat treating processes. Figure 1.0551 gives cooling curves for 1 inch x 6 inch x 6 inch sections cooled in air from various initial temperatures. These data may be used to determine the furnace temperature required to give a desired quenching temperature. It should be noted, however, that the effect of quench delay on strength and toughness of this alloy is small for delay times up to 1 1/2 minutes (see Figures 3.0213 and 3.0333).

1.0551 Cooling rate curves for 1 inch plate cooled in air, Figure 1.0551.

1.06 Hardness

Annealed condition, RC-30 (10).

1.07 Forms and Conditions Available

1.071 Alloy is available as billet, bar, plate, sheet, and wire. Billet and plate size limitations are generally controlled by the size and weight of the ingot and size of the processing equipment. Bar and plate are available in the annealed, as-rolled, or as-hot worked condition. Billet, sheet, and wire are available in the annealed condition.

1.072 All products are normally beta processed (rolled, forged, etc.). On request, however, the alloy may be processed in the alpha-beta region with an improvement in strength at some sacrifice in toughness (9).

1.08 Melting and Casting Practice

1.081 Alloy is multiple melted by the consumable electrode process, using controlled atmosphere and pressure. Ingot sizes produced to date are 30 inch diameter by approximately 10,000 pounds, and 36 inch diameter by approximately 15,000 pounds.

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb-1Ta-0.8Mo

1.09 Special Considerations

1.091 Alloy modification. This alloy, Ti-6Al-2Cb-1Ta-0.8Mo, is being modified to have slightly higher molybdenum (1.2 percent) content to compete with ELI grade Ti-6Al-4V (11). The modified alloy has improved strength over Ti-621/0.8 and is both weldable and seawater stress-corrosion resistant. No information is available, however, regarding its fracture toughness.

RMI has recently announced that it will market Ti-6Al-2Cb-1Ta-0.8Mo and Ti-6Al-2Cb-1Ta-1.2Mo under the single designation Ti-6Al-2Cb-1Ta-1Mo. Variations in molybdenum content will be made to suit the requirements of the customer (11)(9).

1.092 Oxygen and interstitial element contents. Oxygen content influences the strength and toughness of this alloy. Table 3.02113 shows a modest but consistent elevation in smooth tensile strength associated with an increase in oxygen level from 0.058 to 0.122 weight percent. While the comparison is made for materials given slightly different high temperature treatments (1900F vs 1950F), this difference in heat treatments would not be expected to produce the observed difference in strength. Indeed, for water quenched stock, a lesser strength would be expected for the material treated at the higher temperature (see Figure 3.0212). The same difference in oxygen content (0.058 vs 0.122 weight percent) is shown in Table 3.03313 to produce a significant difference in +32F drop-weight tear energy, the higher oxygen level being responsible for lower values. The -80F standard Charpy V impact energy in the same table does not give a consistent measure of the toughness change with oxygen level.

No data are available to assess the influence of oxygen content on the seawater stress-corrosion susceptibility of this alloy. Results (6) on Ti-6Al-2Sn-1Mo-(1-2)V and Ti-6Al-4Zr-(1-2)V compositions show, however, that heavy concentrations of oxygen lower the aqueous salt solution stress-corrosion resistance of these alloys. In the same study, unalloyed titanium containing a low amount of residual Fe, C, N, and H was made sensitive to seawater stress-corrosion by oxygen contents above approximately 0.250 weight percent. Oxygen may indirectly influence the stress corrosion sensitivity of Ti-Al alloys by affecting the solubility of aluminum in primary alpha and by affecting the kinetics of the Ti_3Al precipitation reaction; results on Ti-Al compositions (6) have shown that aluminum in solid solution is not responsible for stress-corrosion cracking, but that such is due to the presence of coherent Ti_3Al.

No results are available to establish the influence of oxygen or other interstitial elements on the fracture toughness of this alloy, nor the possible influence of other interstitial elements on its aqueous salt solution stress-corrosion resistance.

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting point, approximately 3000F.

2.012 Phase changes, beta transus 1860±25F.

2.013 Thermal conductivity, at 70F, 3.7 Btu ft per (hr sq ft F).

2.014 Thermal expansion, mean coefficient from 72 to 1200F, 5×10^{-6} in/in/F.

2.015 Specific heat.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density, 0.162 lb per cu in, 4.48 gr per cu cm.

2.022 Electrical resistivity.

2.023 Magnetic properties; alloy is nonmagnetic.

2.024 Emittance.

2.025 Damping capacity.

2.03 Chemical Properties

2.031 Seawater stress-corrosion tests, general. The presence of a sharp notch is a necessary requirement for stress-corrosion cracking of titanium alloys in seawater. The stress level at which seawater stress-corrosion cracking failures take place in susceptible titanium alloys varies with notch accuity (6). In some instances a sharp machined notch is as damaging as a crack, but this depends on the sensitivity of the alloy. This being the case, it is prudent to use cracked specimens in all comparative evaluations of stress-corrosion susceptibility of materials. All results reported in this chapter were obtained using specimens containing fatigue cracks.

2.032 Step load tests. There are two types of tests in common use for the evaluation of seawater stress-corrosion behavior: step load tests and sustained load tests. The step load test seems to be fairly standard from one investigating laboratory to another. All use a precracked bar subjected to cantilever loading. An initial load of about one-half the anticipated failure load is applied and increased in 10 to 15 ksi increments every 5 to 10 minutes until failure. The failure stress is called the nominal bend strength and is calculated for the net section using simple beam theory. The test is performed in both air and salt water (or seawater) and the ratio of the two results is an indication of stress-corrosion resistance.

Results presented in Figure 2.034 and Table 2.035 show seawater-to-air nominal bend strength ratios greater than 0.8 for base plate and GTA and GMA welded plate. No evidence of corrosion cracking was noted on the fracture surfaces of failed specimens, leading the investigator (3)(6)(13) to the conclusion that the alloy is seawater stress-corrosion resistant.

2.033 Sustained load tests. The sustained load test is less standardized than the step load test. Both specimen size and shape may vary. Thus the results in Figure 2.038 were obtained using specimens of 1 inch x 1/2 inch cross section with a fatigue crack about 50 percent deep and side grooved, while the results in Table 2.037 were obtained from specimens of 1 inch x 7/8 inch cross section with a 30 percent deep fatigue crack without side grooves.

Sustained load test results are presented as the stress intensity factor, K_I, vs time-to-failure. No account was taken of the influence of side grooves for the data reported, as the same calculation for stress intensity factor was used for specimens both with and without side grooves. Nor was any attempt made to assure conditions of plane strain and small scale yielding at the advancing crack tip as the use of K_I would imply. All the results presented in this chapter fail to satisfy the size requirements for plane strain testing as defined by ASTM Committee E-24 on Plane Strain Fracture Toughness of High Strength Metallic Materials (12). Therefore the symbol K_Q is used in this chapter rather than K_I.

Figure 2.036 indicates that a threshold stress intensity factor of about 82 ksi$\sqrt{\text{in}}$ may exist for as-rolled plate on the basis of results to 50 hours holding time at that stress intensity level. Results obtained on conventionally processed Ti-7Al-2Cb-1Ta show that the threshold stress intensity factor determined from short time tests satisfactorily characterizes long time behavior. Specimens of that alloy tested at 5 to 10 ksi$\sqrt{\text{in}}$ less than the indicated threshold stress intensity factor did not fail after 500 hours exposure. On this basis, the threshold stress intensity factor for stress corrosion cracking failure in seawater for the present alloy (82 ksi$\sqrt{\text{in}}$) may be valid.

Figure 2.037 indicates that the threshold stress intensity may be as low as 70 ksi$\sqrt{\text{in}}$ for plate in various heat treated conditions. The same threshold appears to characterize welds of this alloy (see Figure 2.038).

Although these sustained load test results indicate a time-dependent reduction in load carrying capability

of cracked specimens in salt water, the investigators (2)(5)(14) conclude that this alloy is completely stress-corrosion resistant in salt water environment, based on their interpretation that stress-corrosion features are absent on the fracture surfaces of failed specimens. This, of course, suggests that the same reduction in load carrying capacity would be expected for companion tests in air (14).

Fatigue. Figure 2.039 shows no difference in high or low cycle fatigue strength for smooth or mildly-notched specimens as a function of environment (i.e., air vs seawater).

2.034 Seawater stress-corrosion behavior of plate, Figure 2.034

2.035 Seawater stress-corrosion behavior of welded plate, Table 2.035.

2.036 Sustained load seawater stress-corrosion behavior of as-rolled plate, Figure 2.036.

2.037 Sustained load seawater stress-corrosion behavior of plate in several heat treated conditions, Figure 2.037.

2.038 Sustained load salt water stress-corrosion behavior of welded plate, Figure 2.038.

2.039 Effect of seawater environment on low and high cycle fatigue strength of smooth and mild notch specimens, Figure 2.039.

2.04 Nuclear Properties

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb-1Ta-0.8Mo

TABLE 2.035

Source			(3, p. 15)				
Alloy			Ti-6Al-2Cb-1Ta-0.8Mo				
Form			1 inch rolled plate, welded (1)				
	Filler Metal			F_{ty} (2)	Sea Water Stress-Corrosion (3)(4) Heat Affected Zone		
Welding Process	Nominal Composition	Wire Diameter Inch	Condition of Weldment	(0.2 Percent Offset) ksi	$S_{n_{air}}$ ksi	$S_{n_{sw}}$ ksi	$\frac{S_{n_{sw}}}{S_{n_{air}}}$
GTA	Ti-621/0.8	1/8 Flat Strip	As-Welded	115	236	252	1.07
	Ti-621/0.8	1/8 Flat Strip	900F, 2 hrs, AC	115	235	232	1.01
	Ti-621/0.5	0.062	As-Welded	105	230	224	1.02
	Ti-621/0.5	0.062	900F, 2 hrs, AC	109	211	228	1.08
GMA	Ti-621-0.5	0.062	As-Welded	108(5)	222	216	0.97
	Ti-621/0.5	0.062	900F, 2 hrs, AC	113(5)	226	211	0.94
	Ti-621/0.5	0.062	As-Welded	113(6)	---	---	---
	Ti-621/0.5	0.062	900F, 3 hrs, AC	116(6)	---	---	---

(1) See Table 4.031 for weld joint configuration
(2) Remainder of smooth properties corresponding to these stress-corrosion data appear in Table 4.031
(3) See Figure 2.034 for specimen configuration and definition of $S_{n_{air}}$ and $S_{n_{sw}}$.
(4) Properties of weld metal are:

	$S_{n_{air}}$	$S_{n_{sw}}$	$S_{n_{sw}}/S_{n_{air}}$
As-Welded	222	217	0.98
900F, 2 hrs, AC	217	250	1.15

(5) Determined using SR-4 strain gauges mounted on weld metal of specimen
(6) Determined from "all-weld" specimen

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb-1Ta-0.8Mo

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 Producer's guaranteed properties for plate, Table 3.011.

Table 3.011

Source	(1)	
Alloy	Ti-6Al-2Cb-1Ta-1Mo	
Form	Plate	
Condition	As-Rolled*	
Thickness, inch	≤1	>1 to 3
F_{tu}, minimum - ksi	120.0	115.0
F_{ty}, minimum - ksi	110.0	100.0
F_{cy}, minimum - ksi	118.0	108.0
e(1 inch), minimum - percent	10	10
RA, minimum - percent	20	20
Standard Charpy V, minimum - ft-lbs +32F	25	25
-80F	21	21
*Rolled from above the beta transus temperature		

3.012 Producer's guaranteed properties for billet products, Table 3.012.

TABLE 3.012

Source	(1)	
Alloy	Ti-6Al-2Cb-1Ta-1Mo	
Form	Billet Products*	
Test Condition	Full Section ** ≤10 inch rd	Test Forged *** >4 inch rd to 12 inch rd
F_{tu}, minimum - ksi	115.0	125.0
F_{ty}, minimum - ksi	100.0	110.0
F_{cy}, minimum - ksi	105.0	115.0
e(1 inch), minimum - percent	10	10
RA, minimum - percent	20	25
Standard Charpy V, minimum - ft-lbs, +32F	23	25

*Processed from above the beta transus temperature
**As-forged or forged and full annealed 1650F, 1 hr, AC
***Test forge procedure: 3:1 upset to maximum 7/8 inch thick from above beta transus and full annealed 1650F, 1 hr, AC

3.013 Military's specified properties, Table 3.013.

TABLE 3.013

Source	(7)
Alloy	Ti-6Al-2Cb-1Ta-0.8Mo
Form	Plate up to 2.750 inches *
Condition	Mill Annealed
F_{tu}, minimum - ksi	103
F_{ty}, minimum - ksi	95
e(2 inches minimum or 4D) - percent	10.0
*Rolled from above the beta transus temperature	

3.014 Producer's guaranteed properties for alpha-beta processed sheet and plate, Table 3.014.

TABLE 3.014

Source	(9)				
Alloy	Ti-6Al-2Cb-1Ta-0.8Mo				
Form	Sheet and Plate				
Condition	Alpha-Beta Processed + Full Annealed 1650F, 1 hr, AC				
Thickness Inch	≤0.125	>0.125 to 0.500	>0.500 to 1.00	>1.00 to 2.50	>2.50 to 4.00
F_{tu}, minimum - ksi	130	125	125	120	115
F_{ty}, minimum - ksi	120	115	115	110	105
F_{cy}, minimum - ksi			120	115	110
e(2 inches), minimum - percent	10	10	10	10	10
RA, minimum - percent			20	20	20
Standard Charpy V IE @ 32F - ft-lbs			21	23	25
No fracture toughness or sea water stress-corrosion data are available for Alpha-Beta processed material					

3.02 Mechanical Properties at Room Temperature

3.021 Tension (see 3.031)

3.0211 Solution treated tensile properties of plate specimens air cooled or furnace cooled from various solution temperatures, Figure 3.0211.

3.0212 Solution treated tensile properties of plate specimens water quenched from various solution temperatures, Figure 3.0212.

3.0213 Effect of quench delay on solution treated tensile properties of plate, Figure 3.0213.

3.0214 Effect of aging temperature on tensile properties of plate, Figure 3.0214.

3.0215 Effect of aging time on tensile properties of plate, Figure 3.0215.

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb-1Ta-0.8Mo

3.0216 Alpha-beta versus beta solution treatment regarding tensile properties of as-quenched or quenched and aged plate, Table 3.0216.

TABLE 3.0216

Source	(4, p. 10)(5, p. 26)				
Alloy	Ti-6Al-2Cb-1Ta-0.8Mo				
Form	1 inch rolled plate				
Condition	Test Direction	F_{tu} ksi	F_{ty} ksi	e(1 in) %	RA %
As-rolled	L	119.6	101.8	10.8	23.1
	T	123.0	105.0	12.5	33.6
Alpha annealed (1600F, 1 hr, AC)	L	118.2	99.2	12.5	28.0
	T	122.4	107.4	12.5	31.9
Alpha-beta annealed, air-cooled (1815F, 1 hr, AC)	L	118.2	97.7	12.5	31.3
	T	122.2	104.0	13.0	33.0
Alpha-beta solution treated, quenched (1815F, 1 hr, WQ)	L	126.0	101.2	13.0	29.0
	T	129.0	108.4	11.8	30.7
Alpha-beta solution treated, aged (1815F, 1 hr, WQ+1100F, 2 hrs, AC)	L	127.0	108.9	10.5	20.8
	T	135.5	118.9	10.5	22.1
Beta annealed, air-cooled (1900F, 1 hr, AC)	L	123.2	101.4	11.8	24.6
	T	123.2	103.4	12.2	27.7
Beta solution treated, quenched (1900F, 1hr, WQ)	L	131.1	110.2	12.8	31.0
	T	128.1	108.0	8.8	23.8
Beta solution treated, aged (1900F, 1 hr, WQ+1100F, 2 hrs, AC)	L	135.3	117.1	9.5	24.8
	T	135.4	116.2	9.5	21.2

Each value average of two tests.

3.0217 Tensile and compressive properties of 1 inch and 2.5 inch plate from two heats and in several heat treated conditions. Table 3.0217.

TABLE 3.0217

Source	(2, pp. 21, 22, 23, 26)						
Alloy	Ti-6Al-2Cb-1Ta-0.8Mo						
Form	Rolled Plate						
Heat	Plate Thickness Inches	Test Direction	F_{cy} ksi	F_{tu} ksi	F_{ty} ksi	e(1 in) %	RA %
As Rolled							
A	1	L		120.7	99.9	17.0	30.4
		T		123.5	105.6	17.0	28.4
B	1	L	103.6	118.6	95.6	17.0	35.4
		T	109.8	121.6	102.4	11.0	30.6
B	2.5(1)	L	101.2	117.6	96.9	12.5	32.0
		T	99.8	117.4	98.6	12.0	32.8
1650F, 1 Hour, AC							
A	1	L		120.1	102.2	14.0	30.7
		T		120.6	101.0	12.8	26.0
B	1	L	107.6	118.6	94.7	15.5	34.4
		T	115.1	118.5	96.9	14.5	35.2
1875, 1 Hour, WQ							
B	1	L	112.2	127.8	108.6	10.2	18.6
		T	114.0				
B	2.5(1)(2)	L	114.8	125.9	107.0	10.0	23.0
		T	117.8	122.2	106.5	10.0	28.0
1875F, 1 Hour, WQ + 1100F, 2 Hours, AC							
B	1	L	118.0	130.2	111.5	11.2	20.8
		T	121.6	130.8	112.2	9.2	16.2
	2.5(1)(2)	L	123.6	129.3	115.4	10.0	13.4
		T	120.8	128.9	115.8	8.6	14.4
1875F, 1 Hour, WQ + 1100F, 8 Hours, AC							
B	1	L	121.4	127.8	109.7	9.5	20.6
		T	123.6	131.7	114.6	9.8	18.0
2000F, 1 Hour, 70 Seconds Delay (in air), WQ							
A	1	L		126.2	105.8	11.0	24.2
		T		127.5	107.6	9.8	26.8
B	1	L	112.0	124.4	98.8	12.0	26.1
		T	120.4	126.6	102.1	10.2	19.4
2000F, 1 Hour, 70 Seconds Delay (in air), WQ + 1000F, 4 Hrs, AC							
B	1	L	123.4	128.1	105.4	7.5	11.2
		T	122.4	129.6	108.4	9.5	14.7
2000F, 1 Hour, 70 Seconds Delay (in air), WQ + 1100F, 8 Hrs, AC							
A	1	L		126.8	109.8	10.8	20.3
		T		131.6	114.7	10.0	16.2
B	1	L	119.2	128.0	109.1	8.2	10.8
		T	122.0	130.0	111.0	8.8	14.9

Each value average of two tests.
(1) Specimens taken from mid-thickness.
(2) 1.5 hours at solution temperature.

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb-1Ta-0.8Mo

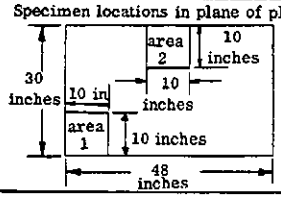
3.0218 Tensile and compressive properties as a function of specimen location and direction for as-rolled 1 inch and 2.5 inch plate from two heats, Table 3.0218.

TABLE 3.0218

Source					(3, p.9)				
Alloy					Ti-6Al-2Cb-1Ta-0.8Mo				
Form					Rolled Plate				
Condition					As-Rolled				
Heat	Plate Thickness Inches	Specimen in Plane of Plate (area)	Location in Plate Thickness-Direction	Specimen Direction	F_{cy} ksi	F_{tu} ksi	F_{ty} ksi	e(1 inch) percent	RA percent
A	1	1	Mid-Thickness	L	110	120	102	12	32
				T	111	121	101	12	23
A	1	2	Mid-Thickness	L	---	120	102	14	35
				T	---	121	101	12	25
B	1	1	Mid-Thickness	L	---	119	98	14	38
				T	---	120	101	12	27
B	2.5	1	Surface	L	106	117	97	12	28
				T	107	120	100	11	30
			Mid-Thickness	L	107	117	96	13	30
				T	105	117	99	11	32
B	2.5	2	Surface	L	---	118	97	12	29
				T	---	120	100	12	23
			Mid-Thickness	L	---	118	97	14	32
				T	---	119	99	14	35
B	2.5	2	--- --- ---	ST	103	117	96	11	38

0.505 inch diameter tensile specimens; each value average of two tests.

Specimen locations in plane of plate



3.0219 Variation in room temperature tensile properties and -80F and +32F standard Charpy V impact energy as a function of specimen location for as-rolled and heat treated 2.5 inch plate, Table 3.0219.

TABLE 3.0219

Source		(3, p.8)					
Alloy		Ta-6Al-2Cb-1Ta-0.8Mo					
Form		2.5 inch Rolled Plate					
		Room Temperature Tensile Properties				Standard Charpy V Impact Energy ft-lbs	
Condition	Specimen Location	F_{tu} ksi	F_{ty} ksi	e(1 in) %	RA %	@ -80F	@ +32F
As-Rolled	Surface	117	97	12	28	27	33
	Mid-Thick	117	96	13	31	26	34
2300F, 1 hr, WQ	Surface	127	108	9	19	29	40
	Mid-Thick	122	104	8	17	29	36
2300F, 1hr, WQ+1100F, 2hrs, AC	Surface	130	114	7	14	26	32
	Mid-Thick	125	108	8	16	25	30

All longitudinal properties.
Heat treatments performed on 5x4x2.5 inch sections, specimens removed from the center of these sections at either the surface or mid-thickness locations.

3.02110 Room temperature tensile and compressive strengths and -80F and +32F impact energies for as-rolled plate of various sizes, Table 3.02110.

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb -1Ta-0.8Mo

TABLE 3.02110

Source	(1)							
Alloy	Ti-6Al-2Cb-1Ta-1Mo							
Form	Rolled Plate							
Condition	As-Rolled							
Size - Inches	Test Direction	Room Temperature Properties					Standard Charpy V Impact Energy ft-lbs	
		F_{cy} ksi	F_{tu} ksi	F_{ty} ksi	e(1 inch) percent	RA percent	+32F	-80F
1/2x24x60	L		135.5	124.2	10.0	34.0	28.0	26.0
	T		138.0	127.4	11.0	36.0	28.0	22.5
1x24x96	L	113.0	121.0	106.0	13.0	41.0	29.0	26.0
	T	126.0	126.0	114.0	12.0	28.0	30.0	22.5
1 3/4x65 diameter	L		120.0	104.0	11.0	35.0		27.0
	T		123.0	108.0	11.0	31.0		27.0
2x40x50	L	124.0	122.5	111.5	12.0	34.0	24.0	27.0
	T	114.0	122.0	110.0	14.0	39.0	27.0	25.0
2 3/8x36x48	L	114.0	122.0	107.0	14.0	25.0	45.5	26.5
	T	126.0	124.0	110.0	13.0	24.0	31.0	25.5
2 3/8x19 1/2x112	L	122.9	121.0	108.5	13.5	33.0	35.0	36.0
	T	116.6	121.0	107.0	15.0	33.5	41.0	34.0
2 3/8x 20x75	L	112.0	120.5	106.5	12.5	29.0	36.0	34.0
	T	119.5	121.5	107.0	13.5	25.0	37.0	34.0
3x46x46	L	111.3	117.4	100.3	13.5	29.5		28.0
	T	113.7	121.5	102.8	14.0	26.0		27.5
4x24x96	L		115.0	97.0	13.0	24.0		29.0
	T		117.7	95.0	14.0	25.0		28.0

Not all from same heat. Center properties. Single Tests.

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb
-1Ta-0.8Mo

3.02111 Room temperature tensile and compressive properties and -80F and +32 impact energies of as-forged pressure vessel cover, Table 3.02111.

TABLE 3.02111

Source	(1)						
Alloy	Ti-6Al-2Cb-1Ta-0.8Mo						
Form	Pressure Vessel Cover						
Condition	As-Forged						
	Room Temperature Properties					Standard Charpy V Impact Energy ft-lbs	
Specimen Location	F_{cy} ksi	F_{tu} ksi	F_{ty} ksi	e(1 in) %	RA %	+32F	-80F
TT-1		126.3	105.9	13	37.2		
TT-2		125.5	110.1	15	39.6		
TT-3		125.6	109.0	13	36.9		
TT-4		127.6	116.8	15	36.6		
TT-5		126.9	111.8	13	22.7		
TT-6		128.3	117.3	15	38.8		
AT-1		126.2	113.3	14	28.6		
AT-2		126.0	113.3	14	36.7		
AT-3		126.3	112.8	14	37.2		
AT-4		126.1	112.9	14	38.6		
RC-1	122.1						
RC-2	118.9						
AC-1	119.5						
AC-2	121.8						
AC-3	123.2						
AC-4	119.6						
TI-1						39.0	
TI-2						44.0	
TI-3						39.0	
TI-4							33.0
TI-5							28.0
TI-6							27.5
AI-1						38.0	
AI-2						43.0	
AI-3						41.0	
AI-4							29.0
AI-5							28.0
AI-6							29.0

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb
-1Ta-0.8Mo

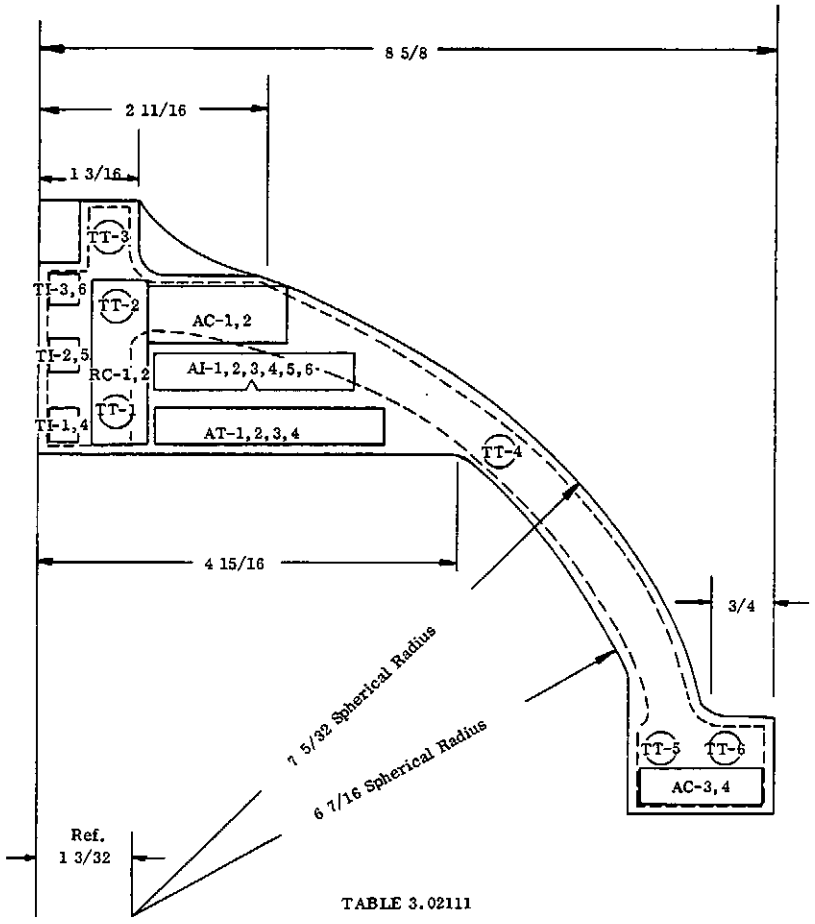


TABLE 3.02111
SPECIMEN LOCATION DIAGRAM

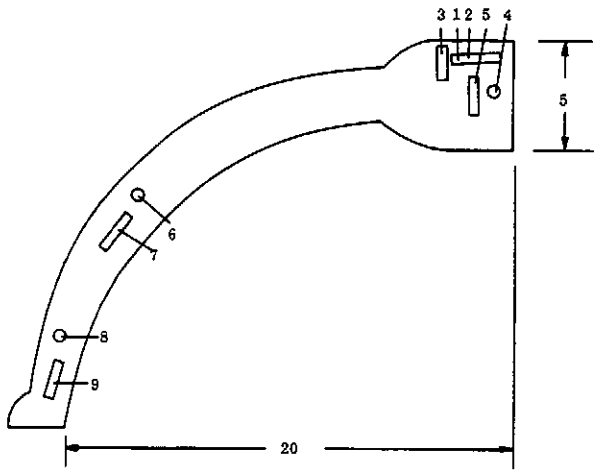
	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb-1Ta-0.8Mo

3.02112 Room temperature tensile properties and +32F impact energy of forged dome, Table 3.02112.

TABLE 3.02112

Source	(1)				
Alloy	Ti-6Al-2Cb-1Ta-0.8Mo				
Form	Forged Dome				
Condition	As-Forged				
Specimen Location	Room Temperature Properties				Standard Charpy V Impact Energy @32F ft-lbs
	F_{tu} ksi	F_{ty} ksi	e(1 in) %	RA %	
1	122.1	107.4	10.5	27.2	
2	122.6	108.2	12.5	29.9	21.0
3	122.6	108.4	12.0	30.5	
4	124.8	113.6	17.0	30.5	
5	130.0	114.0	9.5	22.3	22.0
6	129.4	118.0	17.5	38.8	23.5
7	130.2	118.6	17.5	37.2	23.5
8	135.6	123.8	15.0	37.5	27.0
9	133.4	122.2	15.0	37.2	22.0



3.02113 Effect of oxygen content on tensile properties of plate in various heat treated conditions, Table 3.02113.

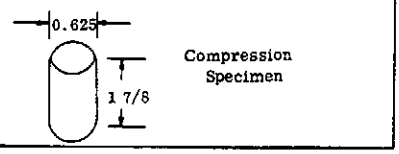
3.02114 True-stress/true-strain curves for 1 inch and 2.5 inch as-rolled plate, Figure 3.02114.

3.022 Compression (see also 3.032 and Tables 3.0217, 3.0218, 3.02110, and 3.02111).

3.0221 Effect of tensile prestrain on compressive yield strength of plate (Bauschinger Effect) with and without stress relief treatment, Table 3.0221.

TABLE 3.0221

Source	(3, p.13)			
Alloy	Ti-6Al-2Cb-1Ta-0.8Mo			
Form	1 Inch Plate			
Condition	As-Rolled			
Tensile Prestrain Percent	Stress Relief Treatment		F_{cy} ksi	
	Temp-F	Hours	(0.01% Offset)	(0.2% Offset)
0.0	RT	--	87	110
1.28	RT	--	45	89
1.28	600	1	63	96
1.28	600	3	65	99
1.28	900	1	75	104



3.023 Impact (see 3.033)

3.024 Bending.

3.025 Torsion and shear.

3.026 Bearing.

3.027 Stress concentration (see 2.03 for influence of seawater on cracked specimens).

3.0271 Notch properties.

TABLE 3.02113

Source	(4, p.10)					
Alloy	Ti-6Al-2Cb-1Ta-0.8Mo					
Form	1 inch Rolled Plate					
Condition	Test Direction	F_{tu} ksi	F_{ty} ksi	e(1 inch) percent	RA percent	
Weight Percent	Al 6.2	Cb 2.40	Ta 1.00	Mo 0.74	Fe 0.06	C 0.02	N 0.006	O 0.058
1900F, 1 Hour, AC	L	123.2	101.4	11.8	24.6			
	T	123.2	103.4	12.2	27.7			
1900F, 1 Hour, WQ	L	131.1	110.2	12.8	31.0			
	T	128.1	108.0	8.8	23.8			
1900F, 1 Hour, WQ + 1100F, 2 Hours, AC	L	135.3	117.1	9.5	24.8			
	T	135.4	116.2	9.5	21.2			
Weight Percent	Al 6.0	Cb 1.98	Ta 0.92	Mo 0.80	Fe 0.05	C 0.03	N 0.006	O 0.122
1950F, 1 Hour, AC	L	127.6	105.5	12.2	27.6			
	T	128.5	106.3	12.5	26.5			
1950F, 1 Hour, WQ	L	135.2	115.0	11.5	27.3			
	T	136.6	116.6	10.8	19.4			
1950F, 1 Hour, WQ + 1100F, 2 Hours, AC	L	137.1	119.8	12.5	25.4			
	T	139.0	121.1	9.2	16.0			

All values average of two tests.

3.0272 Fracture toughness. There exists no information on the plane strain fracture toughness of this alloy, even though the alloy is intended for structural applications in deep diving submersibles where heavy sections may operate under conditions of plane strain. In addition, temperature lower than ambient will be encountered in marine applications, increasing the possibility of plane strain failures.
Judging from the scatter in Charpy V energies (see Figure 3.0331) it might be expected that considerable scatter in fracture toughness values would be encountered.

3.028 Combined properties.

3.03 Mechanical Properties at Various Temperatures

3.031 Tension (see 3.021)

3.0311 Effect of test temperature on tensile properties of stress relieved pancake forging, Figure 3.0311.

3.0312 Effect of test temperature on tensile properties of full annealed pancake forging, Figure 3.0312.

3.0313 Effect of test temperature on tensile properties of solution treated and aged pancake forging, Figure 3.0313.

3.032 Compression.

3.033 Impact (see Tables 3.0219 through 3.02112)

3.0331 Effect of test temperature on standard Charpy V impact energy of 1 inch and 2.5 inch as-rolled plate from two heats, Figure 3.0331.

3.0332 Room temperature yield strength and -80F standard Charpy V impact energy of plate specimens air cooled or water quenched from various solution temperatures, Figure 3.0332.

3.0333 Effect of quench delay on room temperature yield strength and -80F impact energy of solution treated plate, Figure 3.0333.

3.0334 Effect of aging temperature on room temperature yield strength and -80F impact energy of plate, Figure 3.0334.

3.0335 Effect of aging time on room temperature yield strength and -80F impact energy of plate, Figure 3.0335.

3.0336 Room temperature yield strength and +32F standard Charpy V impact energy of plate air cooled from various solution temperatures, with and without subsequent aging, Figure 3.0336.

3.0337 Alpha-beta versus beta solution treatment regarding -80F standard Charpy V and +32F drop weight tear energies of as-quenched or quenched and aged plate, Table 3.0337.

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb -1Ta-0.8Mo

TABLE 3.0337

Source	(4, p.10)(5, p.26)			
Alloy	Ti-6Al-2Cb-1Ta-0.8Mo			
Form	1 Inch Rolled Plate			
Condition	Test Direction	F_{ty} @RT ksi	Standard Charpy V Impact Energy @ -80F ft-lbs	Drop Weight Tear Energy @ +32F ft-lbs
As-Rolled	L	101.8	23.5	2266*
	T	105.0	23.0	2146*
Alpha annealed (1600F, 1 Hour, AC)	L	99.2	29.2	2443
	T	107.4	32.2	2846
Alpha-beta annealed, air-cooled (1815F, 1 Hour, AC)	L	97.7	32.5	2560
	T	104.0	28.2	2266
Alpha-beta solution treated, quenched (1815F, 1 Hour, WQ)	L	101.2	27.8	2560
	T	108.4	32.2	2443
Alpha-beta solution treated, aged (1815F, 1 Hour, WQ + 1100F, 2 Hours, AC)	L	108.0	25.5	2086
	T	118.9	29.0	1905
Beta annealed, air-cooled (1900F, 1 Hour, AC)	L	101.4	33.0	2618
	T	103.4	28.2	1966
Beta solution treated, quenched (1900F, 1 Hour, WQ)	L	110.2	30.5	2266
	T	108.0	26.8	2266
Beta solution treated, aged (1900F, 1 Hour, WQ + 1100F, 2 Hours, AC)	L	117.1	24.0	1723
	T	116.2	23.2	2146

All values average of two tests except DWT values which are individual results.
Smooth tensile properties presented in Table 3.0216 correspond to these impact data.
Same DWT specimen as in Table 3.0338 except 18 inches long by 4.5 inches deep.
*In a separate study on this same heat, the following results were obtained:
2384 ft-lbs(L) and 1784 ft-lbs(T) (5, p.25)

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

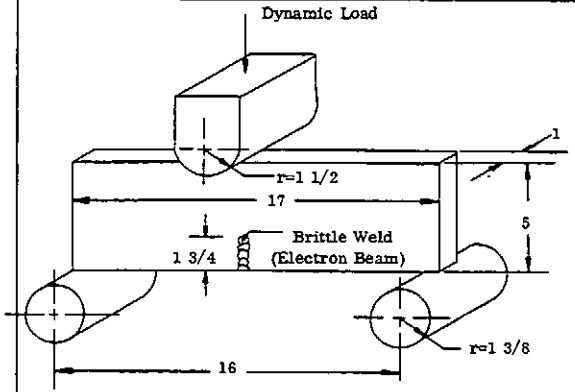
Ti-6Al-2Cb-1Ta-0.8Mo

3.0338 Room temperature yield strength, -80F standard Charpy V and +32F drop weight tear energies of 1 inch plate in several heat treated conditions, Table 3.0338.

TABLE 3.0338

Source		(2, p.23)	
Alloy		Ti-6Al-2Cb-1Ta-0.8Mo	
Form		1 Inch Rolled Plate	
Test Direction	F_{ty} @RT ksi	Standard Charpy V Impact Energy @ -80F ft-lbs	Drop Weight Tear Energy @ +32F ft-lbs
As-Rolled			
L	95.6	32.3	2325*
T	102.4	27.0	1662*
1650F, 1 Hour, AC			
L	94.7	30.5	1966
T	96.9	29.0	1966
			1966**
1875F, 1 Hour, WQ + 1100F, 2 Hours, AC			
L	111.5	25.0	1662
T	112.2	21.5	1630
1875F, 1 Hour, WQ + 1100F, 8 Hours, AC			
L	109.7	24.2	1784
T	114.6	22.8	1478
2000F, 1 Hour, 70 Seconds Delay (in air), WQ			
L	98.8	18.8	1228
T	102.1	19.5	1296
2000F, 1 Hour, 70 Seconds Delay (in air), WQ + 1000F, 4 Hours, AC			
L	105.4	18.5	1296
T	108.4	22.2	1478
			1113**
2000F, 1 Hour, 70 Seconds Delay(in air), WQ + 1100F, 8 Hours, AC			
L	109.1	18.0	1478
T	111.0	18.5	1418

Each value average of two tests.
Smooth tensile and compressive properties for heat B in Table 3.0217 correspond to these impact tests.
*In a preliminary study on this same heat, the following results were obtained: 2206 ft-lbs(L) and 1966 ft-lbs(T). (5, p.25)
**0.025 inch removed from each surface by machining prior to test.



Drop-Weight Tear Test Specimen
(brittle weld initiates crack)

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb-1Ta-0.8Mo

3.0339 Effect of oxygen content on room temperature yield strength and -80F standard Charpy V impact and +32F drop weight tear energies of plate in various heat treated conditions, Table 3.0339.

TABLE 3.0339

Source	(4, p. 10)									
Alloy	Ti-6Al-2Cb-1Ta-0.8Mo									
Form	1 Inch Rolled Plate									
Condition	Test Direction	F_{ty} @RT ksi	Standard Charpy V Impact Energy @ -80F ft-lbs						Drop Weight Tear Energy @ +32F ft-lbs	
		Al	Cb	Ta	Mo	Fe	C	N	O	
Weight Percent		6.2	2.40	1.00	0.74	0.06	0.02	0.006	0.058	
1900F, 1 Hour, AC	L	101.4				33.0				2618
	T	103.4				28.2				1966
1900F, 1 Hour, WQ	L	110.2				30.5				2266
	T	108.0				26.8				2266
1900F, 1 Hour, WQ + 1100F, 2 Hours, AC	L	117.1				24.0				1723
	T	116.2				23.2				2146
		Al	Cb	Ta	Mo	Fe	C	N	O	
Weight Percent		6.0	1.98	0.92	0.80	0.05	0.03	0.006	0.122	
1950F, 1 Hour, AC	L	105.5				24.8				1784
	T	106.3				25.5				----
1950F, 1 Hour, WQ	L	115.0				22.5				----
	T	116.6				24.0				----
1950F, 1 Hour, WQ + 1100F, 2 Hours, AC	L	119.8				22.0				1173
	T	121.1				23.2				----

All values average of two tests, except DWT values, which are individual results.
Smooth tensile properties presented in Table 3.02113 correspond to these impact data.
Same DWT specimen as in Table 3.0338 except 18 inches long by 4.5 inches deep.

3.034 Bending.
3.035 Torsion and shear.
3.036 Bearing.
3.037 Stress concentration.
3.038 Combined properties.

3.04 Creep and Creep Rupture Properties

3.05 Fatigue Properties (See also Figure 2.039)
3.051 Low cycle fatigue crack growth rate for mildly-notched plate specimens, Figure 3.051.
3.06 Elastic properties.
3.061 Poisson's ratio : elastic, 0.31; plastic, 0.42.
3.062 Modulus of elasticity: E_t=17.0 x 10^6 psi; E_c=18.3 x 10^6 psi.
3.063 Modulus of rigidity.
3.064 Tangent modulus: 3.10 x 10^6 psi (0.2 percent offset yield strength).
3.065 Secant modulus: 12.5 x 10^6 psi (0.2 percent offset yield strength).

4. FABRICATION

4.01 Formability
4.011 Recommended forging temperatures: blocking, 1850-1950F; finishing, 1800-1850F.

4.02 Machining
See other titanium alloy chapters and Air Force Machinability Data Center, Metcut Research Assoc., Cincinnati, Ohio 45209.

4.03 Welding
Alloy is weldable (see also Table 2.035 and Figure 2.058).

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

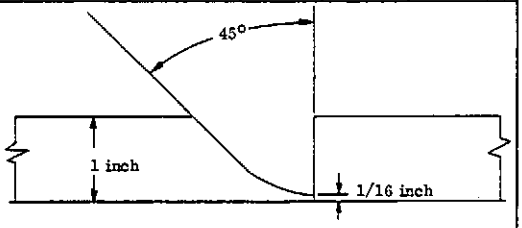
Ti-6Al-2Cb-1Ta-0.8Mo

4.031 Room temperature tensile properties of welded 1 inch plate in as-welded and in stress relieved conditions, Table 4.031.

Table 4.031

Source			(3, p.15)					
Alloy			Ti-6Al-2Cb-1Ta-0.8Mo					
Form			1 Inch Rolled Plate, Welded					
	Filler Metal			Room Temperature Tensile Properties				
Welding Process	Nominal Composition	Wire Diameter Inches	Condition of Weldment	F_{tu} ksi	F_{ty} (0.2% Offset) ksi	e(1 inch) percent	RA percent	Location of Fracture
GTA	Ti-621/0.8	1/8 Flat Strip	As-Welded	127	115	9	26	Base Metal
	Ti-621/0.8	1/8 Flat Strip	900F, 2 Hrs, AC	129	115	10	25	Base Metal
	Ti-621/0.5	0.062	As-Welded	123	105	11	33	Base Metal
	Ti-621/0.5	0.062	900F, 2 Hrs, AC	124	109	11	31	Base Metal
GMA	Ti-621/0.5	0.062	As-Welded	120	108(1)	10	31	Base Metal
	Ti-621/0.5	0.062	900F, 2 Hrs, AC	127	113(1)	9	26	Base Metal
	Ti-621/0.5	0.062	As-Welded	125	113(2)	12	23	Weld
	Ti-621/0.5	0.062	900F, 3 Hrs, AC	127	116(2)	11	25	Weld

(1) Determined using SR-4 strain gauges mounted on weld zone of specimen.
(2) Determined from "all weld" specimen.



"J Groove" Butt Weld

4.032 Stress-strain curve for weld zone of GMA welded plate, Figure 4.032.

4.033 Room temperature yield strength and +32F standard Charpy V impact energy of welded 1 inch plate, Table 4.033.

TABLE 4.033

Source			(3, p.15)			
Alloy			Ti-6Al-2Cb-1Ta-0.8Mo			
Form			1 Inch Rolled Plate, Welded(6)			
	Filler Metal			F_{ty}(5) (0.2 percent Offset)	Standard Charpy V Impact Energy(1) @+32F - ft-lbs	
Welding Process	Nominal Composition	Wire Diameter Inches	Condition of Weldment	ksi	Weld Zone	HAZ
GTA	Ti-621/0.8	1/8 Flat Strip	As-Welded	115	--	49
	Ti-621/0.8	1/8 Flat Strip	900F, 2 Hrs, AC	115	32	41
	Ti-621/0.5	0.062	As-Welded	105	--	43
	Ti-621/0.5	0.062	900F, 2 Hrs, AC	109	--	40
GMA	Ti-621/0.5	0.062	As-Welded	108(2)	39	41
	Ti-621/0.5	0.062	900F, 2 Hrs, AC	113(2)	35	39
	Ti-621/0.5	0.062	As-Welded	113(3)	40(4)	--
	Ti-621/0.5	0.062	900F, 3 Hrs, AC	116(3)	38(4)	--

(1) Drop-weight tear energy for GMA weld using Ti-621/0.8 filler is (5, p.25):
As-welded, 2026 ft-lbs
As-welded + 1900F, 1 Hr, Helium Cool, 2560 ft-lbs
(Same DWT specimen as in Table 3.0338 except 18 inches long x 4.5 inches deep)
(2) Determined using SR-4 strain gauges mounted on weld metal.
(3) Determined from "all weld" specimen.
(4) At -80F, 35 ft-lbs for as-welded and for 900F, 3 hrs, AC conditions.
(5) Remainder of smooth tensile properties corresponding to these impact data appear in Table 4.031.
(6) Weld joint configuration is shown in Table 4.031.

4.04 Heat Treatment

4.05 Surface Treatment

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb-1Ta-0.8Mo

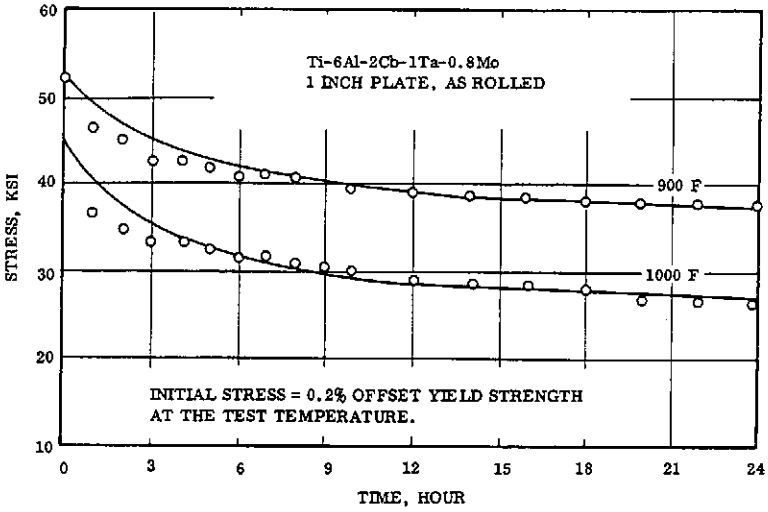


FIG. 1.0511 STRESS RELAXATION OF PLATE AT 900 AND 1000 F

(3, FIG. 8)

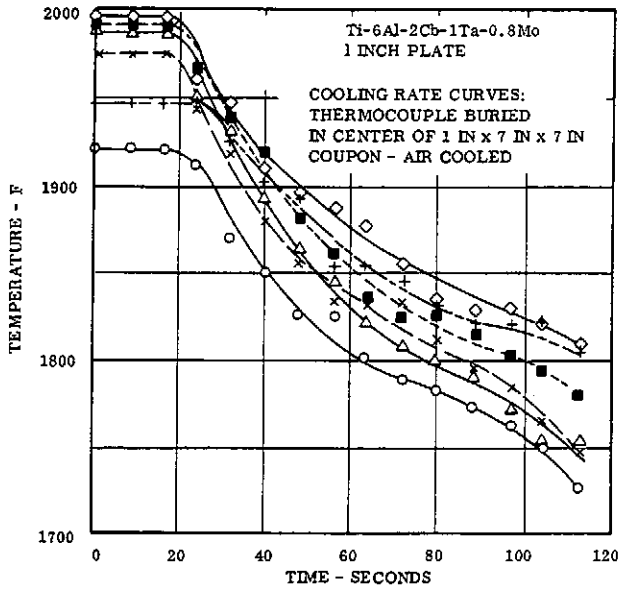
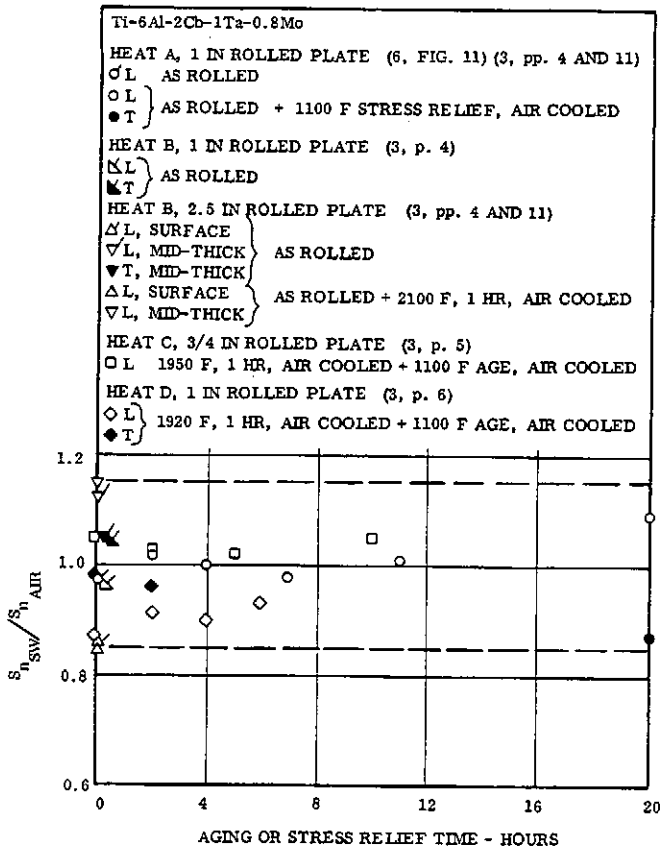


FIG. 1.0551 COOLING RATE CURVES FOR 1 INCH PLATE COOLED IN AIR.

(2, p. 20)

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb
-1Ta-0.8Mo



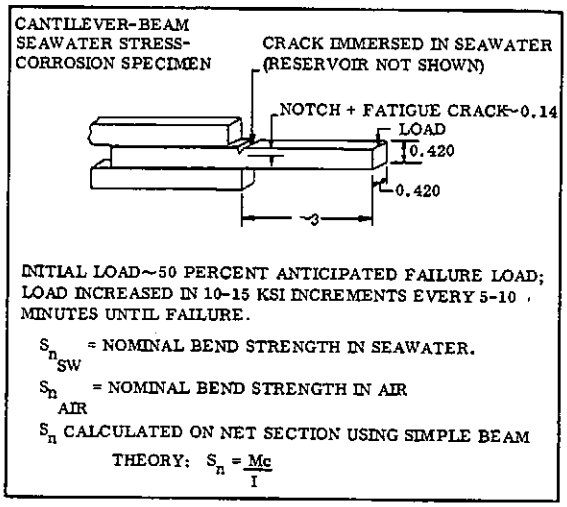
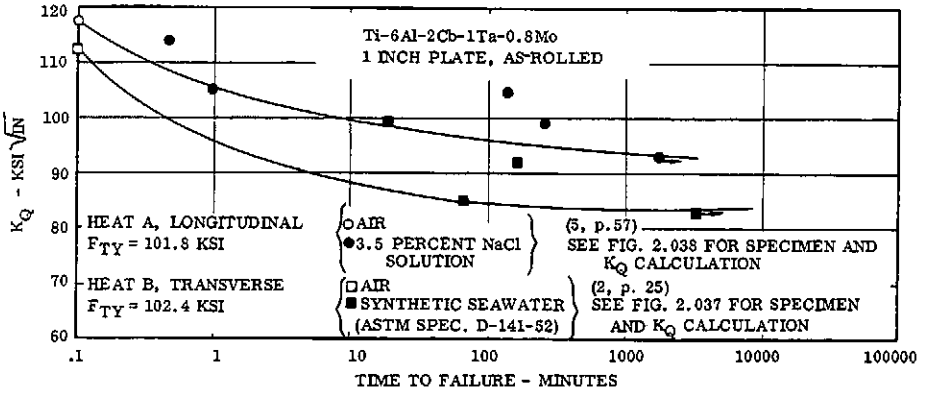


FIG. 2.034 SEAWATER STRESS CORROSION BEHAVIOR OF PLATE.



	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb -1Ta-0.8Mo

FIG. 2.036 SUSTAINED LOAD SALT WATER STRESS-CORROSION BEHAVIOR OF AS ROLLED PLATE.

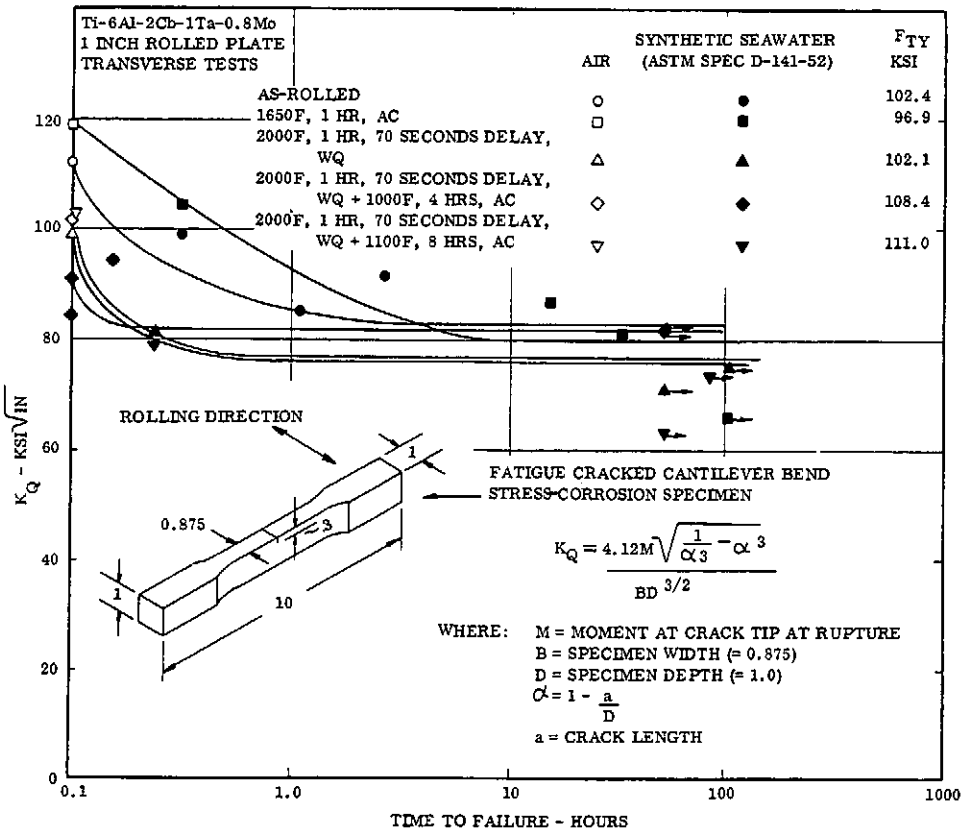


FIG. 2.037 SUSTAINED LOAD SEA WATER STRESS-CORROSION BEHAVIOR OF PLATE IN SEVERAL HEAT TREATED CONDITIONS.

(2, pp. 23 and 25)

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb
-1Ta-0.8Mo

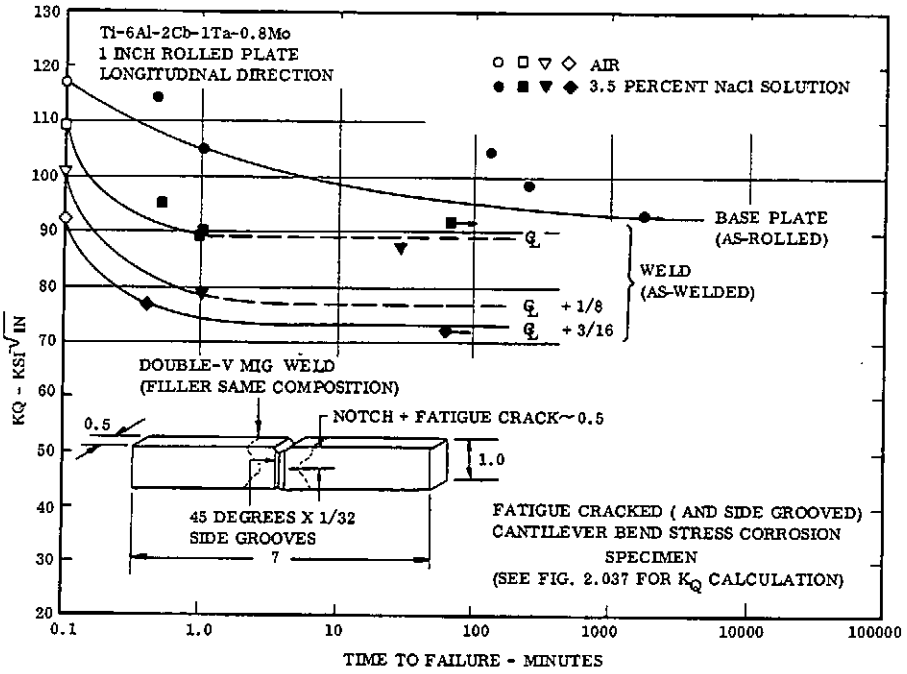


FIG. 2.038 SUSTAINED LOAD SALT WATER STRESS-CORROSION BEHAVIOR OF WELDED PLATE.
(5, pp. 57 AND 59)

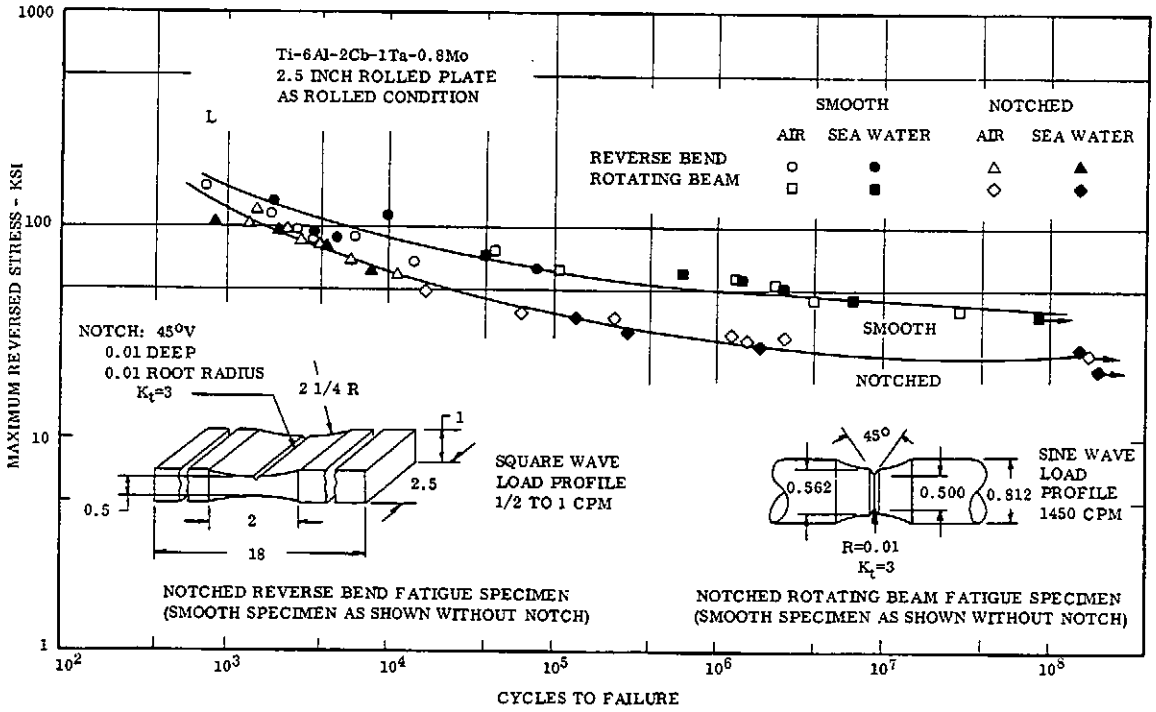


FIG. 2.039 EFFECT OF SEA WATER ENVIRONMENT ON LOW AND HIGH CYCLE FATIGUE STRENGTH OF SMOOTH AND MILD NOTCH SPECIMENS.
(3, Fig. 6 and Appendix B)

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb-1Ta-0.8Mo

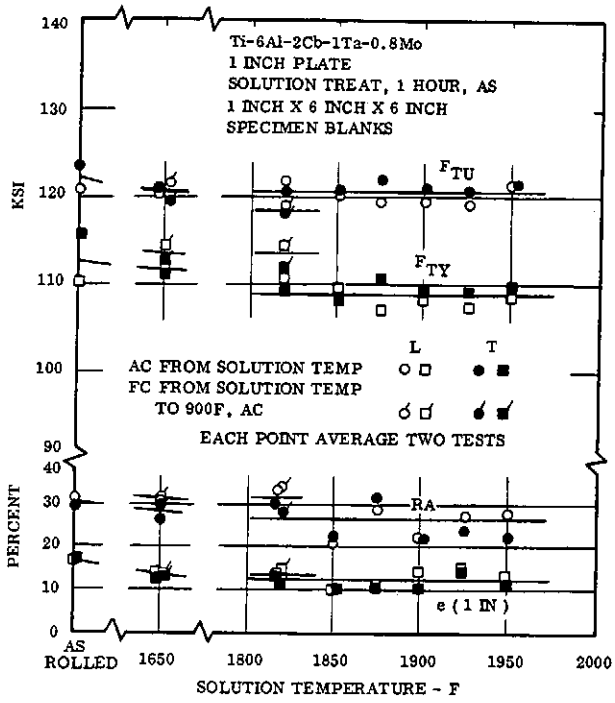


FIG. 3.0211 SOLUTION TREATED TENSILE PROPERTIES OF PLATE SPECIMENS AIR COOLED OR FURNACE COOLED FROM VARIOUS SOLUTION TEMPERATURES. (2, pp 21-22)

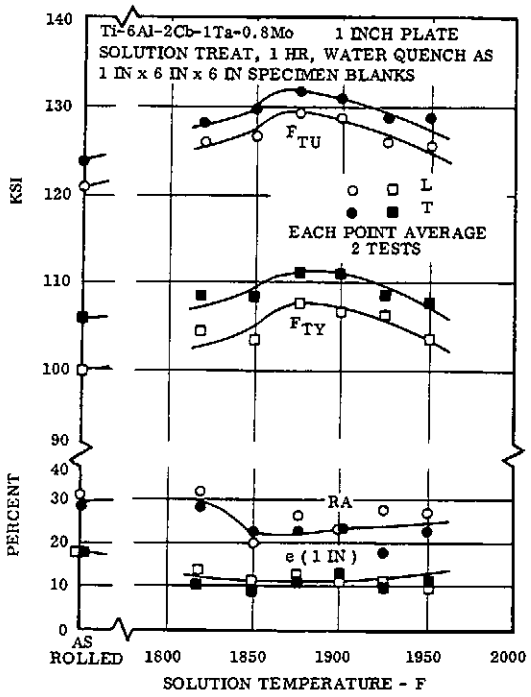


FIG. 3.0212 SOLUTION TREATED TENSILE PROPERTIES OF PLATE SPECIMENS WATER QUENCHED FROM VARIOUS SOLUTION TEMPERATURES. (2, p. 21)

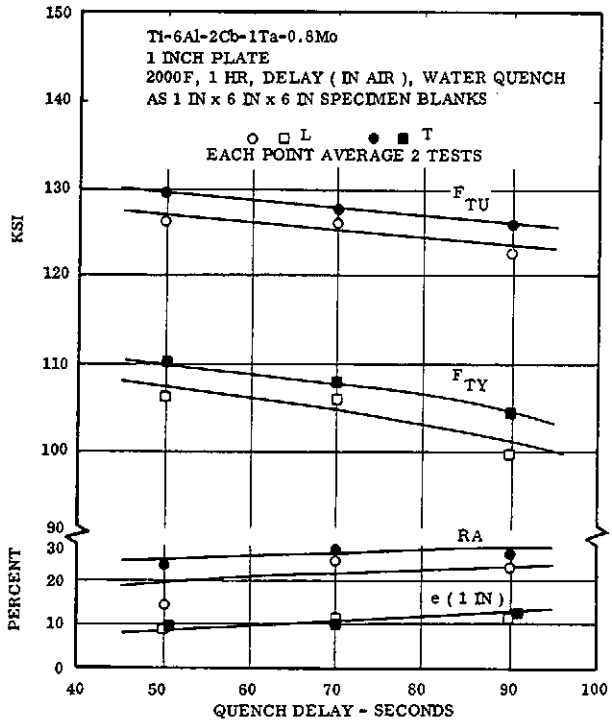


FIG. 3.0213 EFFECT OF QUENCH DELAY ON SOLUTION TREATED TENSILE PROPERTIES OF PLATE. (2, p. 22)

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb -1Ta-0.8Mo

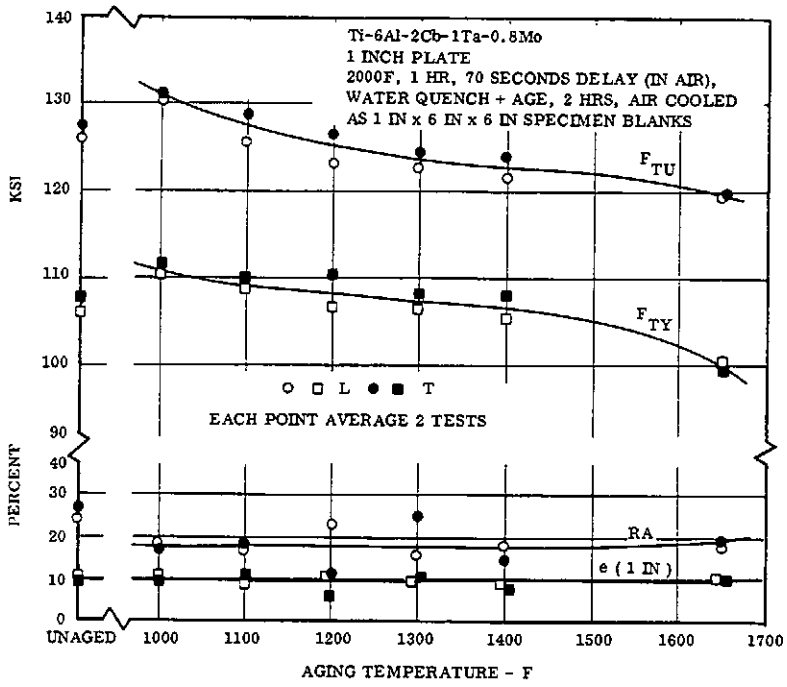


FIG. 3.0214 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF PLATE.
(2, p. 22)

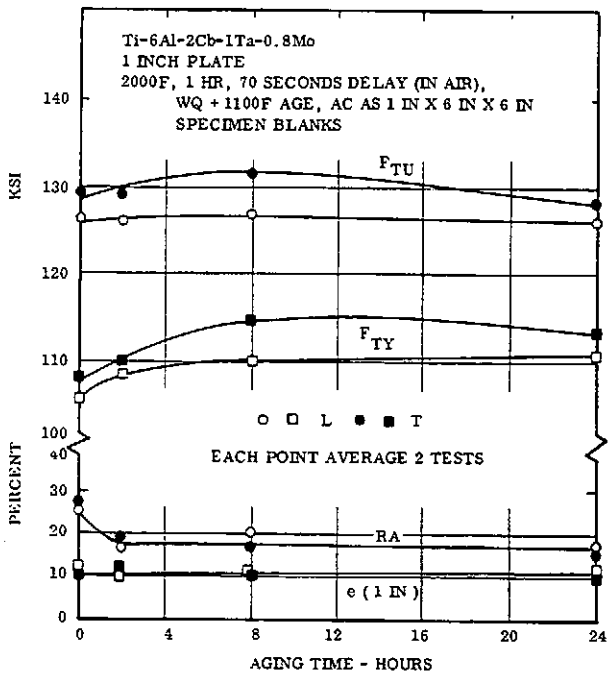


FIG. 3.0215 EFFECT OF AGING TIME ON TENSILE PROPERTIES OF PLATE.
(2, p. 22)

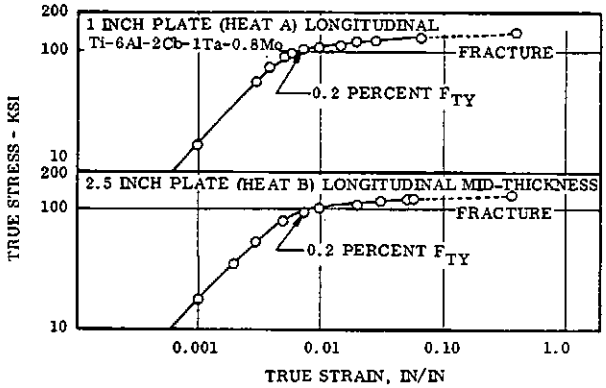


FIG. 3.02114 TRUE STRESS/TRUE STRAIN CURVES FOR 1 INCH AND 2.5 INCH AS-ROLLED PLATE.
(3, FIG. 3)

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb -1Ta-0.8Mo

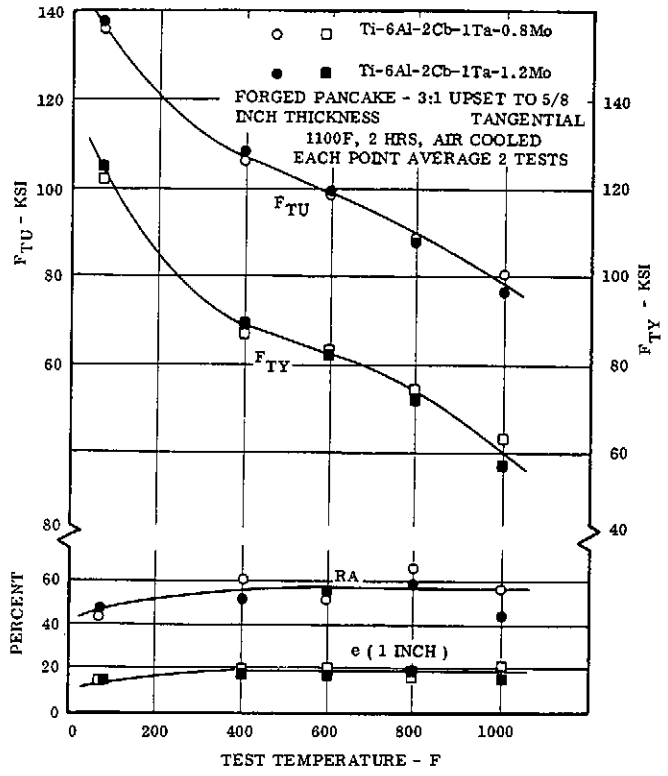


FIG. 3.0311 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF STRESS RELIEVED PANCAKE FORGING (1)

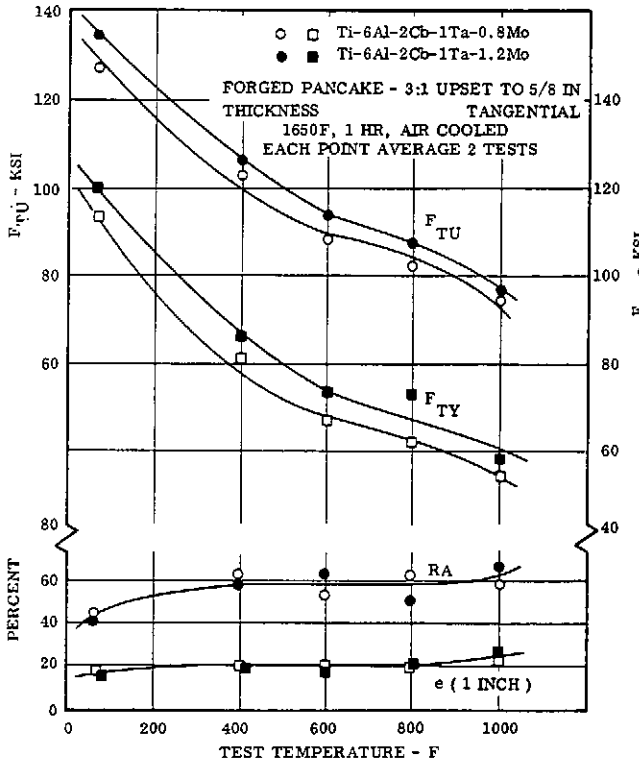


FIG. 3.0312 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF FULL ANNEALED PANCAKE FORGING (1)

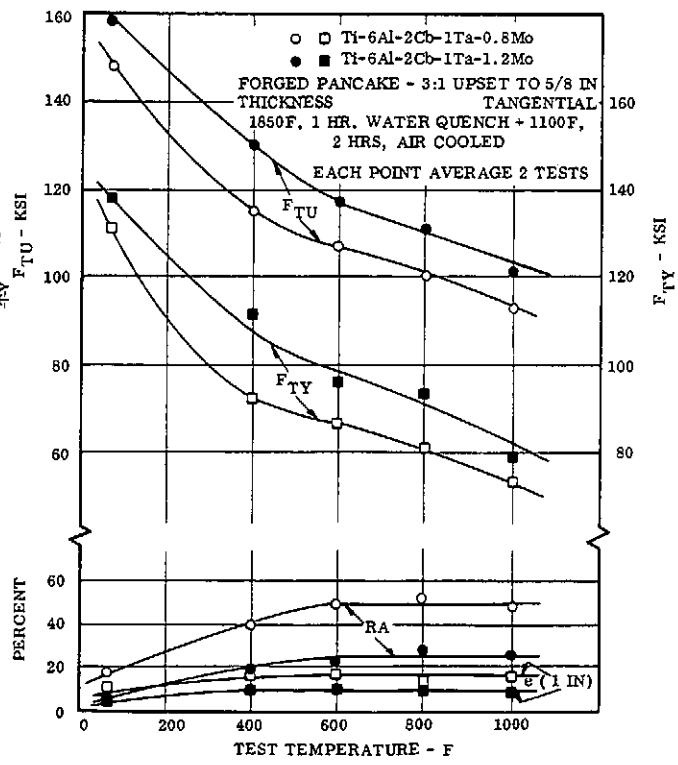


FIG. 3.0313 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION TREATED AND AGED PANCAKE FORGING (1)

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb-1Ta-0.8Mo

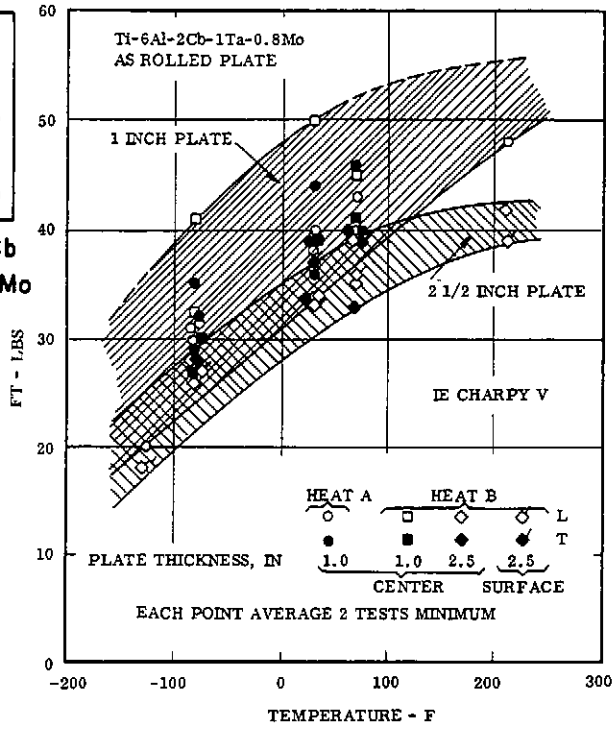


FIG. 3.0331 EFFECT OF TEST TEMPERATURE ON STANDARD CHARPY V IMPACT ENERGY OF 1 AND 2.5 INCH AS-ROLLED PLATE FROM TWO HEATS.
(2, pp. 21, 23 and 26)(3, pp. 4, 7 and 11)

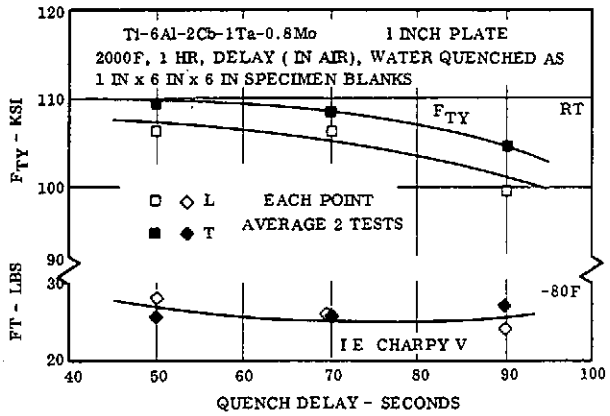


FIG. 3.0333 EFFECT OF QUENCH DELAY ON ROOM TEMPERATURE YIELD STRENGTH AND -80F IMPACT ENERGY OF SOLUTION TREATED PLATE.
(2, p. 22)

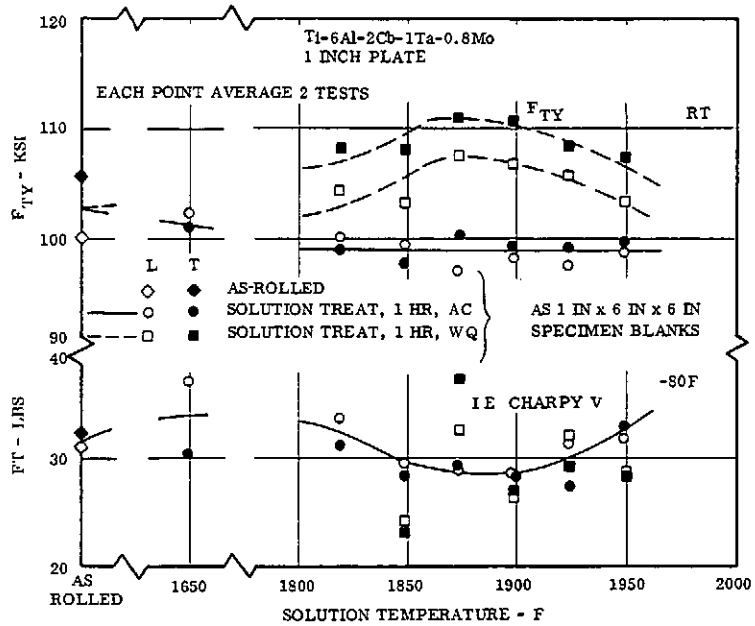


FIG. 3.0332 ROOM TEMPERATURE YIELD STRENGTH AND -80F STANDARD CHARPY V IMPACT ENERGY OF PLATE SPECIMENS AIR COOLED OR WATER QUENCHED FROM VARIOUS SOLUTION TEMPERATURES.
(2, pp. 21 - 22)

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb -1Ta-0.8Mo

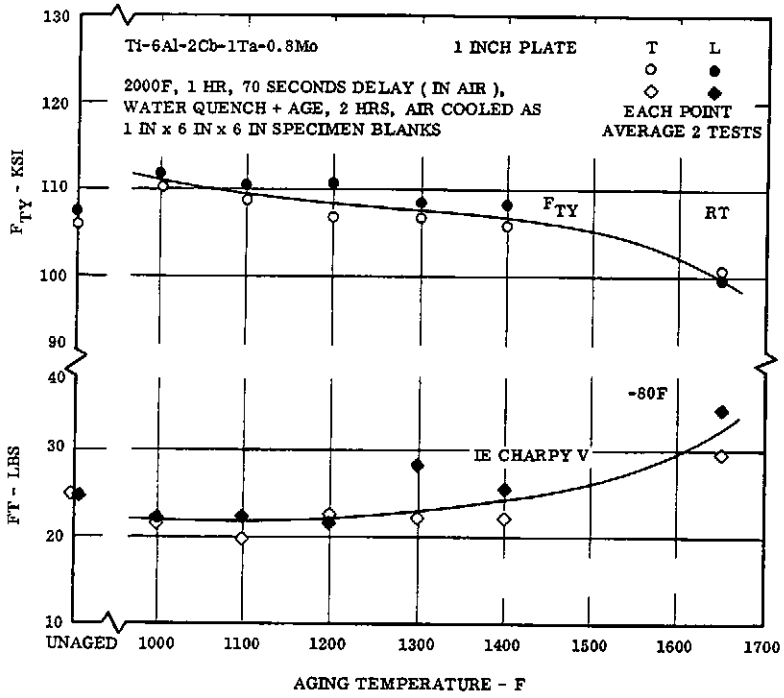


FIG. 3.0334 EFFECT OF AGING TEMPERATURE ON ROOM TEMPERATURE YIELD STRENGTH AND -80F IMPACT ENERGY OF PLATE.

(2, p. 22)

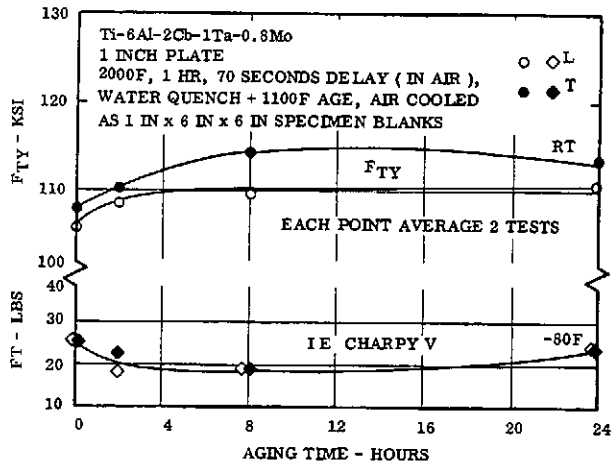


FIG. 3.0335 EFFECT OF AGING TIME ON ROOM TEMPERATURE YIELD STRENGTH AND -80F IMPACT ENERGY OF PLATE.

(2, p. 22)

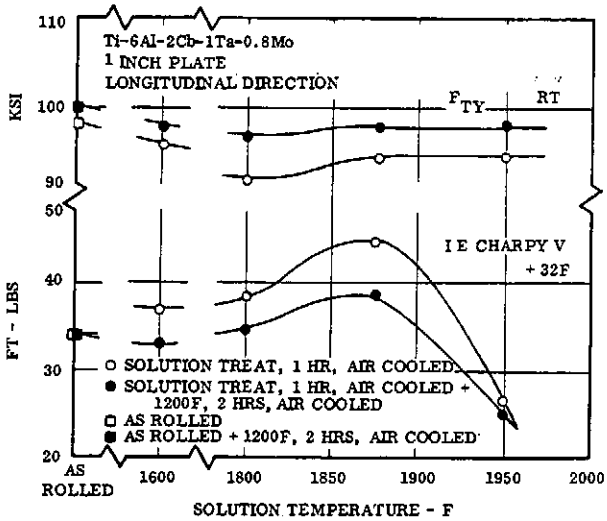


FIG. 3.0336 ROOM TEMPERATURE YIELD STRENGTH AND +32F STANDARD CHARPY V IMPACT ENERGY OF PLATE AIR COOLED FROM VARIOUS SOLUTION TEMPERATURES, WITH AND WITHOUT SUBSEQUENT AGING.

(3, p. 7)

	Ti
6	Al
2	Cb
1	Ta
0.8	Mo

Ti-6Al-2Cb-1Ta-0.8Mo

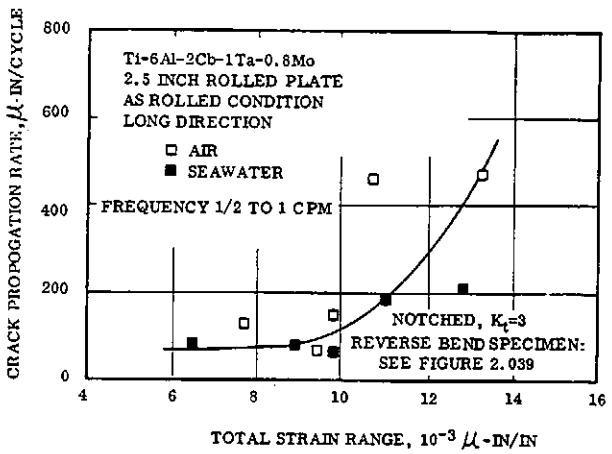


FIG. 3.051 LOW-CYCLE FATIGUE CRACK-GROWTH RATE FOR MILDLY-NOTCHED PLATE SPECIMENS (3, Fig. 7)

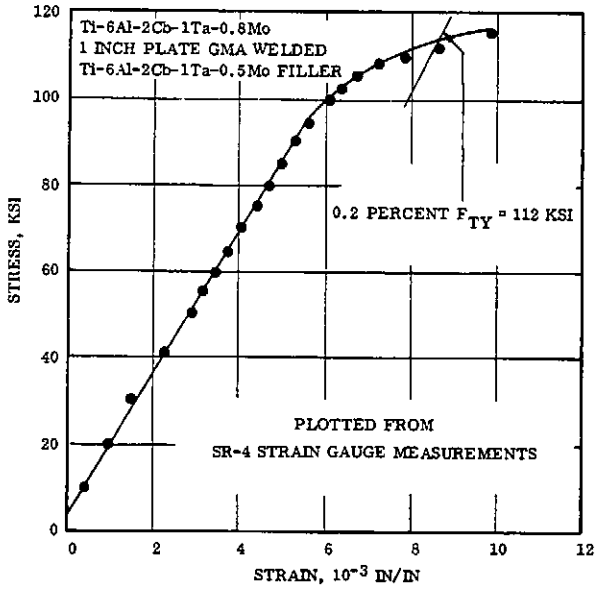


FIG. 4.032 STRESS-STRAIN CURVE FOR WELD ZONE OF GMA WELDED PLATE.

(3, FIG. 9)

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2. R.R. Seeley and S.R. Seagle, "A Heat Treatment Study of Ti-6Al-2Cb-1Ta-0.8Mo Alloy Plate," Reactive Metals Inc., Research and Development Report No. 499 (September 15, 1967)
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10. "Basic Design Facts About Titanium," Reactive Metals Inc., Niles, Ohio
11. I.R. Lane, "Status of Titanium as a Marine Structural Material," Marine Engineering Laboratory, Naval Ship Research and Development Center (December, 1967)
12. "Proposed Recommended Practice for Plane Strain Fracture Toughness Testing of High-Strength Metallic Materials using a Fatigue-Cracked Bend Specimen" American Society for Testing and Materials, 1968 Book of ASTM Standard, Part 31, pp. 1018-1030
13. Private communication with J.L. Cavallaro, U.S. Navy Marine Engineering Laboratory, Annapolis, Maryland (January 13, 1969)
14. Private communication with R.J. Goode, Naval Research Laboratory, Washington, D.C. (January 13, 1969)

1. General

Titanium castings have been produced commercially since the early 1960's. Design shapes that have been produced for aerospace applications for many years include impellers, brackets, window frames, hubs and bearing housings (10). Recent advances in foundry technology have resulted in use of larger complex structural aerospace castings (11). Numerous Ti-6Al-4V cast parts are in use on the airframes of many commercial aircraft as well as military systems (12, 13). The most ambitious structural application is the side of body joint on the F-22 (14).

For comparable heat treat conditions, Ti-6Al-4V castings exhibit the same or nearly the same strength, ductility, creep rupture and fatigue strengths, and elevated temperature stability as their wrought counterparts. The structural advantage of cast structure over built up structure is the elimination of mechanically fastened joints, which may result in a lighter weight structure.

The feeding of this alloy is less than that of steel casting alloys and repair welding is frequently required. Most of the data presented here were obtained from castings which contained sound repair welds. The data indicate that repair welding, if properly done, has no perceptible influence on mechanical properties. Results from castings with obviously defective weld repairs have not been included since such castings would normally be withheld from service.

1.1 Commercial Designations

Ti-6Al-4V

1.2 Alternate Designations

Ti-6-4

1.3 Specifications

AMS 4985
AMS 4991
AMS 4962
ASTM B367 Grade C-5
MIL-T-81915 Type III

Note: Government specifications are being discontinued, and will be reissued as industry specifications, such as AMS specifications.

1.4 Composition

1.4.1 *[Table]* Chemical Composition.

Ti	
Al	6.0
V	4.0

1.5 Thermal/Mechanical Processing

Most Ti-6Al-4V castings produced commercially are supplied in the mill annealed (MA) condition per MIL-H-81200.

Annealing is usually accomplished at 1300-1550F 2-4 hours in vacuum or inert atmosphere.

Beta annealing is accomplished by heating in vacuum to a temperature above the beta transus, 1870-1910F.

Solution treating at a temperature below the beta transus, about 1800F followed by a 1000F age may result in higher tensile properties, but lower ductility.

The hot isostatic pressing process is used to ensure elimination of internal gas shrinkage cavities. This procedure is carried out in an inert atmosphere autoclave at 1650-1750F 2-4 hours at 15ksi pressure.

Some applications have used a beta solution treatment at 1900F followed by a 1000 - 1500F age. This technique is expected to normalize the effects of various casting methods and weld repairs to produce consistent material properties (14, 19). Additional fixturing may be required to maintain dimensional control during the beta heat treating process. Mechanical properties have not been shown to be significantly different from those obtained from standard mill annealed castings of the same configuration from the same producer (29).

A stress relief, consisting of heating to 1350-1550F in a vacuum or inert atmosphere is usually applied after weld repair.

1.6 Hardness

Annealed condition, 311 BHN (3000 kg load) (3).

1.7 Forms and Conditions Available

Castings are available in as-cast and heat treated conditions. Consult casting producer.

1.8 Melting and Casting Practice

1.8.1 General

The usual method of melting titanium for the casting process is to use a consumable electrode vacuum arc system. Other melting methods include resistance heating, induction heating, tungsten arc melting, electron beam melting and plasma arc melting. (20)

Castings are poured either from remelted master heat base metal or directly from the master heat (1, 2). A master heat is metal of a single furnace charge. Gates, sprues, risers and rejected castings may be used in the preparation of a master heat,

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but may not be added directly without first melting and adjusting chemistry, for the pouring of castings (1, 2).

In common with unalloyed titanium and other titanium alloys, Ti-6Al-4V may react with the mold materials producing a contaminated surface layer which is dependent on time, temperature, and the presence of the contaminating interstitial elements carbon, oxygen, hydrogen, and nitrogen. The layer is commonly called "alpha case" and is extremely brittle.

1.8.2 Molding methods

Titanium castings are produced as sand castings from rammed graphite molds or as investment castings from ceramic shells made by the lost wax process. The choice depends on complexity of the part, required dimensional tolerances, surface finish and economic considerations.

The rammed graphite method is the traditional production practice. Tooling is relatively inexpensive. The mold material is pneumatically rammed around a wood pattern and cured at a high temperature. The molding process and tooling are essentially the same as those used in ferrous and nonferrous sand foundries. (19)

The investment casting technique is used to make complex shapes with better surface finish than obtained from rammed graphite molds. However tooling costs are higher. Investment castings rely on the lost wax technique. A ceramic shell is formed around a wax pattern. Several foundries have developed proprietary lost-wax ceramic shell systems.

Foundry practices focus on methods to control the extent of the reaction between the molten metal and the mold material. (19)

Surface contamination of the casting surface, alpha case, is picked up from the mold during pouring. This layer is removed by chemical milling. (16)

Permanent mold casting shows potential to provide lower costs and improved quality, including no alpha case for relatively small parts. The process involves casting into reusable metal molds that are resistant to erosion and reaction with the molten metal. (17, 18)

The tendency for gas formation from an incompletely fired expendable mold or decomposition of absorbed water on the mold and poor feeding characteristics require much heavier gating and risering for Ti-6Al-4V than for a comparable steel casting alloy (7, 8).

1.9 Special Considerations (see also 1.8)

1.9.1 Weld Repair

Weld repair of surface defects is an integral part of the manufacturing process. Tungsten inert gas welding in argon is commonly used. Generally all weld-repaired castings are stress relieved. Weld repair is not detrimental to the mechanical properties of cast Ti-6Al-4V. The HIP treatment can be made either before or after weld repair without any adverse effects (19, 28, 29).

2. Physical Properties and Environmental Effects

2.1 Thermal Properties

2.1.1 Melting Range.
2800-3000F

2.1.2 Phase Changes.
Alloy transforms on cooling from beta to alpha + beta at approximately 1825F. This is referred to as the beta transus temperature.

2.1.2.1 Time-temperature-transformation diagrams

2.1.3 Thermal Conductivity
At 400F, 5.1 Btu ft per (hr sq ft F). See also Ti-6Al-4V, Alloy Code 3707

2.1.4 Thermal Expansion
5.2 x 10-6 in/in/F. See also Ti-6Al-4V, Alloy Code 3707

2.1.5 Specific Heat
0.137 Btu per (lb F) at 400F. See also Ti-6Al-4V, Alloy Code 3707

2.1.6 Thermal Diffusivity

2.2 Other Physical Properties

2.2.1 Density 0.161 lb/cu. in

2.2.2 Electrical Properties
See Ti-6Al-4V, Alloy Code 3707

2.2.3 Magnetic Properties
See Ti-6Al-4V, Alloy Code 3707

2.2.4 Emittance
See Ti-6Al-4V, Alloy Code 3707

2.2.5 Damping Capacity

2.3 Chemical Environments

2.3.1 General Corrosion
See Ti-6Al-4V, Alloy Code 3707

2.3.2 Stress Corrosion
K_{iscc} = 58.3 ksi in $^{1/2}$
Single edge notch cantilever specimen fatigue precracked per ASTM E399 and exposed to seawater under load. (20)

2.4 **Nuclear Environments**

3. Mechanical Properties

3.1 Specified Mechanical Properties

3.1.1 [Table] AMS Specified mechanical properties

3.2 Mechanical Properties at Room Temperature

3.2.1 Tensile Stress-strain Diagrams and Tensile Properties

3.2.1.1 *[Figure]* Typical stress-strain curves for annealed cast ring segments from two heats.

3.2.1.2 *[Table]* Tensile properties including modulus of elasticity of annealed cast ring segments from two heats.

3.2.1.3 *[Table]* Mechanical property comparison for excised vs integrally cast specimens.

3.2.1.4 *[Table]* Comparison of room temperature properties from three sources of cast Ti-6Al-4V test material.

3.2.1.5 *[Table]* Tensile test results for Ti-6Al-4V alloy castings at room temperature.

3.2.1.6 *[Figure]* Frequency distribution of tensile properties of hot isostatically pressed and annealed Ti-6Al-4V casting test bars from 500 heats.

3.2.1.7 *[Figure]* Variation in tensile properties of five master heats for the as-cast and annealed conditions.

3.2.1.8 *[Table]* Comparison of room temperature tensile properties for two heat treatments of cast Ti-6Al-4V alloy.

3.2.1.9 *[Figure]* Effect of solution treat temperature on tensile properties of solution treated and aged cast-to-size specimens.

3.2.1.10 *[Figure]* Effect of solution treat and aging temperatures on tensile properties of cast compressor casing.

3.2.1.11 *[Figure]* Effect of aging temperature on tensile properties of three compressor casings cast from one heat.

3.2.1.12 *[Figure]* Effect of oxygen content on tensile properties of annealed cast-to-size specimens.

3.2.1.13 *[Table]* tensile properties of as-cast, annealed, and solution treated and aged castings from three casting manufacturers.

3.2.1.14 *[Table]* Tensile properties for a solution treated and annealed condition and two solution treated and aged conditions.

3.2.1.15 *[Table]* Effect of aging temperature on tensile properties of cast-to-size specimens.

3.2.1.16 *[Table]* Effect of salvage heat treatment on tensile properties of annealed, low oxygen cast-to-size specimens.

3.2.1.17 *[Table]* Effect of exposure to elevated temperature with load on tensile properties of annealed cast compressor casing.

3.2.1.18 *[Table]* Tensile test results for several solution treat and aging conditions.

3.2.1.19 *[Figure]* Effect of thermal treatment on the 70F tensile properties of cast and HIPied Ti-6Al-4V and the wrought alloy.

3.2.1.20 *[Table]* Tensile test results for two heat treat conditions.

3.2.1.21 *[Table]* Effect of 1000 hours exposure at 550F without load on tensile properties including elastic modulus of annealed cast ring segment from two heats.

3.2.1.22 *[Table]* Effect of beta annealed vs. standard mill anneal on room temperature tensile properties of complex castings.

3.2.2 Compression Stress-strain Diagrams and Compression Properties.

3.2.2.1 *[Table]* Compressive yield strength and modulus of elasticity of cast ring segments from two heats.

3.2.2.2 *[Table]* Compressive yield strength and modulus of elasticity of as-cast, annealed and solution treated and aged castings from two separate casting manufacturers.

3.2.3 Impact

3.2.3.1 *[Table]* Standard Charpy-V impact energy of annealed cast-to-size specimens from two heats.

3.2.3.2 *[Table]* Standard Charpy-V impact energy of annealed cast ring segments from tow heats.

3.2.3.3 *[Table]* Standard Charpy-V impact energy of solution treated and aged casting.

3.2.3.4 *[Table]* Charpy V-notch results for Ti-6Al-4V alloy castings at room temperature.

3.2.3.5 *[Table]* Charpy V-notch and fracture toughness test results for several heat treatments.

3.2.4 Bending

3.2.5 Torsion and Shear

3.2.5.1 *[Table]* Shear strength of annealed cast ring segments from two heats.

3.2.5.2 *[Table]* Double shear strength of solution treated and aged casting.

3.2.6 Bearing

3.2.6.1 *[Table]* Bearing strength of annealed cast ring segments from two heats.

3.2.6.2 *[Table]* Bearing strength of solution treated and aged casting.

3.2.7 Stress Concentration

3.2.7.1 Notch Properties

3.2.7.1.1 *[Table]* Mild-notch strength of annealed cast ring segments from two heats.

3.2.7.2 Fracture Toughness

3.2.7.2.1 *[Table]* Fracture toughness results.

3.2.8 Combined Loading

3.3 Mechanical Properties at Various Temperatures

3.3.1 Tension Stress-strain Diagrams and Tensile Properties

3.3.1.1 *[Figure]* Effect of test temperature on tensile properties of five annealed cast compressor casing from three heats.

3.3.1.2 *[Figure]* Effect of test temperatures on tensile properties of specimens machined from annealed cast compressor casings and annealed cast-to-size specimens each from two heats.

3.3.1.3 *[Figure]* Effect of test temperature on tensile properties of annealed cast ring segments from two heats.

3.3.1.4 *[Table]* Summary of tensile test results at room and low temperatures from Ti-6Al-4V investment castings of standard composition and extra low interstitials from two foundries.

3.3.1.5 *[Figure]* Effect of test temperature on ultimate tensile strength of standard composition and extra low interstitials castings.

3.3.1.6 *[Figure]* Effect of test temperature on percent elongation of standard composition and extra low interstitials castings.

3.3.2 Compression Stress-strain Diagrams and Compression Properties.

3.3.3 Impact

3.3.4 Bending

3.3.5 Torsion and Shear

3.3.6 Bearing

3.3.7 Stress Concentration

3.3.7.1 Notch Properties

3.3.7.1 Fracture Toughness

3.3.7.1.1 *[Table]* Fracture toughness results summary (average KQ) of Ti-6Al-4V investment castings.

3.3.7.1.2 *[Figure]* Effect of test temperature on the fracture toughness of standard composition and extra low interstitials castings.

3.3.8 Combined Loading

3.4 Creep and Creep Rupture Properties

3.4.1 *[Table]* Effect of solution and aging temperatures on 800F, 80 ksi stress rupture life of cast compressor casing.

3.4.2 *[Table]* Room temperature stress rupture results for mild-notch specimens machined from annealed cast compressor casing and annealed cast-to-size specimens.

3.4.3 *[Table]* 500F stress rupture properties of cast-to-size smooth and mild-notch specimens from two heats.

3.4.4 *[Figure]* Stress rupture curves at 700, 800, and 900 F for specimens machined from five annealed cast compressor casings from three heats.

3.4.5 *[Figure]* Creep rupture curves at 700, 800, 900, and 1000 F for specimens machined from annealed cast compressor casing and annealed cast-to-size specimens from one heat.

3.4.6 *[Figure]* Stress rupture curves at 700, 800, and 900 F for specimens machined from cast compressor casing aged at 1000 F.

3.5 Fatigue

3.5.1 Conventional High Cycle Fatigue

3.5.1.1 *[Figure]* High-cycle axial fatigue results at 500 F for annealed smooth and mild-notch cast-to-size specimens from two heats.

3.5.1.2 *[Figure]* 150 hours, 500 F stress range diagram for smooth and mild-notch cast-to-size specimens from two heats.

3.5.1.3 *[Figure]* Room temperature axial load fatigue properties of smooth specimens from five annealed cast ring segments from two heats.

3.5.1.4 *[Figure]* Room temperature axial load fatigue properties of mild-notch specimens from five annealed cast ring segments from two heats.

3.5.1.5 *[Figure]* Room temperature smooth fatigue properties of annealed and solution treated and aged castings.

3.5.1.6 *[Figure]* Room temperature mild-notch fatigue properties of annealed and solution treated and aged castings from two casting manufacturers.

3.5.1.7 *[Table]* Room temperature HCF test results for Ti-6Al-4V cast test bars in various heat treat conditions (10 Hz, R= 0.1, Triangular Wave Form, $K_T = 1.0$).

3.5.1.8 *[Figure]* HCF data for annealed investment cast Ti-6Al-4V test bars.

3.5.1.9 *[Figure]* HCF data for investment cast Ti-6Al-4V test bars in the beta solution treated and aged condition.

3.5.1.10 *[Figure]* Comparison of average fatigue life curves for eight heat treat conditions.

3.5.1.11 *[Figure]* Effect of thermal treatment on the 70F HCF life of cast and HIP'ed Ti-6Al-4V alloy.

3.5.1.12 *[Figure]* Open Hole fatigue data comparing Beta Annealed (BA) to Mill Annealed (MA).

3.5.1.13 *[Figure]* Strain -Life fatigue data comparing Beta Annealed material to standard mill annealed condition.

3.5.2 Low-cycle Fatigue

3.5.2.1 *[Figure]* Low-cycle axial fatigue results at 500F for annealed mild-notched specimens cast - to-size from two heats.

3.5.3 Fatigue Crack Propagation

3.5.3.1 *[Figure]* Fatigue crack-growth rate comparison.

3.5.3.2 *[Figure]* Crack growth rate of Ti-6Al-4V mill annealed casting with no weld repair.

3.5.3.3 *[Figure]* Crack growth rate of weld repaired Ti-6Al-4V casting.

3.6 Elastic Properties

3.6.1 Poisson's Ratio
See Ti-6Al-4V, Alloy Code 3707.

3.6.2 Modulus of Elasticity
See also Tables 3.2.1.2, 3.2.1.21, 3.2.2.1, 3.2.2.2, and 3.3.1.1.

3.6.2.1 *[Figure]* Effect of test temperature on tensile elastic modulus of annealed cast ring segments from two heats.

3.6.3 Modulus of Rigidity
See Ti-6Al-4V, Alloy Code 3707
3.6.4 Tangent Modulus
3.6.5 Secant Modulus

4 Fabrication

4.1 Forming

4.2 Machining and Grinding

Consult Machinability Data Center, Metcut Research Associates, Cincinnati, Ohio.

4.3 Joining

See also Ti-6Al-4V, Alloy Code 3707.

4.4 Surface Treating

Residual surface contamination, known as alpha case, is removed from as-cast parts by chemical milling. (19)

Table 1.4.1 Chemical Composition

SPECIFICATION	AMS 4985 (Ref. 35) AMS 4991 (Ref. 36)		AMS 4962 (Ref. 37)	
Element	Minimum	Maximum	Minimum	Maximum
Aluminum, percent	5.50	6.75	5.75	6.50
Vanadium, percent	3.50	4.50	3.60	4.50
Iron, percent		0.30		0.25
Oxygen, percent		0.20	0.13	0.17
Carbon, percent		0.10		0.07
Nitrogen, percent		0.05	0.01	0.03
Hydrogen, percent		0.015		0.01
Yttrium, percent		0.005		0.005
Residual Elements, each , percent		0.10		0.10
Residual Elements, total , percent		0.40		0.40
Titanium	Remainder		Remainder	

Table 3.1.1 AMS Specified Mechanical Properties

Specification	AMS 4985			AMS 4991			AMS 4962
Property	Separately Cast Bars	Castings		Separately Cast Bars	Castings		Castings
		Designated Areas	Non Designated Areas		Designated Areas	Non Designated Areas	
F_{tu} (ksi)	130	130	125	130	130	127	125
F_{ty} (ksi)	120	120	108	120	120	108	110
e (percent)	6	6	4.5	6	6	4.5	5.5

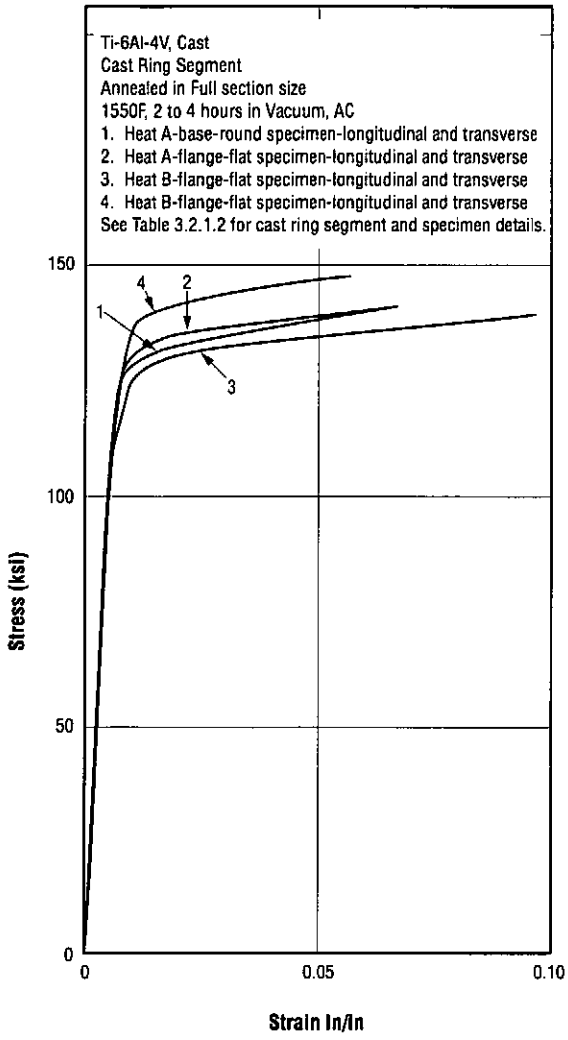


Figure 3.2.1.1 Typical stress-strain curves for annealed cast ring segments from two heats (Ref. 5)

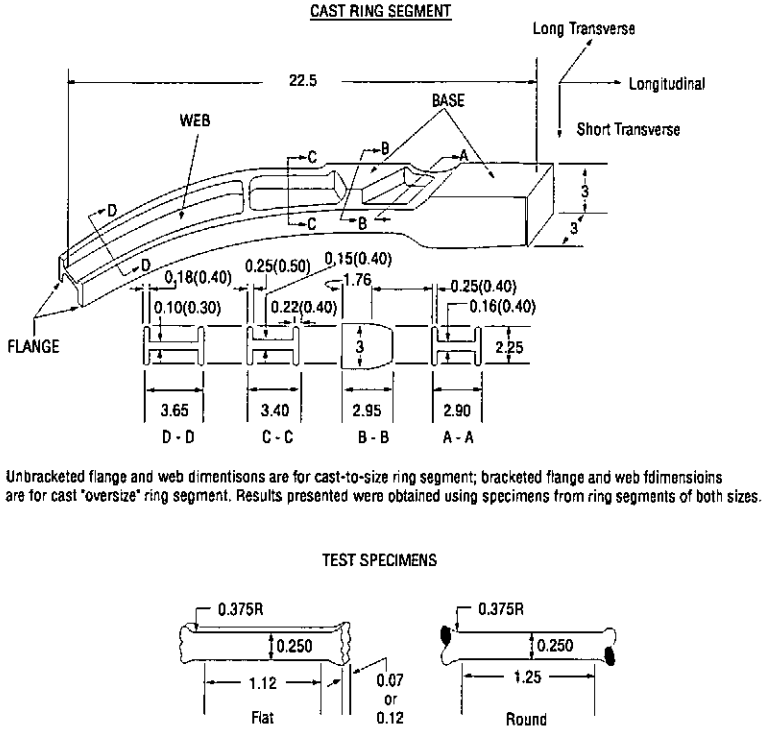
Accompanying Figure for Table 3.2.1.2 on next page

Table 3.2.1.2 Tensile properties including modulus of elasticity of annealed cast ring segments from two heats (Ref. 5)

Source	LTV Aerospace Corporation, Vought Aeronautics Division (5)							
Alloy	Ti–6Al–4V, Cast							
Form	Cast Ring Segment							
Condition	Annealed 1550F, 2 to 4 Hours in Vacuum, AC(a)							
	Tensile Properties (b)							
	Heat A				Heat B			
	Spread of Values	Average	Number of Castings Tested	Total Number of Tests	Spread of Values	Average	Number of Castings Tested	Total Number of Tests
	BASE – Longitudinal, Long Transverse, and Short Transverse Directions (c)							
F_{tu} – ksi	126.7 - 139.0	134.0	3	23	124.0-137.5	132.7	2	15
F_{ty} – ksi	108.4 - 119.6	113.0	3	22(d)	102.1-114.9	110.2	2	15
E – 10^3 ksi	15.3 - 18.2	16.7	3	24	14.9-10.0	16.2	2	16
e (1 inch) percent	6.0 - 9.0	7.3	3	23	4.0-10.0	7.4	2	15
RA – percent	13.5 - 29.6	20.6	2	7	15.8-32.5	24.6	2	6
FLANGE – Longitudinal Direction								
F_{tu} – ksi	136.7 - 146.2	142.1	3	10(e)	135.8-147.9	141.2	3	18
F_{ty} – ksi	111.9 - 129.3	121.1	3	11	111.6-128.7	119.3	3	18
E – 10^3 ksi	15.5 - 17.6	16.6	3	13	14.9-19.0	16.7	3	19
e (1 inch) percent	4.0 - 11.0	6.9	3	10(e)	4.0-14.0	7.8	3	17(f)
WEB – Long transverse Direction								
F_{tu} – ksi	136.7 - 149.6	142.2	3	9	140.1 - 150.5	142.7	3	11
F_{ty} – ksi	114.0 - 132.2	121.7	3	9	111.4 - 130.9	119.3	3	11
E – 10^3 ksi	15.6 - 17.2	16.8	3	9	16.0 - 17.7	16.7	3	11
e (1 inch) percent	4.0 - 10.0	7.0	3	9	4.0 - 11.0	7.5	3	11

(a) Annealed in full section size.
(b) All values determined using flat specimens, except RA values, which were determined from separate round specimens.
(c) No directionality observed
(d) Load-displacement curve incomplete for one test.
(e) One specimen failed outside test section.
(f) Not determined for one specimen.

Figure accompanying Table 3.2.1.2



Unbracketed flange and web dimentisons are for cast-to-size ring segment; bracketed flange and web fdimensioins are for cast "oversize" ring segment. Results presented were obtained using specimens from ring segments of both sizes.

Table 3.2.1.3 Mechanical property comparison for excised vs. intergally cast specimens (Ref. 26)

Heat No.	Ultimate Tensile Strength (ksi)	Tensile Yield Strength (ksi)	Elongation (percent in 4D)	Reduction of Area (percent)
8840 [1]	136.6	127.2	10.0	24.4
Castings from 8840 [2]	133.6	124.2	12.2	21.1
8842 [1]	139.2	127.4	9.0	20.2
Castings from 8842 [2]	133.5	124.1	9.9	18.2
8876 [1]	142.5	133.1	9.0	21.7
Castings from 8876 [2]	136.2	126.9	12.5	16.6
9003 [1]	139.6	129.8	9.0	20.5
Castings from 9003 [2]	136.0	125.7	11.8	17.3

[1] Integrally cast specimen

[2] Excised from casting
Castings consisted of hinge assembly, 38 in x 7 1/2 in, 0.25 – 1.375 in thick, and inlet lip support, 11 in x 5 1/2 in, .14 in – .26 in thick.

Castings were investment cast, AMS 4991 chemistry.
Castings were HIP'ed.

Table 3.2.1.4 Comparison of room temperature properties from three sources of cast Ti-6Al-4V test material (Ref. 29)

Heat treat: HIP 1650F/15 ksi 2 hrs + Anneal 1350F 2 hrs			
	Separately Cast Test Bars Avg. of 312 tests	Cast on Test Part Avg. of 1113 tests	Test Bars Machined form Casting Avg. of 292 tests
F_{tu} (ksi)	131.6	128.5	123.4
F_{ty} (ksi)	119.1	117.5	113.2
e (percent)	10.8	10.1	8.8
RA (percent)	20.8	22.2	16.6

Table 3.2.1.5 Tensile test results for Ti-6Al-4V alloy castings at room temperature (Ref. 27)

Specimen condition [1] and number [2]	F_{tu} (ksi)	F_{ty} (ksi)	e (4D) (percent)	RA (percent)
Cast:				
10E	145.6	131.2	10.0	15.0
10F	146.5	130.5	10.5	19.0
13B	145.8	130.4	10.5	15.5
15B	146.4	131.2	11.0	15.5
15D	144.8	130.3	11.5	13.0
16D [4]	142.0	129.3	9.5	15.5
Mean	145.2	130.5	10.5	15.6
Standard Deviation	1.7	.7	.7	1.9
Cast and hot pressed [5]				
3D	138.1	125.2	12.5	17.5
5D	138.3	126.3	11.0	18.5
9C	138.7	125.5	14.0	18.5
Mean	138.4	125.7	12.5	18.2
Standard Deviation	.3	.6	1.5	.6
Cast, milled and hot pressed [5]				
4C	138.6	126.1	13.0	19.0
4D	138.2	125.9	10.0	15.0
19E	140.2	128.4	14.0	19.0
Mean	139.0	126.8	12.3	17.7
Standard Deviation	1.1	1.4	2.1	2.3

1 All specimens were annealed at 1300F for 2 hrs.

2 Explanation of specimen numbers:20 castings were poured from 5 heats and numbered as follows: Castings 1-4 were from the first heat; Castings 5-8 were from the second heat; Castings 9-12 were from the third heat; Castings 13-16 were from the fourth heat; Castings 17-20 were from the fifth heat. The letter indicates specimen location in each casting: A is adjacent to B; B is adjacent to C, etc. See also Table 3.2.3.4.

3 4D indicates a length equal to 4 Dia of the gauge section.

4 Specimen broke in outer quarter of gauge section.

5 "Hot pressed" refers to hot isostatic pressing, 2 hrs at 1650F and 15ksi.

Note: Although the above table does not show an advantage to HIP on the tensile properties, the advantage of HIP as noted in Section 1.5 is to eliminate internal shrinkage cavities, improving durability and damage tolerance properties. Casting weight 3.3 lbs.

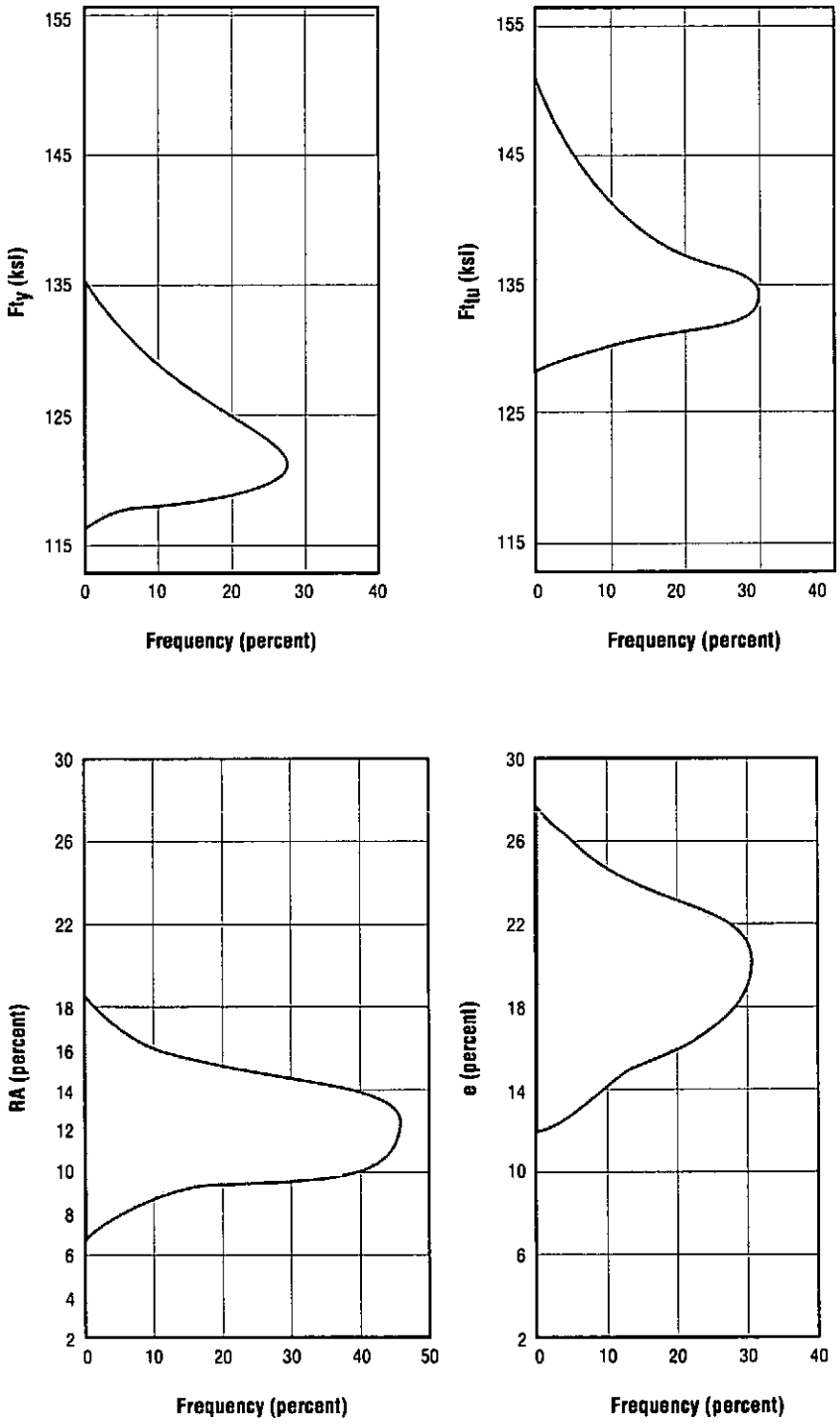


Figure 3.2.1.6 Frequency distribution of tensile properties of hot isostatically pressed and annealed Ti-6Al-4V casting test bars from 500 heats (Ref. 24)

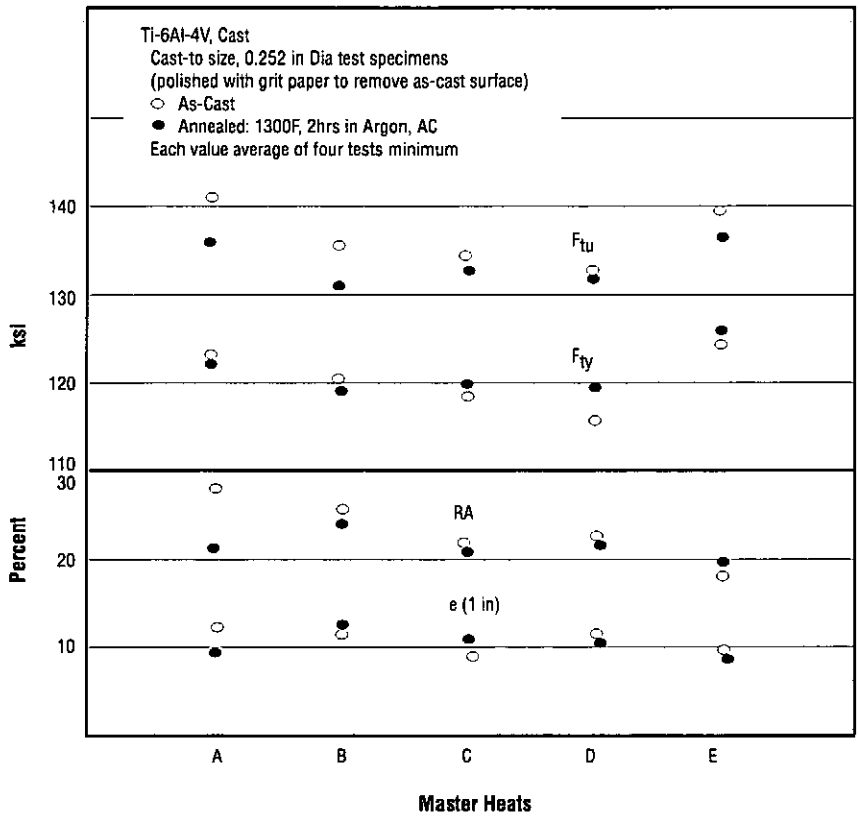


Figure 3.2.1.7 Variation in tensile properties of five master heats for the as-cast and annealed conditions (Ref. 9)

Table 3.2.1.8 Comparison of room temperature tensile properties for two heat treatments of cast Ti-6Al-4V alloy (Ref. 30)

Heat Treatment	HIP 1650F/15 ksi + Anneal 1550F	HIP 1750F/15 ksi + Solution treat 1750F Gas Fan Cool + Age 1150F
	Average of 136 tests	Average of 79 tests
F_{tu} (ksi)	132.0	138.7
F_{ty} (ksi)	118.1	124.8
e (percent)	11.8	9.6
RA (percent)	20.1	19.2

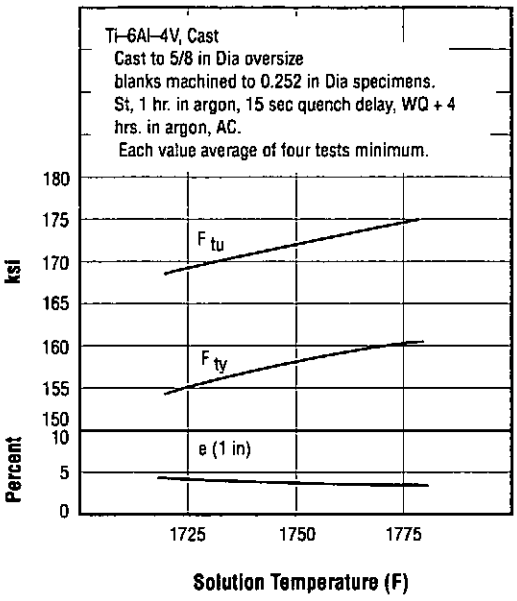


Figure 3.2.1.9 Effect of solution treat temperatures on tensile properties of solution treated and aged cast-to-size specimens (Ref. 9)

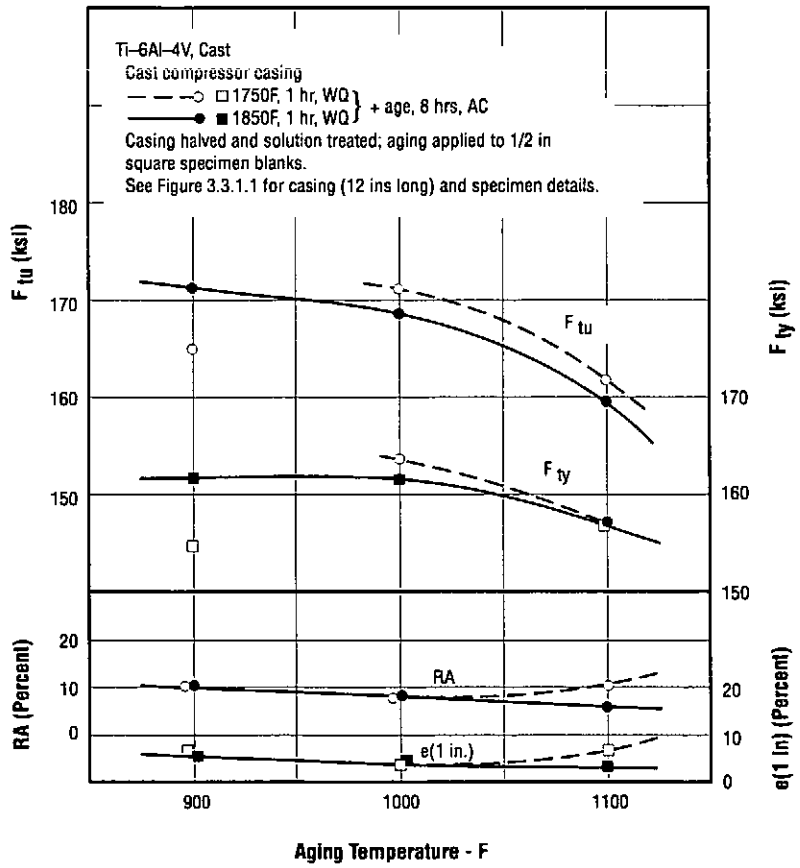


Figure 3.2.1.10 Effect of solution treat and aging temperatures on tensile properties of cast compressor casings (Ref. 4)

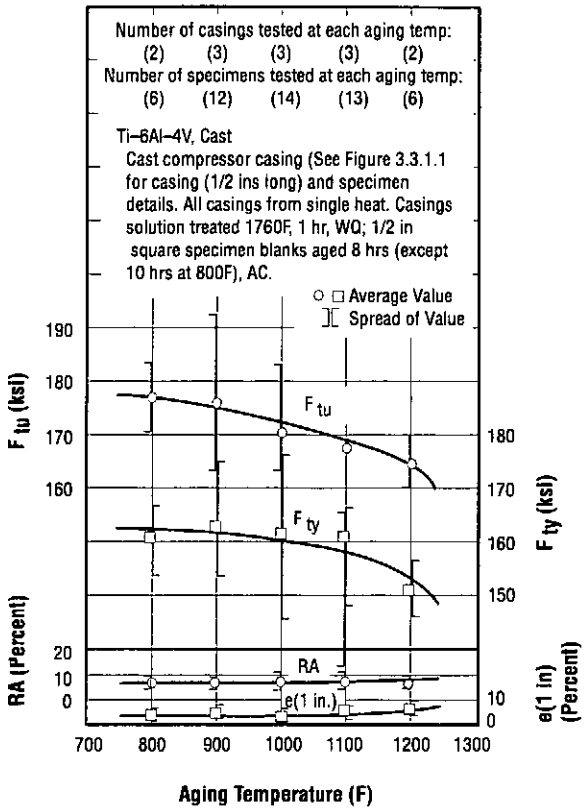


Figure 3.2.1.11 Effect of aging temperatures on tensile properties of three compressor casings cast from one heat (Ref. 4)

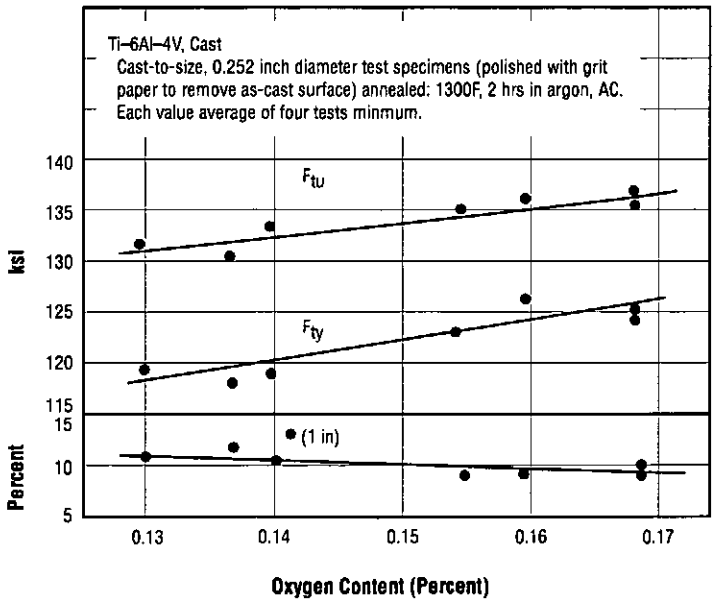


Figure 3.2.1.12 Effect of oxygen content on tensile properties of annealed cast-to-size specimens (Ref. 9)

Table 3.2.1.13 Tensile properties of as-cast, annealed, and solution treated and aged castings from three manufactures (Ref. 8)

Source	Lockheed-Georgia Company (8)			
Alloy	Ti–6Al–4V, Cast			
Form	Precision Castings			
Condition	Room Temperature Tensile Properties			
	F_{tu} (ksi)	F_{ty} (ksi)	e (1 in) (percent)	RA (percent)
Casting Manufacturer Number 1 (a) (b)				
As-Cast	139	127	6.1	15.2
Annealed (c)	134	126	6.6	21.6
Solution Treated + Aged (d)	162	152	3.7	12.2
Casting Manufacturer Number 2 (g) (h)				
Solution Treated + Aged (d)	156	136	3.0	3.1
Casting Manufacturer Number 3 (e) (f)				
Solution Treated + Aged (d)	152	140	8.0	–

(a) 10 lbs casting; section thicknesses from 0.2 in to 2.0 ins; 0.125 in. Dia specimens selected randomly from both thickness extremes and at random orientations with respect to casting geometry.
(b) Each value average of four tests minimum.
(c) Annealed in full section size: 1750F, 25 mins, WQ + 1000F, 4 hrs, AC.
(d) 1 lb casting; section thickness 0.43 in; 0.25 in. Dia specimens, all located parallel to longitudinal axis of casting.
(e) 1 lb casting; section thickness 0.43 in.; 0.25 in Dia specimens, all located parallel to longitudinal axis of casting.
(f) Each value average of three tests.
(g) 1 lb casting; section thickness 0.4 in in vicinity of specimen extraction; 0.25 in Dia specimens, all located in common direction with respect to casting geometry.
(h) Each value average of four tests

Each casting manufacturer uses his own heat.

Table 3.2.1.14 Tensile properties for a solution treated and annealed condition and two solution treated and aged conditions (Ref. 6)

Source	Precision Castparts Corporation (6)		
Alloy	Ti–6Al–4V, Cast		
Form	Precision Castings		
Condition	Solution Treat + Anneal	Solution Treat + Age	
	(a)	(b)	(c)
F_{tu} (ksi)	146.5	168.6	155.0
F_{ty} (ksi)	134.0	152.3	140.5
e (4D) (percent)	7.5	4.0	6.3
RA(percent)	11.9	8.0	12.7

(a) 1735F, 1 hr in Argon, 15 sec quench delay, WQ + 1300F, 2 hrs in Argon, AC
(b) 1750F, 1 hr in Argon, 15 sec quench delay, WQ + 1000F, 4 hrs in Argon, AC
(c) 1650F, 1 hr in Argon, 15 sec quench delay, WQ + 1000F, 4 hrs in Argon, AC

Table 3.2.1.15 Effects of aging temperature on tensile properties of cast-to-size specimens (Ref. 9)

Source		Precision Castparts Corporation (9)			
Alloy		Ti–6Al–4V, Cast			
Form		Cast- to-Size Specimens [a]			
Condition		1725F, 1 hr in Argon, 15 sec Quench Delay, WQ + Age			
Aging		Room temperature Tensile Properties [b]			
Temperature (F)	Time (Hours)	F_{tu} (ksi)	F_{ty} (ksi)	e (4D) (percent)	RA (percent)
950	2	178.9	163.3	3.0	5.1
1000	4	173.3	160.4	3.7	5.0
1100	4	170.0	158.2	4.4	6.1

(a) Cast to 5/8 in. Dia blanks and machined to 0.252 in. Dia specimens.
(b) Each value average of two tests.

Table 3.2.1.16 Effects of salvage heat treatment on tensile properties of annealed, low-oxygen cast-to-size specimens (Ref. 9)

Source	Precision Castparts Corporation (9)			
Alloy	Ti–6Al–4V, Cast			
Form	Cast- to-Size Specimens			
Oxygen Content Weight Percent	Heat Treatment	Room temperature Tensile Properties[a]		
		F_{tu} (ksi)	F_{ty} (ksi)	e (4D) (percent)
0.113/0.116	Anneal (b) Salavage (c)	131.0 143.9	118.4 131.6	11.5 8.3
0.118/0.124	Anneal (b) Salavage (c)	132.3 148.4	119.4 136.9	10.7 8.1

(a) Each value average of eight tests on six master heats.
(b) 1300F, 2 hrs., AC
(c) 1750F, 1 hr., WQ + 1300F, 2 hrs AC.

Table 3.2.1.17 Effects of exposure to elevated temperatures with load on tensile properties of annealed cast compressor casing (Ref. 4)

Source			AVCO Corporation, Lycoming Division (4)			
Alloy			Ti–6Al–4V, Cast			
Form			Cast Compressor or casing (a)			
Condition			Annealed 1300F, 2 hrs, AC (b)			
Specimen Exposure Conditions			Subsequent Room Temperature Tensile Properties (c) (d)			
Temp (F)	Stress (ksi)	Time (Hours)	F_{tu} (ksi)	F_{ty} (ksi)	e (1 in) (percent)	RA(percent)
Unexposed { Average Spread			143.9 161.5/139.5	131.0 143.1/126.5	9.4 12.0/4.0	15.5 20.3/7.9
700	90	529.3	148.6	146.5	3.0	5.4
700	85	528.0	152.8	148.2	4.0	7.2
700	85	1510.0	155.1	154.7	2.0	8.2
700	80	1603.0	152.8	147.4	7.0	12.6
900	45	500.0	153.1	150.2	6.0	8.9

(a) Seee Figure 3.3.1.1 for compressor casing (20 in long) and specimen details.
(b) Casing annealed in full section size.
(c) Specimens tested as exposed: surface not dressed.
(d) Unexposed values from fifteen test; exposed values from individual tests.

Table 3.2.1.18 Tensile test results for several solution heat treat and aging conditions (Ref. 31)

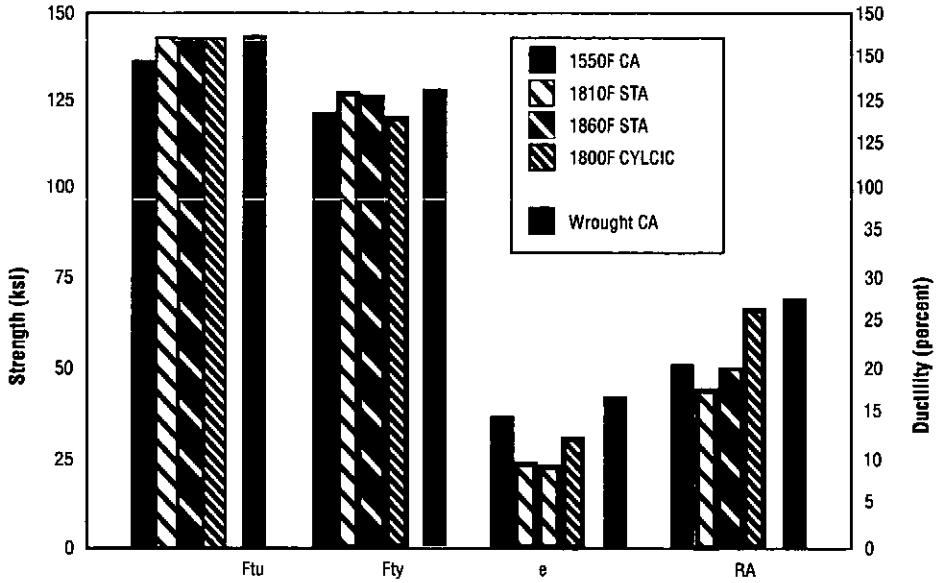
Condition	Avg F_{tu} (ksi)	Avg F_{ty} (ksi)	Avg e (percent)	Avg RA (percent)	No. of Specimens
1 (Baseline)	139	122	11	19	6
2	153	134	7	13	6
3	152	136	7	12	6
4	146	130	8	12	5
5	150	134	8	15	5
6	153	135	9	15	6
7	148	135	8	12	6
8	150	136	6	13	6

Heat treat conditions:

1. Baseline (no solution treatment or aging).
2. Soln. treat 1880F/0.5 hr./water quench/1500F age/24hrs/air cool.
3. Soln. treat 1880F/0.5 hr./oil quench/1500F age/24hrs/air cool.
4. Soln. treat 1880F/0.5 hr./gas fan cool/1500F age/24hrs/air cool.
5. Soln. treat 1880F/0.5 hr./gas fan cool/1150F age/2 hrs/air cool.
6. Soln. treat 1880F/0.5 hr./gas fan cool/1000F age/8 hrs/air cool.
7. Soln. treat 1750F/1 hr./gas fan cool/1150F age/ 2 hrs/air cool.
8. Soln. treat 1750F/1 hr./gas fan cool/1000F age/ 8 hrs/air cool.

Beta transus. calculated to be 1825F.
All material was HIP'ed at 1650F/15ksi /2hrs.
Castings were oversized test bars, cast in clusters of 28.

Chemical composition in accordance with AMS4985.



1550F CA	Conventional anneal at 1550F/2 hrs. in vacuum/argon fan cool
1810F STA	A "below beta" solution treatment and age, consisting of solution treatment at 1810F/1hr. in vacuum, an inert gas fan cool at a rate equivalent to air cooling (GFC)
1860F STA	An "above beta" solution treatment and age, consisting of 1860F/1 hr. in vacuum /GFC + 1000F/8hrs in vacuum/GFC
1800 Cyclic	A "below beta" cyclic exposure involving six cycles of 1800F/10 min in vacuum/GCF to 1000F/10 min. in vacuum/heat to 1800F, followed by a gas fan cool to 70F
Wrought CA	Conventional anneal applied to wrought products, 1550F/2 hrs.

Figure 3.2.1.19 Effect of thermal treatment on the 70F tensile properties of cast and HIP'ed Ti-6Al-4V alloy and the wrought alloy (Ref. 32)

Table 3.2.1.20 Tensile test results for two heat treat conditions (Ref. 28)

Ti-6Al-4V investment cast oversize test bars, .063 in. Dia x 5 in long Chemistry per AMS 4992						
Condition	Specimen No.	F_{tu} (ksi)	F_{ty} (ksi)	e (percent)	RA (percent)	E_c x10^6
Annealed	1	129			22	
1550 F , 2 hrs.,	2	133	122	10	19	18
Gas furnace cool	3	137	125	7	22	18
	Average	135	124	9	21	18
Beta Solution Treated	1	142	128	10	20	18
1880 F , 30 min.,	2	145	132	9	16	17
Gas furnace cool,	3	146	133	9	15	17
+ 1150 F 2 hrs., air cool	Average	144	131	9	17	17

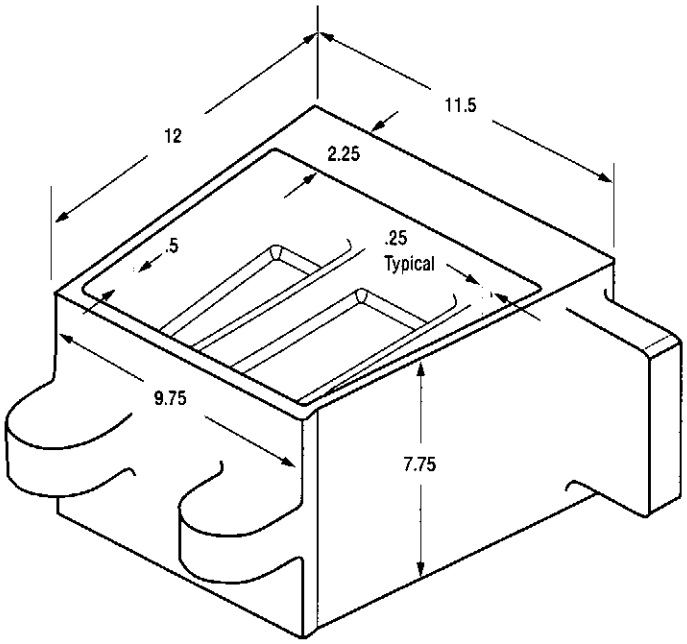
Table 3.2.1.21 Effect of 1000 hours exposure at 550F without load on tensile properties including elastic modulus of annealed ring segments from two heats (Ref. 5)

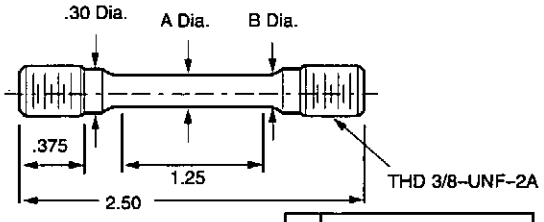
Source	LTV Aerospace Corporation, Vought Aeronautics					
Alloy	Ti-6Al-4V, Cast					
Form	Cast Ring Segments (a)					
Condition	Annealed 1550F, 2 to 4 hrs in Vacuum, AC (b)					
			Room Temperature Tensile Property			
Casting	Specimen (c) Orientation	Exposure Condition	F_u ksi	F_{ty} ksi	E 10^3 ksi	e (1 in) (percent)
BASE (a) – Heat A						
1	Long Trans	Unexposed	134.6	111.9	15.4	8.0
1	Long Trans	Unexposed	135.4	110.0	16.5	9.0
1	Long Trans	Exposed (d)	134.5	123.0	17.1	3.0
2	Short Trans	Unexposed	126.7	110.7	16.6	8.0
2	Short Trans	Unexposed	138.4	(e)	(e)	9.0
2	Short Trans	Exposed (d)	140.7	125.1	16.8	7.0
BASE (a) – Heat B						
1	Long Trans	Unexposed	135.9	112.6	16.0	9.0
1	Long Trans	Unexposed	131.6	108.5	17.5	6.0
1	Long Trans	Exposed (d)	147.4	124.8	16.8	8.0
2	Short Trans	Unexposed	129.9	103.7	14.9	10.0
2	Short Trans	Unexposed	136.7	112.0	15.2	7.0
2	Short Trans	Unexposed	137.5	114.8	16.0	4.0
2	Short Trans	Exposed (d)	144.3	124.4	16.5	9.0
FLANGE (a) – Heat A						
1	Longitudinal	Unexposed	140.9	116.2	17.0	5.0
1	Longitudinal	Unexposed	140.8	115.8	16.3	7.0
1	Longitudinal	Unexposed	139.8	113.8	16.4	6.0
1	Longitudinal	Unexposed	136.7	111.9	16.2	6.0
1	Longitudinal	Unexposed	–	–	17.5	–
1	Longitudinal	Unexposed	142.6	121.0	16.6	6.0
1	Longitudinal	Exposed (d)	146.1	133.0	17.1	5.0
2	Longitudinal	Unexposed	143.3	120.7	17.3	9.0
2	Longitudinal	Unexposed	–	–	16.3	–
2	Longitudinal	Unexposed	146.2	129.3	16.5	11.0
2	Longitudinal	Exposed (d)	149.7	131.4	17.5	4.0
FLANGE (a) – Heat B						
1	Longitudinal	Unexposed	139.5	115.8	16.7	6.0
1	Longitudinal	Unexposed	138.9	113.7	16.8	7.0
1	Longitudinal	Unexposed	143.6	117.8	16.8	10.0
1	Longitudinal	Unexposed	137.1	111.6	15.2	7.0
1	Longitudinal	Unexposed	144.3	118.1	16.4	6.0
1	Longitudinal	Unexposed	140.5	117.8	16.3	10.0
1	Longitudinal	Unexposed	–	–	17.7	–
1	Longitudinal	Unexposed	143.3	123.5	19.0	8.0
1	Longitudinal	Unexposed	142.1	124.2	16.4	6.0
1	Longitudinal	Unexposed	138.5	112.8	17.7	8.0
1	Longitudinal	Unexposed	142.5	128.7	14.9	4.0
1	Longitudinal	Exposed (d)	148.3	130.1	17.0	9.0
2	Longitudinal	Unexposed	140.2	116.5	17.2	10.0
2	Longitudinal	Unexposed	143.7	122.3	16.0	12.0
2	Longitudinal	Unexposed	139.2	119.9	16.7	14.0
2	Longitudinal	Unexposed	135.8	117.7	16.4	7.0
2	Longitudinal	Unexposed	142.1	126.7	16.9	(f)
2	Longitudinal	Exposed (d)	148.3	130.1	17.6	6.0

(a) See Table 3.2.1.2 for ring segment details.
(b) Annealed in full section size.
(c) See Table 3.2.1.2 for specimen configuration (flat type) and orientation.
(d) Exposed 350F, 1000 hrs.
(e) Incomplete load – displacement curve.
(f) Bad reading.

Table 3.2.1.22 Effect of beta anneal vs standard mill anneal on room temperature tensile properties of complex castings (Ref. 34)

Heat Treatment	Anneal at 1900F + 1550F age	Mill anneal at 1550F
F_{tu} (ksi)	130 - 144	130 - 135
F_{ty} (ksi)	120 - 128	113 - 124





A	.250 Max – .245 Min
B	A +.002 TO A +.003

Dimensions are in Inches

Tensile Specimen Configuration

Two castings were supplied by Howmet. Each contained extensive planned weld repairs. One casting was HIP'ed at 1650F followed by 1550F anneal. The other was HIP'ed at 1650F followed by beta anneal at 1900F and aged at 1550F.

Table 3.2.2.1 Compressive strength and modulus of elasticity of cast ring segments from two heats (Ref. 5)

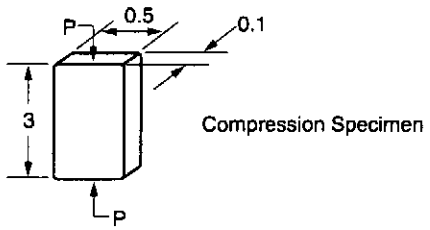
Source		LTV Aerospace Corporation, Vought Aeronautics			
Alloy		Ti-6Al-4V, Cast			
Form		Cast Ring Segments (a)			
Condition		Annealed 1550F, 2 to 4 hrs in Vacuum, AC (b)			
		Specimen (c)		Room Temperature Tensile Property	
Heat	Casting	Location(a)	Exposure Condition	F_{cy} (ksi)	E_c (10^3 ksi)(b)
A	1	Base	Longitudinal	124.9	21.6
A	1	Base	Long Trans	123.5	20.5
A	2	Base	Short Trans	121.9	15.8
A	2	Base	Short Trans	129.5	17.5
B	1	Base	Longitudinal	130.6	17.5
B	1	Base	Long Trans	125.6	16.9
B	2	Base	Short Trans	123.1	17.5
A	2	Flange	Longitudinal	146.4	15.4
B	2	Flange	Longitudinal	145.4	17.4
A	3	Web	Longitudinal	151.4	16.9
A	3	Web	Longitudinal	154.1	16.5
B	1	Web	Longitudinal	140.4	18.5
B	1	Web	Longitudinal	132.4	17.1
B	2	Web	Long Trans	140.1	18.3
B	3	Web	Long Trans	136.4	16.4

(a) See Table 3.2.1.2 for ring segment and specimen orientation details.
(b) Annealed in full section size.
(c) Specimen 2.70 ins long, 0.65 in wide and 0.10 in thick.

For comparative tensible properties, see Table 3.2.1.2

Table 3.2.2.2 Compressive yield strength and modulus of elasticity of as-cast, annealed and solution treated and aged castings from two separate casting manufactures (Ref. 8)

Source	Lockheed – Georgia Company (8)		
Alloy	Ti-6Al-4V, Cast		
Form	Precision Castings		
	Room Temperature Properties		
Condition	F_{ty} (ksi) (a)	F_{cy} (ksi) (b)	E_c (0^3ksi) (b)
Casting Manufacturer Number 1 (c)			
As-Cast	127	137	16.7
Annealed (d)	126	148	17.0
Solution Treat + Age (e)	152	179	17.2
Casting Manufacturer Number 2 (f)			
SolutionTreat + Age (e)	136	145	–



Compression Specimen

(a) Each value average of three tests minimum.
(b) Each value average of two tests minimum.
(c) 10 lb casting; section thicknesses from 0.2 in to 2.0 ins; specimens selected randomly from both thickness extremes and at random orientations with respect to casting geometry.
(d) Annealed in full section size: 1300F, 2 hrs., AC.
(e) Solution treated and aged in full section size: 1750F, 25 mins., WQ +1000F, 4 hrs., AC.
(f) 1 lb casting; section thickness 0.43 in; all specimens located parallel to longitudinal axis of casting.

Castings furnished by manufacturer Number 1 were from different heat than castings furnished by manufacturer Number 2.

Table 3.2.3.1 Standard Charpy-V impact energy of annealed cast-to-size specimen from two heats (Ref. 4)

Source		AVCO Corporation Lycoming Division (4)
Alloy		Ti-6Al-4V, Cast
Form		Cast-to-Size specimens
Condition		Annealed 1300F, 2 hrs., AC(1)
Heat	Specimen Number	Standard Charpy-V (ft lbs)
A	1	19.5
A	2	20.0
A	3	20.0
A	4	21.0
A	5	20.0
B	1	21.0
B	2	19.0
B	3	20.0
B	4	21.0
B	5	20.0

(1) Conventional tensile properties:

Heat A: F_{tu} = 144.8 ksi, F_{ty} = 127.3 ksi, e(1 in) = 11.7 percent, RA = 25.8 percent

Heat B: F_{tu} = 145.1 ksi, F_{ty} = 132.7 ksi, e(1 in) = 10.5 percent, RA = 21.6 percent

Table 3.2.3.2 Standard Charpy-V impact energy of annealed cast ring segments from two heats (Ref. 5)

Source		LTV Aerospace Corporation, Vought Aeronautics Division (5)			
Alloy		Ti-6Al-4V, Cast			
Form		Cast Ring Segments (a)			
Condition		Annealed 1550F, 2 to 4 hrs in Vacuum, AC (b)			
				Room Temperature Properties	
Heat	Casting	Specimen Location(a)	Specimen Orientation (a)	F_{ty} (ksi)	IE, Std. Charpy -V (ft lbs)
A	1	Base	Long Trans	111.9	19.0
A	1	Base	Long Trans	110.0	16.0
A	1	Base	Short Trans	114.9	15.0
A	1	Base	Short Trans	110.9	15.0
A	2	Base	Longitudinal	110.2	18.0
A	2	Base	Longitudinal	111.8	–
A	2	Base	Long Trans	111.1	16.0
A	2	Base	Short Trans	110.7	18.0
B	1	Base	Short Trans	114.3	15.0
B	1	Base	Short Trans	102.1	15.0
B	2	Base	Longitudinal	104.8	21.0
B	2	Base	Longitudinal	108.5	–
B	2	Base	Long Trans	110.4	18.0
B	2	Base	Long Trans	110.9	19.0
B	2	Base	Long Trans	114.9	17.0
B	2	Base	Short Trans	103.7	14.0
B	2	Base	Short Trans	112.0	–
B	2	Base	Short Trans	114.8	–
A	1	Flange	Longitudinal	111.9–121.0 (c)	14.0
B	1	Flange	Longitudinal	111.6-128.7 (d)	14.0

(a) See Table 3.2.1.2 for ring segment and specimen orientation details.
(b) Annealed in full section size.
(c) Range of values from five tests.
(d) Range of values from ten tests.

Table 3.2.3.3 Standard Charpy-V impact energy of solution treated and aged casting (Ref. 8)

Source	Lockheed – Georgia Company (8)
Alloy	Ti-6Al-4V, Cast
Form	Precision Casting (a)
Condition	Solution Treat – Aged (b)
Standard Charpy-V (ft lbs)	8.46 (a)

(a) 1 lb casting; section thickness 0.43 in.
(b) Solution treated and aged in full section size: 1750F, 25 mins., WQ +1000F, 4 hrs., AC
(c) Single value from specimen oriented parallel to longitudinal axis of casting.

Table 3.2.3.4 Charpy V-notch results for Ti-6Al-4V alloy castings at room temperature (Ref. 27)

Specimen condition [1] and number [2]	Impact strength [3] (ft lb)
Cast:	
1A	23.0
7A	22.5
10A	23.3
11A	20.2
16A	19.9
20A	20.0
Mean	21.5 [5]
Std. Dev.	1.6
Cast and hot pressed: [4]	
5A	17.5
17A	19.0
18A	20.7
Mean	19.1 [5]
Std. Dev.	1.6
Cast, milled, and hot pressed: [4]	
2A	18.0
6A	18.5
19A	16.9
Mean	17.8 [5]
St. Dev.	0.8

1 All specimens were annealed at 1300F for 2 hrs.

2 See Table 3.2.1.5 for explanation of specimen numbers and tensile properties.

3 Fracture type ductile.

4 "Hot pressed" refers to hot isostatic pressing.

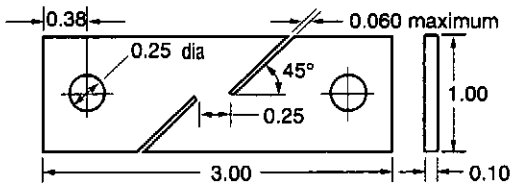
5 Compare with average of 19.2 for specimens machined from investment cast aircraft parts.

Table 3.2.3.5 Charpy V-notch and fracture toughness test results for several heat treatments (Ref. 32).

Heat Treatment (See Fig. 3.2.1.19 for explanation of heat treatment)	Charpy V-Notch Impact Energy (ft lbs)	Fracture Toughness, K_Q (ksi $in^{-1/2}$)
1550F CA	25.6	96.7
	24.9	88.5
	24.8	96.0
Mean	25.1	93.7
1810 F STA	22.6	
	21.2	
	20.8	
Mean	21.5	
1860F STA	20.0	
	19.2	
	21.2	
Mean	20.1	
1800F Cyclic	29.9	
	22.1	
	26.2	
Mean	26.1	

Table 3.2.5.1 Shear strength of annealed cast ring segments from two heats (Ref 5)

Source		LTV Aerospace Corporation, Vought Aeronautics Division (5)
Alloy		Ti-6Al-4V, Cast
Form		Cast Ring Segments (a)
Condition		Annealed 1550F, 2 to 4 hrs in Vacuum, AC (b)
Heat	Casting	F_{su} (c) (d) (ksi)
A	1	93.9
A	2	95.3
A	3	95.3
B	1	94.4
B	2	102.5



(a) See Table 3.2.1.2 for ring segment details.
(b) Annealed in full section size.
(c) Flange location, longitudinal direction (see Table 3.02141).
(d) Values average of from two to seven tests for each casting.
See table 3.2.1.2 for corresponding conventional tensile properties.

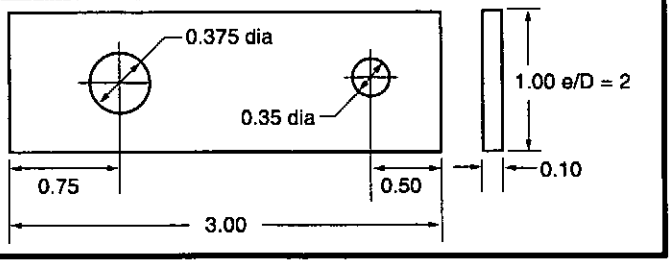
Table 3.2.5.2 Double shear strength of solution treated and aged casting (Ref. 8)

Source	Lockheed – Georgia Company (8)
Alloy	Ti-6Al-4V, Cast
Form	Precision Casting (a)
Condition	Solution Treat + Aged (b)
F_{su} (ksi)	94.7 (c)

(a) 1-lb casting; section thickness 0.43 in; 0.375 in. Dia double-shear specimens oriented parallel to longitudinal axis of casting.
(b) Solution treated and aged in full section size: 1750F, 25 mins., WQ + 100F, 4 hrs., AQ.
(c) Average of two test.

Table 3.2.6.1 Bearing strength of annealed cast ring segments from two heats (Ref. 5).

Source		LTV Aerospace Corporation, Vought Aeronautics Division (5)	
Alloy		Ti-6Al-4V, Cast	
Form		Cast Ring Segments (a)	
Condition		Annealed 1550F, 2 to 4 hrs in Vacuum, AC (b)	
Heat	Casting	F_{bru} (c) (d) (ksi)	F_{bry} (c) (d) (ksi)
A	1	283.0	224.6
A	2	279.4	227.7
A	3	253.3	209.1
B	1	279.6	214.9
B	2	300.1	245.4



(a) See Table 3.2.1.2 for ring segment details.
(b) Annealed in full section size.
(c) Flange location, longitudinal direction (see Table 3.0212).
(d) All values are averages of from two to six tests for each casting except that for casting 2, Heat B, which is a single datum point.

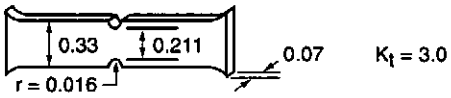
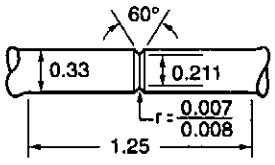
See table 3.2.1.2 for corresponding conventional tensile properties.

Table 3.2.6.2 Bearing strength of solution treated and aged castings (Ref. 8)

Source	LTV Aerospace Corporation, Vought Aeronautics Division (8)	
Alloy	Ti-6Al-4V, Cast	
Form	Precision Casting (a)	
Condition	Solution Treat + Age (b)	
Room temperature Bearing Properties (c)		
F_{bru} (c) (d) (ksi)	F_{bry} (c) (d) (ksi)	e/D
216	(d)	1.50
240	234	1.52
214	224	1.50

(a) 1-lb casting; section thickness 0.43 in; specimens oriented parallel to longitudinal axis of casting.
(b) Solution treated and aged in full section size: 1750F, 25 mins., WQ + 1000F, 4 hrs., AQ.
(c) Specimen thickness = 0.090 in; D = 0.187 in.
(d) Bearing failure occured before 0.2 percent strain was achieved.

Table 3.2.7.1.1 Mild-notch strength of annealed casting segments from two heats (Ref. 5).

Source	LTV Aerospace Corporation, Vought Aeronautics Division (5)		
Alloy	Ti-6Al-4V, Cast		
Form	Cast Ring Segments (a)		
Condition	Annealed 1550F, 2 to 4 hrs in Vacuum, AC (b)		
		Room Temperature Property	
Casting	Specimen Orientation (c)	F_{ty} (ksi)	NTS (ksi)
			
BASE (a) – Heat A			
1	Long Transverse	110.0	166.1
1	Long Transverse	111.9	–
2	Longitudinal	110.2	172.4
2	Longitudinal	111.8	–
2	Short Transverse	110.7	146.0
BASE (a) – Heat B			
1	Long Transverse	112.6	152.2
1	Long Transverse	108.5	–
2	Longitudinal	104.8	159.5
2	Longitudinal	108.5	–
2	Short Transverse	103.7	155.9
2	Short Transverse	112.0	–
2	Short Transverse	114.8	–
FLANGE (a) – Heat A			
2	Longitudinal	120.7	167.9
2	Longitudinal	129.3	–
FLANGE (a) – Heat B			
2	Longitudinal	116.5	165.2
2	Longitudinal	122.3	–
2	Longitudinal	119.9	–
2	Longitudinal	117.7	–
2	Longitudinal	126.7	–
WEB (a) – Heat B			
1	Longitudinal	113.6	160.3
1	Longitudinal	118.4	–
1	Longitudinal	111.4	–
2	Long Transverse	120.2	168.4
2	Long Transverse	126.7	–
2	Long Transverse	123.1	–
2	Long Transverse	123.0	–
			
BASE (a) – Heat A			
2	Longitudinal	122.5	157.3
2	Longitudinal	123.5	–
BASE (a) – Heat B			
2	Longitudinal	118.6	154.2
2	Longitudinal	125.2	–

(a) See Table 3.2.1.2 for ring segment details.
(b) Annealed in full section size.

Table 3.2.7.2.1 Fracture toughness test results (Ref. 26)

Fracture Toughness (K_Q) (ksi in.$^{1/2}$)	
Ti-6Al-4V investment castings	
HIP'ed at 1650F/15 ksi/2 hrs	
Compact Tension (Per ASTM E-399)	Short-rod (Per SAE ARP 1704)
97.3	102.0
99.5	113.3
89.7	113.1
97.1	106.9
102.3	110.3

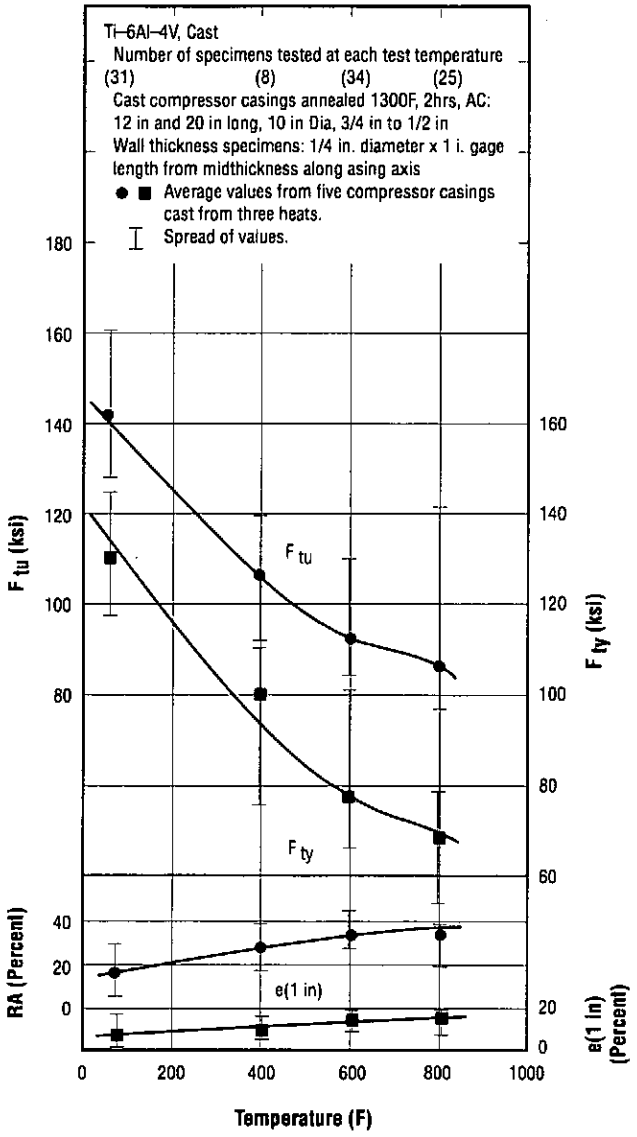


Figure 3.3.1.1 Effect of test temperatures on tensile properties of five annealed cast compressor casings from three heats (Ref. 4)

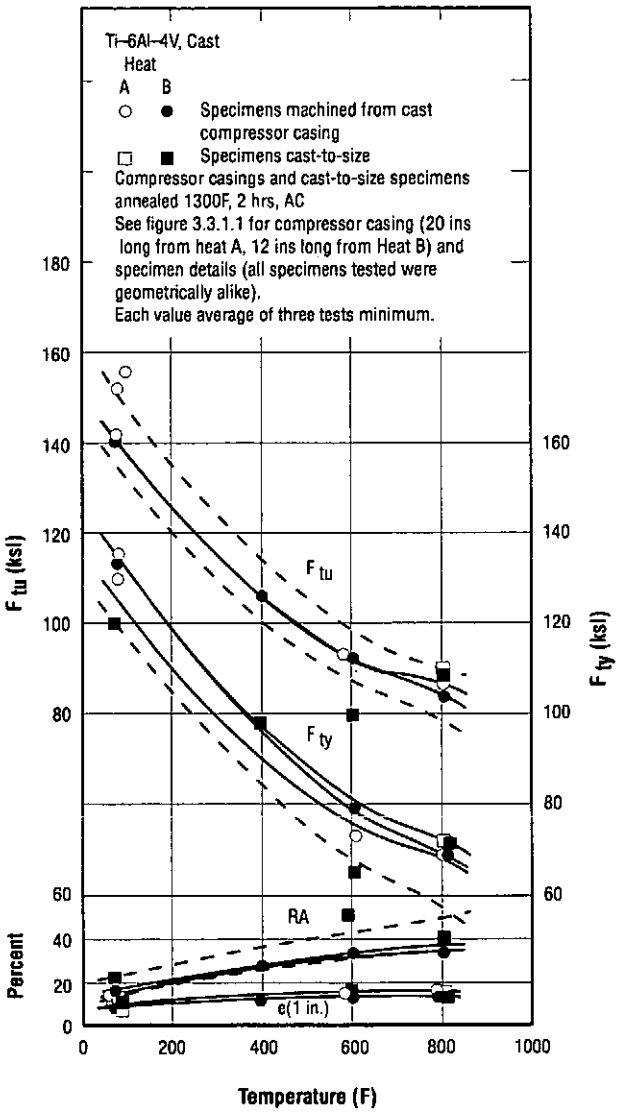


Figure 3.3.1.2 Effect of test temperatures on tensile properties of specimens machined from annealed cast compressor casings and annealed cast-to-size specimens each from two heats (Ref. 4)

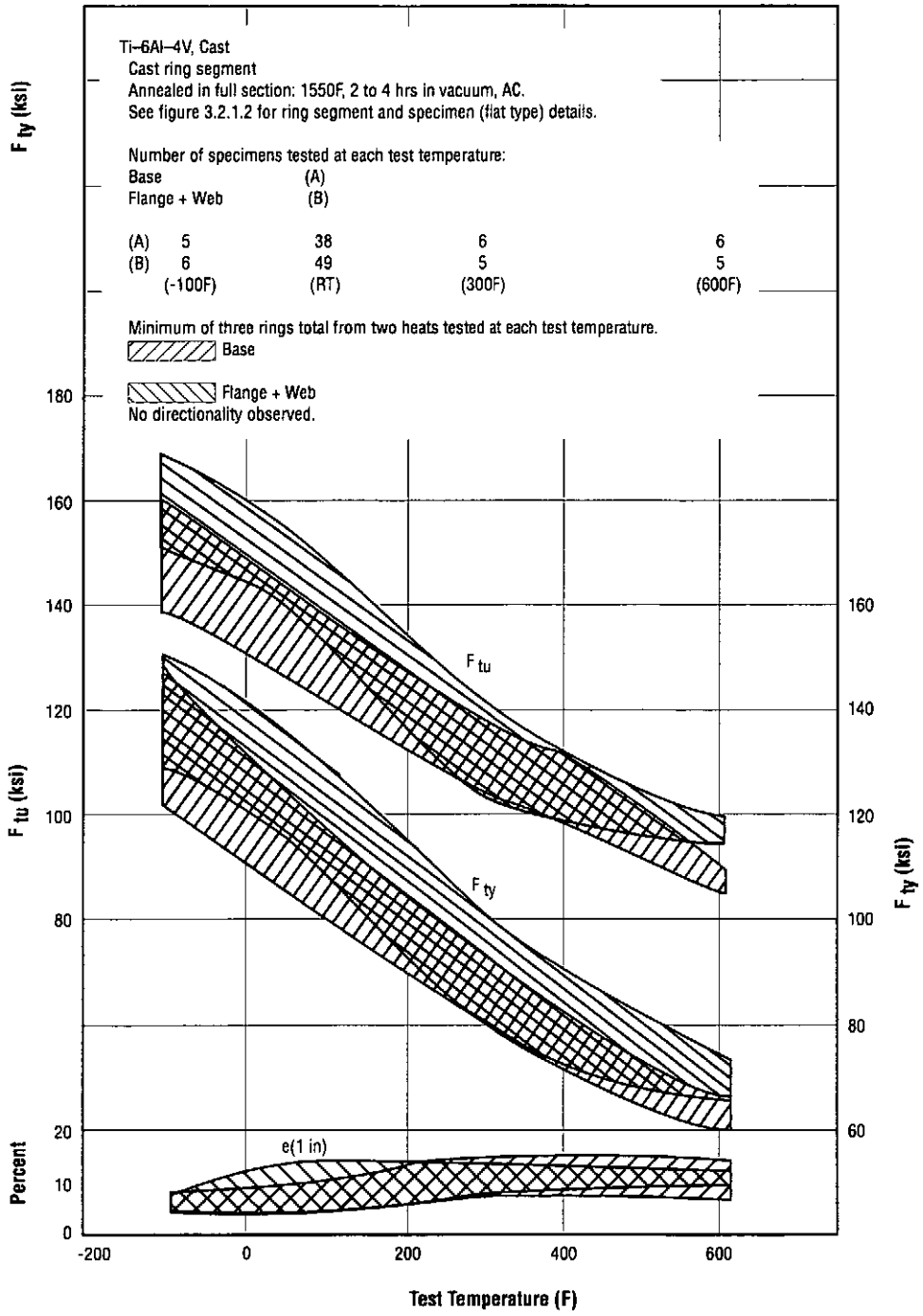


Figure 3.3.1.3 Effect of test temperatures on tensile properties of annealed cast ring segments from two heats (Ref. 5)

Table 3.3.1.4 Summary of tensile test results at room and low temperatures from Ti-6Al-4V investment castings of standard composition and extra low interstitials from two foundries (Ref. 28)

Test group	Test Temperature (F)	F_{tu} (ksi)	F_{ty} (ksi)	e (percent)
Foundry A ELI [1]	RT	128.52	123.58	7.5
	-320	201.28	186.76	2.7
	-423	225.30	210.67	2.0
Foundry B STD [2]	RT	129.23	118.33	6.16
	-320	206.77	197.20	4.0
	-423	221.30	213.40	2.75
Foundry A STD [2] 1350 F Anneal	RT	135.83	129.38	9.3
	-320	211.09	201.33	6.0
	-423	241.99	223.61	4.5
Foundry B STD [2] 1550 F Anneal	RT	133.61	123.93	7.67
	-32	210.76	197.39	6.0
	-4230	236.27	217.18	5.3

[1] Extra low interstitials

[2] Standard chemistry per AMS 4985

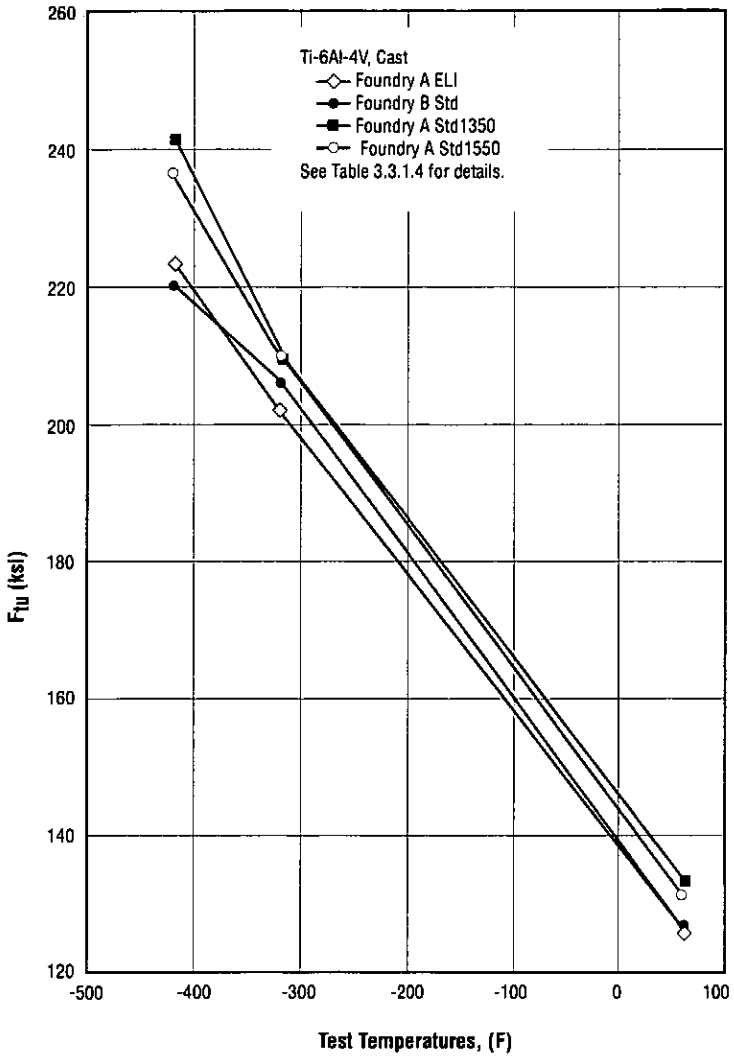


Figure 3.3.1.5 Effects of test temperature on ultimate tensile strength of standard composition and extra low interstitials casings (Ref. 28)

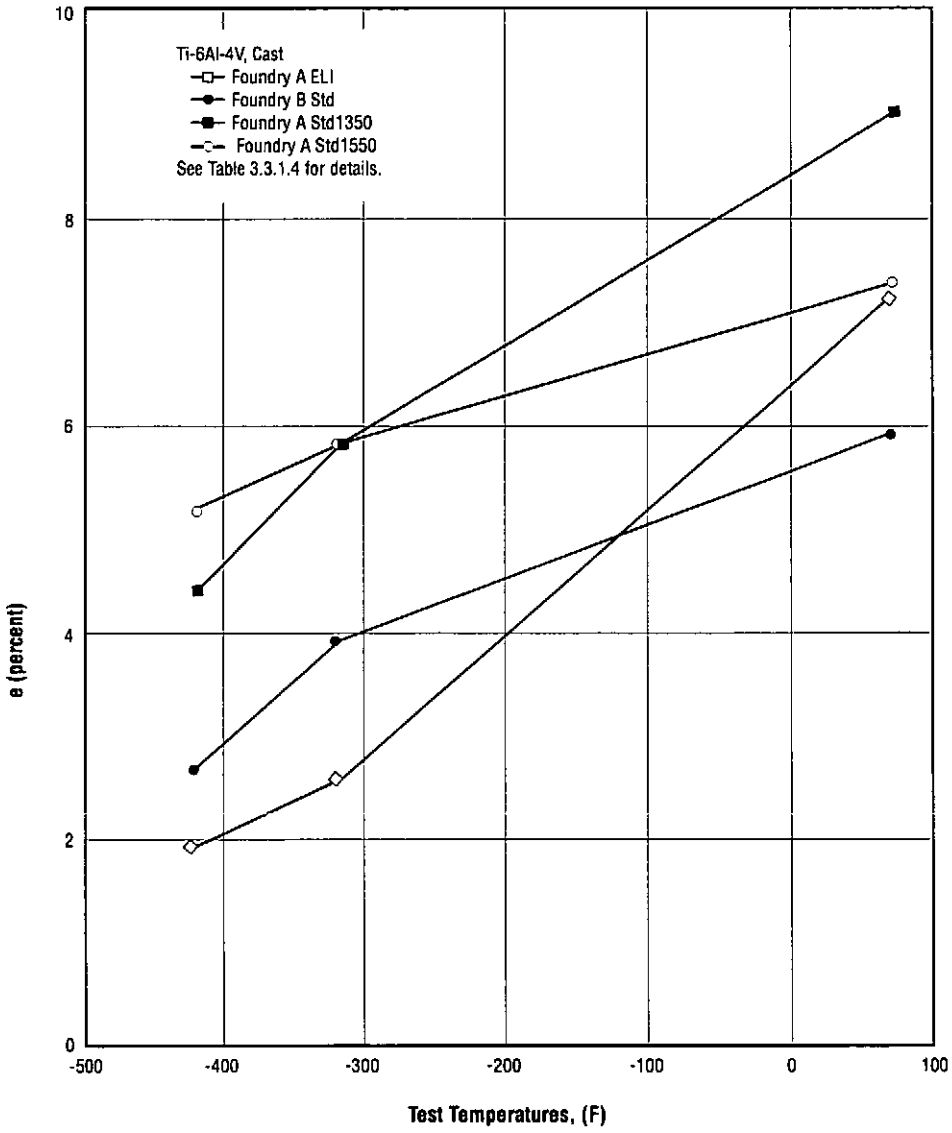


Figure 3.3.1.6 Effects of test temperature on percent elongation of standard composition and extra low interstitials casings (Ref. 28)

Table 3.3.7.1.1 Fracture toughness results summary of Ti-6Al-4V investment castings (Ref. 28)

Test Group [1]	Test Temp (F)	K_Q, (ksi in.$^{1/2}$)
Foundry A ELI	RT -320 -423	102.44 76.76 67.49
Foundry B STD	RT -320 -423	102.86 70.91 67.99
Foundry A STD 1350F Anneal	RT -320 -423	94.39 60.21 54.84
Foundry A STD 1550F Anneal	RT -320 -423	86.73 63.95 56.95

[1] See Table 3.3.1.4 for tensile properties and explanation of test group

[2] K_Q per ASTM E399

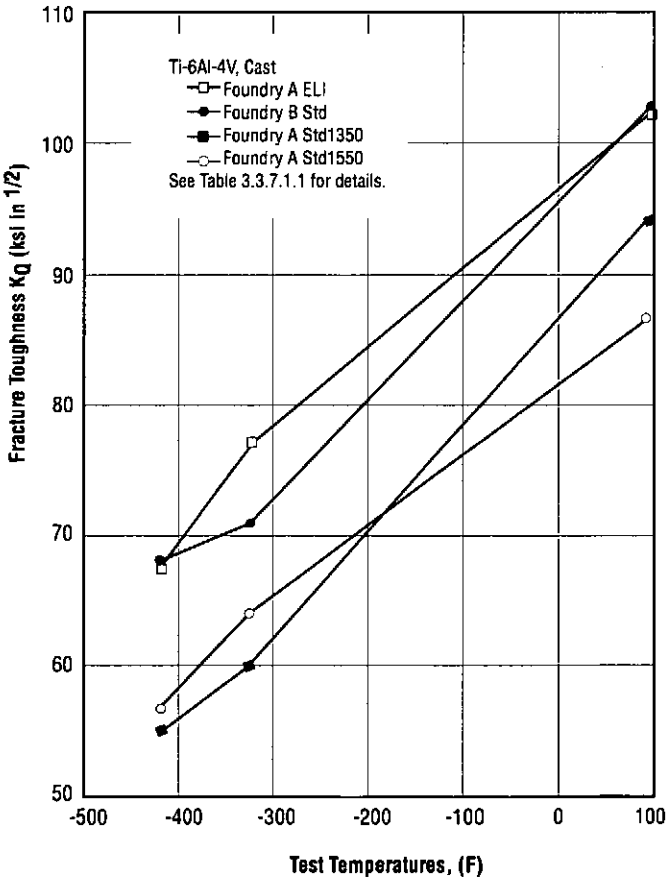


Figure 3.3.7.1.2 Effects of test temperature on the fracture toughness of standard composition and extra low interstitials casings (Ref. 28)

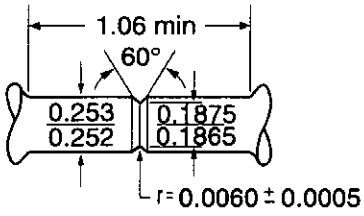
Table 3.4.1 Effects of solution treat and aging temperatures on 800F, 80ksi stress rupture life of cast compressor casing (Ref.4)

Source	AVCO Corporation, Lycoming Division (4)	
Alloy	Ti-6Al-4V, Cast	
Form	Cast Compressor Casing (a)	
Condition	Solution Treated and Aged (b)	
	Stress Rupture Properties at 800F, 80 ksi	
Age Temperature, 8 hrs, AC (F)	Time to Rupture (hrs)	e (1 inch) (percent)
Solution Treat 1750F, 1 hr., WQ		
900	500.2	–
900	510.7	–
900	512.8	–
1000	502.1 (c)	–
1000	501.2 (c)	–
1000	504.3 (c)	–
1000	757.3	14.6
1100	502.1 (c)	–
1100	503.2 (c)	–
Solution Treat 1850F, 1 hr., WQ		
900	549.6 (c)	–
900	548.4 (c)	–
900	546.6 (c)	–
1000	540.5 (c)	–
1000	526.8 (c)	–
1000	521.7 (c)	–
1100	506.6 (c)	–
1100	504.5 (c)	–
1100	504.2 (c)	–

(a) See Figure 3.3.1.1 for compressor casing (12 ins long) and specimen details.
(b) Casing halved and solution treated; aging applied to 1/2 in square specimen blanks. See Figure 3.2.1.10 for room temperature tensile properties of material tested.
(d) Test retired.

Table 3.4.2 Room temperature stress rupture results for mild-notch specimens machined from annealed cast comp[ressor casing and cast-to-size specimens (Ref.4)

Source		AVCO Corporation, Lycoming Division (4)				
Alloy		Ti-6Al-4V, Cast				
Form		Cast Compressor Casing (a) or Cast-to-Size Specimens (b)				
Condition		Annealed 1300F, 2 hrs, AC (c)				
Heat	Specimen Number	Room Temperature Mild-Notch Stress Rupture Properties				
		Hrs at Indicated Stress				Total Life
		160 ksi	170 ksi	180 ksi	190 ksi	hrs
Cast Compressor Casing						
A	1	–	1.2	–	–	1.2
A	2	10.0	–	–	–	(d)
A	3	9.0	–	–	–	(d)
B	1	–	5.0	1.1	–	6.1
B	2	–	5.0	0.2	–	5.2
B	3	–	9.9	0.4	–	10.3
B	4	–	6.8	–	–	6.8
C	1	–	10.6	5.0	1.2	16.8
C	2	–	5.2	–	–	5.2
C	3	–	5.8	1.9	–	7.7
C	4	–	10.3	0.7	–	11.0
C	5	–	5.0	2.8	–	7.8



(a) See Figure 3.3.1.1 for compressor casing (20 ins long) and specimen details.
(b) Specimens cast to 1/2 in. Dia oversize specimen blanks subsequently machined to finished specimens.
(c) Cast compressor casing annealed in full section size: F_{tu} = 143.9 ksi, F_{ty} = 131.0 ksi, e (1 in) = 9.4 percent, RA = 15.5 percent.
Cast-to-size specimens annealed as oversize specimen blanks: Heat B, F_{tu} = 144.8 ksi, F_{ty} = 127.3 ksi, e (1 in) = 11.7 percent, RA = 25.8 percent.
Heat C, F_{tu} = 145.1 ksi, F_{ty} = 132.7 ksi, e (1 in) = 10.5 percent, RA = 21.6 percent.
(d) Test retired.

Table 3.4.3 500F stress rupture properties of cast-tosize smooth and mild-notch specimens from two heats (Ref.4)

Source		AVCO Corporation, Lycoming Division (4)		
Alloy		Ti-6Al-4V, Cast		
Form		Cast-to-Size Specimens (a)		
Condition		Annealed 1300F, 2 hrs., AC (c)		
		500F Stress Rupture Properties		
Heat	Specimen Number	Stress (ksi)	Life (hrs)	e (1 inch) (percent)
Smooth (c)				
A	1	100.0	(d)	12.0
A	2	95.0	200.8 (e)	–
A	3	90.0	253.3 (e)	–
B	1	100.0	245.7 (e)	–
B	2	98.5	209.6 (e)	–
B	3	97.5	204.9 (e)	–
Mild-Notch (f)				
A	1	175.0	(d)	–
A	2	165.0	(d)	–
A	3	155.0	(d)	–
B	1	154.0	(d)	–
B	2	152.0	200.8 (e)	–
B	3	150.0	238.1 (e)	–

(a) 1/2 in. Dia cast oversize specimen blanks subsequently machined to finished specimens.
(b) Annealed as oversize specimen blanks: Room Temperature
Tensile Properties – Heat A; F_{tu} = 144.8 ksi F_{ty} = 127.3 ksi, e (1 in) = 11.7 percent, RA – 25.8 percent.
Heat B; F_{tu} = 145.1 ksi F_{ty} = 132.7 ksi, e (1 in) = 10.5 percent, RA – 21.6 percent.
(c) Smooth specimens 1/4 in. Dia x 1 in gage length.
(d) Broke immediately after loading to indicated stress.
(e) Test discontinued.
(f) See Table 3.4.2 for mild-notch specimen configuration.

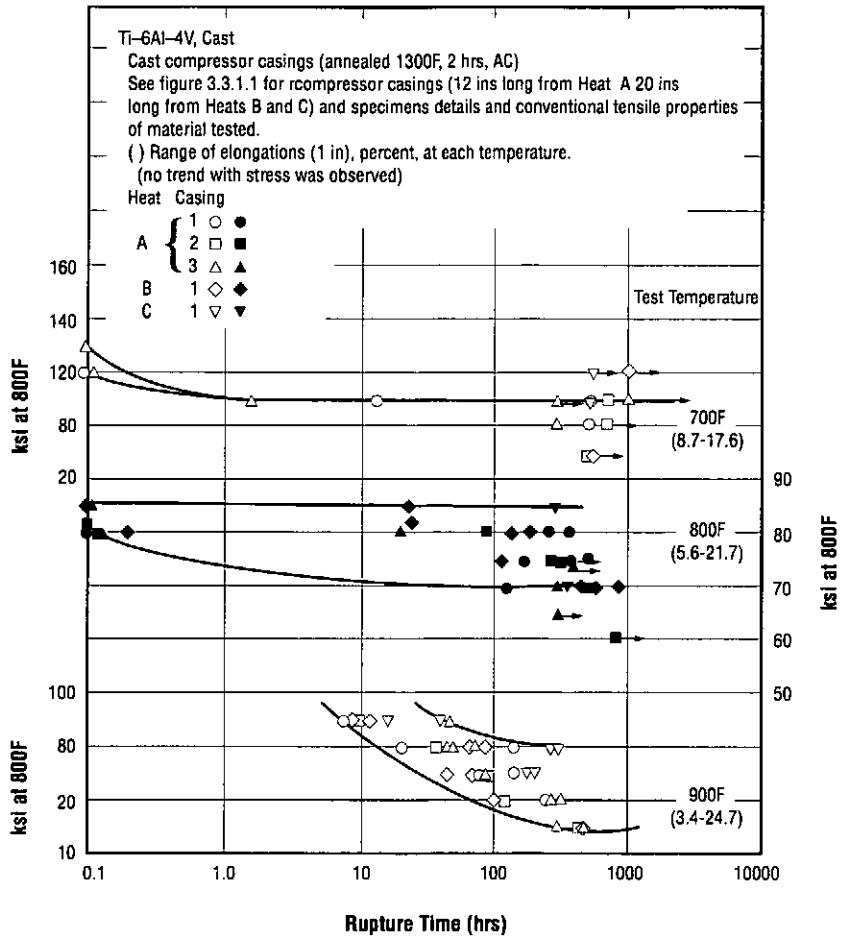


Figure 3.4.4 Stress reputure curves at 700, 800 and 900F for specimens machined from five annealed cast compressor casings from three heats (Ref. 5)

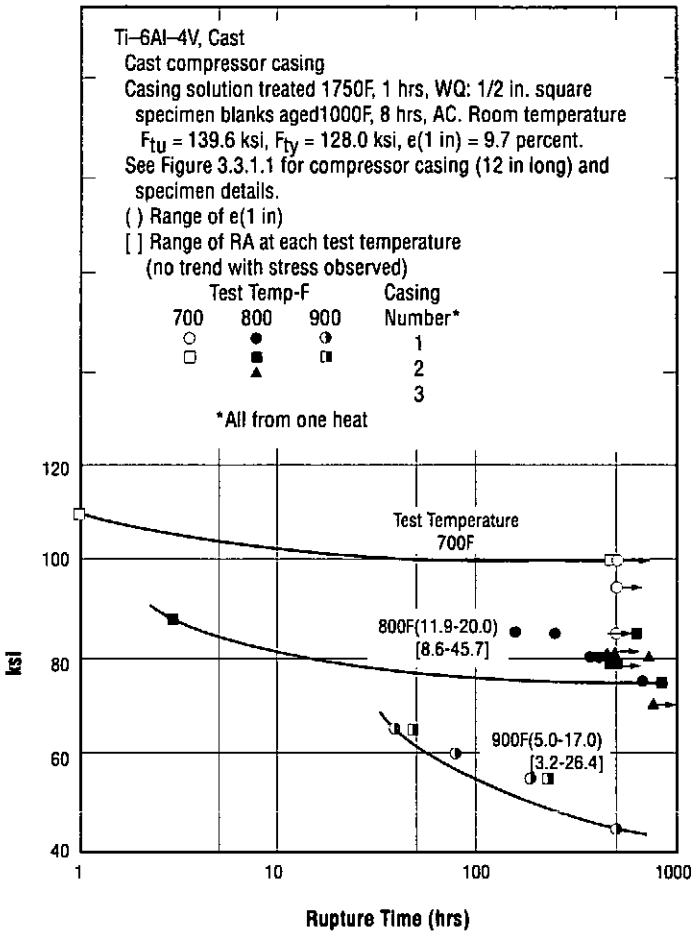


Figure 3.4.6 Stress reputure curves at 700, 800, and 900F for specimens machined from cast compressor casing aged at 1000F (Ref. 4)

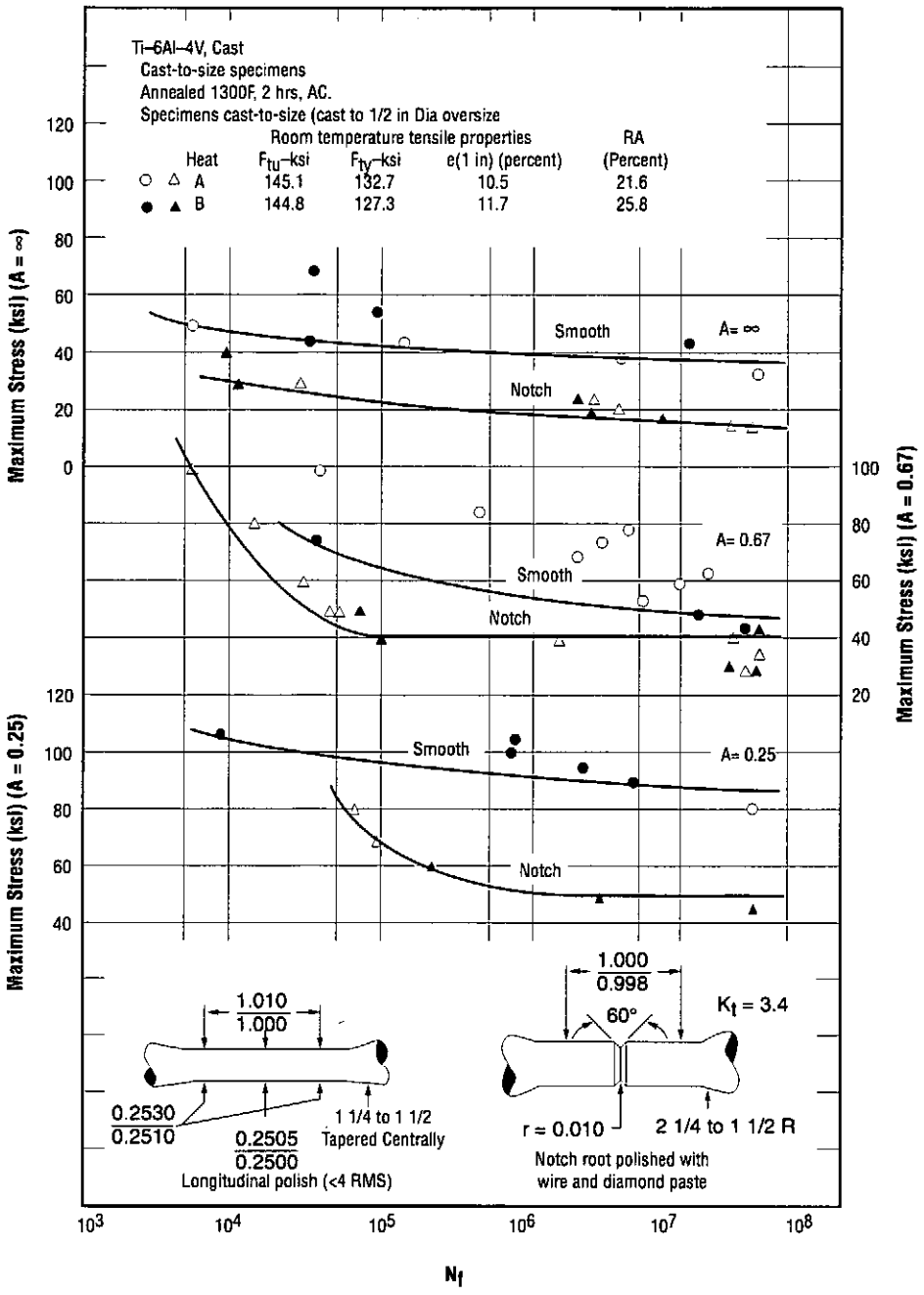


Figure 3.5.1.1 High-cycle axial fatigue results at 500F for annealed smooth and mild-notch cast-to-size specimens from two heats (Ref. 4)

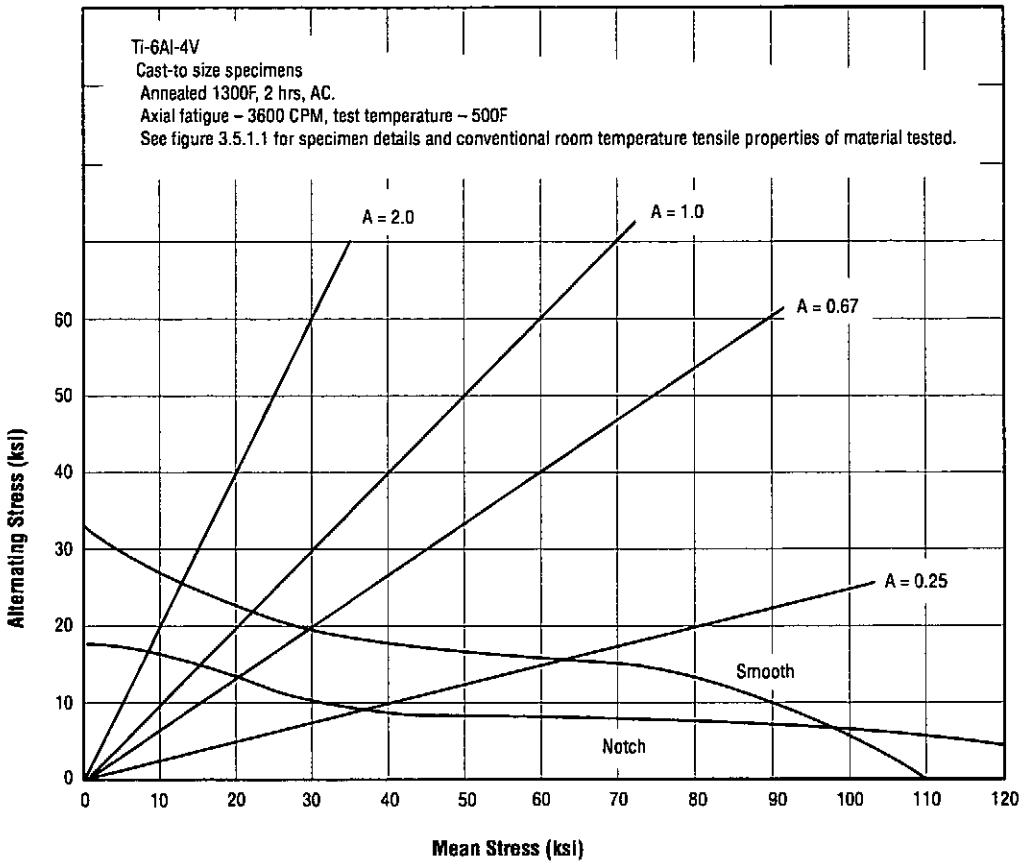


Figure 3.5.1.2 150 hours, 500F stress range diagram for smooth and mild-notch cast-to-size specimens from two heats (Ref. 4)

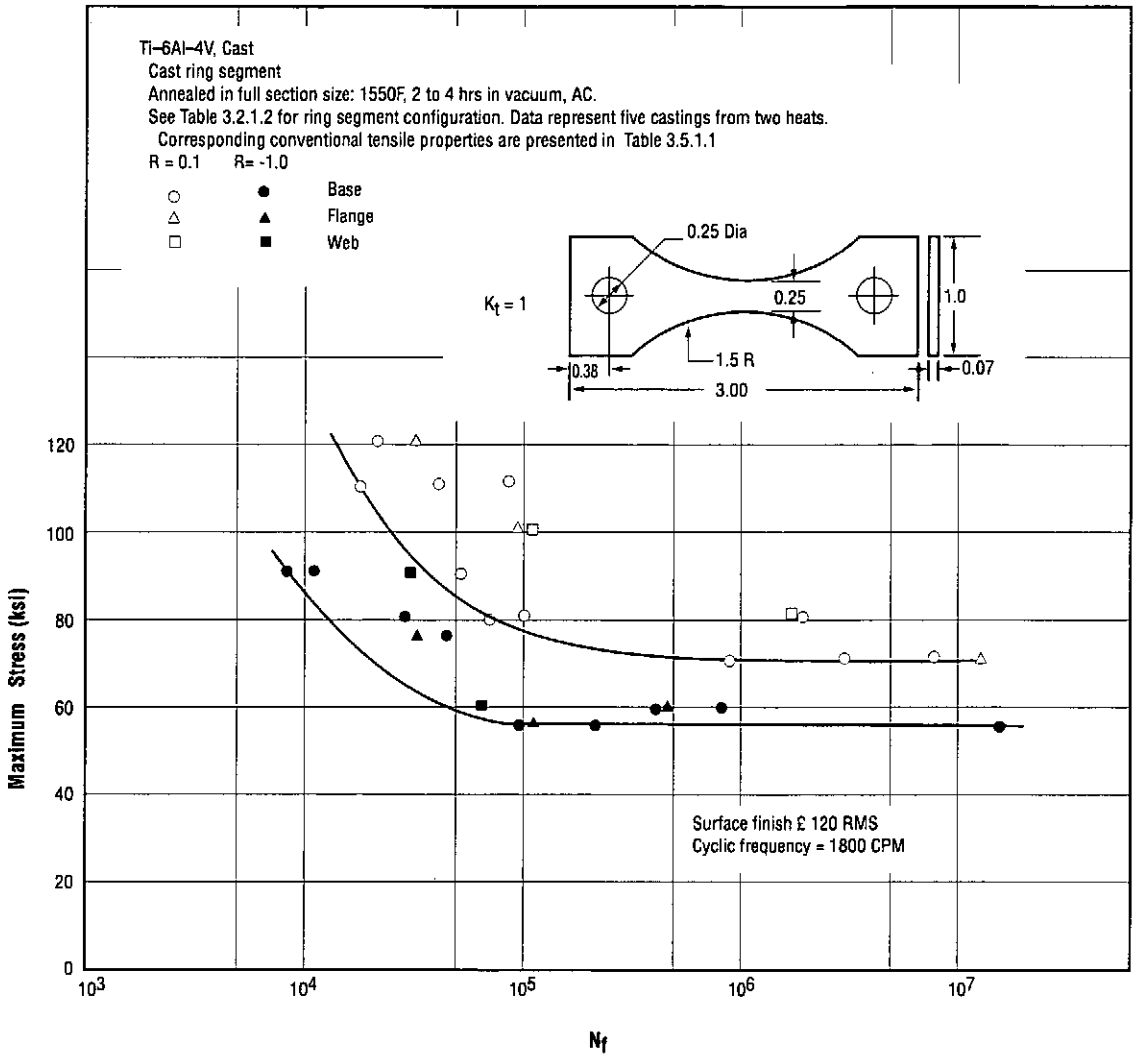


Figure 3.5.1.3 Room temperature axial load fatigue properties of smooth specimens from five heats (Ref. 5)

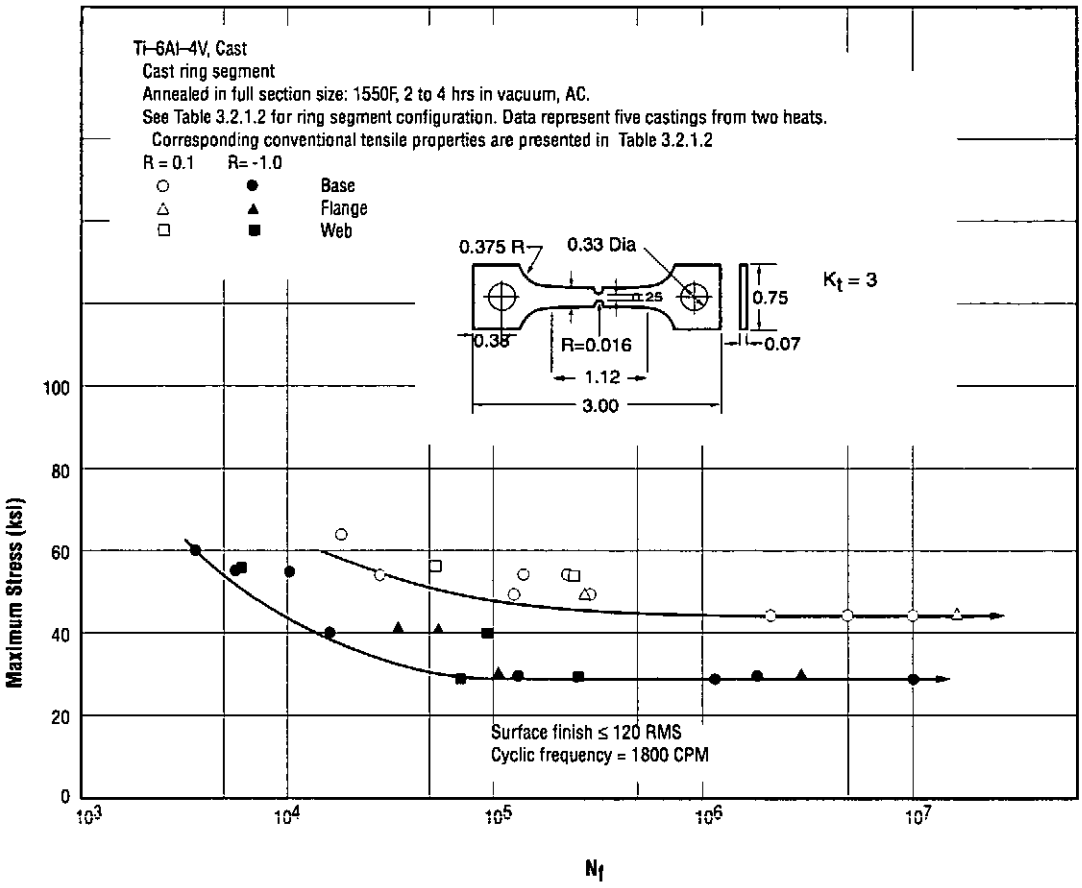


Figure 3.5.1.4 Room temperature axial load fatigue properties of mild-notch specimens from five annealed cast ring segments from two heats (Ref. 5)

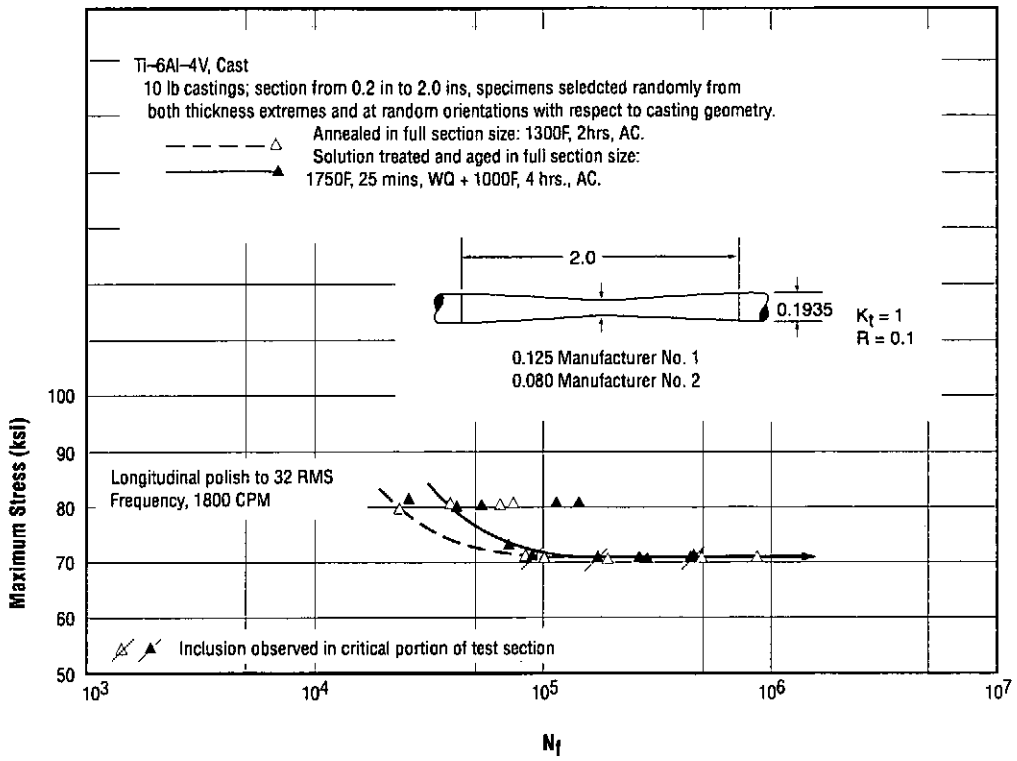


Figure 3.5.1.5 Room temperature smooth fatigue properties of annealed and solution treated and aged castings (Ref. 8)

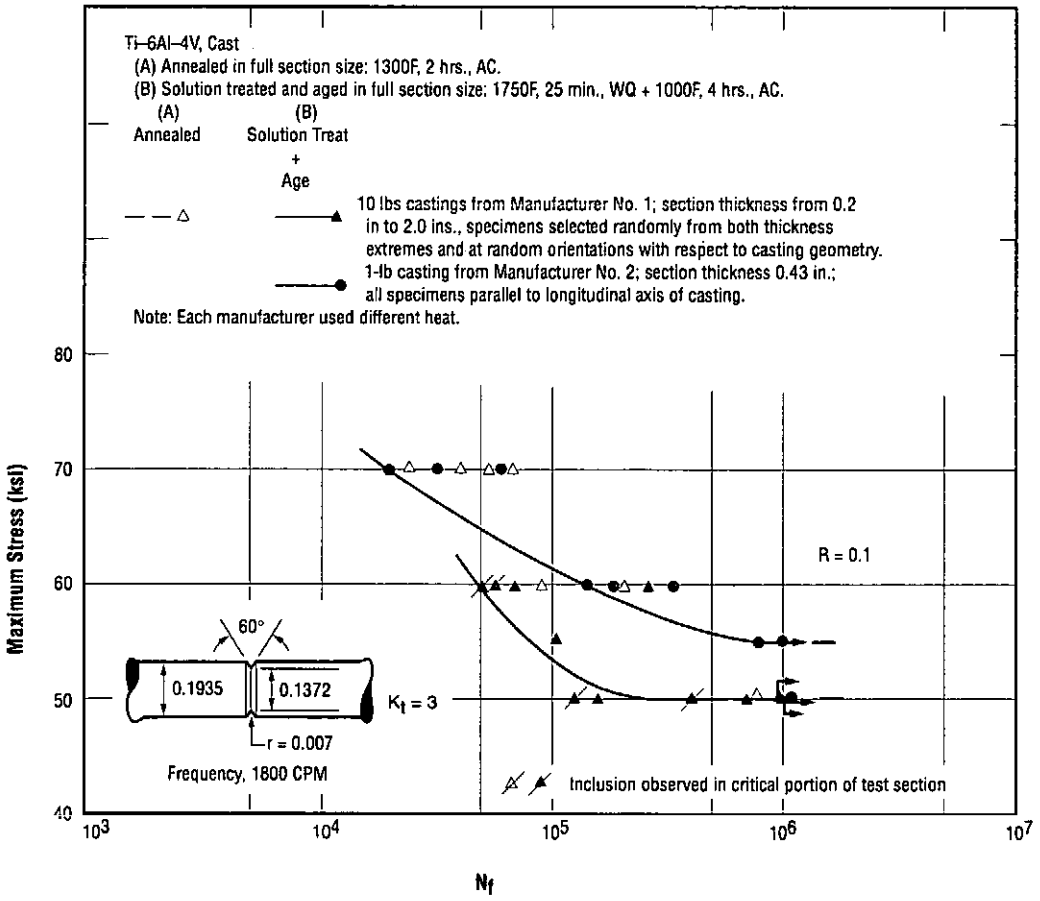


Figure 3.5.1.6 Room temperature mild-notch fatigue properties of annealed and solution treated and aged castings from two casting manufacturers (Ref. 8)

Table 3.5.1.7 Room temperature HCF test results for Ti-6Al-4V cast test bars in various heat treat conditions (Ref. 28)

Condition [1]	Max. Stress (ksi)	N_f
Annealed	105.0	72,100
	90.0	1,038,900
	87.5	1,034,300
	85.0	928,200
	84.0	1,426,200
	82.3	1,098,200
	82.0	1,413,400
	81.0	963,900
	81.0	433,300
	80.0	2,924,100
BST	115.0	31,400
	110.0	87,500
	105.0	229,500
	102.0	700,000
	100.0	870,200
	98.0	508,500
	97.5	639,600
	95.0	1,819,500
	92.5	5,500,000
	90.0	3,650,000 [2]
	90.0	2,162,200
	88.0	2,557,400

10 Hz, R=0.1, Triangular wave form $K_T = 1.0$

[1] See Table 3.2.1.20 for room temperature tensile test results and definition of condition.

[2] Run-out.

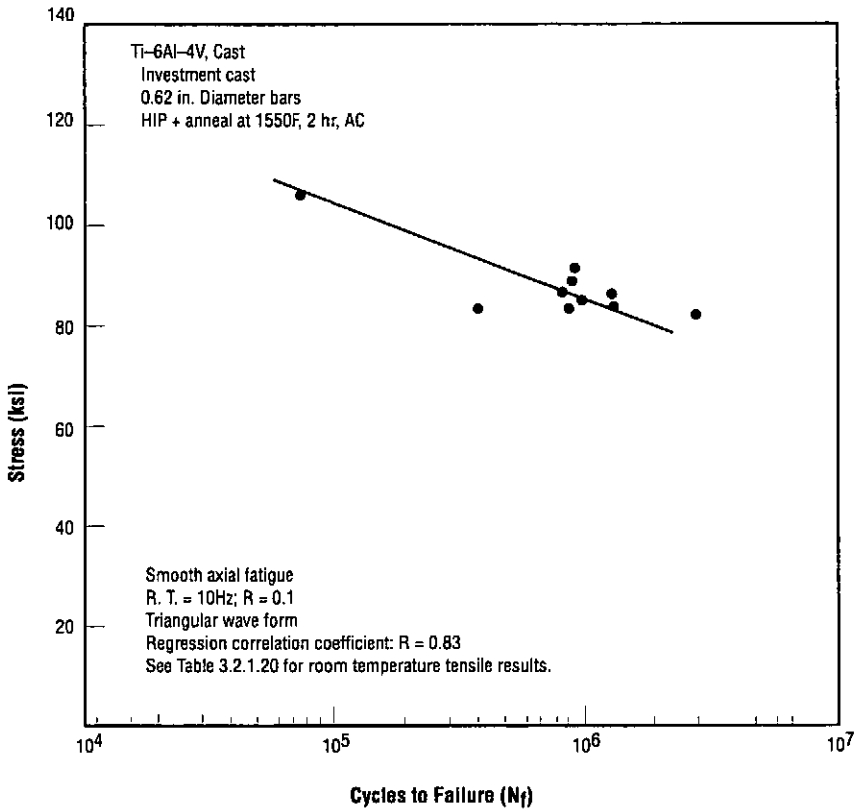


Figure 3.5.1.8 HCF data for annealed investment cast Ti-6Al-4V test bars (Ref. 28)

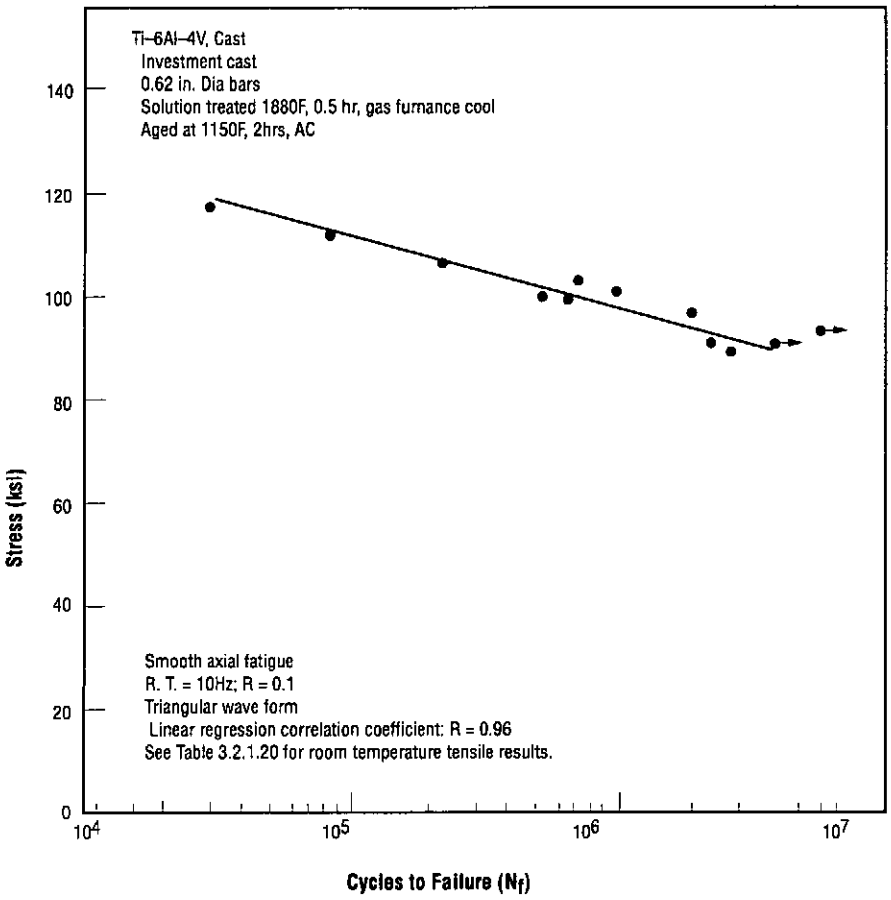


Figure 3.5.1.9 HCF data for investment cast Ti-6Al-4V test bars in the beta solution treated and aged condition (Ref. 28)

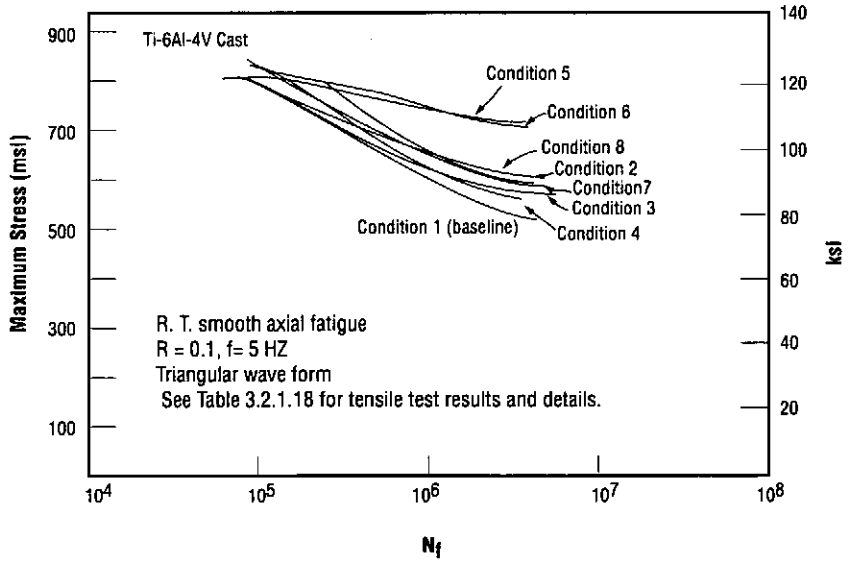


Figure 3.5.1.10 Comparison of average fatigue life curves for eight conditions (Ref. 31)

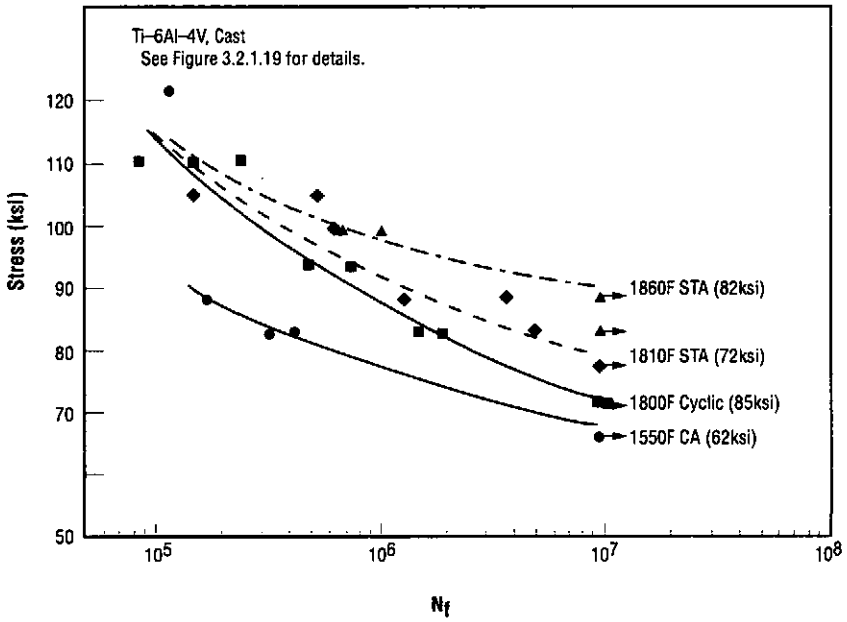
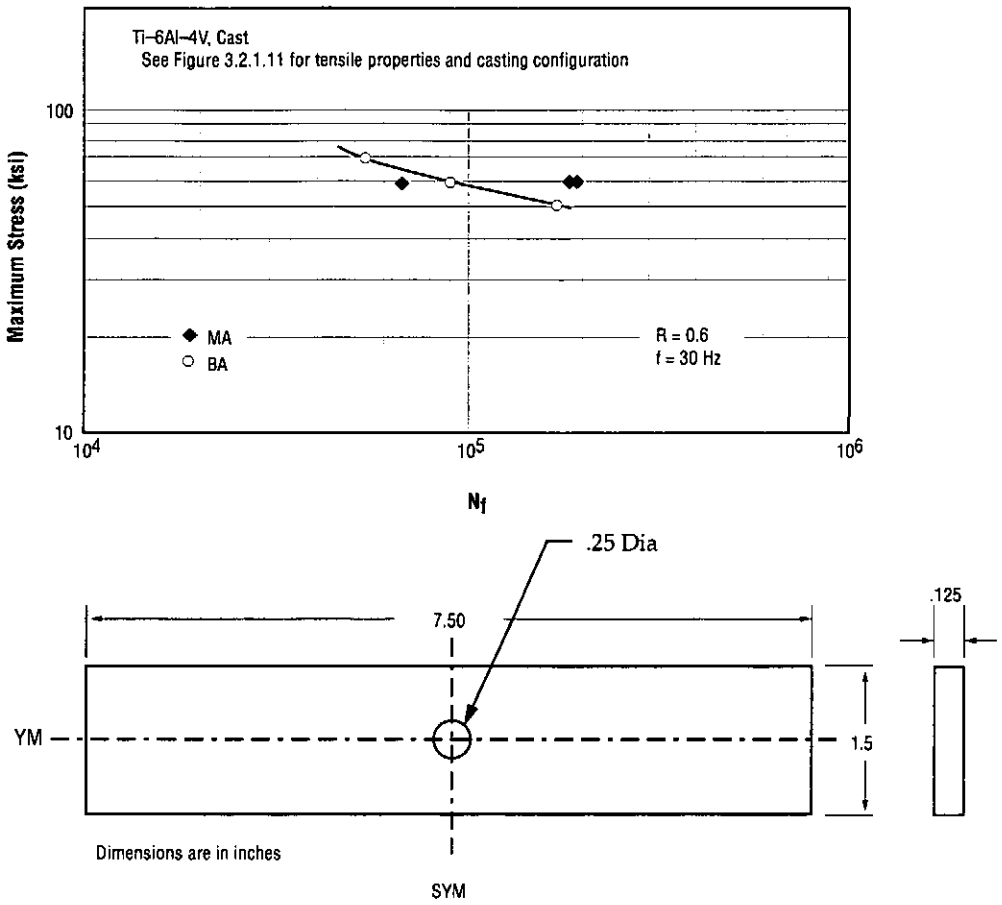
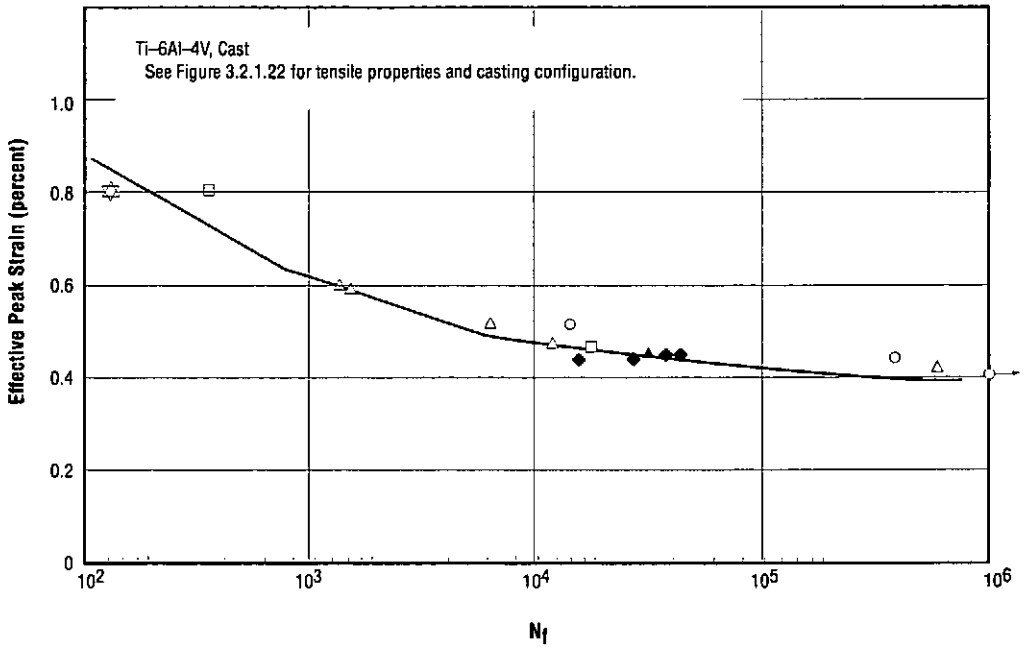


Figure 3.5.1.11 Effects of thermal treatment on the 70F HCF life of cast and HIP'ed Ti-6Al-4V alloy (Ref. 32)

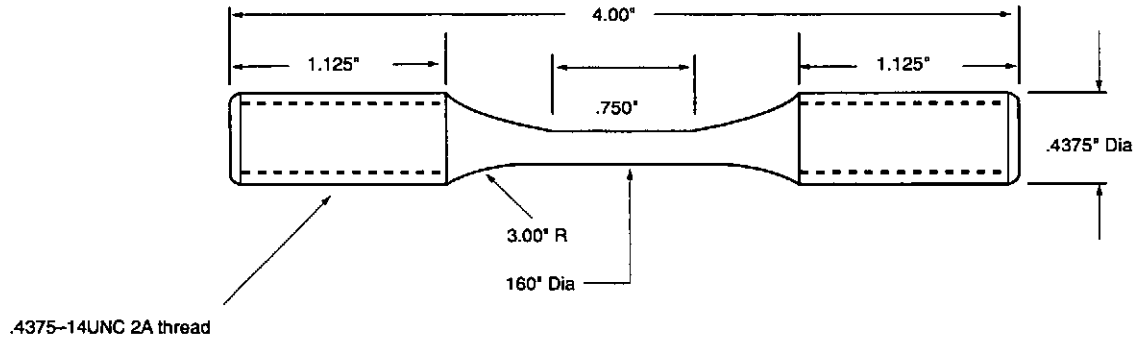


Open-hole fatigue specimen configuration, $K_t = 3.1$

Figure 3.5.1.12 Open-hole fatigue data comparing beta annealed (BA) to mill annealed (MA) (Ref. 34)



Open symbols represent beta annealed data with cooling rates of 67-157F/min. The solid symbols represent mill annealed data using a forced argon cool.



Strain life fatigue specimen configuration, $K_t = 1.0$

Figure 3.5.1.13 Strain-life fatigue data comparing beta annealed material to standard mill annealed condition (Ref. 34)

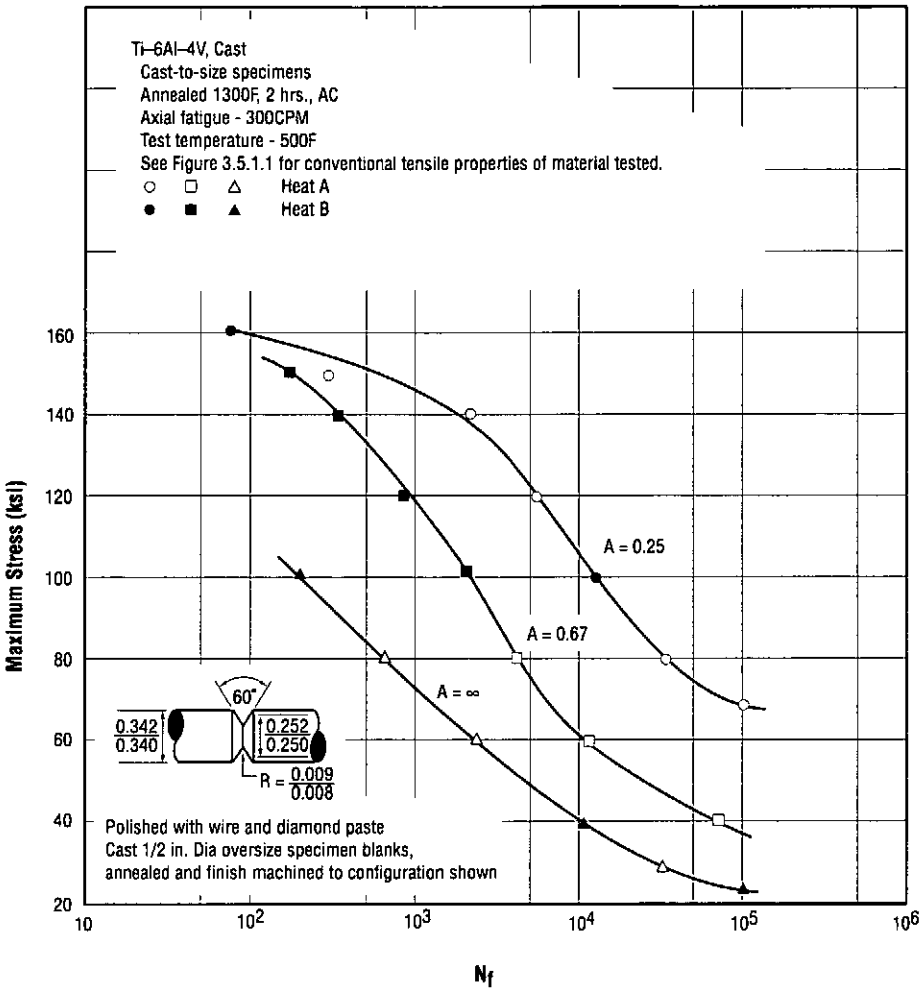


Figure 3.5.2.1 Low-cycle axial fatigue results at 500F for annealed mild-notch specimens cast-to-size from two heats (Ref. 4)

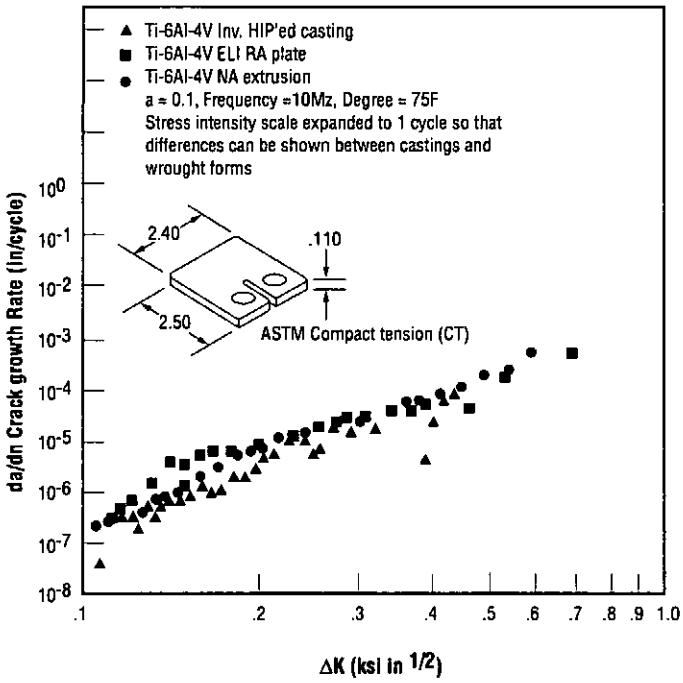


Figure 3.5.3.1 Fatigue crack-growth comparison (Ref. 26)

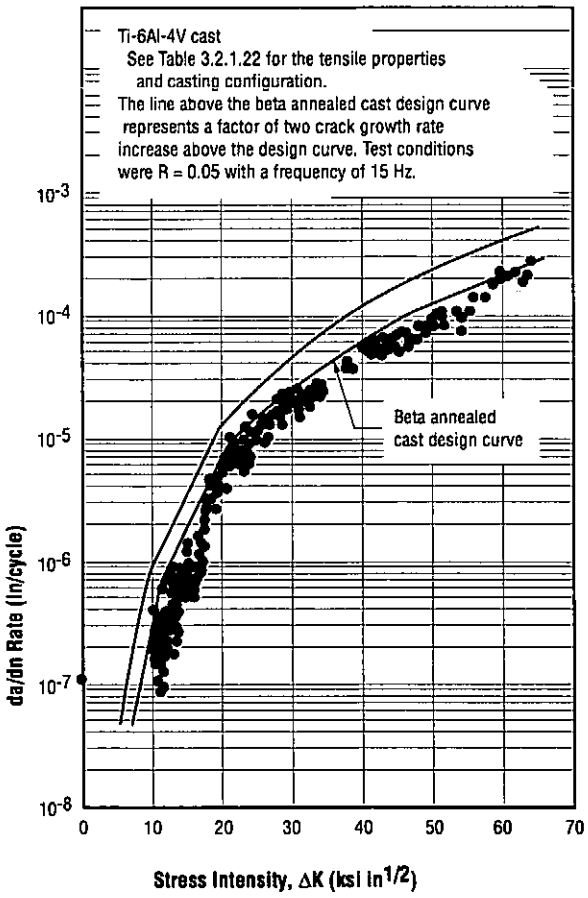


Figure 3.5.3.2 Crack-growth rate of Ti-6Al-4V mill annealed casting with no weld repair (Ref. 34)

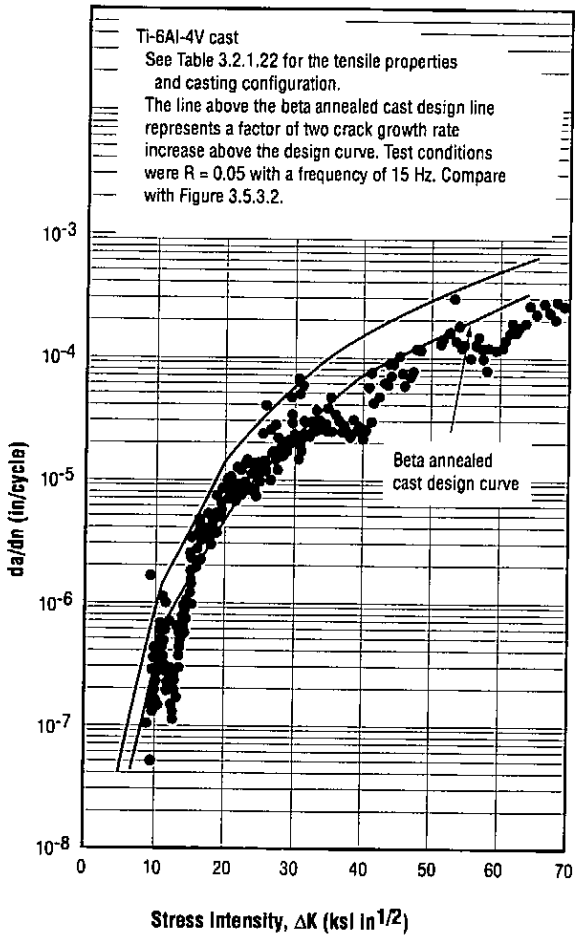


Figure 3.5.3.3 Crack-growth rate of weld repaired Ti-6Al-4V mill annealed casting (Ref. 34)

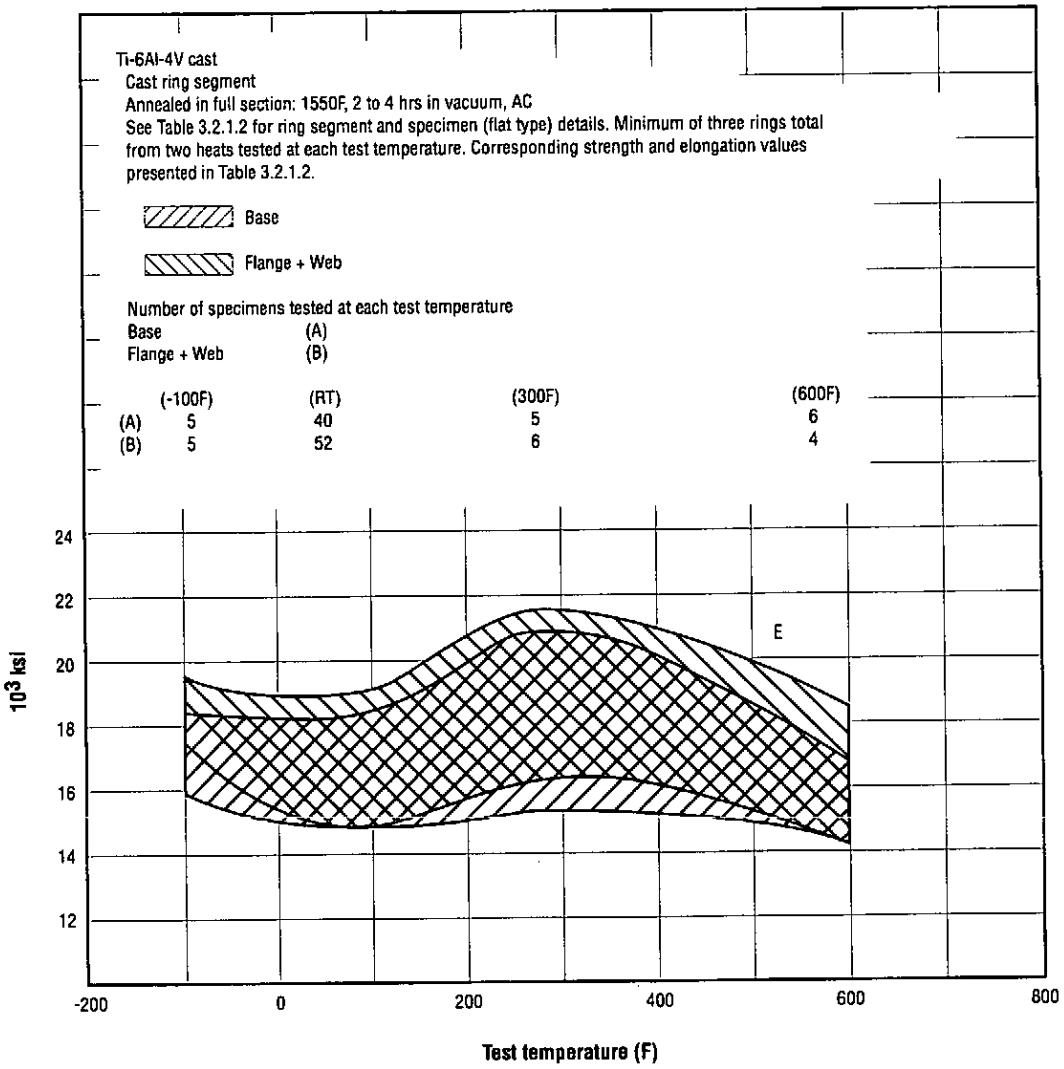


Figure 3.6.2.1 Effects of test temperature on tensile elastic modulus of elasticity of annealed cast ring segments from two heats (Ref. 5)

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RELEASED: MARCH 1970
AUTHOR: J. L. SHANNON

NONFERROUS ALLOYS

Ti
6 Al
4 V

Ti-6Al-4V Cast

1. GENERAL

Titanium castings have been produced commercially since the early 1960's. Most have been of static structural components, but applications involving rotating parts such as impellers, radial flow compressor wheels, and stub shafts are presently being considered (9). Design shapes that have been produced for aerospace applications include some impellers, brackets, window frames, hubs and bearing housings (11).

For comparable heat-treated conditions, Ti-6Al-4V castings exhibit the same or somewhat lower strength, ductility, creep rupture and fatigue strengths, and elevated temperature stability than their wrought counterparts.

The feeding of this alloy is less than that of steel casting alloys and repair welding is frequently required. Most of the data presented were obtained from castings which contained sound repair welds. The data indicate that repair welding, if done properly, has no perceptible influence on mechanical properties. Results from castings with obviously defective repair welds have not been included since such castings would normally be withheld from service.

1.01 Commercial Designation
6Al-4V Titanium Alloy, Cast.

1.02 Alternate Designations
Ti-6Al-4V, Cast; OMC 165-A; OMC 164-B.

1.03 Specifications
Table 1.03.

TABLE 1.03

Alloy	Ti-6Al-4V, Cast
Form	Investment Castings
Condition	Specification
As-cast	AVCO Corporation, Lycoming Division, Specification M3407, November 30, 1966
As-cast or annealed 1300 to 1550F, 1 to 8 hours in inert atmosphere or vacuum, cool in inert atmosphere	Precision Castparts Corporation, Specification TD-TCD-1, April 29, 1968
Annealed 1525 to 1575F, 2 to 4 hours, air cool	LTV Aerospace Corporation, Vought Aeronautics Division, Specification 207-4-401 Boeing Airplane Company Material Specification BMS 7-181* Lockheed Material, Specification C-03-1069*

* Copy of specification unavailable to author at time of writing.

1.04 Composition
1.041 Casting manufacturer's proposed specified composition, Table 1.041.

TABLE 1.041

Source	Precision Castparts Corporation (2)	
	Weight Percent	
	Minimum	Maximum
Aluminum	5.50	6.75
Vanadium	3.50	4.50
Iron	-	0.30
Carbon	-	0.10
Oxygen	-	0.20
Hydrogen	-	0.015
Nitrogen	-	0.07
Other Elements*	-	0.40
Titanium	Balance	

* Need not be reported.
(see 1.083 for preparation of metal for pouring)

1.042 User's specified composition, Table 1.042.

TABLE 1.042

Source	AVCO Corporation, Lycoming Division (1)	
	Weight Percent	
	Minimum	Maximum
Aluminum	5.50	6.75
Vanadium	3.50	4.50
Iron	-	0.30
Carbon	-	0.10
Oxygen	-	0.20
Hydrogen	-	0.0125
Nitrogen	-	0.05
Other Elements*	-	0.40
Titanium	Balance	

* Need not be reported.
(see 1.083 for preparation of metal for pouring)

1.05 Heat Treatment
(see also Ti-6Al-4V, Alloy Code 3707)

1.051 Anneal, 1300 to 1550F, 1 to 8 hours, AC.

1.052 Solution treat and age. Recommended solution treating and aging schedules have not yet been established. However, some developmental results are now available. Figure 3.0216 shows that solution temperatures high in the alpha-beta region result in increased strength but reduced ductility, and Figure 3.0217 shows that beta solution treating results in a reversion to low strength at aging temperatures of 1000 to 1100F with no improvement in ductility. Aging between 900 and 1100F provides only a modest range of achievable strength levels (Figures 3.0217 and 3.0218 and Table 3.0219). Quench delay time after solution treating in excess of 10 to 15 seconds produces lowered tensile properties with increased ductility (9)(6).

1.053 Salvage heat treatment. The strength of this alloy is markedly influenced by its oxygen content. As shown in Figure 3.03113, oxygen variations of as little as 0.01 weight percent can alter the strength by 1000 to 1500 psi. Master heats with oxygen levels below 0.13 weight percent often do not meet minimum strength requirements for the annealed condition. These heats require a salvage heat treatment of the type developed for forgings worked above the beta transus (9): 1750F, 1 hour, WQ + 1300F, 2 hours, AC.

1.0531 Effect of salvage heat treatment on the room temperature tensile properties of annealed, low oxygen cast-to-size specimens, Table 3.02110.

1.06 Hardness
Annealed condition, 311 BHN (3000 kg load) (3).

1.07 Forms and Conditions Available
Castings available in as-cast, annealed, and solution treated and aged conditions.

1.08 Melting and Casting Practice
1.081 Design parameters for precision castings for two casting manufacturers, Table 1.081

Ti
6 Al
4 V

Ti-6Al-4V
Cast

TABLE 1.081

Alloy	Ti-6Al-4V, Cast	
Form	Precision Castings	
Source	Precision Castparts Corporation (6)	Howmet Corporation, Misco Division (10)
Linear Tolerances	Length≤1 inch ± 0.010 inch per inch Length >1 inch ± 0.015 inch per inch	± 0.005 inch per inch minimum
Section Thickness	0.060 inch minimum wall	0.115 inch ± 0.015 inch minimum wall
Fillet Radii	1 to 2 1/2 times the adjoining section thickness	0.030 inch ± 0.015 inch minimum
Corners and Edges	0.030 inch ± 0.030 inch	0.030 inch ± 0.015 inch minimum
Draft	Preferred, 2 degrees	Preferred, 3 degrees
Core Limits:		
Supported Both Ends		
Length	4 x diameter maximum	3 x diameter maximum
Diameter	0.100 inch minimum	0.250 inch minimum
Supported one End		
Length	3 x diameter maximum	2 x diameter maximum
Diameter	0.200 inch minimum	0.250 inch minimum
Surface Quality	125 RMS or better	90 to 125 RMS
Size of Casting	12 inch depth, 20 inch diameter present 42 inch x 50 inch x 7 inch length, future.	24 inch x 24 inch x 24 inch
Weight of Casting	150 pounds maximum	

1.082 Skull melting. Early attempts at melting and casting titanium using induction furnaces were unsuccessful because of molten titanium's reactivity with and contamination from the furnace crucible. Noncontaminated melts are now produced by consumable electrode "skull" melting in a water-cooled or NaK-cooled copper crucible. A skin of solid titanium, called a "skull", is formed which provides a nonreactive wall between the molten titanium and the copper crucible. Melting is done under an inert gas or vacuum to prevent contamination with the atmosphere. When done under vacuum, 100 microns maximum pressure is claimed to result in the best arc stability and, consequently, minimal losses in alloy content (9).

The basic operation of skull melting is identical to conventional consumable arc melting, except that arc power (current) requirements are about twice that of conventional arc melting (9). This is so that a large molten pool forms rapidly and that a minimum of alloy solidifies before the melt is poured (13). The size of the molten pool will depend on melt rate, crucible size, and electrode configuration. When a sufficient pool is formed, the power is cut, the electrode stub withdrawn, and the charge poured into the mold by tilting the copper crucible. The complete sequence takes only a matter of minutes, with the casting portion taking only seconds. The time from electrode withdrawal to completion of pour is very critical due to the narrow solidification range of most titanium alloys, particularly Ti-6Al-4V (9).

The temperature of the melt is a continuous gradient from the hottest region (near the arc) to the coldest (near the crucible wall). It is desirable to estimate the melt temperature before pouring so that the optimum pouring temperature be established whereby castings free of laps, cold shuts, seams and misruns will be consistently poured (13). Direct temperature measurement is not easily made. With arc furnaces, radiation from the arc makes precise temperature measurements using optical pyrometers impossible. At least one attempt to use a thermocouple measurement of melt temperature was unsuccessful, but for unknown reason (13). Presently the average melt temperature is computed from the total energy input, and the heat distribution derived from the volume and temperature of the crucible coolant (9). Heat input is closely controlled by current and voltage settings to provide consistency among melts.

1.083 Master heats. Castings are poured either from remelted master heat metal or directly from the master heat (1)(2). A master heat is metal of a single furnace charge multiple melted using consumable electrode practice, at least one of the melting cycles being performed under vacuum. Gates, sprues, risers and rejected castings may be used in the preparation of a master heat but may not be remelted directly, without refining, for pouring of castings (1)(2). Castings are poured without loss of protective vacuum or inert gas atmosphere between melting and pouring.

1.09 Special Considerations

1.091 Metal-mold reaction. In common with unalloyed titanium and other titanium alloys, Ti-6Al-4V may react with mold materials producing a contaminated surface layer which is dependent on time, temperature, and the presence of the contaminating interstitial elements carbon, oxygen, hydrogen, and nitrogen. The layer is sometimes called "alpha case" (usually oxygen stabilized) and is extremely brittle, being as much as 20 RC higher in hardness than the uncontaminated base metal (6). Two of the three largest casting manufacturers allow metal-mold reactions to take place and subsequently chemically mill to remove contamination. The third casting manufacturer has developed a proprietary process by which he claims surface contamination is avoided, eliminating the need for subsequent processing. In all instances, case-free, dimensionally-accurate castings are furnished.

1.092 Fluidity, feeding and superheating. There appears to be some misuse of terms in the titanium casting literature as regards the ability to produce a sound casting of intricate detail. If fluidity is defined as the distance molten metal will flow in a given mold cavity, then titanium may be said to possess good fluidity (6). Feeding, on the other hand, is a term used to define the distance that will be soundly filled; and in this category titanium falls a bit short. Superheating before pouring will improve feeding for most alloys. However, effective superheating in the consumable electrode melting process cannot be accomplished because as the input power is increased, the electrode consumption rate is increased, not the temperature of the molten pool. This, coupled with the narrow solidification range for Ti-6Al-4V is responsible for its poor feeding characteristics. Since the stream of metal flowing into the mold is very near its solidification point, progressive solidification starts immediately with little chance for proper thermal gradients to set up and produce directional solidification. This leads to centerline shrinkage and entrapped gas porosity.

The tendency for gas formation (from an incompletely fired expendable mold or decomposition of absorbed water on the mold) and the poor feeding characteristics require much heavier gating and risering for Ti-6Al-4V than for a comparable steel casting alloy (7)(9).

While many experimental details are unavailable at the time of this writing, a recent study has shown that porosity in smooth, axial-load fatigue specimens does not appreciably influence performance unless the porosity is near or at the surface of the specimens (11). The influence of porosity on other material properties or of other types of casting imperfections on any property has not been investigated. Indeed, more study is indicated, particularly on the effect of casting defects on toughness, before extensive use of titanium castings in structural applications can be made.

1.093 Stability. For certain applications (particularly in commercial aircraft), metallurgical stability is an important design consideration. While no systematic investigations have been made to establish the threshold combinations of stress-time-temperature below which the alloy is metallurgically stable, very limited data (Tables 3.02111 and 3.02112) suggest that caution be excercised in the use of this alloy if stability is a design requirement.

1.094 Stress corrosion. The results presented in section 2.031 are too limited to form general conclusions regarding the stress corrosion characteristics of this alloy. On the basis of the results obtained on other titanium alloys, however, particular attention should be given to the influence of aggressive environments in the presence of cracks. Such environments include aqueous chloride solutions and possibly certain organic solvents such as methanol. For some applications, as in jet engines, hot salt stress corrosion characteristics would be necessary design information.

1.095 Erosion. It has been reported that titanium erodes approximately 40 percent faster than steel in engine-blading applications in jet engines (15). No data on this relatively unfamiliar characteristic are available at the time of this writing.

1.096 Interstitials. (see Ti-6Al-4V, Alloy Code 3707).

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range, 2800 to 3000F.

2.012 Phase changes. Alloy transforms on cooling from beta to alpha + beta at approximately 1825F.

2.0121 Time-temperature-transformation diagrams.

2.013 Thermal conductivity. At 400F, 5.1 Btu ft per (hr sq ft F), (see also Ti-6Al-4V, Alloy Code 3707).

2.014 Thermal expansion. From 68 to 800F, 5.2×10^{-6} inch per inch per F (see also Ti-6Al-4V, Alloy Code 3707).

2.015 Specific heat. At 400F, 0.137 Btu per (lb F). (see also Ti-6Al-4V, Alloy Code 3707).

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density, 0.161 lb per cu in, 4.5 gr per cu cm.

2.022 Electrical properties (see Ti-6Al-4V, Alloy Code 3707).

2.023 Magnetic properties (see Ti-6Al-4V, Alloy Code 3707).

2.024 Emittance (see Ti-6Al-4V, Alloy Code 3707).

2.025 Damping capacity.

2.03 Chemical Properties
(see also Ti-6Al-4V, Alloy Code 3707)

2.031 Bend specimens 6.0 inch x 0.50 inch x 0.06 inch were extracted from the web location, longitudinal direction of two cast ring segments of the type shown in Table 3.0212 and were exposed 1000 hours each at 80 and 100 ksi nominal stress levels in both 5 percent NaCl salt spray at 95F and NaCl coat at 550F with no failures or apparent damage (5).

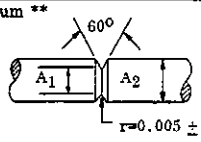
2.04 Nuclear Properties

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 Casting manufacturer's proposed specified mechanical properties, Table 3.011.

TABLE 3.011

Source	Precision Castparts Corporation (2)
Alloy	Ti-6Al-4V, Cast
Form	Investment Casting
Condition	As-Cast or Annealed 1300 to 1550F, 1 to 8 Hours in Inert Atmosphere or Vacuum, Cool in Inert Atmosphere
Conventional Room Temperature Tensile Properties*	
F_{tu} - ksi, minimum	130
F_{ty} - ksi, minimum	120
e(4D) - percent, minimum	5
RA - percent, minimum	10
Hardness, RC maximum	39
Room Temperature Notched Stress Rupture	
At 170 ksi, 5 hours minimum **	 Area A_1 = 1/2 Area A_2

* Separately cast smooth specimens from each master heat, cast in manner representative of parts to be cast, or smooth specimens machined from randomly selected castings; specimens of standard proportions with 0.25 inch uniform diameter.

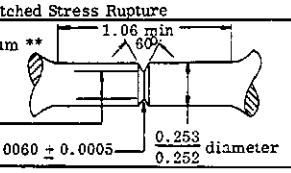
**Initial load may be less than 170 ksi and increased to 170 ksi in 10 ksi increments at intervals of not less than 5 hours.

Ti 6 Al 4 V

Ti-6Al-4V Cast

3.012 User's specified mechanical properties, Table 3.012.

TABLE 3.012

Source	AVCO Corporation, Lycoming Division (1)
Alloy	Ti-6Al-4V, Cast
Form	Investment Casting
Condition	As-Cast
Conventional Room Temperature Tensile Properties*	
F_{tu} - ksi, minimum	130
F_{ty} - ksi, minimum	120
e(4D) - percent, minimum	6.0
RA - percent, minimum	12.0
Room Temperature Notched Stress Rupture	
At 170 ksi, 5 hours minimum **	

* Eight separately cast smooth specimens required from each master heat, cast in manner representative of parts to be cast: 0.252 inch to 0.253 inch diameter x 1.06 inch minimum gage length.
Smooth specimens machined from randomly selected castings: 0.155 inch to 0.157 inch diameter x 1.06 inch minimum gage length.

**Initial load may be less than 170 ksi and increased to 170 ksi in 10 ksi increments at intervals of not less than 5 hours.

3.02 Mechanical Properties at Room Temperature

3.021 Tension (see also 3.031).

3.0211 Typical mechanical properties for as-cast condition, Table 3.0211.

TABLE 3.0211

Source	DMIC (3)	
Alloy	Ti-6Al-4V, Cast	
Form	Castings	
Condition	As-Cast	
Quality	Nonaircraft	Aircraft*
F_{tu} - ksi	145	147
F_{ty} - ksi	130	130
e - percent	8	10
E - 10^3 ksi	17.0	17.0
Hardness, BHN (3000 Kg Load)	321	311
IE, Standard Charpy-V ft lbs	15	17

* Low oxygen

Ti
6 Al
4 V

Ti-6Al-4V
Cast

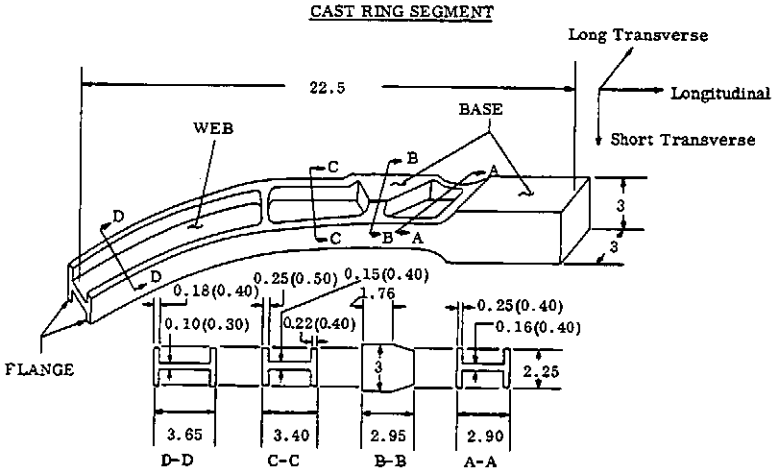
3.0212 Tensile properties including modulus of elasticity of annealed cast ring segments from two heats, Table 3.0212.

TABLE 3.0212

Source	LTV Aerospace Corporation, Vought Aeronautics Division (5)							
Alloy	Ti-6Al-4V, Cast							
Form	Cast Ring Segment							
Condition	Annealed 1550F, 2 to 4 Hours in Vacuum, AC (a)							
	Tensile Properties (b)							
	Heat A				Heat B			
	Spread of Values	Average	Number of Castings Tested	Total Number of Tests	Spread of Values	Average	Number of Castings Tested	Total Number of Tests
	BASE - Longitudinal, Long Transverse, and Short Transverse Directions (c)							
F_{tu} - ksi	126.7-139.0	134.0	3	23	124.0-137.5	132.7	2	15
F_{ty} - ksi	108.4-119.6	113.0	3	22(d)	102.1-114.9	110.2	2	15
E - 10^3 ksi	15.3- 18.2	16.7	3	24	14.9- 17.5	16.2	2	16
e(1 inch) percent	6.0- 9.0	7.3	3	23	4.0- 10.0	7.4	2	15
RA - percent	13.5- 29.6	20.6	2	7	15.8- 32.5	24.6	2	6
FLANGE - Longitudinal Direction								
F_{tu} - ksi	136.7-146.2	142.1	3	10(e)	135.8-147.9	141.2	3	18
F_{ty} - ksi	111.9-129.3	121.1	3	11	111.6-128.7	119.3	3	18
E - 10^3 ksi	15.5- 17.6	16.6	3	13	14.9- 19.0	16.7	3	19
e(1 inch) percent	4.0- 11.0	6.9	3	10(e)	4.0- 14.0	7.8	3	17(f)
WEB - Long Transverse Direction								
F_{tu} - ksi	136.7-149.6	142.2	3	9	140.1-150.5	142.7	3	11
F_{ty} - ksi	114.0-132.2	121.7	3	9	111.4-130.9	119.3	3	11
E - 10^3 ksi	15.6- 17.2	16.8	3	9	16.0- 17.7	16.7	3	11
e(1 inch) percent	4.0- 10.0	7.0	3	9	4.0- 11.0	7.5	3	11

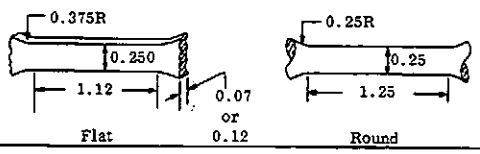
(a) Annealed in full section size.
(b) All values determined using flat specimens, except RA values, which were determined from separate round specimens.
(c) No directionality observed.
(d) Load-displacement curve incomplete for one test.
(e) One specimen failed outside test section.
(f) Not determined for one specimen.

CAST RING SEGMENT



Unbracketed flange and web dimensions are for cast-to-size ring segment; bracketed flange and web dimensions are for cast "oversize" ring segment. Results presented were obtained using specimens from ring segments of both sizes.

TEST SPECIMENS



Ti
6 Al
4 V

Ti-6Al-4V
Cast

3.0213 Tensile properties of as-cast, annealed, and solution treated and aged castings from three casting manufacturers, Table 3.0213.

TABLE 3.0213

Source	Lockheed-Georgia Company (8)			
Alloy	Ti-6Al-4V, Cast			
Form	Precision Castings			
	Room Temperature Tensile Properties			
Condition	F_{tu} ksi	F_{ty} ksi	e(1 inch) percent	RA percent
Casting Manufacturer Number 1 (a)(b)				
As-Cast	139	127	6.1	15.2
Annealed (c)	134	126	6.6	21.6
Solution Treated + Age (d)	162	152	3.7	12.2
Casting Manufacturer Number 2 (e)(f)				
Solution Treat + Age (d)	156	136	3.0	3.1
Casting Manufacturer Number 3 (g)(h)				
Solution Treat + Age (d)	152	140	8.0	-

(a) 10 pound casting; section thicknesses from 0.2 inch to 2.0 inches; 0.125 inch diameter specimens selected randomly from both thickness extremes and at random orientations with respect to casting geometry.
(b) Each value average of four tests minimum.
(c) Annealed in full section size: 1300F, 2 hours, AC.
(d) Solution treated and aged in full section size: 1750F, 25 minutes, WQ + 1000F, 4 hours, AC.
(e) 1 pound casting; section thickness 0.43 inch; 0.25 inch diameter specimens, all located parallel to longitudinal axis of casting.
(f) Each value average of three tests.
(g) 1 pound casting; section thickness 0.4 inch in vicinity of specimen extraction; 0.25 inch diameter specimens, all located in common direction with respect to casting geometry.
(h) Each value average of four tests.

Each casting manufacturer used his own heat.

3.0214 Variation in tensile properties of five master heats for the as-cast and annealed conditions, Figure 3.0214.

3.0215 Typical tensile properties for a solution treated and annealed condition and two solution treated and aged conditions, Table 3.0215.

TABLE 3.0215

Source	Precision Castparts Corporation (6)		
Alloy	Ti-6Al-4V, Cast		
Form	Precision Castings		
Condition	Solution Treat+ Anneal	Solution Treat + Age	
	(a)	(b)	(c)
F_{tu} - ksi	146.5	168.6	155.0
F_{ty} - ksi	134.0	152.3	140.5
e(4D) - percent	7.5	4.0	6.3
RA - percent	11.9	8.0	12.7

(a) 1735F, 1 hour in Argon, 15 second quench delay, WQ + 1300F, 2 hours in Argon, AC.
(b) 1750F, 1 hour in Argon, 15 second quench delay, WQ + 1000F, 4 hours in Argon, AC.
(c) 1650F, 1 hour in Argon, 15 second quench delay, WQ + 1000F, 4 hours in Argon, AC.

3.0216 Effect of solution treat temperature on tensile properties of solution treated and aged cast-to-size specimens Figure 3.0217.

3.0217 Effect of solution treat and aging temperatures on tensile properties of cast compressor casing, Figure 3.0217.

3.0218 Effect of aging temperature on tensile properties of three compressor casings cast from one heat, Figure 3.0218.

3.0219 Effect of aging temperature on tensile properties of cast-to-size specimens, Table 3.0219.

TABLE 3.0219

Source	Precision Castparts Corporation (9)				
Alloy	Ti-6Al-4V, Cast				
Form	Cast-to-Size Specimens*				
Condition	1725F, 1 Hour in Argon, 15 Second Quench Delay, WQ + Age				
Aging		Room Temperature Tensile Properties**			
Temperature F	Time Hours	F_{tu} ksi	F_{ty} ksi	e(1 inch) percent	RA percent
950	2	178.9	163.3	3.0	5.1
1000	4	173.3	160.4	3.7	5.0
1100	4	170.0	158.2	4.4	6.1

* Cast to 5/8 inch diameter blanks and machined to 0.252 inch diameter specimens.
** Each value average of two tests.

3.02110 Effect of salvage heat treatment on tensile properties of annealed, low-oxygen cast-to-size specimens, Table 3.02110.

TABLE 3.02110

Source	Precision Castparts Corporation (9)			
Alloy	Ti-6Al-4V, Cast			
Form	Cast-to-Size Specimens			
		Room Temperature Tensile Properties (a)		
Oxygen Content Weight Percent	Heat Treatment	F_{tu} ksi	F_{ty} ksi	e(1 inch) percent
0.113 / 0.116	Anneal (b)	131.0	118.4	11.5
	Salvage (c)	143.9	131.6	8.3
0.118 / 0.124	Anneal (b)	132.3	119.4	10.7
	Salvage (c)	148.4	136.9	8.1

(a) Each value average of eight tests on six master heats.
(b) 1300F, 2 hours, AC.
(c) 1750F, 1 hour, WQ + 1300F, 2 hours, AC.

3.02111 Effect of exposure to elevated temperatures with load on tensile properties of annealed cast compressor casing, Table 3.02111.

TABLE 3.02111

Source			AVCO Corporation, Lycoming Division (4)			
Alloy			Ti-6Al-4V, Cast			
Form			Cast Compressor Casing (a)			
Condition			Annealed 1300F, 2 Hours, AC (b)			
Specimen Exposure Conditions			Subsequent Room Temperature Tensile Properties (c)(d)			
Temp F	Stress ksi	Time Hours	F_{tu} ksi	F_{ty} ksi	e(1 inch) percent	RA percent
Unexposed		Average	143.9	131.0	9.4	15.5
		Spread	161.5/139.5	143.1/126.5	12.0/4.0	20.3/7.9
700	90	529.3	148.6	146.5	3.0	5.4
700	85	528.9	152.8	148.2	4.0	7.2
700	85	1510.0	155.1	154.7	2.0	8.2
700	80	1603.3	152.8	147.4	7.0	12.6
900	45	500.0	153.1	150.2	6.0	8.9

(a) See Figure 3.0311 for compressor casing (20 inches long) and specimen details.
(b) Casing annealed in full section size.
(c) Specimens tested as exposed; surface not dressed.
(d) Unexposed values from fifteen tests; exposed values from individual tests.

Ti
6 Al
4 V

Ti-6Al-4V Cast

3.02112 Effect of 1000 hours exposure at 550F without load on tensile properties including elastic modulus of annealed cast ring segment from two heats, Table 3.02112.

TABLE 3.02112

Source	LTV Aerospace Corporation, Vought Aeronautics Division (5)					
Alloy	Ti-6Al-4V, Cast					
Form	Cast Ring Segment (a)					
Condition	Annealed 1550F, 2 to 4 Hours in Vacuum, AC (b)					
			Room Temperature Tensile Properties			
Casting	Specimen (c) Orientation	Exposure Condition	F_{tu} ksi	F_{ty} ksi	E 10^3ksi	e(1 inch) percent
BASE (a) - Heat A						
1	Long Trans	Unexposed	134.6	111.9	15.4	8.0
1	Long Trans	Unexposed	135.4	110.0	16.5	9.0
1	Long Trans	Exposed (d)	134.5	123.0	17.1	3.0
2	Short Trans	Unexposed	126.7	110.7	16.6	8.0
2	Short Trans	Unexposed	138.4	(e)	(e)	9.0
2	Short Trans	Exposed (d)	140.7	125.1	16.8	7.0
BASE (a) - Heat B						
1	Long Trans	Unexposed	135.9	112.6	16.0	9.0
1	Long Trans	Unexposed	131.6	108.5	17.5	6.0
1	Long Trans	Exposed (d)	147.4	124.8	16.8	8.0
2	Short Trans	Unexposed	129.9	103.7	14.9	10.0
2	Short Trans	Unexposed	136.7	112.0	15.2	7.0
2	Short Trans	Unexposed	137.5	114.8	16.0	4.0
2	Short Trans	Exposed (d)	144.3	124.4	16.5	9.0
FLANGE (a) - Heat A						
1	Longitudinal	Unexposed	140.9	116.2	17.0	5.0
1	Longitudinal	Unexposed	140.8	115.8	16.3	7.0
1	Longitudinal	Unexposed	139.8	113.8	16.4	6.0
1	Longitudinal	Unexposed	136.7	111.9	16.2	6.0
1	Longitudinal	Unexposed	-	-	17.5	-
1	Longitudinal	Unexposed	142.6	121.0	16.6	6.0
1	Longitudinal	Exposed (d)	146.1	133.0	17.1	5.0
2	Longitudinal	Unexposed	143.3	120.7	17.3	9.0
2	Longitudinal	Unexposed	-	-	16.3	-
2	Longitudinal	Unexposed	146.2	129.3	16.5	11.0
2	Longitudinal	Exposed (d)	149.7	131.4	17.5	4.0
FLANGE (a) - Heat B						
1	Longitudinal	Unexposed	139.5	115.8	16.7	6.0
1	Longitudinal	Unexposed	138.9	113.7	16.8	7.0
1	Longitudinal	Unexposed	143.6	117.8	16.8	10.0
1	Longitudinal	Unexposed	137.1	111.6	15.2	7.0
1	Longitudinal	Unexposed	144.3	118.1	16.4	6.0
1	Longitudinal	Unexposed	140.5	117.8	16.3	10.0
1	Longitudinal	Unexposed	-	-	17.7	-
1	Longitudinal	Unexposed	143.3	123.5	19.0	8.0
1	Longitudinal	Unexposed	142.1	124.2	16.4	6.0
1	Longitudinal	Unexposed	138.5	112.8	17.7	8.0
1	Longitudinal	Unexposed	142.5	128.7	14.9	4.0
1	Longitudinal	Exposed (d)	148.3	130.1	17.0	9.0
2	Longitudinal	Unexposed	140.2	116.5	17.2	10.0
2	Longitudinal	Unexposed	143.7	122.3	16.0	12.0
2	Longitudinal	Unexposed	139.2	119.9	16.7	14.0
2	Longitudinal	Unexposed	135.8	117.7	16.4	7.0
2	Longitudinal	Unexposed	142.1	126.7	16.9	(f)
2	Longitudinal	Exposed (d)	148.3	130.1	17.6	6.0

(a) See Table 3.0212 for ring segment details.
(b) Annealed in full section size.
(c) See Table 3.0212 for specimen configuration (flat type) and orientation.
(d) Exposed 550F, 1000 hours.
(e) Incomplete load-displacement curve.
(f) Bad reading.

3.02113 Effect of oxygen content on tensile properties of annealed cast-to-size specimens, Figure 3.02113.

3.02114. Typical room temperature stress-strain curves for annealed cast ring segments from two heats, Figure 3.02114.

3.022 Compression.

3.0221 Compressive yield strength and modulus of elasticity of cast ring segments from two heats, Table 3.0221.

TABLE 3.0221

Source	LTV Aerospace Corporation, Vought Aeronautics Division (5)			
Alloy	Ti-6Al-4V, Cast			
Form	Cast Ring Segment (a)			
Condition	Annealed 1550F, 2 to 4 Hours in Vacuum, AC (b)			
	Specimen (c)		Room Temperature Compressive Properties	
Heat	Casting	Location(a)	Orientation (a)	F_{cy} ksi	E_c 10^3 ksi
A	1	Base	Longitudinal	124.9	21.6
A	1	Base	Long Trans	123.5	20.5
A	2	Base	Short Trans	121.9	15.8
A	2	Base	Short Trans	129.5	17.5
B	1	Base	Longitudinal	130.6	17.5
B	1	Base	Long Trans	125.6	16.9
B	2	Base	Short Trans	123.1	17.5
A	2	Flange	Longitudinal	145.4	15.4
B	2	Flange	Longitudinal	145.4	17.4
A	3	Web	Longitudinal	151.4	16.9
A	3	Web	Longitudinal	154.1	16.5
B	1	Web	Longitudinal	140.4	18.5
B	1	Web	Longitudinal	132.4	17.1
B	2	Web	Long Trans	140.1	18.3
B	3	Web	Long Trans	136.4	16.4

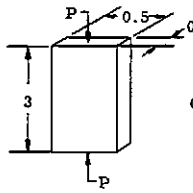
(a) See Table 3.0212 for ring segment and specimen orientation details.
(b) Annealed in full section size.
(c) Specimen 2.70 inches long, 0.65 inch wide and 0.10 inch thick.

For comparative tensile properties, see Table 3.0212

3.0222 Compressive yield strength and modulus of elasticity of as-cast, annealed and solution treated and aged castings from two separate casting manufacturers, Table 3.0222.

TABLE 3.0222

Source	Lockheed-Georgia Company (8)		
Alloy	Ti-6Al-4V, Cast		
Form	Precision Castings		
	Room Temperature Properties		
Condition	F_{ty} - ksi (a)	F_{cy} - ksi (b)	E_c - 10^3 ksi (b)
Casting Manufacturer Number 1 (c)			
As-Cast	127	137	16.7
Anneal (d)	126	143	17.0
Solution Treat+Age (e)	152	179	17.2
Casting Manufacturer Number 2 (f)			
Solution Treat+Age (e)	136	145	-



Compression Specimen

(a) Each value average of three tests minimum.
(b) Each value average of two tests minimum.
(c) 10 pound casting; section thicknesses from 0.2 inch to 2.0 inches; specimens selected randomly from both thickness extremes and at random orientations with respect to casting geometry.
(d) Annealed in full section size: 1300F, 2 hours, AC.
(e) Solution treated and aged in full section size: 1750F, 25 minutes, WQ + 1000F, 4 hours, AC.
(f) 1 pound casting; section thickness 0.43 inch; all specimens located parallel to longitudinal axis of casting.

Castings furnished by manufacturer Number 1 were from different heat than castings furnished by manufacturer Number 2.

3.023 Impact (see also Table 3.0211).
3.0231 Standard Charpy-V impact energy of annealed cast-to-size specimens from two heats, Table 3.0231.

TABLE 3.0231

Source		AVCO Corporation, Lycoming Division (4)
Alloy		Ti-6Al-4V, Cast
Form		Cast-to-Size Specimens
Condition		Annealed 1300F, 2 Hours, AC*
Heat	Specimen Number	IE, Standard Charpy-V ft lbs
A	1	19.5
A	2	20.0
A	3	20.0
A	4	21.0
A	5	20.0
B	1	21.0
B	2	19.0
B	3	20.0
B	4	21.0
B	5	20.0

*Conventional tensile properties:
Heat A: F_{tu} = 144.8 ksi, F_{ty} = 127.3 ksi, e(1 inch) = 11.7 percent, RA = 25.8 percent
Heat B: F_{tu} = 145.1 ksi, F_{ty} = 132.7 ksi, e(1 inch)= 10.5 percent, RA = 21.6 percent

3.0232 Standard Charpy-V impact energy of annealed cast ring segments from two heats, Table 3.0232.

TABLE 3.0232

Source		LTV Aerospace Corporation, Vought Aeronautics Division (5)			
Alloy		Ti-6Al-4V, Cast			
Form		Cast Ring Segment (a)			
Condition		Annealed 1550F, 2 to 4 Hours in Vacuum, AC (b)			
				Room Temperature Properties	
Heat	Casting	Specimen Location(a)	Specimen Orientation(a)	F_{ty} ksi	IE, Std Charpy-V ft lbs
A	1	Base	Long Trans	111.9	19.0
A	1	Base	Long Trans	110.0	16.0
A	1	Base	Short Trans	114.9	15.0
A	1	Base	Short Trans	110.9	15.0
A	2	Base	Longitudinal	110.2	18.0
A	2	Base	Longitudinal	111.8	-
A	2	Base	Long Trans	111.1	16.0
A	2	Base	Short Trans	110.7	18.0
B	1	Base	Short Trans	114.3	15.0
B	1	Base	Short Trans	102.1	15.0
B	2	Base	Longitudinal	104.8	21.0
B	2	Base	Longitudinal	108.5	-
B	2	Base	Long Trans	110.4	18.0
B	2	Base	Long Trans	110.9	19.0
B	2	Base	Long Trans	114.9	17.0
B	2	Base	Short Trans	103.7	14.0
B	2	Base	Short Trans	112.0	-
B	2	Base	Short Trans	114.8	-
A	1	Flange	Longitudinal	111.9-121.0(c)	14.0
B	1	Flange	Longitudinal	111.6-128.7(d)	14.0

(a) See Table 3.0212 for ring segment and specimen orientation details.
(b) Annealed in full section size.
(c) Range of values from five tests.
(d) Range of values from ten tests.

3.0233 Standard Charpy-V impact energy of solution treated and aged casting, Table 3.0233.

Ti	
6	Al
4	V

Ti-6Al-4V Cast

TABLE 3.0233

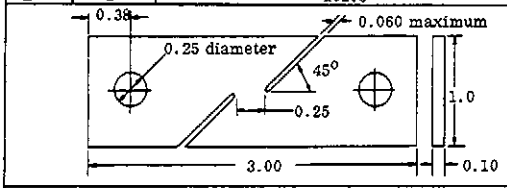
Source	Lockheed-Georgia Company (8)
Alloy	Ti-6Al-4V, Cast
Form	Precision Casting (a)
Condition	Solution Treat + Age (b)
IE, Standard Charpy-V (ft lbs)	8.46 (c)

(a) 1 pound casting; section thickness 0.43 inch.
(b) Solution treated and aged in full section size: 1750F, 25 minutes, WQ + 1000F, 4 hours, AC.
(c) Single value from specimen oriented parallel to longitudinal axis of casting.

3.024 Bending.
3.025 Torsion and shear.
3.0251 Shear strength of annealed cast ring segments from two heats, Table 3.0251.

TABLE 3.0251

Source		LTV Aerospace Corporation, Vought Aeronautics Division (5)
Alloy		Ti-6Al-4V, Cast
Form		Cast Ring Segment (a)
Condition		Annealed 1550F, 2 to 4 Hours in Vacuum, AC (b)
Heat	Casting	F_{su} (c)(d) - ksi
A	1	93.9
A	2	95.3
A	3	95.3
B	1	94.4
B	2	102.5



(a) See Table 3.0212 for ring segment details.
(b) Annealed in full section size.
(c) Flange location, longitudinal direction (see Table 3.02141).
(d) Values average of from two to seven tests for each casting.
See Table 3.0212 for corresponding conventional tensile properties.

3.0252 Double shear strength of solution treated and aged casting, Table 3.0252.

TABLE 3.0252

Source	Lockheed-Georgia Company (8)
Alloy	Ti-6Al-4V, Cast
Form	Precision Casting (a)
Condition	Solution Treat + Age (b)
F_{su} - ksi	94.7(c)

(a) 1-pound casting; section thickness 0.43 inch; 0.375 inch diameter double-shear specimens oriented parallel to longitudinal axis of casting.
(b) Solution treated and aged in full section size: 1750F, 25 minutes, WQ + 1000F, 4 hours, AC.
(c) Average of two tests.

Ti
6 Al
4 V

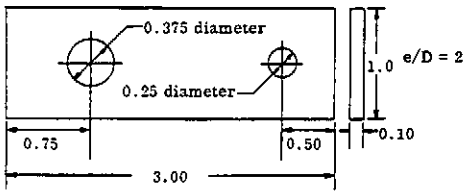
Ti-6Al-4V
Cast

3.026 Bearing.
3.0261 Bearing strength of annealed cast ring segments from two heats, Table 3.0261.

3.027 Stress concentration.
3.0271 Notch properties.
3.02711 Mild-notch strength of annealed cast ring segments from two heats, Table 3.02711.

TABLE 3.0261

Source	LTV Aerospace Corporation, Vought Aeronautics Division (5)		
Alloy	Ti-6Al-4V, Cast		
Form	Cast Ring Segment (a)		
Condition	Annealed 1550F, 2 to 4 Hours in Vacuum, AC (b)		
Heat	Casting	F_{bru}(c)(d) - ksi	F_{bry}(c)(d) - ksi
A	1	283.0	224.6
A	2	279.4	227.7
A	3	253.3	209.1
B	1	279.6	214.9
B	2	300.1	245.4



(a) See Table 3.0212 for ring segment details.
(b) Annealed in full section size.
(c) Flange location, longitudinal direction (see Table 3.0212).
(d) All values are averages of from two to six tests for each casting except that for casting 2, Heat B, which is a single datum point.
See Table 3.0212 for corresponding conventional tensile properties.

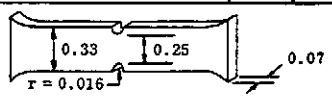
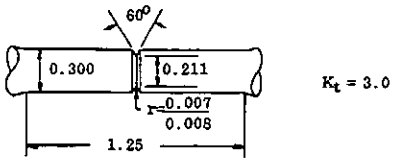
3.0262 Bearing strength of solution treated and aged casting, Table 3.0262.

TABLE 3.0262

Source	Lockheed-Georgia Company (8)	
Alloy	Ti-6Al-4V, Cast	
Form	Precision Casting (a)	
Condition	Solution Treat + Age (b)	
Room Temperature Bearing Properties (c)		
F_{bru} - ksi	F_{bry} - ksi	e/D
216	(d)	1.50
240	234	1.52
244	224	1.50

(a) 1 pound casting; section thickness 0.43 inch; specimens oriented parallel to longitudinal axis of casting.
(b) Solution treated and aged in full section size: 1750F, 25 minutes, WQ + 1000F, 4 hours, AC.
(c) Specimen thickness = 0.090 inch; D = 0.187 inch.
(d) Bearing failure occurred before 0.2 percent strain was achieved.

TABLE 3.02711

Source	LTV Aerospace Corporation, Vought Aeronautics Division (5)		
Alloy	Ti-6Al-4V, Cast		
Form	Cast Ring Segment (a)		
Condition	Annealed 1550F, 2 to 4 Hours in Vacuum, AC (b)		
		Room Temperature Properties	
Casting	Specimen Orientation (c)	F_{ty} - ksi	NTS - ksi
			K_t = 3.0
	BASE (a) - Heat A		
1	Long Transverse	110.0	166.1
1	Long Transverse	111.9	-
2	Longitudinal	110.2	172.4
2	Longitudinal	111.8	-
2	Short Transverse	110.7	146.0
	BASE (a) - Heat B		
1	Long Transverse	112.6	152.2
1	Long Transverse	108.5	-
2	Longitudinal	104.8	159.5
2	Longitudinal	108.5	-
2	Short Transverse	103.7	155.9
2	Short Transverse	112.0	-
2	Short Transverse	114.8	-
	FLANGE (a) - Heat A		
2	Longitudinal	120.7	167.9
2	Longitudinal	129.3	-
	FLANGE (a) - Heat B		
2	Longitudinal	116.5	165.2
2	Longitudinal	122.3	-
2	Longitudinal	119.9	-
2	Longitudinal	117.7	-
2	Longitudinal	126.7	
	WEB (a) - Heat B		
1	Longitudinal	113.6	160.3
1	Longitudinal	118.4	-
1	Longitudinal	111.4	-
2	Long Transverse	120.2	168.4
2	Long Transverse	126.7	-
2	Long Transverse	123.1	-
2	Long Transverse	123.0	-
			K_t = 3.0
	BASE (a) - Heat A		
2	Longitudinal	122.5	157.3
2	Longitudinal	123.5	-
	BASE (a) - Heat B		
2	Longitudinal	118.6	154.2
2	Longitudinal	125.2	-

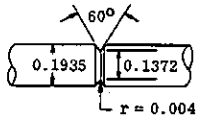
(a) See Table 3.0212 for ring segment details.
(b) Annealed in full section size.
(c) See Table 3.0212 for specimen orientations relative to casting configuration.

Ti
6 Al
4 V
Ti-6Al-4V
Cast

3.02712 Mild-notch strength of as-cast, annealed, and solution treated and aged castings, Table 3.02712.

TABLE 3.02712

Source	Lockheed-Georgia Company (8)	
Alloy	Ti-6Al-4V, Cast	
Form	Precision Casting (a)	
	Room Temperature Properties	
Condition	F_{tv} - ksi (b)	NTS - ksi (c)
As-Cast	127	202
Anneal (d)	126	207
Solution Treat + Age (e)	152	216



$K_t = 3.9$

(a) 10 pound casting; section thicknesses from 0.2 inch to 2.0 inches, specimens selected randomly from both thickness extremes and at random orientations with respect to casting geometry.
(b) Each value average of four tests minimum.
(c) Each value average of three tests.
(d) Annealed in full section size: 1300F, 2 hours, AC.
(e) Solution treated and aged in full section size: 1750F, 25 minutes, WQ + 1000F, 4 hours, AC.

3.0272 Fracture toughness. No data are available on the plane strain fracture toughness of this alloy in the cast condition. For applications where the alloy's fracture toughness may be the limiting design consideration, these data should be developed. Inasmuch as the ductility of this alloy in the cast form is less than that for its wrought counterpart, to say nothing of the basic difference in structure for the two forms, existing toughness data for the wrought form should not be applied to cast material.

3.028 Combined properties.

3.03 Mechanical Properties at Various Temperatures

3.031 Tension.

3.0311 Effect of test temperature on tensile properties of five annealed cast compressor casings from three heats, Figure 3.0311.

3.0312 Effect of test temperature on tensile properties of specimens machined from annealed cast compressor casings and annealed cast-to-size specimens each from two heats, Figure 3.0312.

3.0313 Effect of test temperature on tensile properties of annealed cast ring segments from two heats, Figure 3.0313.

3.0314 Stress-strain diagrams (see 3.02111).

3.032 Compression (see 3.022).

3.0321 Stress-strain diagrams.

3.033 Impact (see 3.023).

3.034 Bending.

3.035 Torsion and shear (see 3.025).

3.036 Bearing (see 3.026).

3.037 Stress concentration.

3.0371 Notch properties (see 3.0271).

3.0372 Fracture toughness (see 3.0272).

3.038 Combined properties.

3.04 Creep and Creep Rupture Properties

3.041 Stress rupture curves at 700, 800, and 900F for specimens machined from five annealed cast compressor casings from three heats, Figure 3.041.

3.042 Creep rupture curves at 700, 800, 900, and 1000F for specimens machined from annealed cast compressor casing and annealed cast-to-size specimens from one heat, Figure 3.042.

3.043 Stress rupture curves at 700, 800, and 900F for specimens machined from cast compressor casing aged at 1000F, Figure 3.043.

3.044 Effect of solution treat and aging temperatures on 800F, 80 ksi stress rupture life of cast compressor casing, Table 3.044.

TABLE 3.044

Source	AVCO Corporation, Lycoming Division (4)	
Alloy	Ti-6Al-4V, Cast	
Form	Cast Compressor Casing (a)	
Condition	Solution Treated and Aged (b)	
	Stress Rupture Properties at 800F, 80 ksi	
Age Temperature, 8 hours, AC F	Time to Rupture hours	e(1 inch) percent
Solution Treat 1750F, 1 hour, WQ		
900	500.2	-
900	510.7	-
900	512.8	-
1000	502.1 (c)	-
1000	501.2 (c)	-
1000	504.3 (c)	-
1000	757.3	14.6
1100	502.1 (c)	-
1100	503.2 (c)	-
Solution Treat 1850F, 1 hour, WQ		
900	549.6 (c)	-
900	548.4 (c)	-
900	546.6 (c)	-
1000	540.5 (c)	-
1000	526.8 (c)	-
1000	521.7 (c)	-
1100	506.6 (c)	-
1100	504.5 (c)	-
1100	504.2 (c)	-

(a) See Figure 3.0311 for compressor casing (12 inches long) and specimen details.
(b) Casing halved and solution treated; aging applied to 1/2 inch square specimen blanks. See Figure 3.0217 for room temperature tensile properties of material tested.
(c) Test retired.

Ti
6 Al
4 V

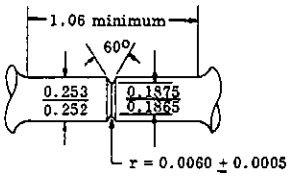
Ti-6Al-4V Cast

3.045 Room temperature stress rupture results for mild-notch specimens machined from annealed cast compressor casing and annealed cast-to-size specimens, Table 3.045.

3.046 500F stress rupture properties of cast-to-size smooth and mild-notch specimens from two heats, Table 3.046.

TABLE 3.045

Source		AVCO Corporation, Lycoming Division (4)				
Alloy		Ti-6Al-4V, Cast				
Form		Cast Compressor Casing (a) or Cast- to-Size Specimens (b)				
Condition		Annealed 1300F, 2 hours, AC (c)				
		Room Temperature Mild-Notch Stress Rupture Properties				
	Specimen	Hours at Indicated Stress				Total Life
Heat	Number	160 ksi	170 ksi	180 ksi	190 ksi	hours
Cast Compressor Casing						
A	1	-	1.2	-	-	1.2
A	2	10.0	-	-	-	(d)
A	3	9.0	-	-	-	(d)
Cast-to-Size Specimens						
B	1	-	5.0	1.1	-	6.1
B	2	-	5.0	0.2	-	5.2
B	3	-	9.9	0.4	-	10.3
B	4	-	6.8	-	-	6.8
C	1	-	10.6	5.0	1.2	16.8
C	2	-	5.2	-	-	5.2
C	3	-	5.8	1.9	-	7.7
C	4	-	10.3	0.7	-	11.0
C	5	-	5.0	2.8	-	7.8



(a) See Figure 3.0311 for compressor casing (20 inches long) details.
(b) Specimens cast to 1/2 inch diameter oversize specimen blanks subsequently machined to finished specimens.
(c) Cast compressor casing annealed in full section size: F_{tu} = 143.9 ksi, F_{ty} = 131.0 ksi, e(1 inch) = 9.4 percent, RA = 15.5 percent.
Cast-to-size specimens annealed as oversize specimen blanks:
Heat B, F_{tu}=144.8 ksi, F_{ty}=127.3 ksi, e(1 inch)=11.7 percent, RA=25.8 percent
Heat C, F_{tu}=145.1 ksi, F_{ty}=132.7 ksi, e(1 inch)=10.5 percent, RA=21.6 percent
(d) Test retired.

TABLE 3.046

Source		AVCO Corporation, Lycoming Division (4)		
Alloy		Ti-6Al-4V, Cast		
Form		Cast-to-Size Specimens (a)		
Condition		Annealed 1300F, 2 hours, AC (b)		
		500F Stress Rupture Properties		
		Stress	Life	e(1 inch)
Heat	Specimen Number	ksi	hours	percent
Smooth (c)				
A	1	100.0	(d)	12.0
A	2	95.0	200.8 (e)	-
A	3	90.0	253.3 (e)	-
B	1	100.0	245.7 (e)	-
B	2	98.5	209.6 (e)	-
B	3	97.5	204.9 (e)	-
Mild-Notch (f)				
A	1	175.0	(d)	-
A	2	165.0	(d)	-
A	3	155.0	(d)	-
B	1	154.0	(d)	-
B	2	152.0	200.8 (e)	-
B	3	150.0	238.1 (e)	-

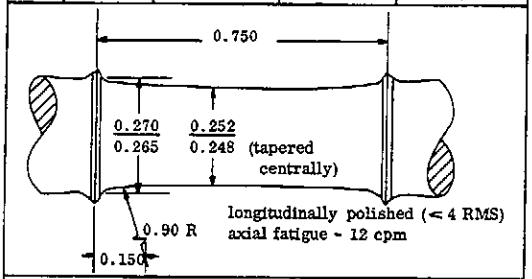
(a) 1/2 inch diameter cast oversize specimen blanks subsequently machined to finished specimens.
(b) Annealed as oversize specimen blanks: Room Temperature Tensile Properties - Heat A; F_{tu} = 144.8 ksi, F_{ty} = 127.3 ksi, e(1 inch) = 11.7 percent, RA - 25.8 percent
Heat B; F_{tu} = 145.1 ksi, F_{ty} = 132.7 ksi, e(1 inch) = 10.5 percent, RA = 21.6 percent
(c) Smooth specimens 1/4 inch diameter x 1 inch gage length.
(d) Broke immediately after loading to indicated stress.
(e) Test discontinued.
(f) See Table 3.045 for mild-notch specimen configuration.

3.05 Fatigue Properties

3.051 Low-cycle axial fatigue results at 500F for annealed smooth specimens cast-to-size from two heats, Table 3.051.

TABLE 3.051

Source		AVCO Corporation, Lycoming Division (4)		
Alloy		Ti-6Al-4V, Cast		
Form		Cast-to-Size Specimens (a)		
Condition		Annealed 1300F, 2 Hours, AC (b)		
		500F Low-Cycle Fatigue Properties		
Heat	Strain Ratio, A	Alternating Strain in / in	Maximum Strain in / in	Cycles to Failure
(c)	∞	0.0145	0.0145	144
A	∞	0.0115	0.0115	508
A	∞	0.0115	0.0115	290
A	∞	0.0115	0.0115	450
A	∞	0.010	0.010	1,060
B	∞	0.0076	0.0076	1,700
A	∞	0.0058	0.0058	3,803
B	∞	0.0049	0.0049	13,925
B	∞	0.004	0.004	50,067(d)
(c)	0.67	0.016	0.040	1,002
B	0.67	0.008	0.020	873
B	0.67	0.005	0.0125	2,509
B	0.25	0.010	0.050	325
A	0.25	0.008	0.040	9,722



(a) Specimens cast to 1/2 inch diameter oversize specimen blanks, subsequently machined to configuration shown.
(b) Annealed as oversize specimen blanks: see Figure 3.053 for conventional room temperature tensile properties of material tested.
(c) Not identified, except as from same producer as of other two heats.
(d) Test retired.

3.052 Low-cycle axial fatigue results at 500F for annealed mild-notch specimens cast-to-size from two heats, Figure 3.052.

3.053 High-cycle axial fatigue results at 500F for annealed smooth and mild-notch cast-to-size specimens from two heats, Figure 3.053.

3.054 150 hours, 500F stress range diagram for smooth and mild-notch cast-to-size specimens from two heats, Figure 3.054.

3.055 Room temperature axial load fatigue properties of smooth specimens from five annealed cast ring segments from two heats, Figure 3.055.

3.056 Room temperature axial load fatigue properties of mild-notch specimens from five annealed cast ring segments from two heats, Figure 3.056.

3.057 Room temperature smooth fatigue properties of annealed and solution treated and aged, castings, Figure 3.057.

3.058 Room temperature mild-notch fatigue properties of annealed and solution treated and aged castings from two casting manufacturers, Figure 3.058.

3.06 Elastic Properties

(For E, see also Tables 3.0211, 3.0212 and 3.02112. For E_c, see also Tables 3.0221 and 3.0222)

3.061 Effect of test temperature on tensile elastic modulus of annealed cast ring segments from two heats, Figure 3.061.

4. FABRICATION

4.01 Formability

4.02 Machining and Grinding

Consult Air Force Machinability Data Center, Metcut Research Associates, Cincinnati, Ohio 45209.

4.03 Welding

Repair welding of titanium castings is a common practice and, according to one source, will probably be necessary for the forseeable future because of the poor feeding characteristics of titanium (see 1.092)(14). Most of the data reported in this chapter (from references 5, 8, 11, and 14) were from castings for which weld repairs were allowed. Thus the influence of repair welding is reflected in the data scatter. It should be pointed out, however, that unsound welds or welds containing obvious defects were not included in the published results. This was considered acceptable since weld-repaired castings with obvious weld defects would normally be withheld from service. Weld repair procedures are outlined in references 7 and 12.

4.04 Surface Treatment

	Ti
6	Al
4	V

Ti-6Al-4V Cast

	Ti
6	Al
4	V

Ti-6Al-4V
Cast

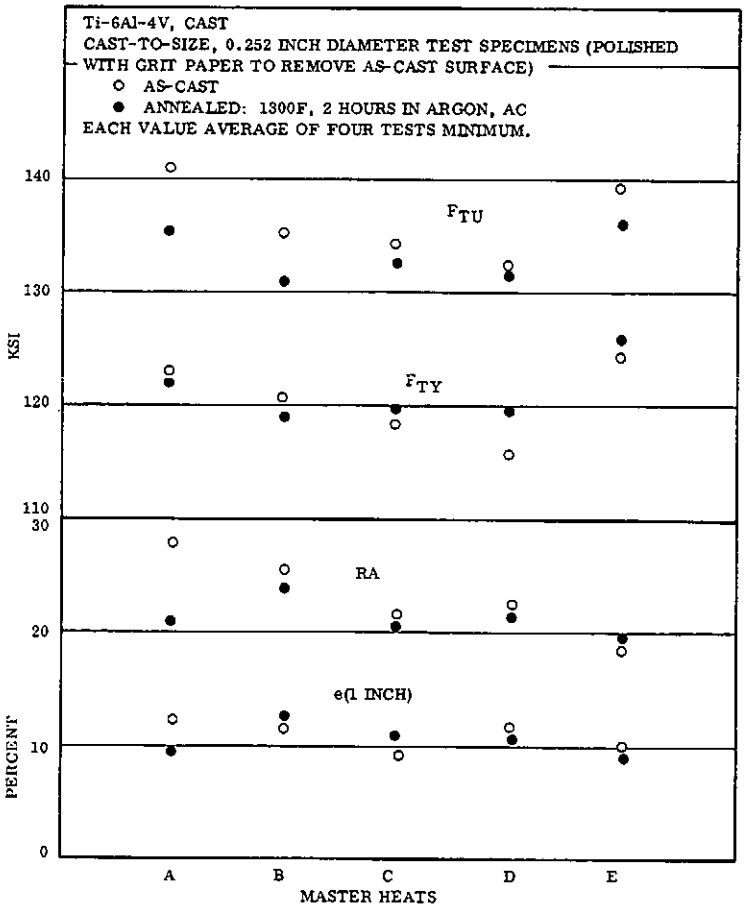


FIG. 3.0214 VARIATION IN TENSILE PROPERTIES OF FIVE MASTER HEATS FOR THE AS-CAST AND ANNEALED CONDITIONS. (9)

Ti
6 Al
4 V

Ti-6Al-4V
Cast

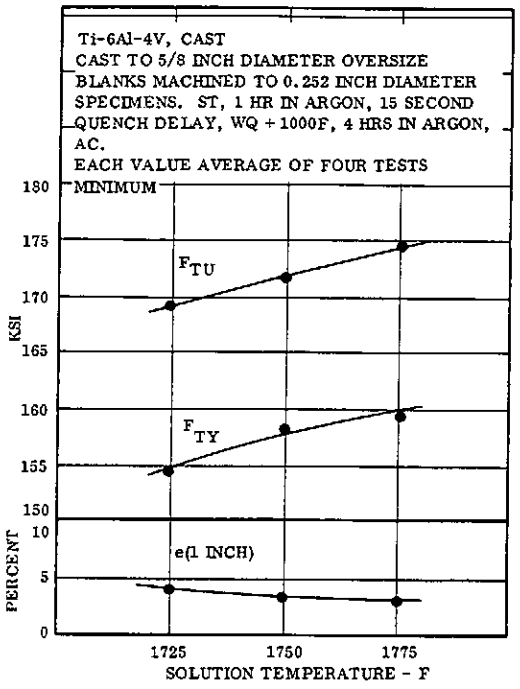


FIG. 3.0216 EFFECT OF SOLUTION TREAT TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION TREATED AND AGED CAST-TO-SIZE SPECIMENS. (9)

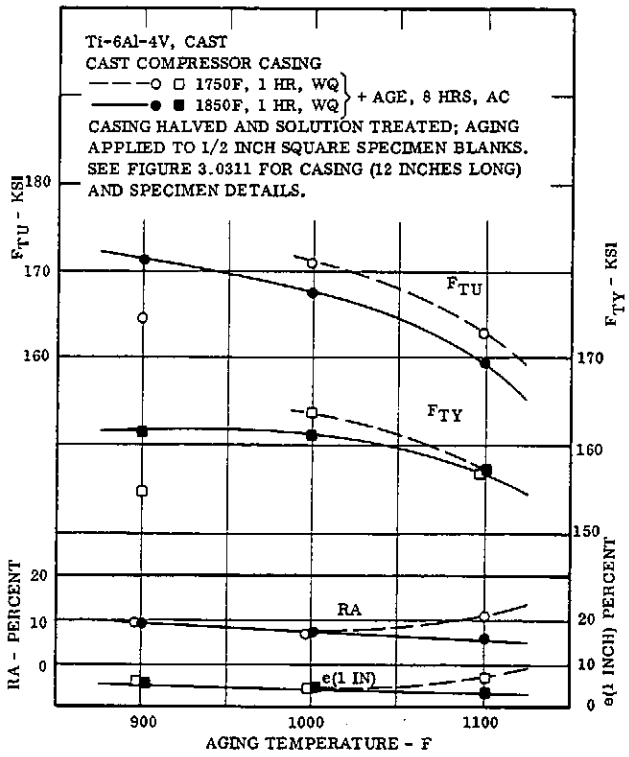


FIG. 3.0217 EFFECT OF SOLUTION TREAT AND AGING TEMPERATURES ON TENSILE PROPERTIES OF CAST COMPRESSOR CASING. (4)

	Ti
6	Al
4	V

Ti-6Al-4V Cast

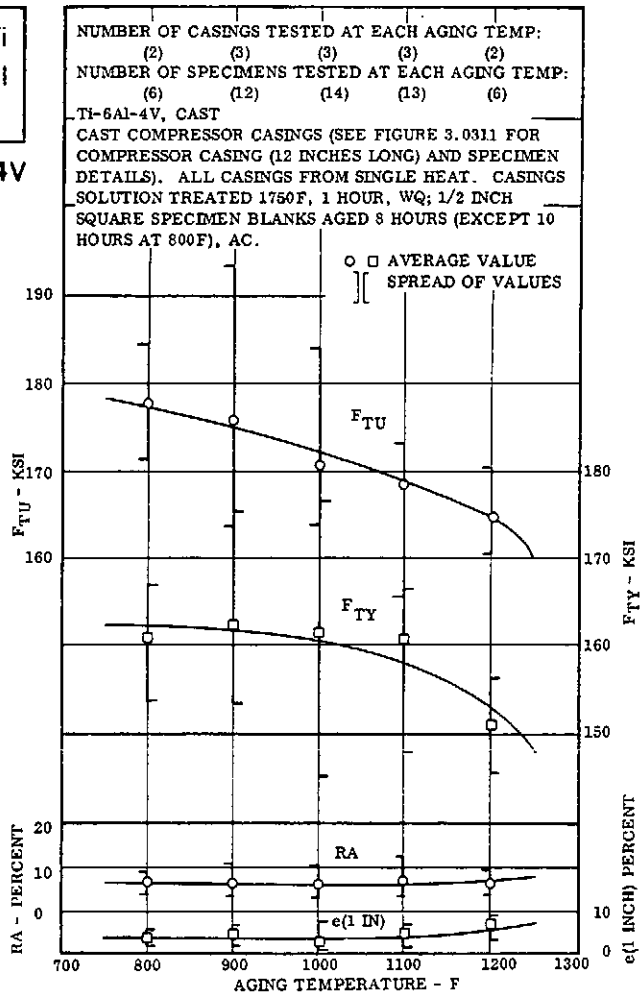


FIG. 3.0218 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF THREE COMPRESSOR CASINGS CAST FROM ONE HEAT. (4)

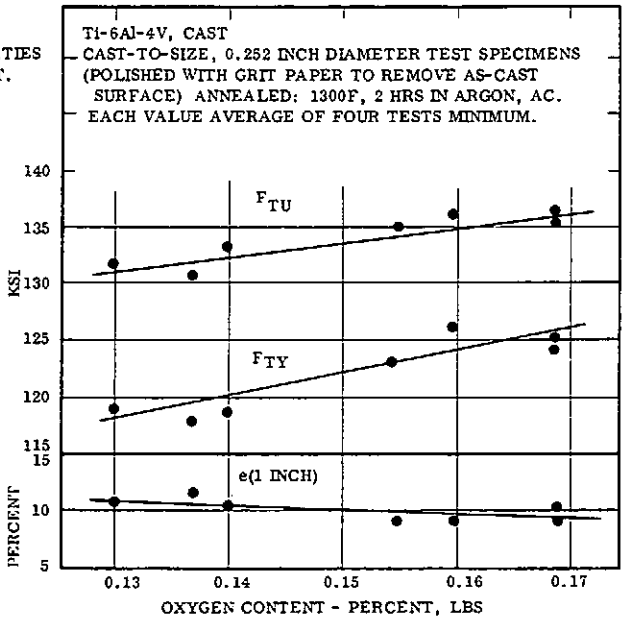


FIG. 3.02113 EFFECT OF OXYGEN CONTENT ON TENSILE PROPERTIES OF ANNEALED CAST-TO-SIZE SPECIMENS. (9)

	Ti
6	Al
4	V

Ti-6Al-4V
Cast

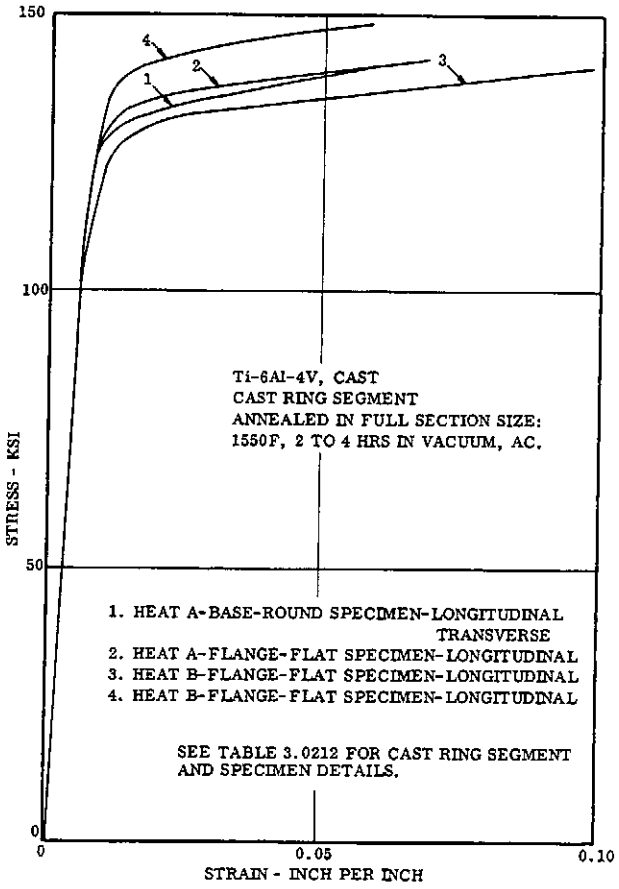


FIG. 3.02114 TYPICAL STRESS-STRAIN CURVES FOR ANNEALED CAST RING SEGMENTS FROM TWO HEATS. (5)

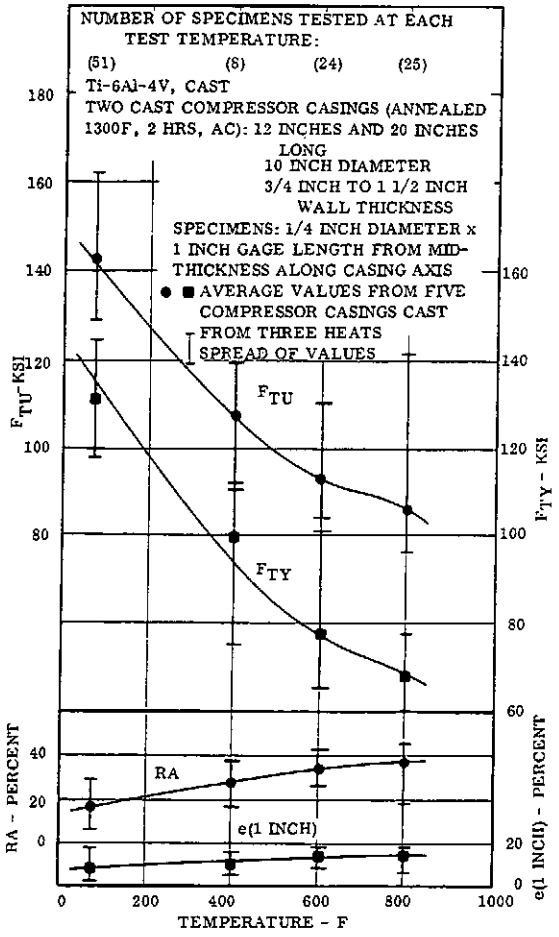


FIG. 3.0311 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF FIVE ANNEALED CAST COMPRESSOR CASING FROM THREE HEATS. (4)

Ti
6 Al
4 V

Ti-6Al-4V Cast

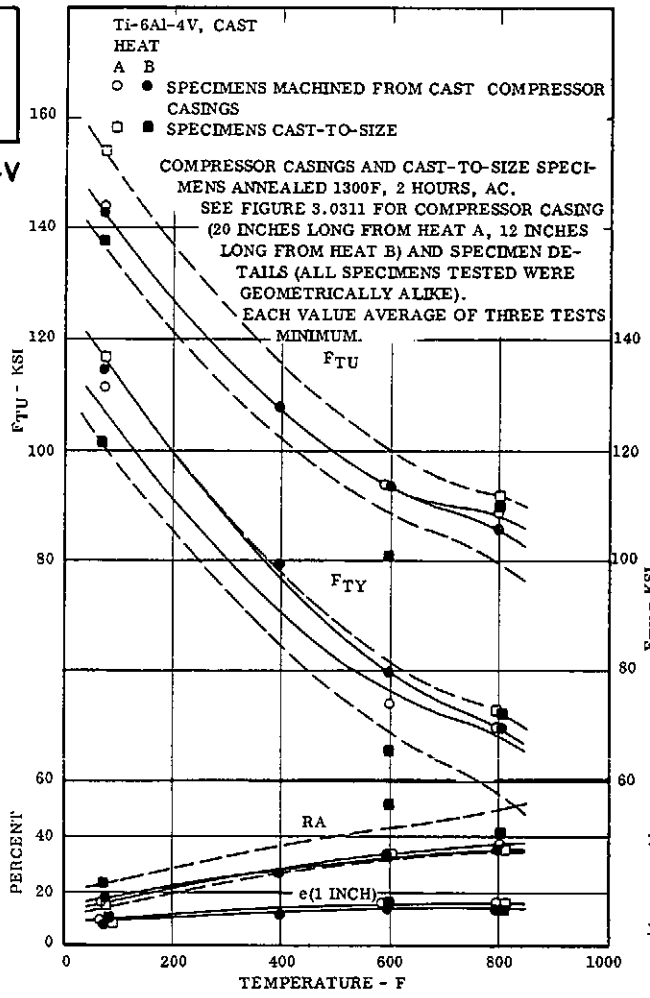


FIG. 3.0312 EFFECT OF TEST TEMPERATURES ON TENSILE PROPERTIES OF SPECIMENS MACHINED FROM ANNEALED CAST COMPRESSOR CASINGS AND ANNEALED CAST-TO-SIZE SPECIMENS EACH FROM TWO HEATS. (4)

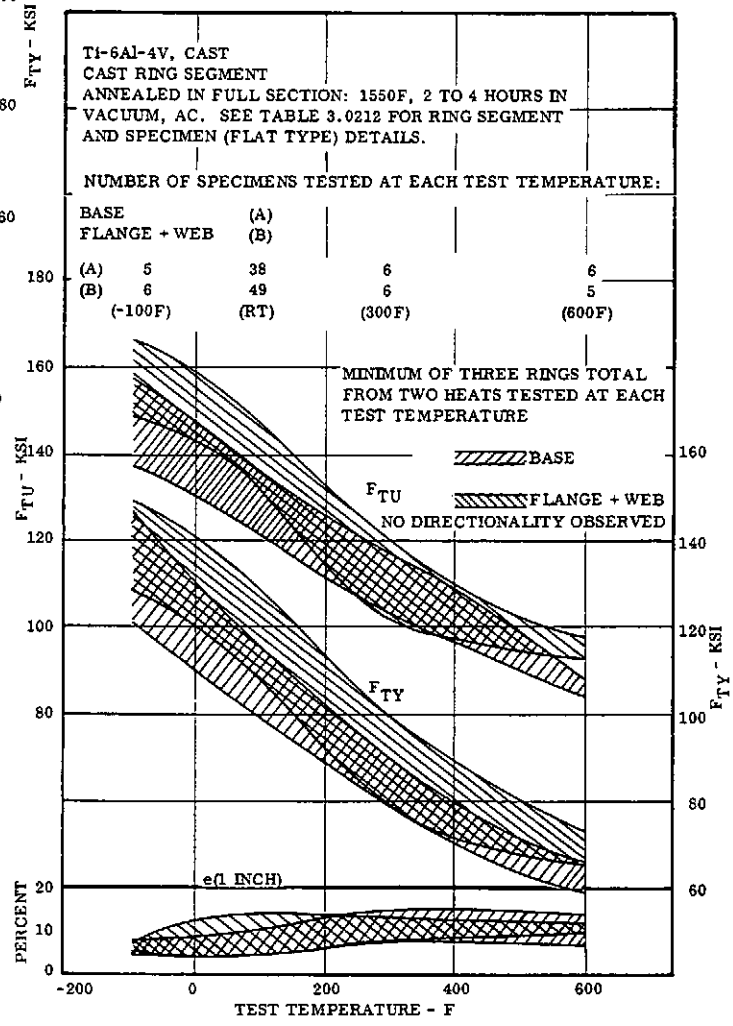


FIG. 3.0313 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED CAST RING SEGMENTS FROM TWO HEATS. (5)

Ti
6 Al
4 V

Ti-6Al-4V
Cast

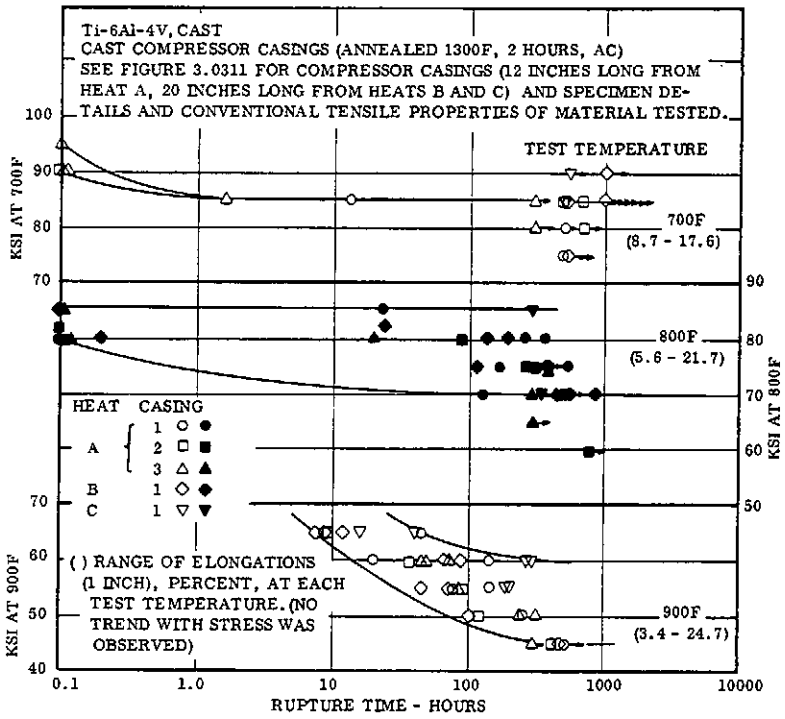


FIG. 3.041 STRESS RUPTURE CURVES AT 700, 800, AND 900F FOR SPECIMENS MACHINED FROM FIVE ANNEALED CAST COMPRESSOR CASINGS FROM THREE HEATS. (4)

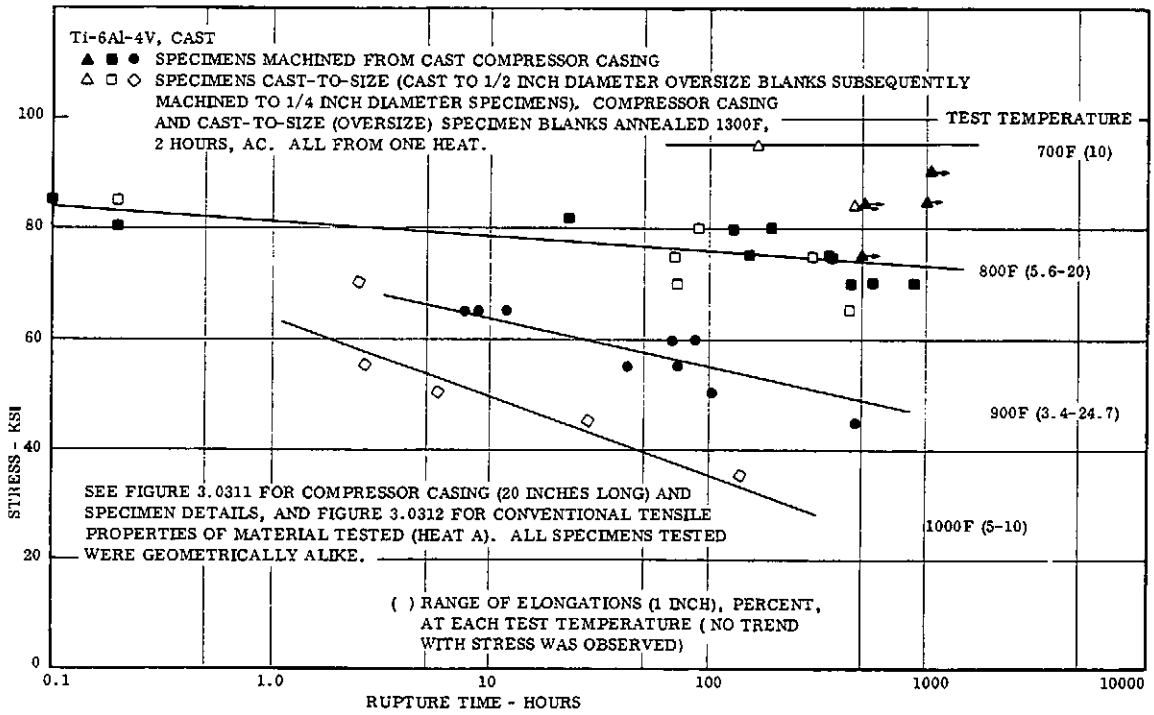


FIG. 3.042 CREEP RUPTURE CURVES AT 700, 800, 900, AND 1000F FOR SPECIMENS MACHINED FROM ANNEALED CAST COMPRESSOR CASING AND ANNEALED CAST-TO-SIZE SPECIMENS FROM ONE HEAT. (4)

	Ti
6	Al
4	V

Ti-6Al-4V
Cast

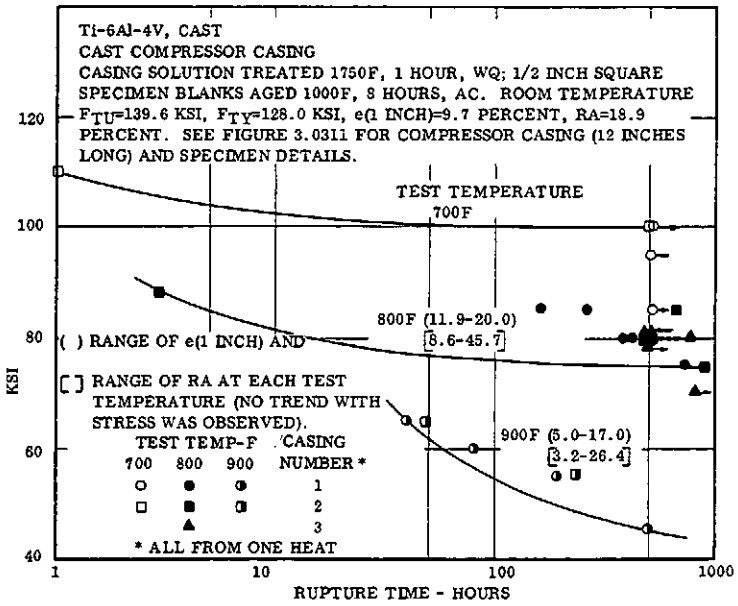


FIG. 3.043 STRESS RUPTURE CURVES AT 700, 800, AND 900F FOR SPECIMENS MACHINED FROM CAST COMPRESSOR CASING AGED AT 1000F. (4)

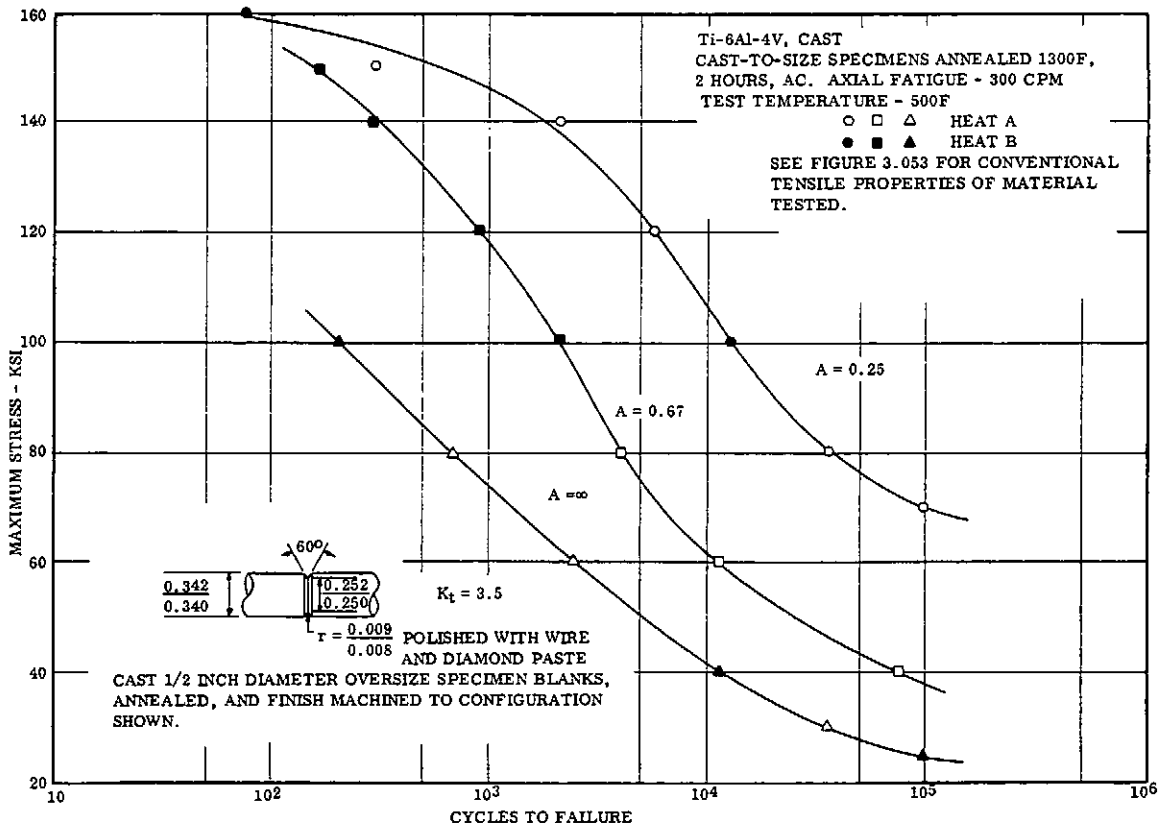


FIG. 3.052 LOW-CYCLE AXIAL FATIGUE RESULTS AT 500F FOR ANNEALED MILD-NOTCH SPECIMENS CAST-TO-SIZE FROM TWO HEATS. (4)

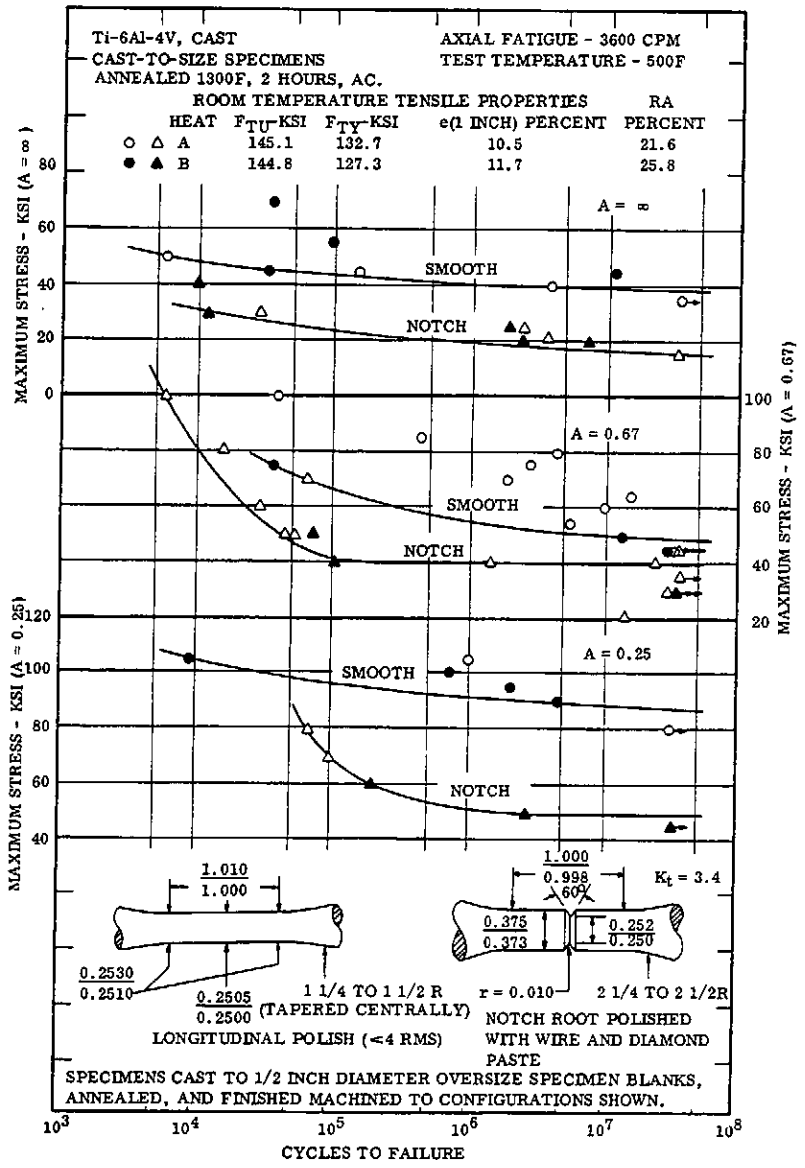


FIG. 3.053 HIGH-CYCLE AXIAL FATIGUE RESULTS AT 500F FOR ANNEALED SMOOTH AND MILD-NOTCH CAST-TO-SIZE SPECIMENS FROM TWO HEATS. (4)

Ti
6 Al
4 V

Ti-6Al-4V
Cast

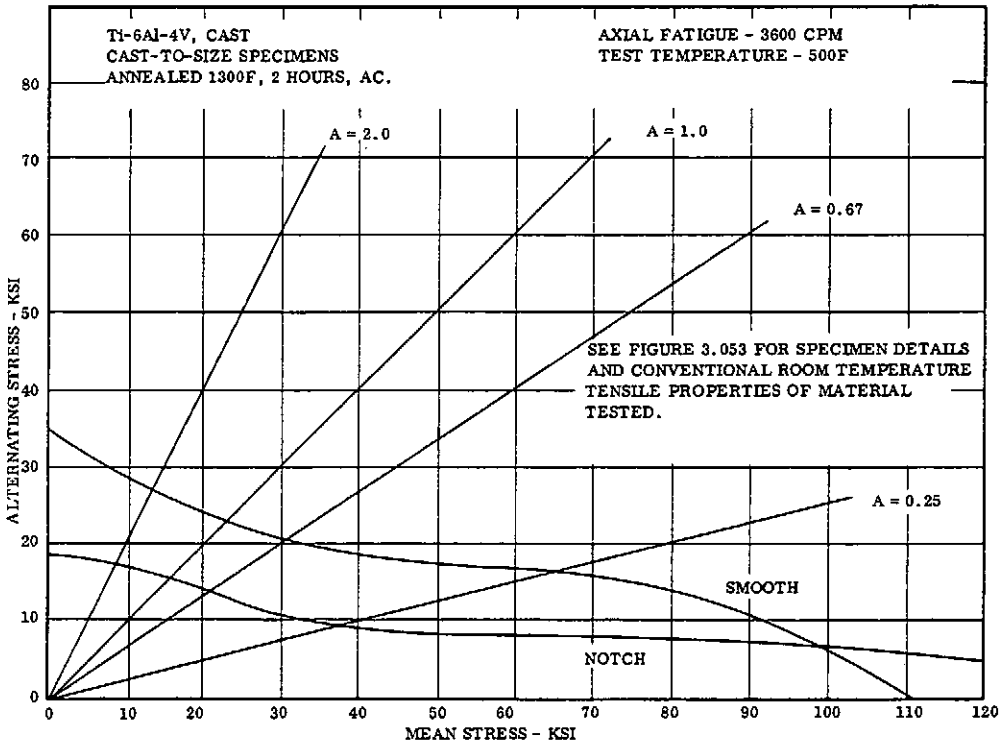


FIG. 3.054 150 HOURS, 500F STRESS RANGE DIAGRAM FOR SMOOTH AND MILD-NOTCH CAST-TO-SIZE SPECIMENS FROM TWO HEATS. (4)

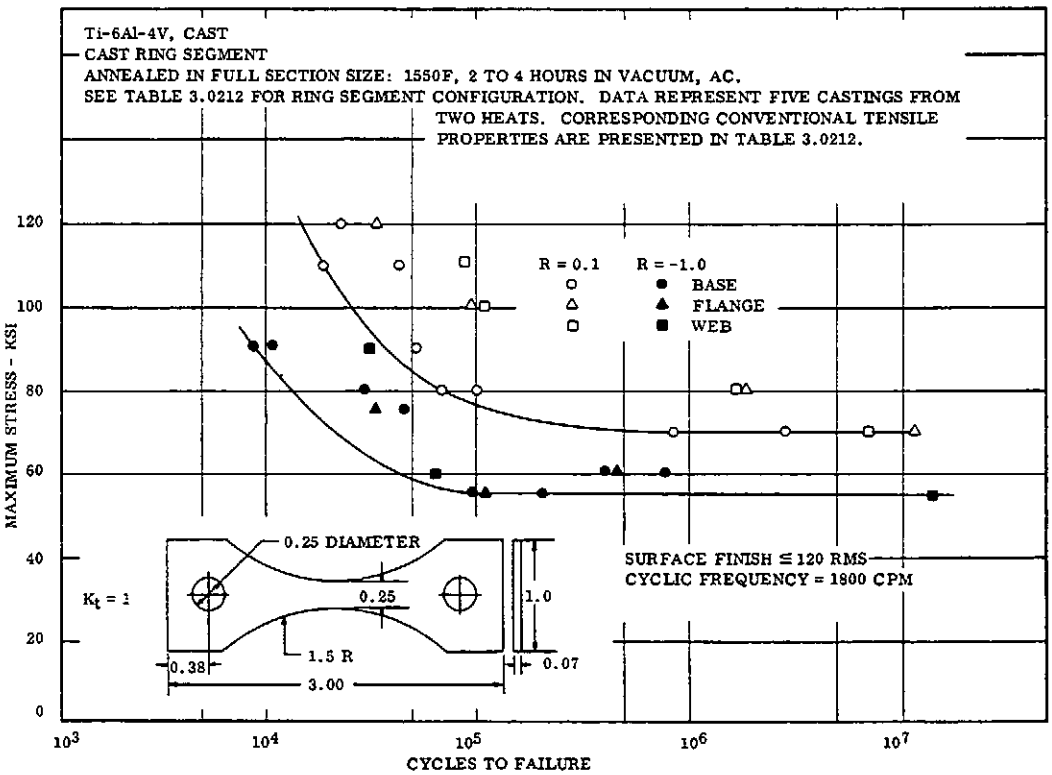


FIG. 3.055 ROOM TEMPERATURE AXIAL LOAD FATIGUE PROPERTIES OF SMOOTH SPECIMENS FROM FIVE ANNEALED CAST RING SEGMENTS FROM TWO HEATS. (5)

Ti
6 Al
4 V

Ti-6Al-4V
Cast

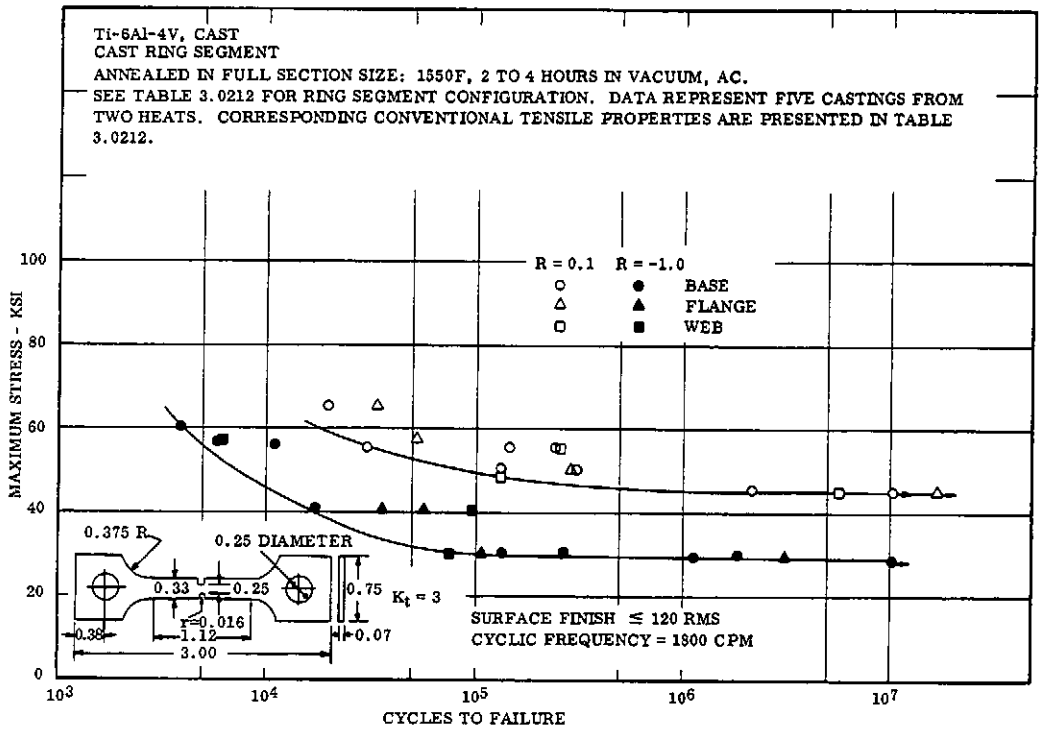


FIG. 3.056 ROOM TEMPERATURE AXIAL LOAD FATIGUE PROPERTIES OF MILD-NOTCH SPECIMENS FROM FIVE ANNEALED CAST RING SEGMENTS FROM TWO HEATS. (5)

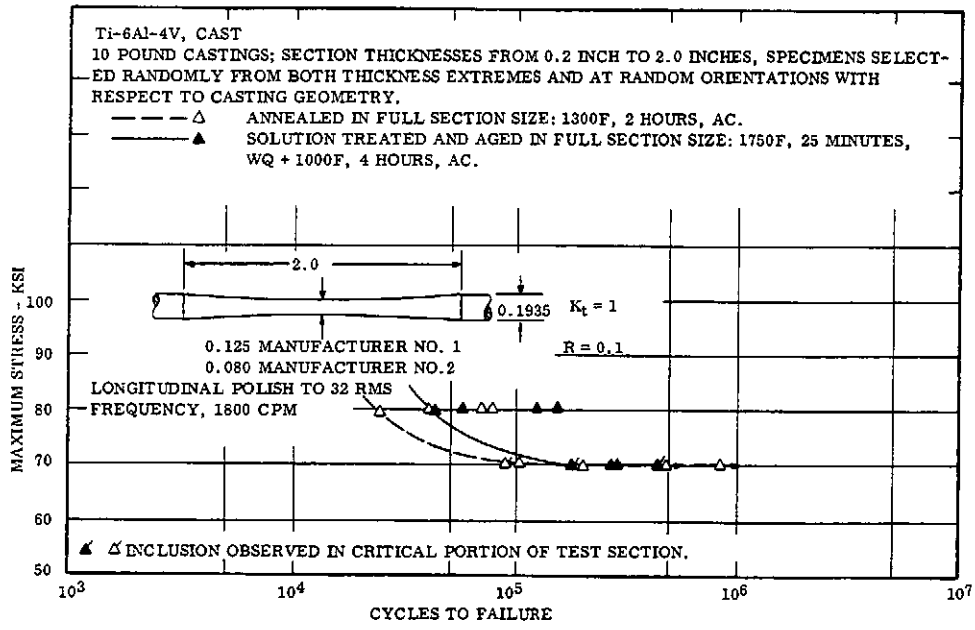


FIG. 3.057 ROOM TEMPERATURE SMOOTH FATIGUE PROPERTIES OF ANNEALED AND SOLUTION TREATED AND AGED CASTINGS. (8)

Ti
6 Al
4 V

Ti-6Al-4V
Cast

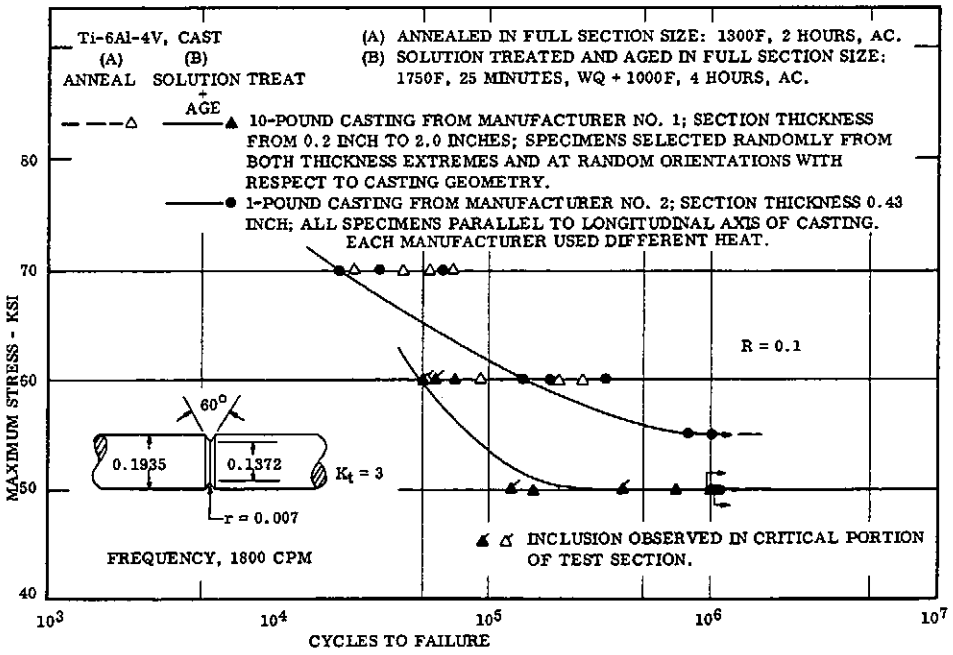


FIG. 3.058 ROOM TEMPERATURE MILD-NOTCH FATIGUE PROPERTIES OF ANNEALED AND SOLUTION TREATED AND AGED CASTINGS FROM TWO CASTING MANUFACTURERS. (8)

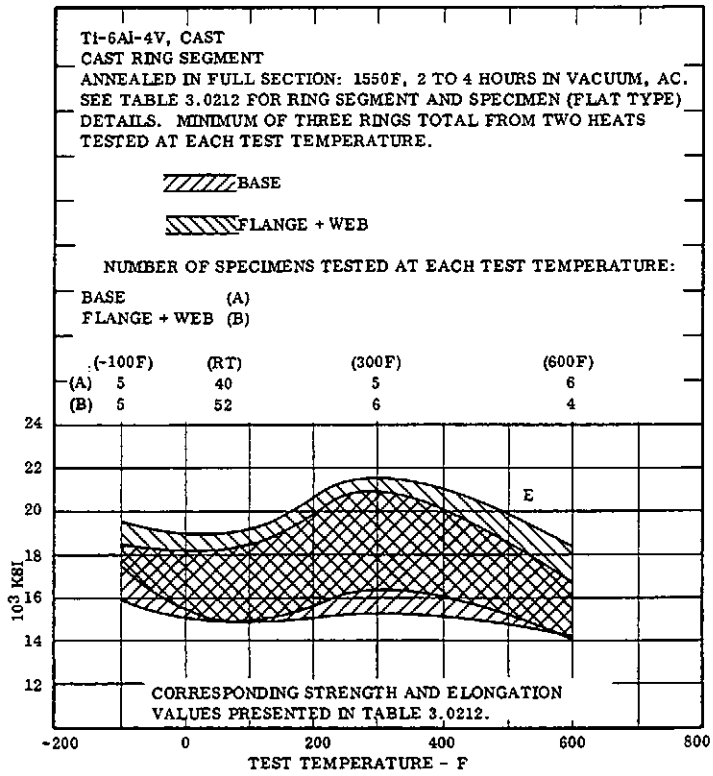


FIG. 3.061 EFFECT OF TEST TEMPERATURE ON TENSILE ELASTIC MODULUS OF ANNEALED CAST RING SEGMENTS FROM TWO HEATS. (5)

	Ti
6	Al
4	V

Ti-6Al-4V
Cast

REFERENCES

1. AVCO Corporation, Lycoming Division, Stratford, Connecticut, Specification No. M3407 (November 30, 1966).
2. Precision Castparts Corporation, Portland, Oregon, Specification No. TD-TCD-1 (April 29, 1968).
3. Wood, R. A. "A Tabulation of Designations, Properties, and Treatments of Titanium and Titanium Alloys," DMIC Memorandum 171 (July 15, 1963).
4. Private communication with R. P. Dalal of AVCO Corporation, Lycoming Division, Stratford, Connecticut.
5. McClaren, S. W., Cook, O. H., and Pascador, G., "Processing, Evaluation, and Standardization of Titanium Alloy Castings," LTV Aerospace Corporation, Vought Aeronautics Division, work performed under Contract F33615-67-C-1173 (BPSN 66-139999-2001-9169-99) with Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, 45433, and published as Technical Report AFML-TR-68-264 (April, 1969).
6. Private communication with M. Lasker of Precision Castparts Corporation, Portland, Oregon.
7. Poole, H. G., "Fundamentals of Casting Titanium," Oregon Metallurgical Corporation, Albany, Oregon, presented at Titanium Metallurgy Course, New York University School of Engineering and Science (September 13-15, 1965).
8. Private communication with H. W. Stemme of Lockheed-Georgia Company, Marietta, Georgia.
9. Coney, D. M., and Lasker, M. F., "Precision Casting of Ti-6Al-4V," Precision Castparts Corporation, Portland, Oregon (June 18, 1969).
10. Published in reference No. 5 above.
11. Soffa, L. L., "Titanium Castings for Airframe Structural Applications," Lockheed-California Company, Division of Lockheed Aircraft Corporation, Burbank, California (September 8, 1967).
12. "Now Available: Cast Titanium and Zirconium," Oregon Metallurgical Corporation, Albany, Oregon.
13. Lang, R. M., Schippereit, G. H., and Kura, J. G., "Production of Titanium Shaped Castings," TML Report No. 60, Titanium Metallurgical Laboratory, Battelle Memorial Institute, Columbus 1, Ohio (December 12, 1956).
14. Harmsworth, C. L., McClaren, S. W., and Cook, O. H., "Castings," Machine Design, pp. 167-171 (June 20, 1968).
15. Jahnke, L. P.,"Titanium in Jet Engines," Aircraft Engine Technology Division, General Electric Company, Cincinnati, Ohio, paper presented at the International Conference on Titanium, London, England (May 21-24, 1968) referenced by R. A. Wood and D. J. Maykuth, "Titanium and Titanium Alloys," Review of Recent Developments, Battelle Memorial Institute (August 23, 1968).

The following report contains very recent data on Ti-6Al-4V, Cast in several heat treated conditions, but was unavailable to the author at the time of this writing: Parkinson, F. L., "Mechanical Property Data on Ti-6Al-4V Castings," Boeing Report T6-3606 (1969).

Ti
6 Al
4 V

Ti-6Al-4V

3.012 Producers guaranteed mechanical properties for annealed material, Table 3.012.

TABLE 3.012

Source	(52)(53)	
Alloy	Ti-6Al-4V	
Form	Sheet, plate and bar	
Condition	Ann	
Grade	Normal	ELI (a)
F_{tu}, -min-ksi	130	130
F_{ty}, -min-ksi	120	120
e(2in) -min-percent	10 (b)	10 (c)
RA, -min-percent	20	-
Impact charpy V min, ft-lb RT	12	
-80F (d)	10	15

(a) Specifications apply to plate < 1 inch thick and bar < 2 inch dia.
(b) Applies to section >0.025 inch thick.
(c) 0.012 through 0.020, 8 percent; plate 10 percent.
(d) Applies to plate ≤ 1 1/2 inch

3.013 Producers guaranteed tensile properties for bar and forgings solution treated and aged in full section size, Table 3.013.

TABLE 3.013

Source	(9, p. 1)								
Alloy	Ti-6Al-4V								
Form	Bar and forgings								
Condition	1650 to 1750F, 15 to 30 min, WQ + 900 to 1000F, 4 to 8 hr								
Thickness, as received - in	≤ 1	1 to 2		2 to 3			3 to 5		
Thickness, as heat treated - in	≤ 1	≤ 1	> 1 to 2	≤ 1	> 1 to 2	> 2 to 3	≤ 1	> 1 to 2	> 2 to 5
F_{tu}, -min-ksi	160	155	150	155	145	140	150	140	130
F_{ty}, -min-ksi	150	145	140	145	135	130	140	130	120
e(4D) -min-percent L	10	10	8	8	8	8	6	6	6
T	8	8	6	6	6	6	4	4	4
RA, -min-percent L	25	25	20	20	20	20	15	15	15
T	20	20	15	15	15	15	10	10	10

3.014 Producers specified mechanical properties for heat treated bar and forgings, Table 3.014.

TABLE 3.014

Source	(50)									
Alloy	Ti-6Al-4V									
Form	Bar and forgings									
Condition	HT in full section size 1750F, 2 hr, WQ + 1000F, 4 hr, AC									
Width - in	up to 4					> 4 to 8				
Thickness - in (a)	up to 1/2	>1/2 to 1	>1 to 1 1/2	>1 1/2 to 2	> 2 to 3	up to 1/2	>1/2 to 1	>1 to 1 1/2	>1 1/2 to 2	> 2 to 3
F_{tu}, -min-ksi	160	155	150	145	135	160	150	145	140	135
F_{ty}, -min-ksi	150	145	140	135	125	150	140	135	130	125

(a) Thickness > 3 inch, annealed properties apply (F_{tu} = 130 ksi, F_{ty} = 120 ksi)

3.02 Mechanical Properties at Room Temperature
See also 3.03.
3.021 Tension
3.0211 Stress-strain diagrams. See 3.0311.
3.0212 Effect of annealing temperature on the tensile properties of ELI plate, Fig. 3.0212.
3.0213 Effect of aging temperature on the tensile properties of sheet and forgings, Fig. 3.0213
3.0214 Effect of stretching after solution treating on tensile properties of aged sheet, Fig. 3.0214.
3.0215 Effect of stretching on compressive and tensile yield strengths of annealed and aged sheet (Bauschinger effect), Fig. 3.0215.
3.0216 Effect of exposure to elevated temperatures with and without load on tensile properties of annealed sheet, Fig. 3.0216.
3.0217 Effect of exposure to elevated temperatures with load on tensile properties of annealed bar, Fig. 3.0217.
3.0218 Effect of short time exposure to elevated temperatures on tensile properties of aged sheet, Fig. 3.0218.
3.0219 Effect of strain rate on tensile properties of annealed and aged bar, Fig. 3.0219.
3.022 Compression (see Fig. 3.0214 and 3.032).
3.0221 Stress-strain diagrams (see 3.0321).
3.023 Impact (see 3.033)
3.024 Bending
3.025 Torsion and shear
3.0251 Effect of thickness on shear strength of annealed sheet, Fig. 3.0251.
3.026 Bearing
3.027 Stress concentration
3.0271 Notch properties
3.02711 Effect of stress concentration on notch strength of aged sheet, Fig. 3.02711.
3.02712 Effect of notch geometry on notch strength ratio of aged sheet and plate at room temperature, Fig. 3.02712
3.02713 Effect of aging temperature on the sharp notch strength of sheet, Fig. 3.02713.
3.0272 Fracture toughness (see also 3.0372).
3.02721 Sharp notch strength and plane strain fracture toughness of surface cracked specimens cut from solution treated forgings and aged at various temperatures, Fig. 3.02721.
3.02722 Effect of surface crack length on sharp notch properties of solution treated and aged specimens cut from forgings, Fig. 3.02722.
3.028 Combined properties

3.03 Mechanical Properties at Various Temperatures
3.031 Tension
3.0311 Stress-strain diagrams
3.03111 Stress-strain curves at various temperatures for annealed sheet, Fig. 3.03111.
3.03112 Stress-strain curves at room and elevated temperatures for annealed bar, Fig. 3.03112.
3.03113 Longitudinal tension stress-strain curves at elevated temperatures for aged sheet, Fig. 3.03113.
3.03114 Transverse tension stress-strain curves at elevated temperature for aged sheet, Fig. 3.03114.
3.03115 Stress-strain curves at low temperatures for aged sheet, Fig. 3.03115.
3.0312 Spread of tensile test data at room and elevated temperatures for annealed sheet and bar, Fig. 3.0312.
3.0313 Effect of low test temperature on tensile properties of annealed sheet, Fig. 3.0313.
3.0314 Effect of low test temperature on tensile properties of annealed sheet and bar, Fig. 3.0314.
3.0315 Tensile data for aged sheet.
3.03151 Spread of tensile data at room and elevated temperatures for eight heats of aged sheet, Fig. 3.03151.
3.03152 Effect of test temperature and testing direction on tensile properties of aged sheet, Fig. 3.03152.
3.03153 Effect of low and elevated temperatures on the tensile properties of aged sheet, Fig. 3.03153.
3.03154 Effect of exposure and test temperature on tensile properties of aged sheet, Fig. 3.03154.
3.03155 Effect of elevated temperature exposure on room and elevated temperature tensile properties of aged sheet, Fig. 3.03155.

Ti
6 Al
4 V

Ti-6Al-4V

3.03156 Effect of test temperature on tensile properties of aged bar, Fig. 3.03156.

3.03157 Effect of test temperature on tensile properties of solution treated and aged specimens cut from forging, Fig. 3.03157.

3.032 Compression

3.0321 Stress-strain diagrams

3.03211 Stress-strain curves in compression at room and elevated temperatures for annealed sheet, Fig. 3.03211.

3.03212 Longitudinal compression stress-strain curves at elevated temperature for aged sheet, Fig. 3.03212.

3.03213 Transverse compression stress-strain curves at elevated temperature for aged sheet, Fig. 3.03213.

3.03214 Stress-strain curves in compression at room and elevated temperatures for annealed bar, Fig. 3.03214.

3.0322 Compressive yield strength

3.03221 Spread of compressive yield strength at room and elevated temperatures for eight heats of aged sheet, Fig. 3.03221.

3.03222 Directionality of compressive yield strength at room temperature and 800F for annealed and for aged sheet, Table 3.03222.

TABLE 3.03222

Source	(32)											
Alloy	Ti-6Al-4V											
Form	0.051 in sheet											
Condition	Ann, 1550F, 5 hr, FC						1700F, 20 min, WQ + 1000F, 4 hr, AC					
Temp-F	RT			800			RT			800		
Direction	L	45	T	L	45	T	L	45	T	L	45	T
F_{cy} -ksi	142	136	184	63	63	113	165	168	227	106	83	133

3.03223 Effect of exposure and test temperature on compressive yield strength of annealed and aged sheet and bar, Fig. 3.03223.

3.033 Impact (see also Fig. 4.034).

3.0331 Effect of test temperature on impact strength of annealed and aged plate and bar, Fig. 3.0331.

3.034 Bending

3.035 Torsion and shear

3.0351 Spread of shear strength at room and elevated temperature for eight heats of aged sheet, Fig. 3.0351.

3.0352 Effect of test temperature on shear strength of annealed and aged sheet and bar, Fig. 3.0352.

3.036 Bearing

3.0361 Spread of bearing strength at room and elevated temperature for eight heats of aged sheet, Fig. 3.0361.

3.0362 Effect of test temperature on bearing properties of annealed sheet and bar, Fig. 3.0362.

3.0363 Effect of exposure and test temperature on bearing properties of aged sheet, Fig. 3.0363.

3.037 Stress concentration

3.0371 Notch properties

3.03711 Notch strength ratio as a function of stress-concentration factor for annealed sheet tested at room temperature and -320F, Fig. 3.03711.

3.03712 Notch strength ratio as a function of stress-concentration factor for aged sheet tested at room temperature and -320F, Fig. 3.03712.

3.03713 Effect of test temperature and stress-concentration factor on notch strength of aged sheet, Fig. 3.03713.

3.03714 Effect of low test temperatures on the mild and sharp notch properties of annealed ELI sheet, Fig. 3.03714.

3.03715 Effect of crack length on sharp notch properties of annealed sheet, tested at several temperatures, Fig. 3.03715.

3.03716 Effect of test temperature on sharp notch properties of several heats of mill annealed sheet, Fig. 3.03716.

3.03717 Effect of test temperature on sharp notch strength of annealed sheet before and after elevated temperature exposure, Fig. 3.03717.

3.03718 Effect of test temperature on sharp notch strength of aged sheet before and after elevated temperature exposure, Fig. 3.03718.

3.03719 Effect of test temperature on the sharp notch properties of solution treated and aged specimens of various thicknesses cut from forging, Fig. 3.03719.

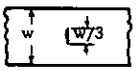
3.0372 Fracture toughness

3.03721 Effect of test temperature and specimen thickness on the fracture toughness of solution treated and aged specimen cut from forging, Table 3.03721.

TABLE 3.03721

Source	(26)							
Alloy	Ti-6Al-4V							
Form	3 x 9 in forging							
Condition	1650F, 1hr, WQ, + 1100F, 4 hr, AC*							
Thickness - in	3/16				3/8		1.0	
Width - in	3				3		9	
Temp - F	-110		RT		-110	RT	-110	RT
Direction	L	T	L	T	L			
F_{ty}, - ksi	176	174	147	152	176	147	176	147
K_{c1}, -ksi-$\sqrt{in}$	111	75	150	110	117	156	76	96

* Applied to specimens



Center fatigue crack specimen heat treat before cracking; slow crack extension by motion pictures

3.03722 Plane strain fracture toughness of annealed plate at low temperatures, Fig. 3.03722.

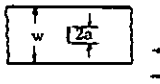
3.03723 Effect of test temperature on sharp notch strength ratio and plane strain fracture toughness of solution treated and aged round bars cut from forging, Fig. 3.03723.

3.03724 Low temperature sharp notch strength and plane strain fracture toughness of annealed plate and solution treated and aged specimens cut from extrusion, Table 3.03724.

TABLE 3.03724

Source	(30)(31)	
Alloy	Ti-6Al-4V	
Form	1/2 in plate ( )	Extrusion OD = 44 in ID = 4.34 in
Condition*	1300F, 1 hr, FC	1500F, 10 min, WQ + 1000F, 7 hr, AC
Direction		Circumferential
-320F property		
F_{ty}, - ksi	212	213
Notch strength-ksi	152	86
K_{Ic}, - ksi - $\sqrt{in}$	69	41

* Specimen blanks cut and then heat treated



	w	t	2a	b
Plate	6	1/4	~1/2	~0.07
Extrusion	2	0.3	0.33	~0.1

Surface crack specimens heat treated before cracking

3.03725 Sharp notch strength ratio and plane strain fracture toughness of solution treated and aged specimens cut from forging, Table 3.03725.

TABLE 3.03725

Source	(26)							
Alloy	Ti-6Al-4V							
Form	3 x 9 in forging							
Condition	1650F, 1hr, WQ + 1100F, 4 hr, AC(b)							
Exposure (c)	25ksi, 650F, 1000hr				None			
Temp - F	-110	RT	400	650	-110	RT	400	650
F_{ty}, - ksi	178	153	111	94	175	152	112	98
Sharp notch-yield strength ratio	0.33	0.48	1.24	1.37	0.45	0.56	1.47	1.63
K_{Ic}, ksi-$\sqrt{in(a)}$	25	32	-	-	35	37	-	-

(a) For specimen details see Fig. 3.03723 (D = 1 1/8 inch, Dir. - T)

(b) Applies to specimens

(c) Exposed before specimen preparation

3.038 Combined properties

3.04 Creep and Creep Rupture Properties

3.041 Average creep and rupture curves at several temperatures for aged sheet from three heats, Fig. 3.041.

3.042 Creep and creep ruptures curves at 750 and 850F for annealed bar, Fig. 3.042.

3.043 Creep and creep rupture curves at 650 to 850F for aged bar, Fig. 3.043.

3.05 Fatigue Properties

3.051 Axial fatigue properties for aged sheet at room and elevated temperatures, Table 3.051.

3.054 Stress range diagram at 10^7 cycles for smooth and notched specimens of mill annealed sheet, Fig. 3.054.

3.055 Stress range diagram at 10^7 cycles for smooth and notched specimens of aged sheet, Fig. 3.055.

3.06 Elastic Properties

3.061 Effect of test temperature on Poisson's ratio, Fig. 3.061.

3.062 Modulus of elasticity

3.0621 Spread of elastic modulus at room and elevated tem peratures for eight heats of aged sheet, Fig. 3.0621.

3.0622 Modulus of elasticity at low and elevated temperature for annealed sheet, Fig. 3.0622.

TABLE 3.051

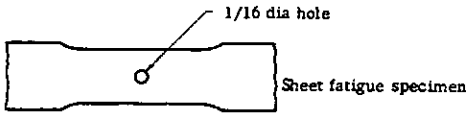
Source	(41)														
Alloy	Ti-6Al-4V														
Form	0.063 and 0.125 in sheet, L														
Condition	1700F, 3 to 20 min, WQ + 900 to 950F, 4 hr														
Method	Direct stress K_t = 1														
Stress ratio	A = ∞			R = 1		A = 1			R = 0		A = 0.3			R = 0.5	
Cycles	10^3	10^4	10^5	10^6	10^7	10^3	10^4	10^5	10^6	10^7	10^3	10^4	10^5	10^6	10^7
Fatigue strength, ksi at temp															
RT	152	120	70	55	54	180	150	100	85	78	180	178	135	107	105
400F	115	90	58	40	35	155	40	77	65	60	150	148	120	100	100
600F	105	82	50	37	35	-	120	76	62	60	140	138	115	100	98
800F	100	80	45	33	28	125	110	73	60	55	135	132	93	83	78
900F	93	65	40	32	25	120	97	70	60	50	112	110	85	65	55

3.052 Axial fatigue properties at K_t = 2.82 for 0.063 inch aged sheet at room and elevated temperatures, Table 3.052.

3.0623 Dynamic modulus of elasticity for annealed bar at elevated temperatures, Fig. 3.0623.

TABLE 3.052

Source	(41)														
Alloy	Ti-6Al-4V														
Form	0.063 in sheet														
Condition	1700F, 3 min to 20 min, WQ + 900 to 950F, 4 hr, AC														
Method	Direct stress K_t = 2.82*														
Stress ratio	A = ∞			R = 1		A = 1			R = 0		A = 0.3			R = 0.5	
Cycles	10^3	10^4	10^5	10^6	10^7	10^3	10^4	10^5	10^6	10^7	10^3	10^4	10^5	10^6	10^7
Fatigue strength, ksi at temp															
RT	100	60	40	25	22	150	95	50	40	40	180	140	80	60	57
400F	120	60	35	24	21	123	85	47	38	37	160	130	70	60	60
600F	85	55	30	20	19	120	80	40	37	37	145	120	70	60	58
800F	80	50	25	18	17	120	70	40	37	37	130	115	60	50	40
900F	70	45	24	18	17	118	70	40	35	35	115	95	60	50	40



Sheet fatigue specimen

3.053 Axial fatigue properties at K_t = 2.82 for 0.125 inch aged sheet at room and elevated temperatures, Table 3.053.

3.0624 Spread of elastic compressive modulus at room and elevated temperature for eight heats of aged sheet, Fig. 3.0624.

3.063 Modulus of ridigity

3.064 Tangent modulus

3.0641 Tangent modulus curves in compression at room and elevated temperatures for annealed sheet, Fig. 3.0641.

3.0642 Longitudinal tensile tangent modulus curves at elevated temperatures for aged sheet, Fig. 3.0642.

3.0643 Transverse tensile tangent modulus curves at elevated temperatures for aged sheet, Fig. 3.0643.

TABLE 3.053

Source	(41)														
Alloy	Ti-6Al-4V														
Form	0.125 in sheet														
Condition	1700F, 3 min to 20 min, WQ + 900 to 950F, 4 hr, AC														
Method	Direct stress K_t = 2.82*														
Stress ratio	A = ∞			R = 1		A = 1			R = 1		A = 0.3			R = 0.5	
Cycles	10^3	10^4	10^5	10^6	10^7	10^3	10^4	10^5	10^6	10^7	10^3	10^4	10^5	10^6	10^7
Fatigue strength, ksi at temp															
RT	100	60	40	35	34	140	100	60	40	40	170	135	80	60	50
400F	88	60	40	30	25	120	80	45	38	38	145	120	70	58	50
600F	90	60	35	22	20	120	78	45	35	30	130	115	70	55	50
800F	75	55	30	20	18	115	70	42	32	27	123	110	70	55	50
900F	62	40	27	20	18	105	65	40	30	26	110	100	70	55	50

* For specimen See Table 3.052.

Ti
6 Al
4 V

Ti-6Al-4V

3.0644 Longitudinal compression tangent modulus curves at elevated temperatures for aged sheet, Fig. 3.0644.

3.0645 Transverse compression tangent modulus curves at elevated temperatures for aged sheet, Fig. 3.0645.

3.065 Secant modulus

3.0651 Longitudinal compression secant modulus curves at elevated temperatures for aged sheet, Fig. 3.0651.

3.0652 Transverse compression secant modulus curves at elevated temperatures for aged sheet, Fig. 3.0652.

4. FABRICATION

4.01 Formability

4.011 General. Annealed Ti-6Al-4V is one of the most difficult to form among annealed titanium alloys. Heating to 1200F can be used for severe forming operations.

4.012 Parts to be aged are preferably formed in the solution treated Condition, either cold or hot, depending upon the severity of the operation, and finish formed by one of several methods developed for heat treated titanium alloys and specifically for this alloy. One of the most promising methods is finish forming combined with aging in dies heated to 950 to 1000F and held at temperature for 6 to 10 hours. In the aged Condition this alloy can be bent at room temperature to moderate radii and subjected to somewhat more severe operations at temperatures below the aging temperature.

4.013 Bending

4.0131 TMCA specified bend factors for sheet at room temperature ≤ 0.070 in $R/t = 4.5$ and > 0.070 in, $R/t = 5.0$.

4.0132 Effect of test temperature on bend factor for annealed sheet, Fig. 4.0132.

4.014 Forging. Starting temperature, 1850F maximum, finishing temperature, 1450F minimum. To obtain optimum properties, reductions equivalent to 25 to 40 percent should be performed in the alpha + beta range in the final forging operation. Subsequent reheating, such as required for sizing operations, should not exceed, generally, a temperature of about 200F below the beta to alpha + beta transformation temperature.

4.02 Machining and Grinding

See Ti Commercially Pure.

4.03 Welding

4.031 General. Extreme cleanliness is necessary in order to avoid porosity and weld cracking. However, proper procedures are now well developed and the alloy may be welded successfully.

4.032 Fusion welding is accomplished by using complete inert gas shielding. Both tungsten arc and consumable electrode processes have given good results. Ti-6Al-4V, Ti-3Al alloy or Commercially Pure Titanium filler rod is used.

4.033 Resistance welding requires techniques similar to those used for austenitic stainless steels.

4.034 Effect of test temperature on the impact properties of plate welded with various fillers, Fig. 4.034.

4.04 Heat Treatment

See Ti, Commercially Pure. Only complementary or different information is listed below.

4.041 Solution treatment of sheet or other thin section requires supporting and restraining fixtures to prevent sagging during heating and severe distortion on quenching in water or oil. To insure maximum response to aging, quenching delay must be minimized.

4.042 To maintain formed tolerances during aging, parts should be supported or jigged.

4.05 Surface Treating

See Ti, Commercially Pure.

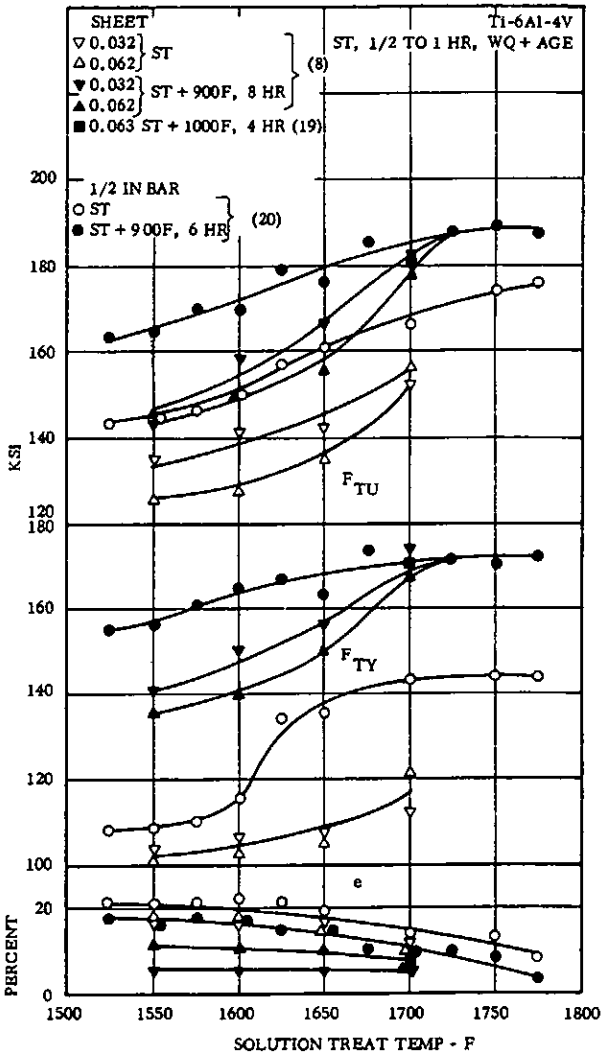


FIG. 1.0544 EFFECT OF SOLUTION TREAT TEMPERATURE ON TENSILE PROPERTIES OF SHEET AND BAR (8, p. G-14, 15)(19)(20)

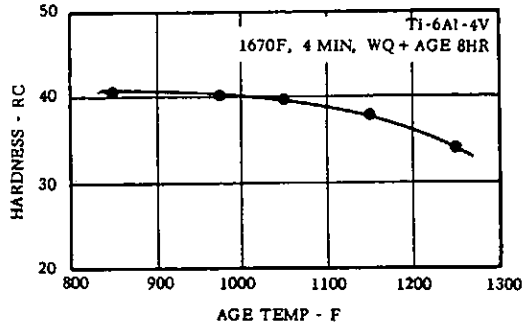


FIG. 1.061 EFFECT OF AGING TEMPERATURE ON HARDNESS OF SOLUTION TREATEL SHEET (49)

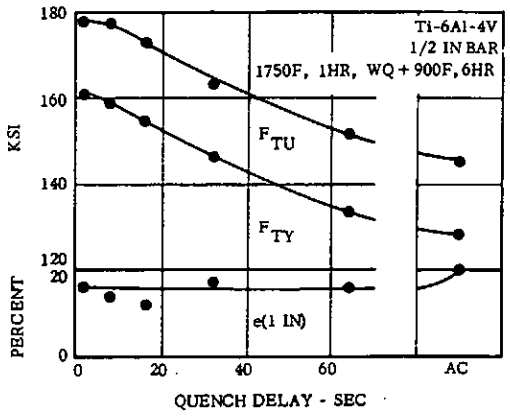


FIG. 1.062 EFFECT OF QUENCH DELAY ON TENSILE PROPERTIES OF AGED BAR (21)

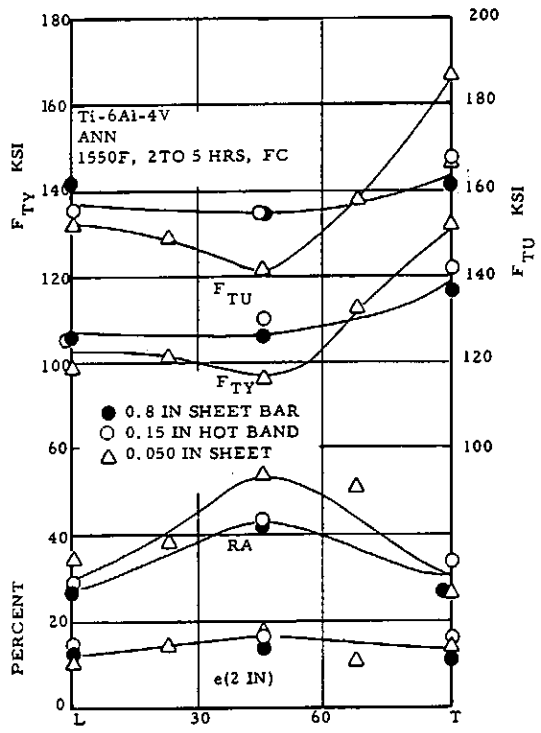


FIG. 1.0911 DIRECTIONALITY OF TENSILE PROPERTIES FOR STRIP PRODUCT IN ANNEALED CONDITION (32, Tables 31, 30, 35)

	Ti
6	Al
4	V

Ti-6Al-4V

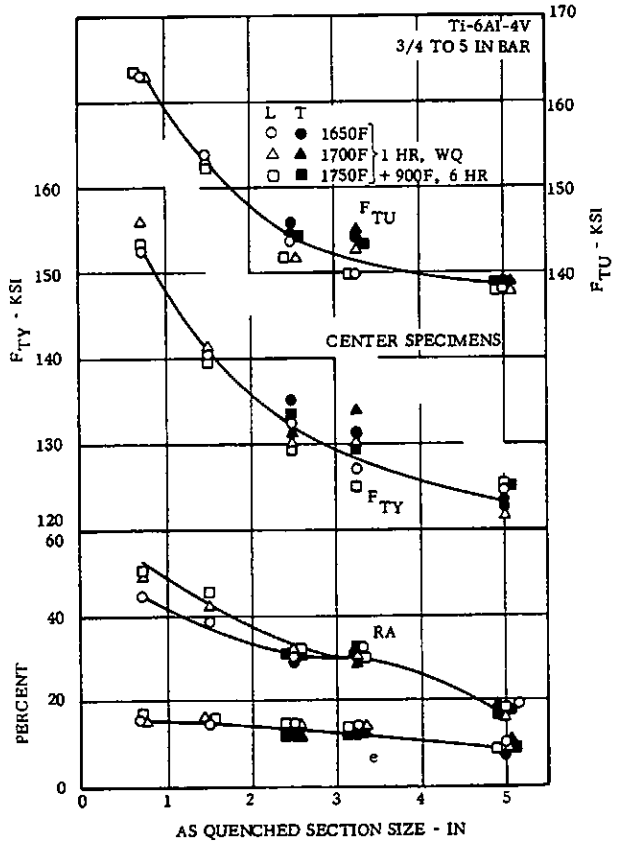


FIG. 1.063 EFFECT OF AS QUENCHED SECTION SIZE ON TENSILE PROPERTIES OF AGED BAR (13, p. 21-26)

Ti
6 Al
4 V

Ti-6Al-4V

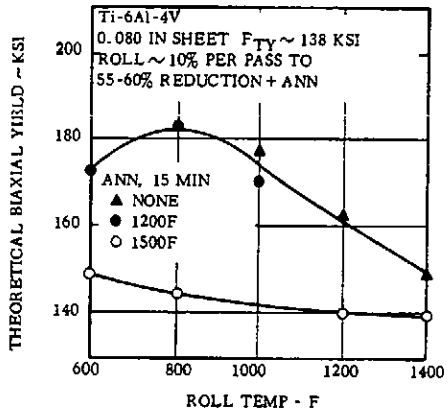


FIG. 1.0912 EFFECT OF ROLLING TEMPERATURE AND ANNEALING TREATMENT ON THE THEORETICAL YIELD STRENGTH IN 2:1 BIAXIAL STRESS FIELD (45, p. 11)

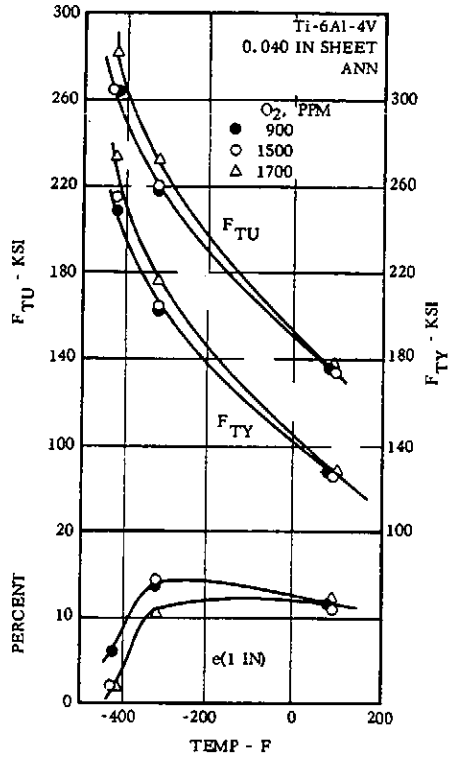


FIG. 1.0921 EFFECT OF OXYGEN CONTENT ON LOW TEMPERATURE TENSILE PROPERTIES OF ANNEALED SHEET (29, Table 3)

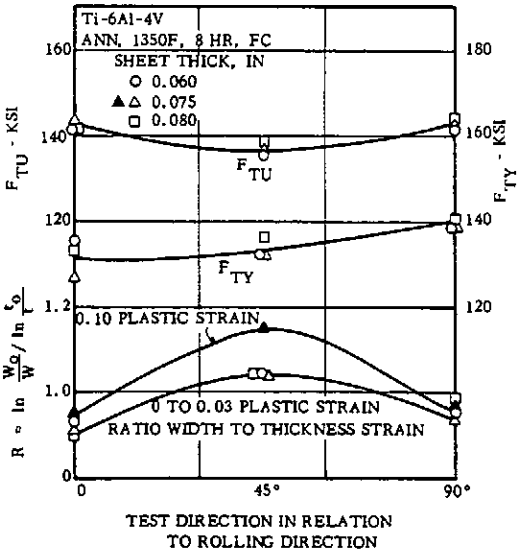


FIG. 1.0913 DIRECTIONALITY OF STRENGTH AND STRAIN FOR TENSILE TESTS ON THREE HEATS OF ANNEALED SHEET (33, Table 5)

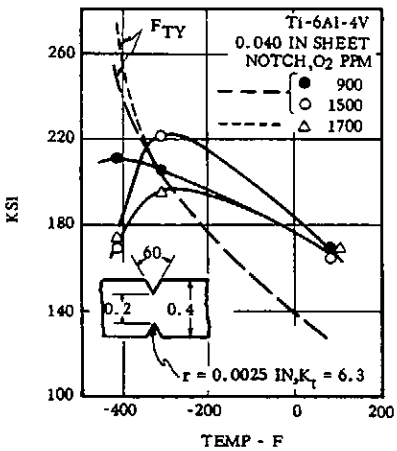


FIG. 1.0922 EFFECT OF OXYGEN CONTENT ON LOW TEMPERATURE MILD NOTCH PROPERTIES OF ANNEALED SHEET (29)

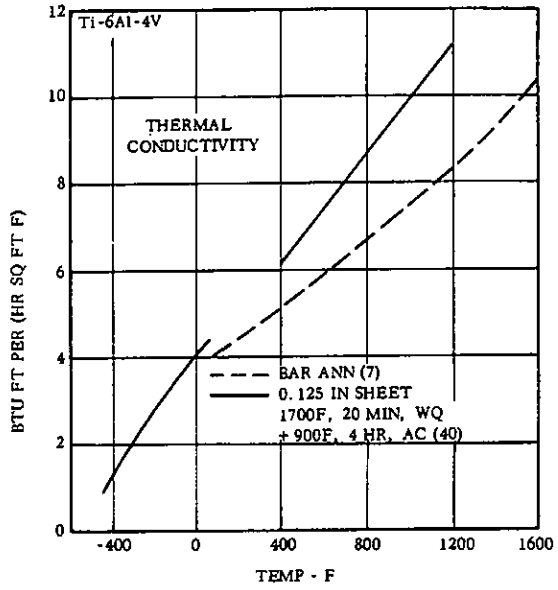


FIG. 2.013 THERMAL CONDUCTIVITY (7)(40, p. 286)

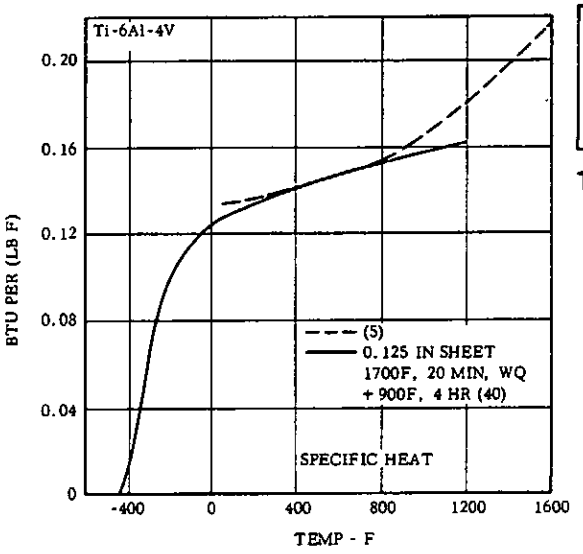


FIG. 2.015 SPECIFIC HEAT (5)(40, p. 287)

Ti
6 Al
4 V

Ti-6Al-4V

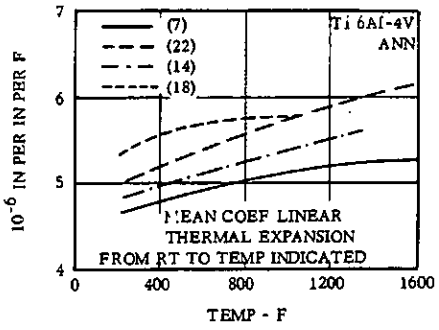


FIG. 2.0141 THERMAL EXPANSION FOR ANNEALED ALLOY (7, p. 3)(14, p. 2)(18, p. 50)(22)

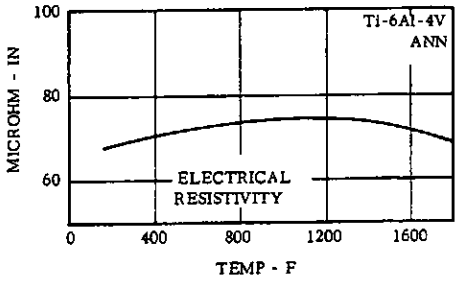


FIG. 2.022 ELECTRICAL RESISTIVITY (5, p. W-3, 4)

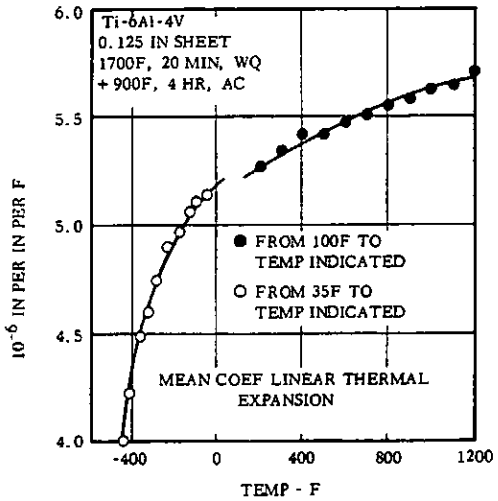


FIG. 2.0142 THERMAL EXPANSION FOR AGED SHEET (39, p. 137-138)

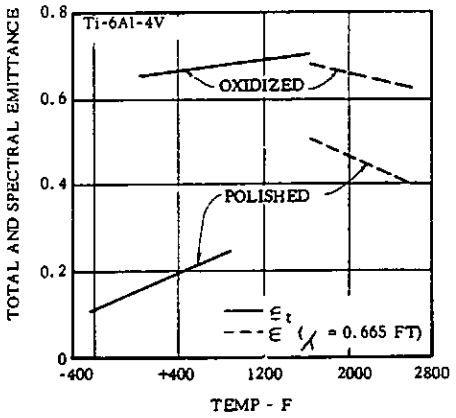


FIG. 2.0241 TOTAL AND SPECTRAL NORMAL EMITTANCE FOR OXIDIZED AND POLISHED SURFACES (37, p. 46, 47)

Ti
6 Al
4 V

Ti-6Al-4V

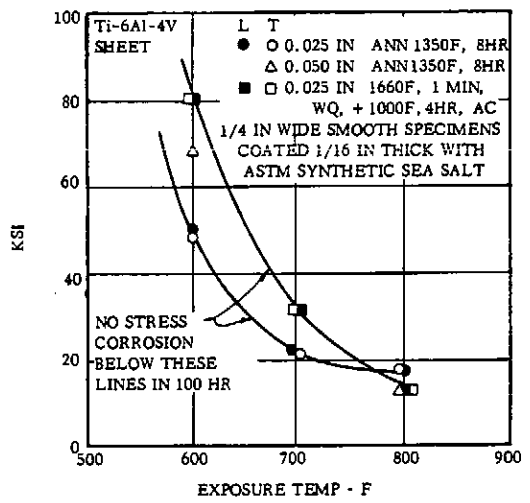


FIG. 2.0341 EFFECT OF STRESS AND TEMPERATURE ON 100 HOUR STRESS CORROSION OF ANNEALED AND AGED SHEET (46, Tables 96, 97, 98)

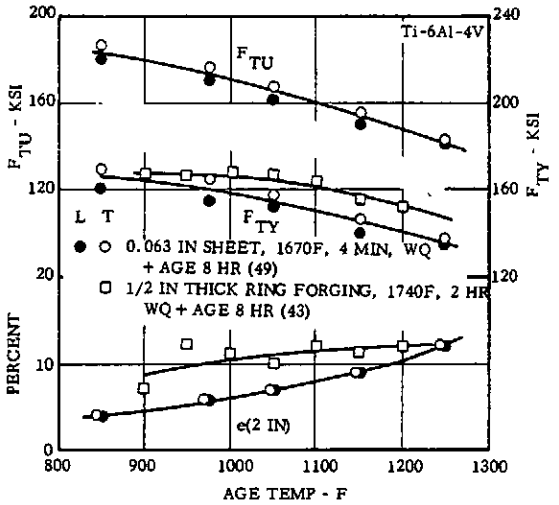


FIG. 3.0213 EFFECT OF AGING TEMPERATURE ON THE TENSILE PROPERTIES OF SHEET AND FORGINGS (43)(49)

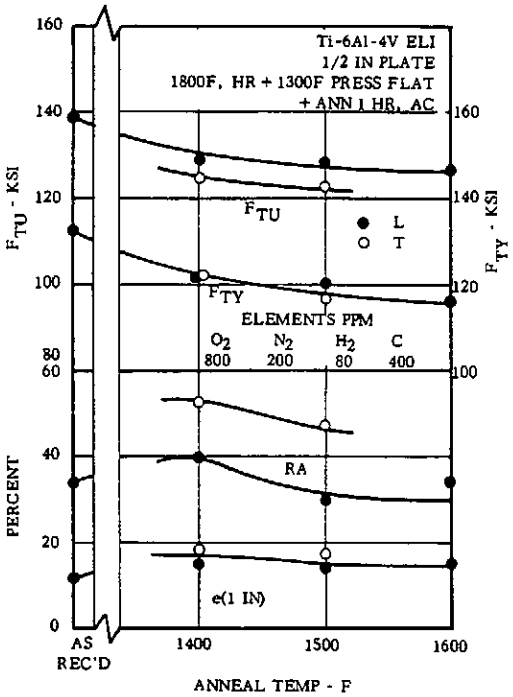


FIG. 3.0212 EFFECT OF ANNEALING TEMPERATURE ON THE TENSILE PROPERTIES OF ELI PLATE (53)

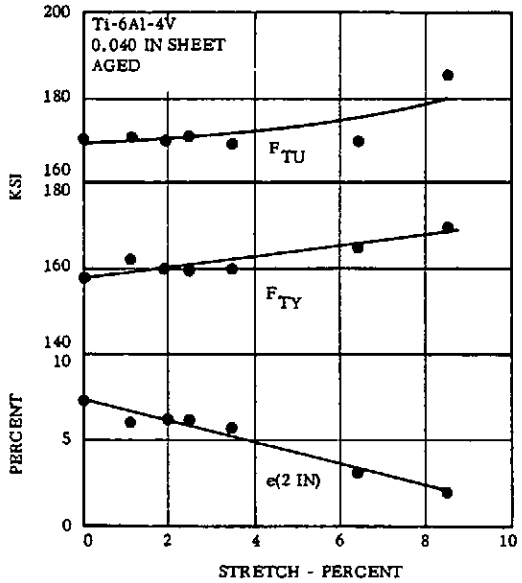


FIG. 3.0214 EFFECT OF STRETCHING AFTER SOLUTION TREATING ON TENSILE PROPERTIES OF AGED SHEET (19)

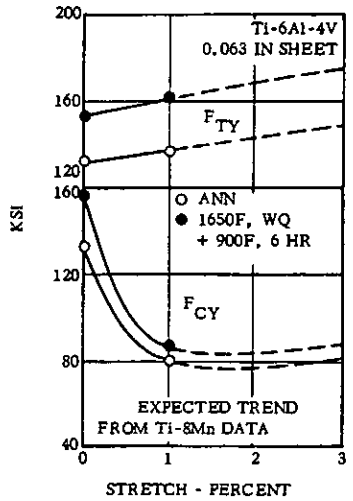


FIG. 3.0215 EFFECT OF STRETCHING ON COMPRESSIVE AND TENSILE YIELD STRENGTHS OF ANNEALED AND AGED SHEET (BAUSCHINGER EFFECT) (17)

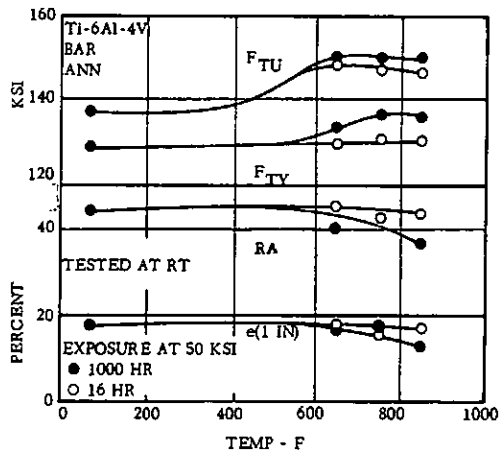


FIG. 3.0217 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURES WITH LOAD ON TENSILE PROPERTIES OF ANNEALED BAR (18, p. 33-36)

Ti
6 Al
4 V
Ti-6Al-4V

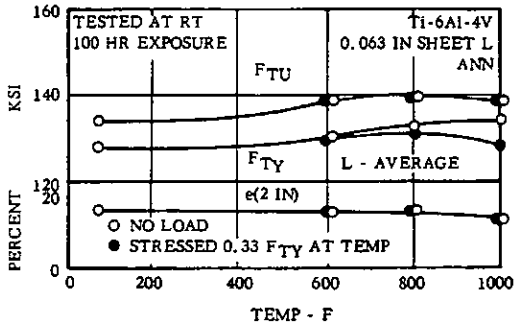


FIG. 3.0216 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURES WITH AND WITHOUT LOAD ON TENSILE PROPERTIES OF ANNEALED SHEET (3, p. 93-96)

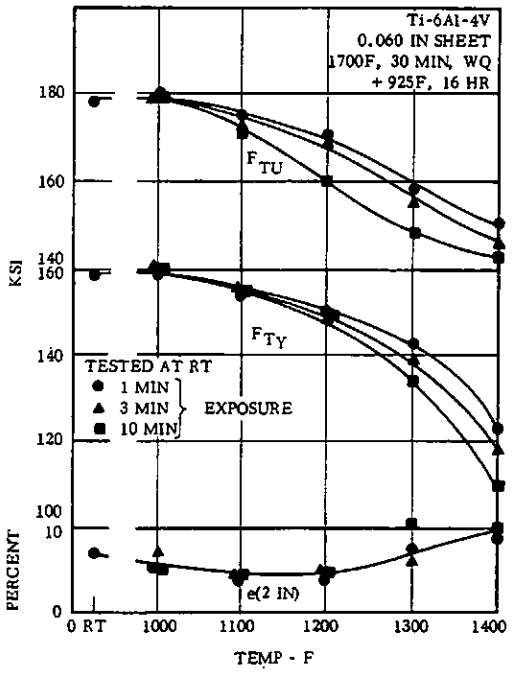


FIG. 3.0218 EFFECT OF SHORT TIME EXPOSURE TO ELEVATED TEMPERATURES ON TENSILE PROPERTIES OF AGED SHEET (23)

	Ti
6	Al
4	V

Ti-6Al-4V

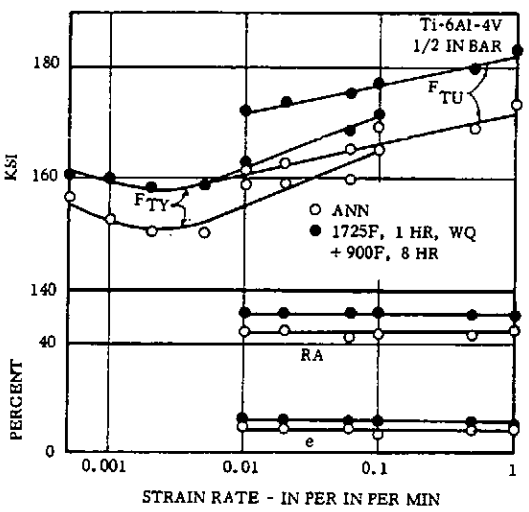


FIG. 3.0219 EFFECT OF STRAIN RATE ON TENSILE PROPERTIES OF ANNEALED AND AGED BAR (13, p. 9)

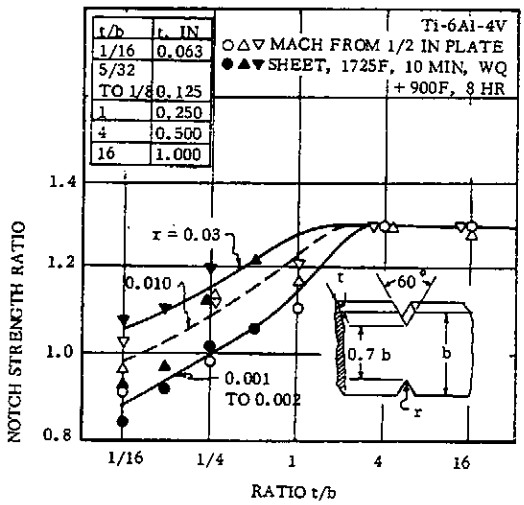


FIG. 3.02712 EFFECT OF NOTCH GEOMETRY ON NOTCH STRENGTH RATIO OF AGED SHEET AND PLATE AT ROOM TEMPERATURE (11, p. 7)

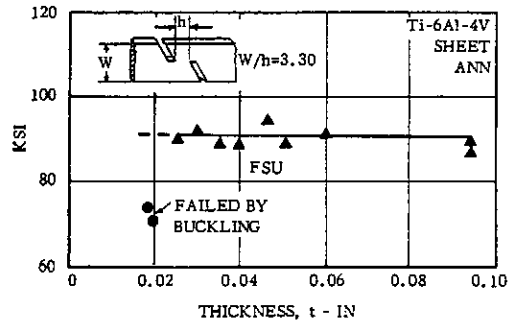


FIG. 3.0251 EFFECT OF THICKNESS ON SHEAR STRENGTH OF ANNEALED SHEET (16, p. A-13, 14)

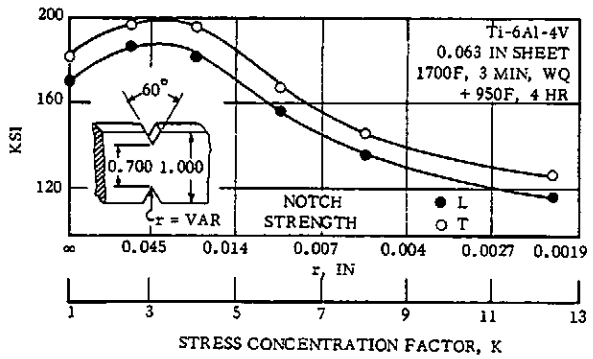


FIG. 3.02711 EFFECT OF STRESS CONCENTRATION ON NOTCH STRENGTH OF AGED SHEET (10, p. 19)

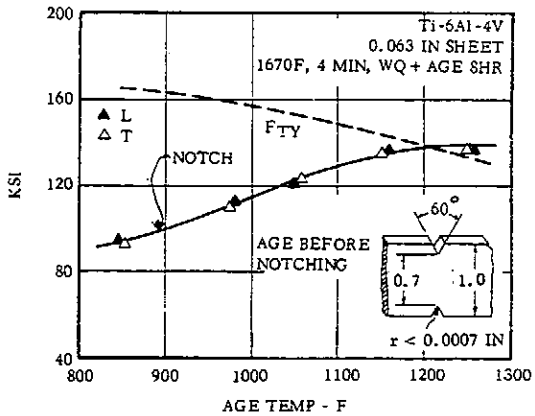


FIG. 3.02713 EFFECT OF AGING TEMPERATURE ON THE SHARP NOTCH STRENGTH OF SHEET (49)

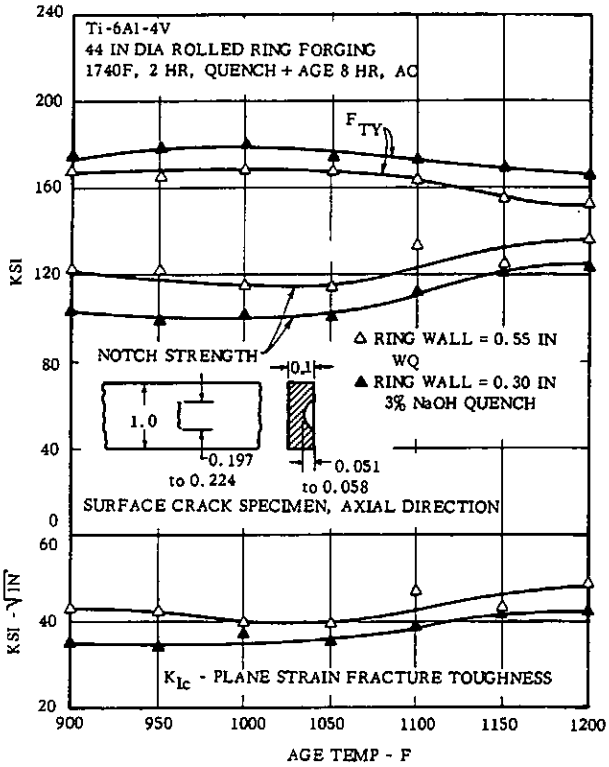


FIG. 3.02721 SHARP NOTCH STRENGTH AND PLANE STRAIN FRACTURE TOUGHNESS OF SURFACE CRACKED SPECIMENS CUT FROM SOLUTION TREATED FORGINGS AND AGED AT VARIOUS TEMPERATURES (43)

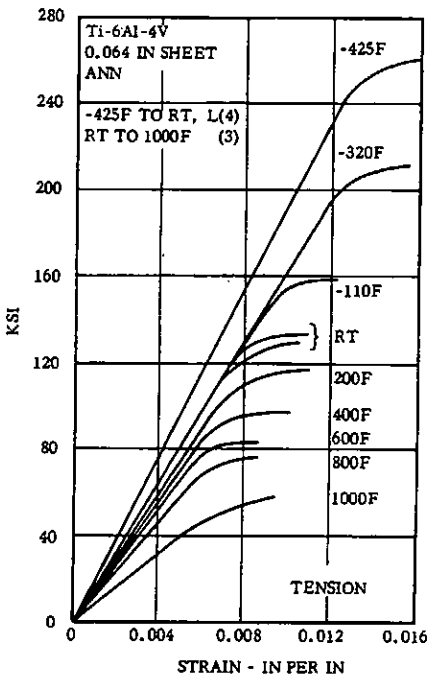


FIG. 3.03111 STRESS-STRAIN CURVES AT VARIOUS TEMPERATURES FOR ANNEALED SHEET (3)(4, p. 44)

Ti
6 Al
4 V
Ti-6Al-4V

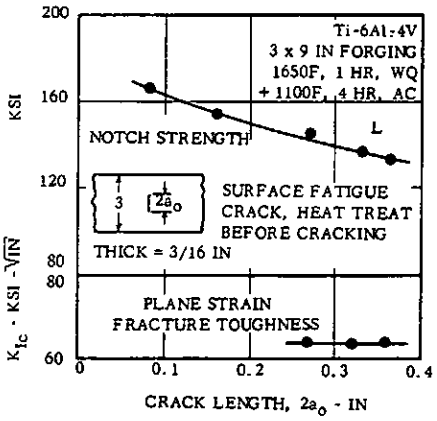


FIG. 3.02722 EFFECT OF SURFACE CRACK LENGTH ON SHARP NOTCH PROPERTIES OF SOLUTION TREATED AND AGED SPECIMENS CUT FROM FORGING (26, Table 32)

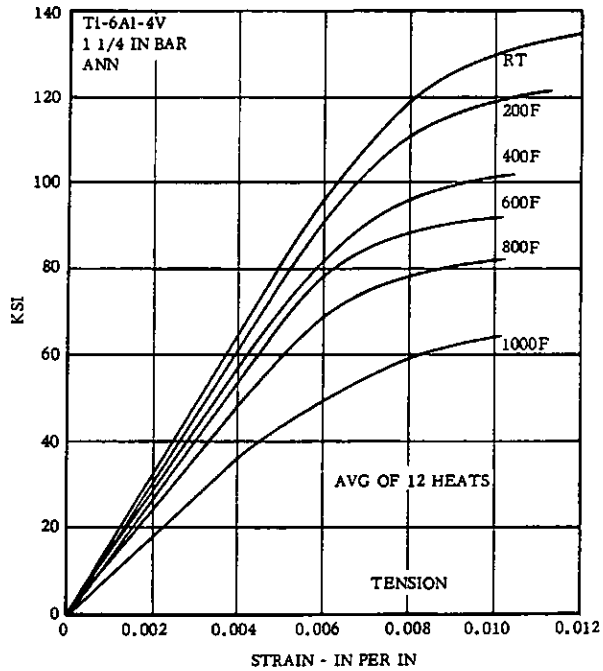


FIG. 3.03112 STRESS-STRAIN CURVES AT ROOM AND ELEVATED TEMPERATURES FOR ANNEALED BAR (3)

	Ti
6	Al
4	V

Ti-6Al-4V

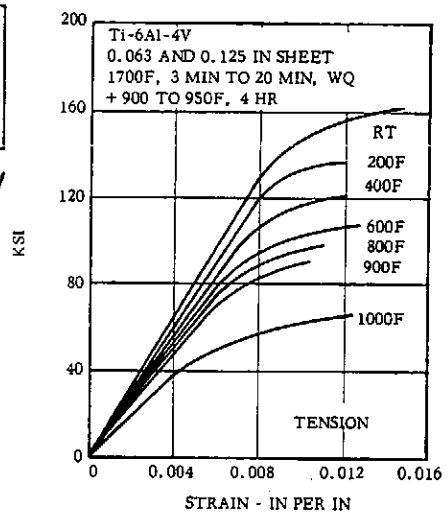


FIG. 3.03113 LONGITUDINAL TENSION STRESS-STRAIN CURVES AT ELEVATED TEMPERATURES FOR AGED SHEET (42, p. 27, 28)

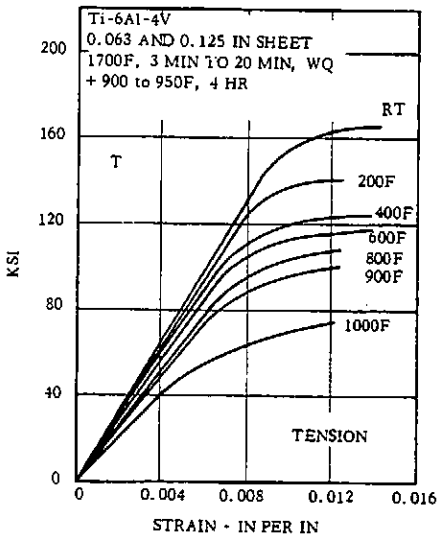


FIG. 3.03114 TRANSVERSE TENSION STRESS-STRAIN CURVES AT ELEVATED TEMPERATURES FOR AGED SHEET (42, p. 27, 28)

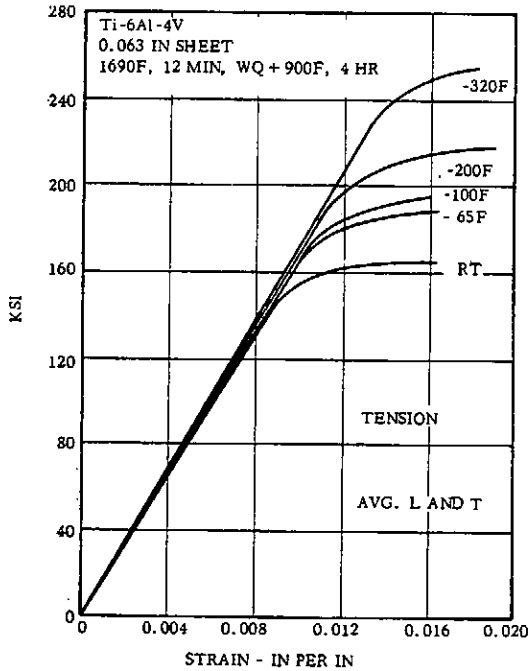


FIG. 3.03115 STRESS-STRAIN CURVES AT LOW TEMPERATURES FOR AGED SHEET

(40, p. 283, 284)

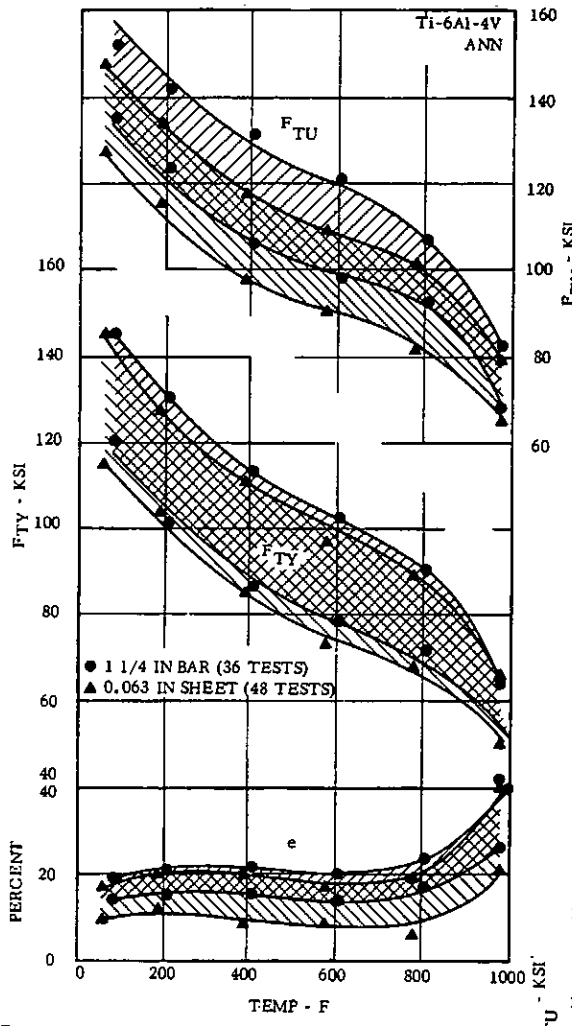


FIG. 3.0312 SPREAD OF TENSILE TEST DATA AT ROOM AND ELEVATED TEMPERATURES FOR ANNEALED SHEET AND BAR (3)

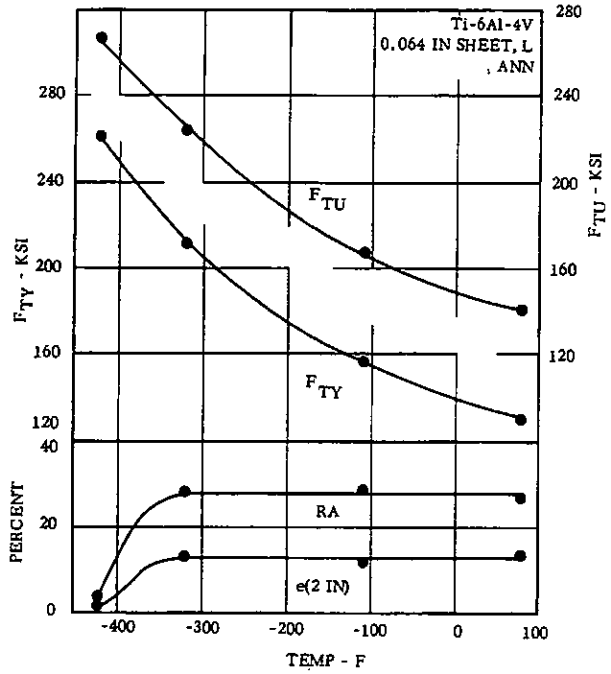


FIG. 3.0313 EFFECT OF LOW TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED SHEET (4, p. 37)

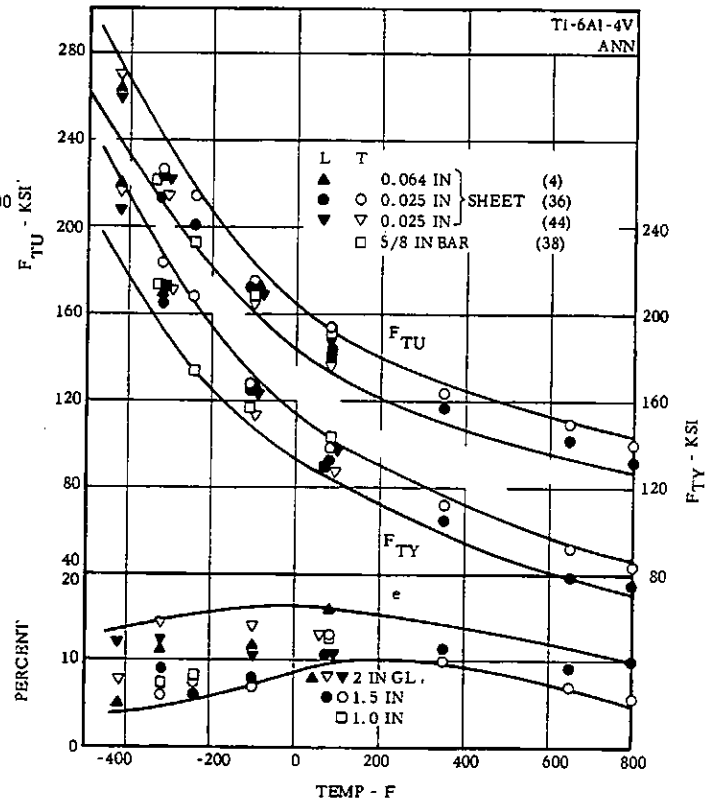


FIG. 3.0314 EFFECT OF LOW TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED SHEET AND BAR (4, p. 37)(36, p. 48)(38, Table 3)(44, p. 114)

Ti
6 Al
4 V
Ti-6Al-4V

	Ti
6	Al
4	V

Ti-6Al-4V

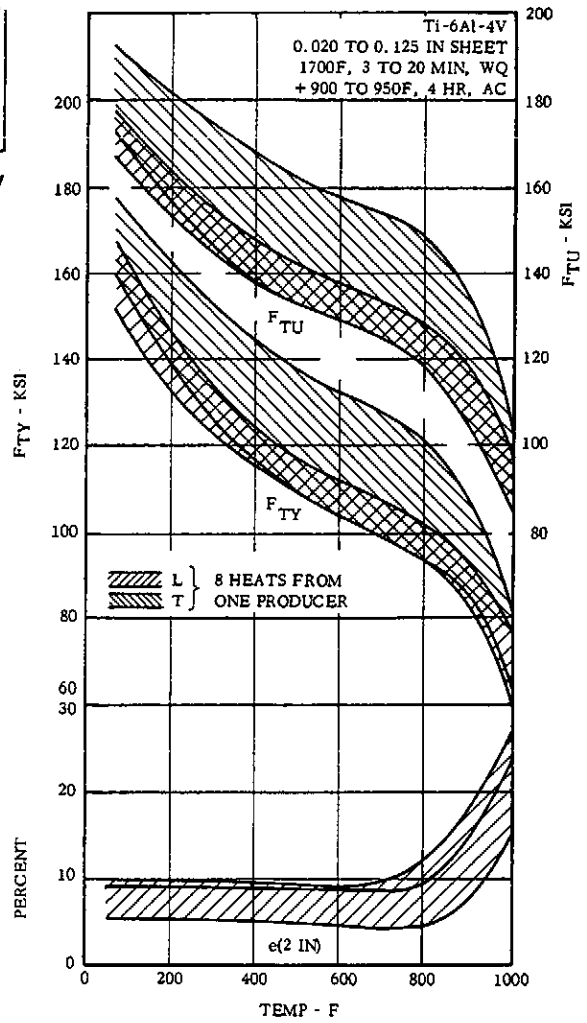


FIG. 3.03151 SPREAD OF TENSILE DATA AT ROOM AND ELEVATED TEMPERATURES FOR EIGHT HEATS OF AGED SHEET (39, p. 68-73)

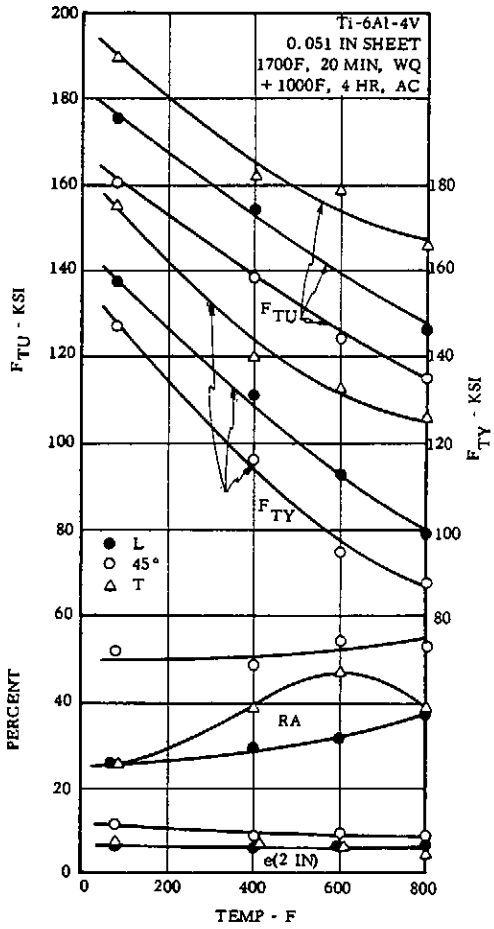


FIG. 3.03152 EFFECT OF TEST TEMPERATURE AND TESTING DIRECTION ON TENSILE PROPERTIES OF AGED SHEET

	Ti
6	Al
4	V

Ti-6Al-4V

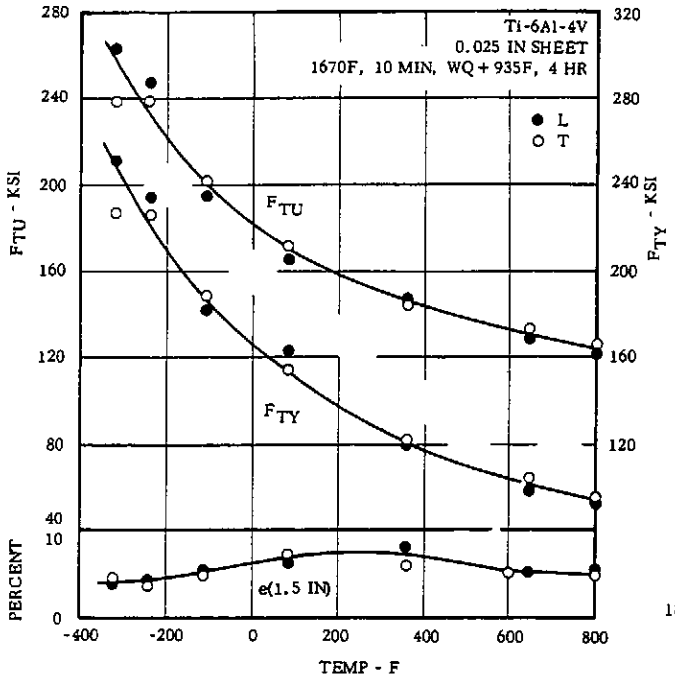


FIG. 3.03153 EFFECT OF LOW AND ELEVATED TEMPERATURES ON THE TENSILE PROPERTIES OF AGED SHEET (36, p. 51)

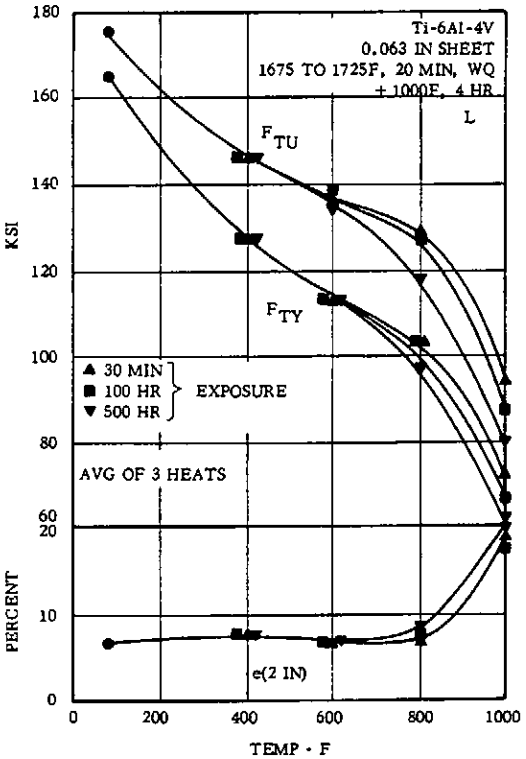


FIG. 3.03154 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON TENSILE PROPERTIES OF AGED SHEET (15, p. 217-219)

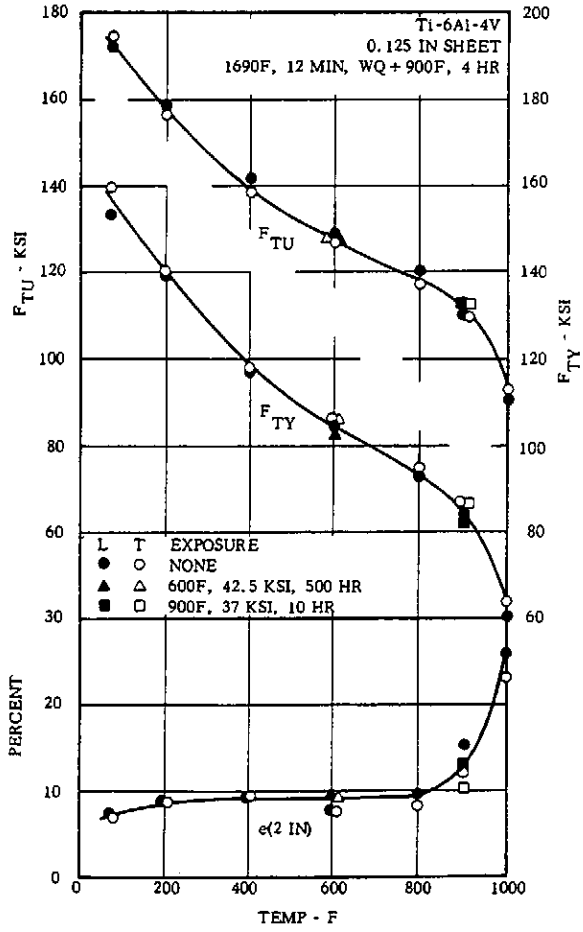


FIG. 3.03155 EFFECT OF ELEVATED TEMPERATURE EXPOSURE ON THE ROOM AND ELEVATED TEMPERATURE TENSILE PROPERTIES OF AGED SHEET (40)

	Ti
6	Al
4	V

Ti-6Al-4V

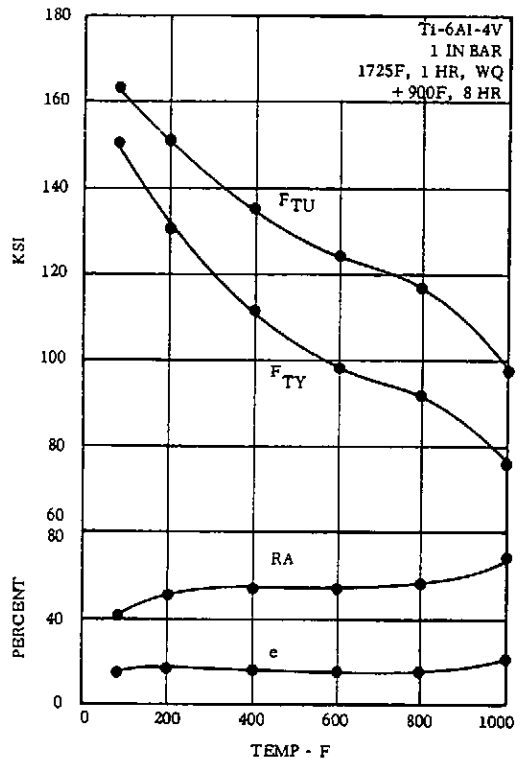


FIG. 3.03156 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF AGED BAR (13, p. 5)

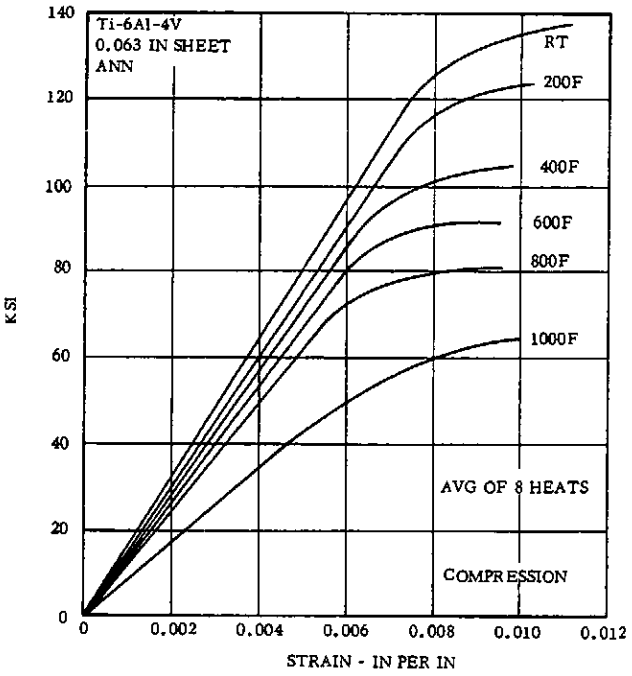


FIG. 3.03211 STRESS-STRAIN CURVES IN COMPRESSION AT ROOM AND ELEVATED TEMPERATURES FOR ANNEALED SHEET (3)

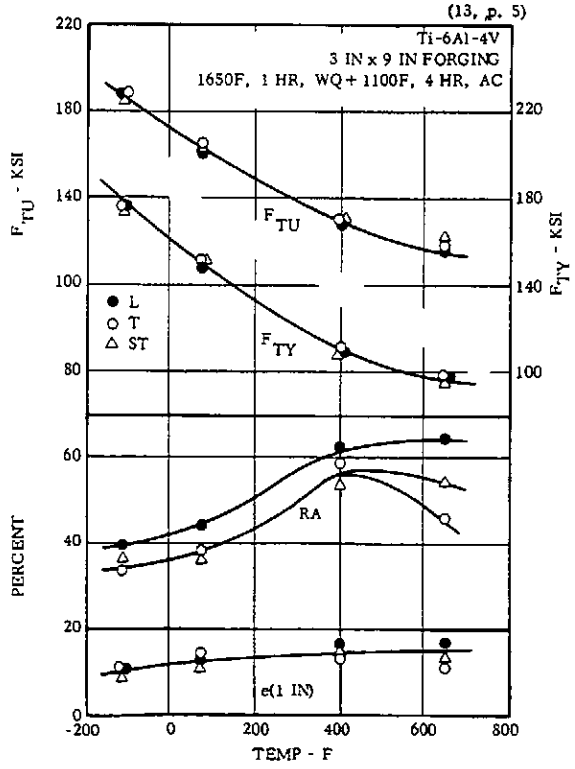


FIG. 3.03157 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION TREATED AND AGED SPECIMENS CUT FROM FORGING (26, Table 7)

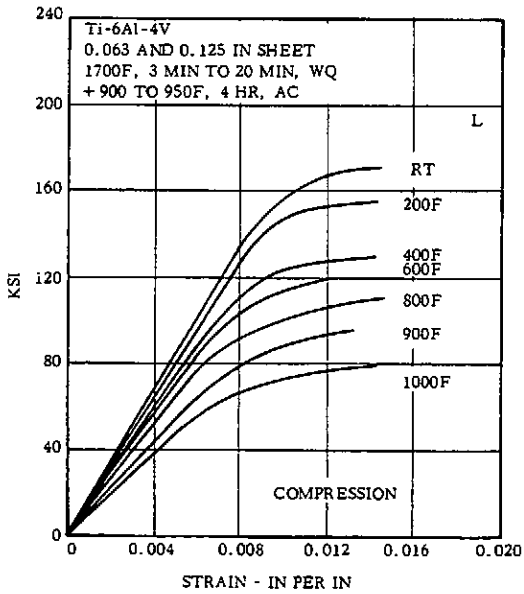


FIG. 3.03212 LONGITUDINAL COMPRESSION STRESS-STRAIN CURVES AT ELEVATED TEMPERATURE FOR AGED SHEET (42, p. 29, 30)

	Ti
6	Al
4	V

Ti-6Al-4V

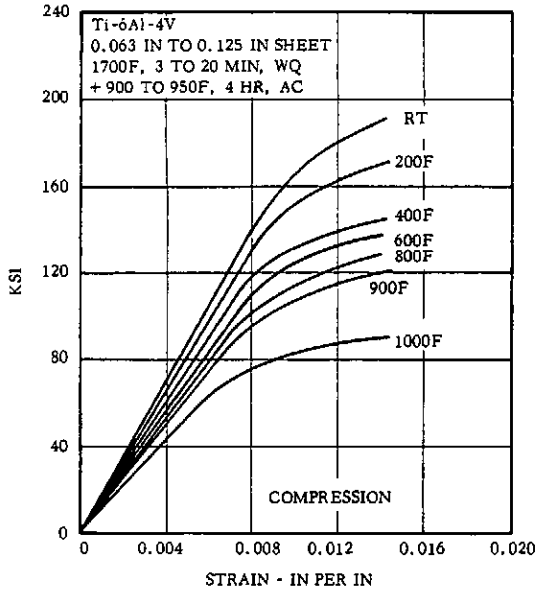


FIG. 3.03213 TRANSVERSE COMPRESSION STRESS - STRAIN CURVE AT ELEVATED TEMPERATURES FOR AGED SHEET (42, p. 29, 30)

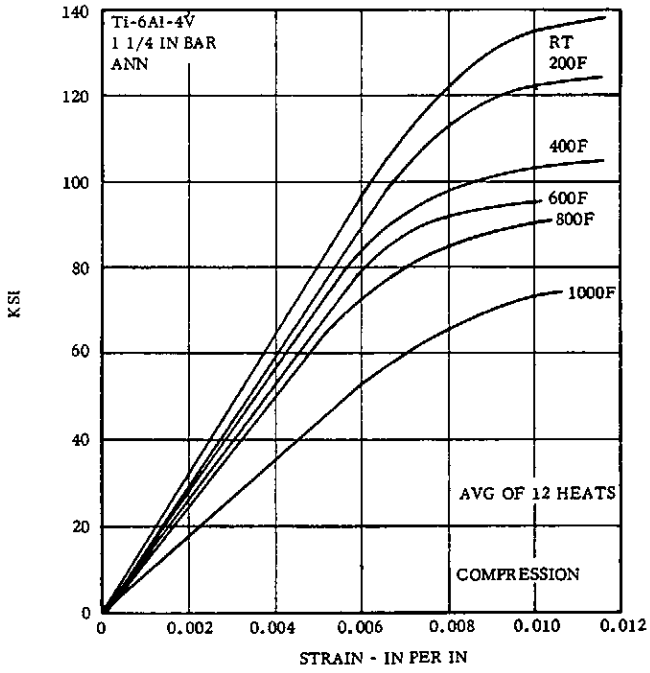


FIG. 3.03214 STRESS-STRAIN CURVES IN COMPRESSION AT ROOM AND ELEVATED TEMPERATURES FOR ANNEALED BAR (3)

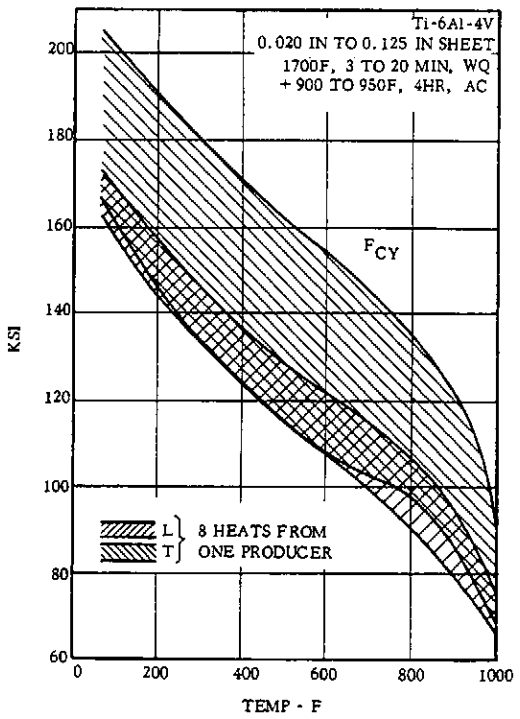


FIG. 3.03221 SPREAD OF COMPRESSIVE YIELD STRENGTH AT ROOM AND ELEVATED TEMPERATURES FOR EIGHT HEATS OF AGED SHEET (39, p. 74-79)

Ti
6 Al
4 V

Ti-6Al-4V

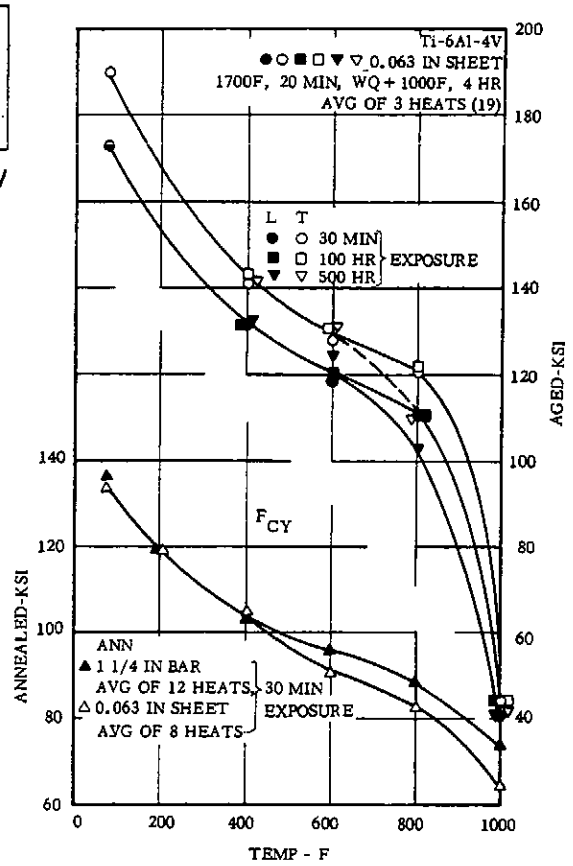


FIG. 3.03223 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF ANNEALED AND AGED SHEET AND BAR (15, p. 229-232)(19).

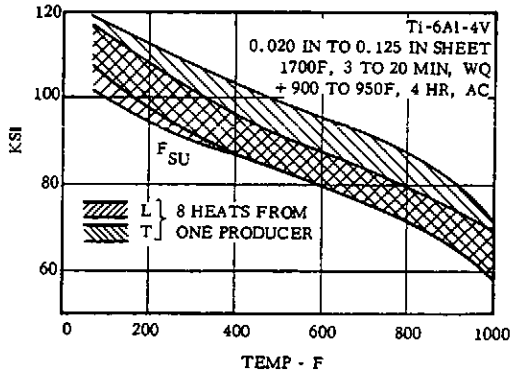


FIG. 3.0351 SPREAD OF SHEAR STRENGTH AT ROOM AND ELEVATED TEMPERATURE FOR EIGHT HEATS OF AGED SHEET (39)

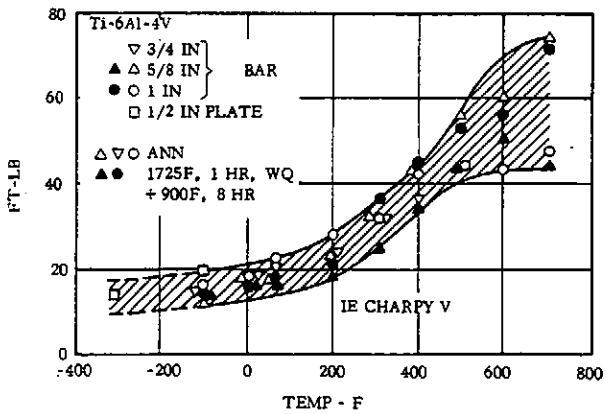


FIG. 3.0331 EFFECT OF TEST TEMPERATURE ON IMPACT STRENGTH OF ANNEALED AND AGED PLATE AND BAR (13, p. 34, 35)

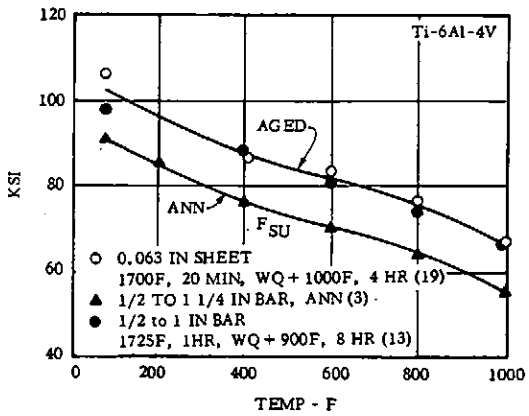


FIG. 3.0352 EFFECT OF TEST TEMPERATURE ON SHEAR STRENGTH OF ANNEALED AND AGED SHEET AND BAR (3)(13, p. 19)(19)

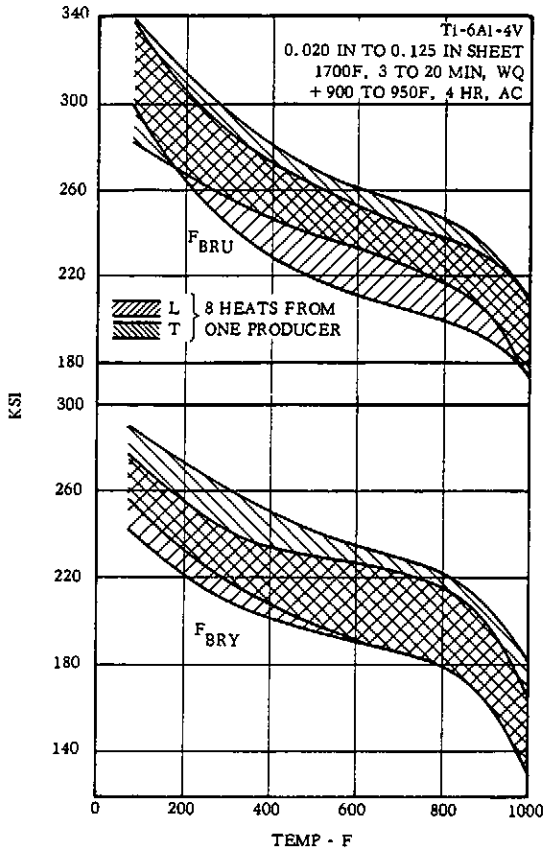
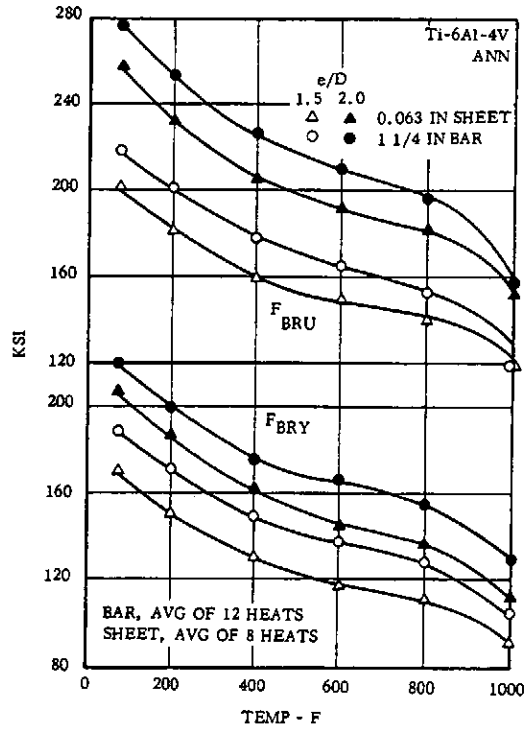


FIG. 3.0361 SPREAD OF BEARING STRENGTH AT ROOM AND ELEVATED TEMPERATURES FOR EIGHT HEATS OF AGED SHEET (39, p. 91-97)



Ti
6 Al
4 V
Ti-6Al-4V

FIG. 3.0362 EFFECT OF TEST TEMPERATURE ON BEARING PROPERTIES OF ANNEALED SHEET AND BAR (3)(7, p. 102)

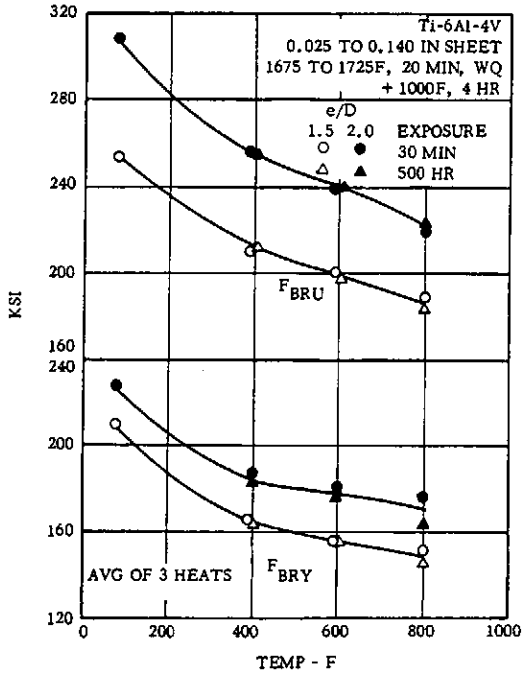


FIG. 3.0363 EFFECT OF EXPOSURE AND TEST TEMPERATURE OF BEARING PROPERTIES OF AGED SHEET (15, p. 234-235)

Ti	
6	Al
4	V

Ti-6Al-4V

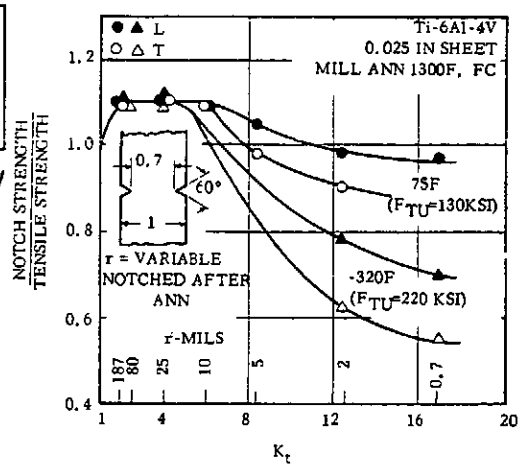


FIG. 3.03711 NOTCH STRENGTH RATIO AS FUNCTION OF STRESS-CONCENTRATION FACTOR FOR ANNEALED SHEET TESTED AT ROOM TEMPERATURE AND -320F (36, p. 114)

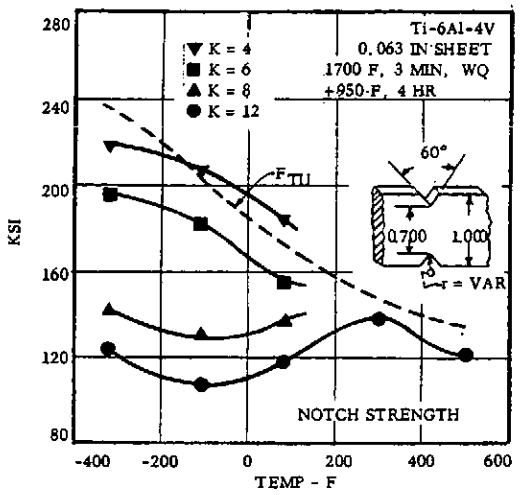


FIG. 3.03713 EFFECT OF TEST TEMPERATURE AND STRESS CONCENTRATION FACTOR ON NOTCH STRENGTH OF AGED SHEET (10, p. 25)

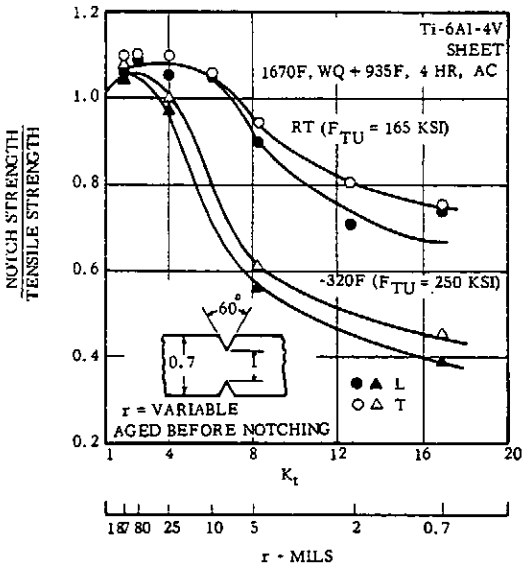


FIG. 3.03712 NOTCH STRENGTH RATIO AS FUNCTION OF STRESS CONCENTRATION FACTOR FOR AGED SHEET TESTED AT ROOM TEMPERATURE AND -320F (26, p. 115)

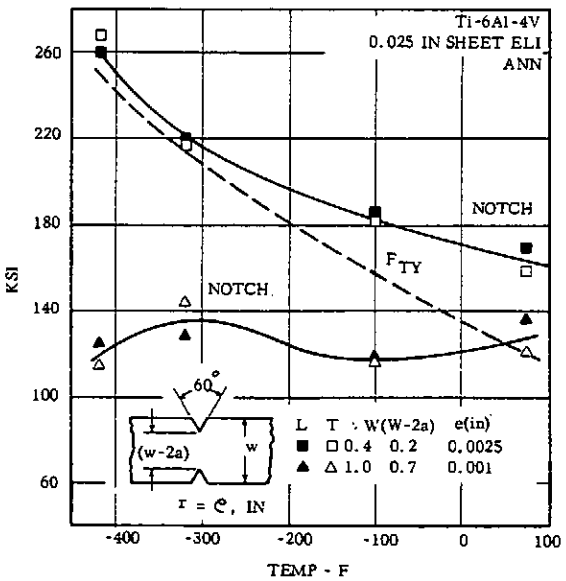


FIG. 3.03714 EFFECT OF LOW TEST TEMPERATURES ON THE MILD AND SHARP NOTCH PROPERTIES OF ANNEALED ELI SHEET (44, p. 414-117)

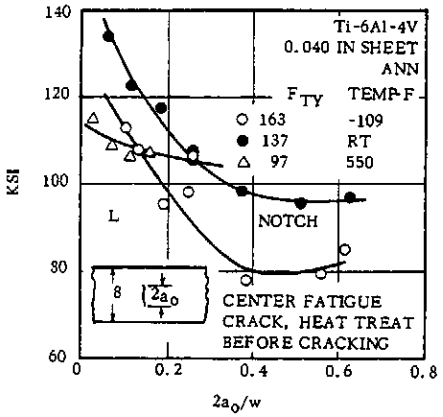
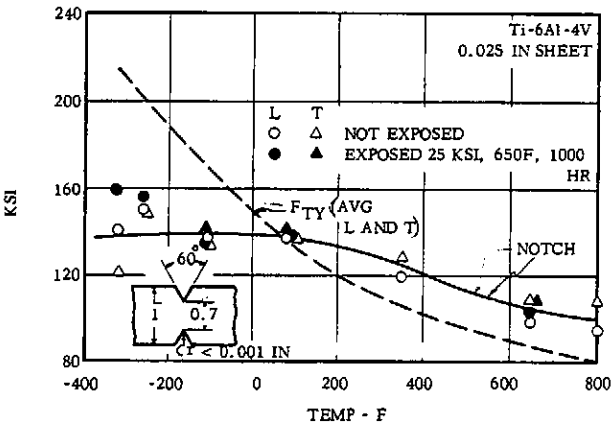


FIG. 3.03715 EFFECT OF CRACK LENGTH ON THE SHARP NOTCH PROPERTIES OF ANNEALED SHEET, TESTED AT SEVERAL TEMPERATURES (35, Table 3)



Ti
6 Al
4 V
Ti-6Al-4V

FIG. 3.03717 EFFECT OF TEST TEMPERATURE ON SHARP NOTCH STRENGTH OF ANNEALED SHEET BEFORE AND AFTER ELEVATED TEMPERATURE EXPOSURE (36, p. 49, 50)

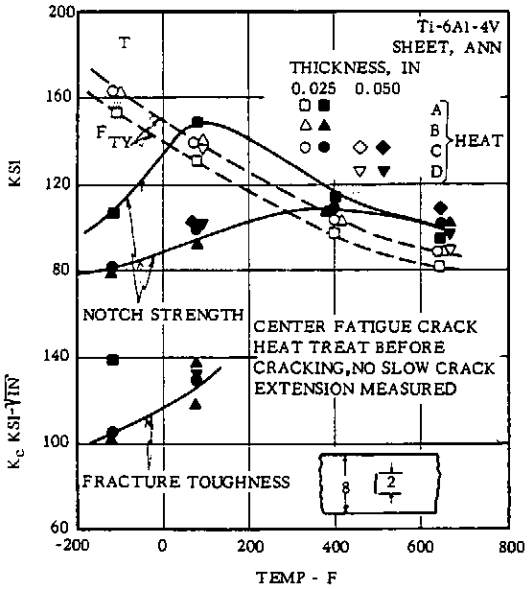


FIG. 3.03716 EFFECT OF TEST TEMPERATURE ON SHARP NOTCH PROPERTIES OF SEVERAL HEATS OF MILL ANNEALED SHEET (34, p. 131, 133)

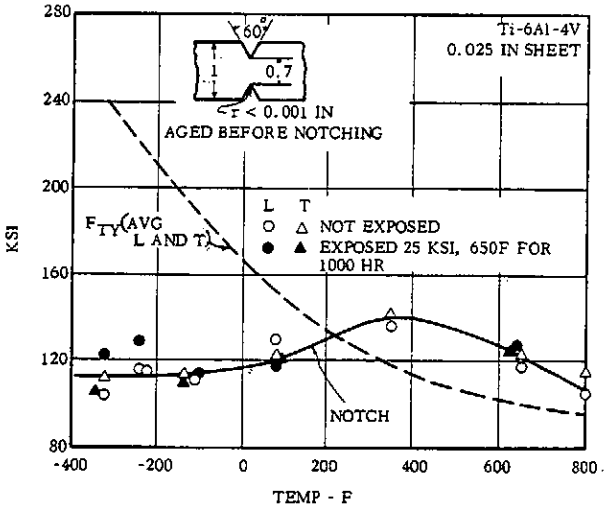


FIG. 3.03718 EFFECT OF TEST TEMPERATURE ON SHARP NOTCH STRENGTH OF AGED SHEET BEFORE AND AFTER ELEVATED TEMPERATURE EXPOSURE (36, p. 52, 53)

	Ti
6	Al
4	V

Ti-6Al-4V

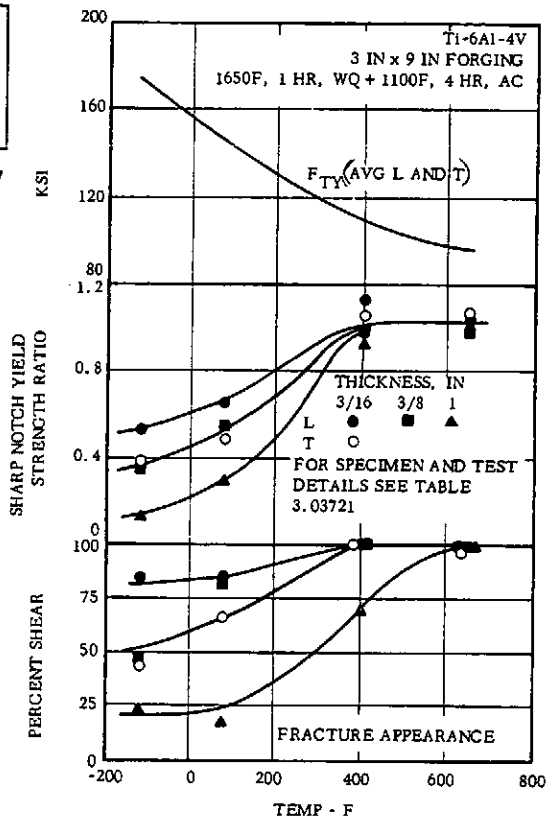


FIG. 3.03719 EFFECT OF TEST TEMPERATURE ON THE SHARP NOTCH PROPERTIES OF SOLUTION TREATED AND AGED SPECIMENS OF VARIOUS THICKNESSES CUT FROM FORGING (26, Table 18)

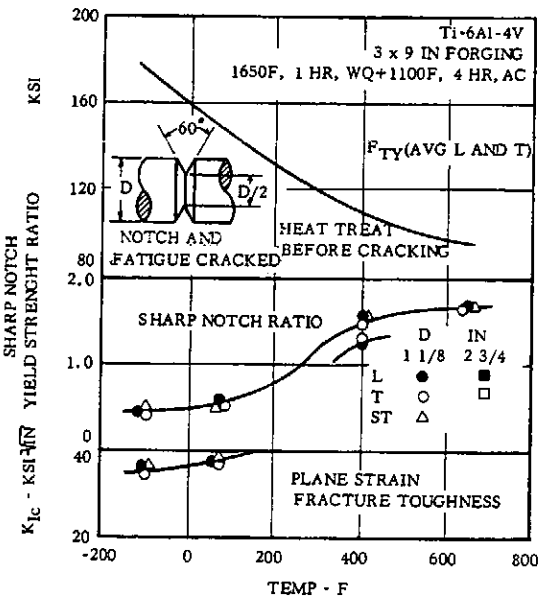


FIG. 3.03723 EFFECT OF TEST TEMPERATURE ON SHARP NOTCH STRENGTH RATIO AND PLANE STRAIN FRACTURE TOUGHNESS AND OF SOLUTION TREATED AND AGED ROUND BARS CUT FROM FORGING (26, Table 27 and 31)

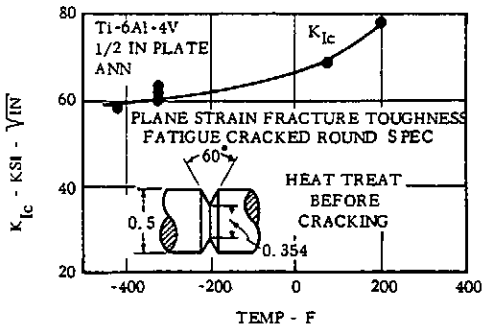


FIG. 3.03722 PLANE STRAIN FRACTURE TOUGHNESS OF ANNEALED PLATE AT LOW TEMPERATURES (30, Fig. 11)

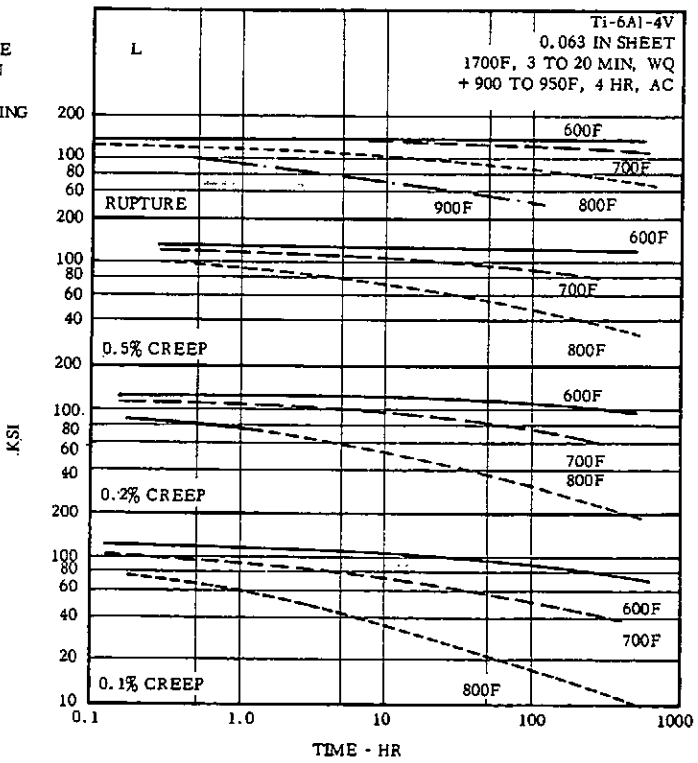


FIG. 3.041 AVERAGE CREEP AND RUPTURE CURVES AT SEVERAL TEMPERATURES FOR AGED SHEET FROM THREE HEATS (41, p. 57-59)

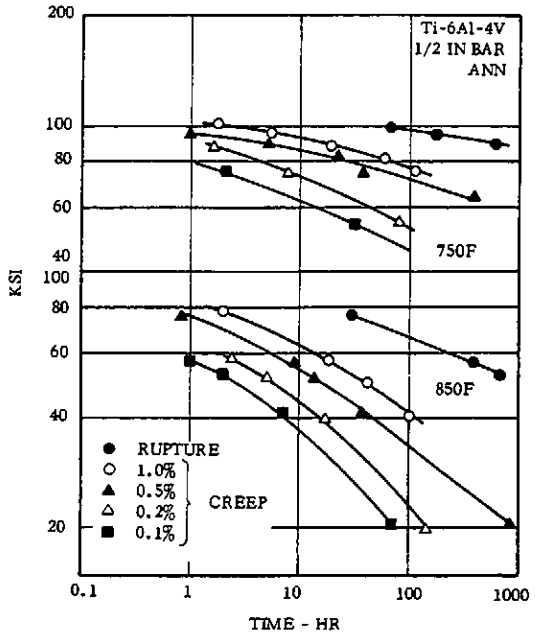


FIG. 3.042 CREEP AND CREEP RUPTURE CURVES AT 750 AND 850F FOR ANNEALED BAR (9, p. 23)

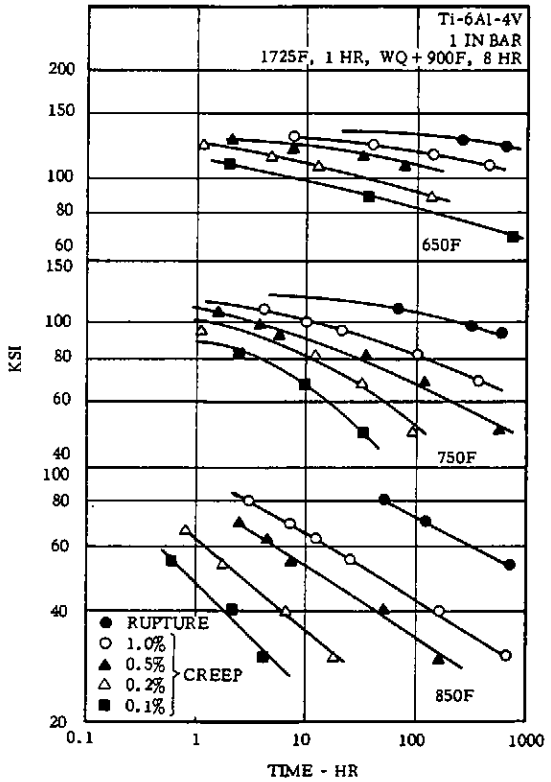


FIG. 3.043 CREEP AND CREEP RUPTURE CURVES AT 650 TO 850F FOR AGED BAR (5, G-16-18)

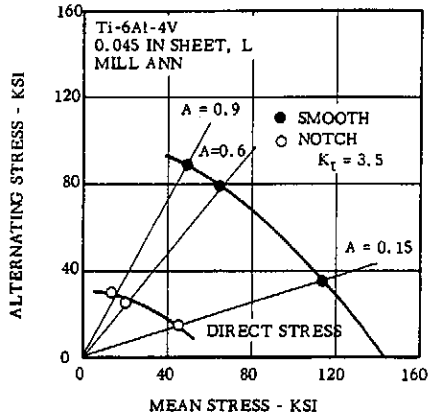


FIG. 3.054 STRESS RANGE DIAGRAM AT 10^7 CYCLES FOR SMOOTH AND NOTCHED SPECIMENS OF MILL ANNEALED SHEET (27, Fig. 11)

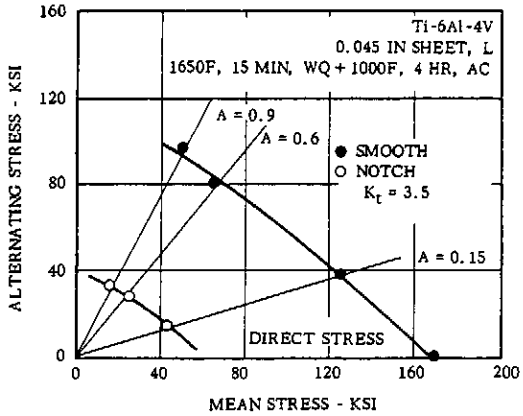


FIG. 3.055 STRESS RANGE DIAGRAM AT 10^7 CYCLES FOR SMOOTH AND NOTCHED SPECIMENS OF AGED SHEET (27, Fig. 12)

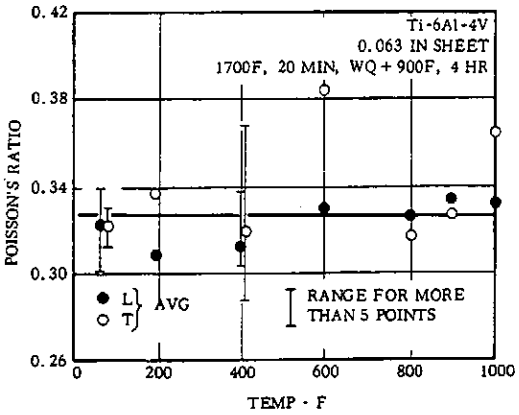


FIG. 3.061 EFFECT OF TEST TEMPERATURE ON POISSON'S RATIO (40, p. 242)

Ti
6 Al
4 V
Ti-6Al-4V

Ti
6 Al
4 V

Ti-6Al-4V

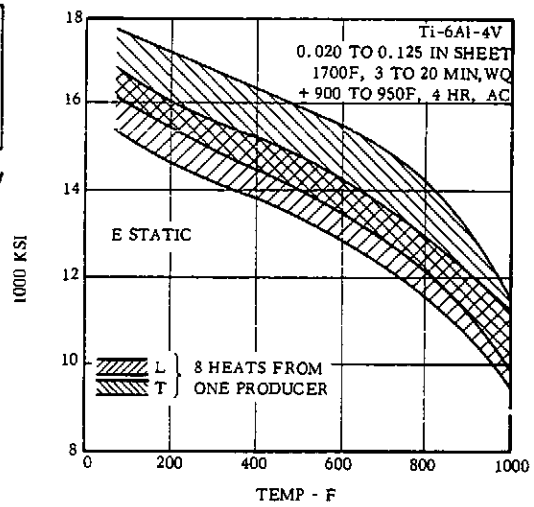


FIG. 3.0621 SPREAD OF ELASTIC MODULUS AT ROOM AND ELEVATED TEMPERATURE FOR EIGHT HEATS OF AGED SHEET (39, p. 68-73)

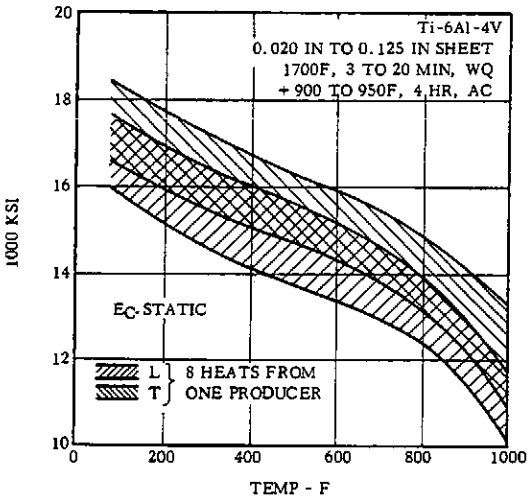


FIG. 3.0624 SPREAD OF ELASTIC COMPRESSIVE MODULUS AT ROOM AND ELEVATED TEMPERATURE FOR EIGHT HEATS OF AGED SHEET (39, p. 74-79)

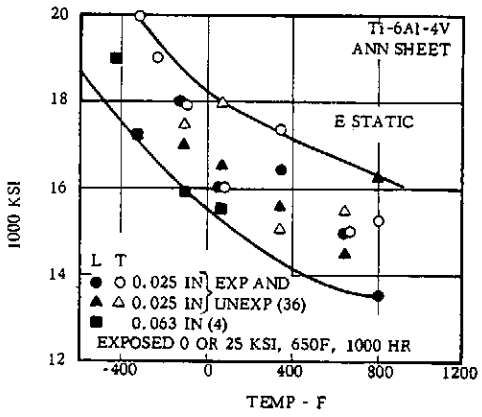


FIG. 3.0622 MODULUS OF ELASTICITY AT LOW AND ELEVATED TEMPERATURES FOR ANNEALED SHEET (4, p. 39)(36, p. 28, 30)

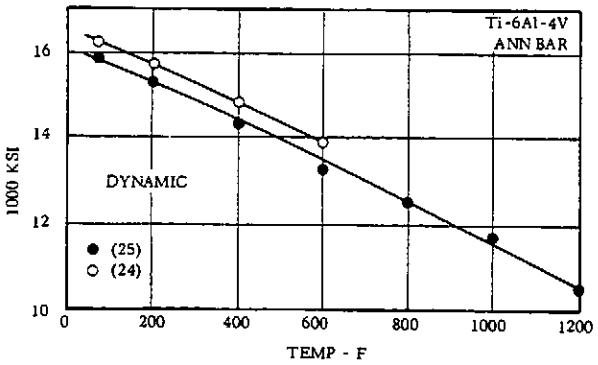


FIG. 3.0623 DYNAMIC MODULUS OF ELASTICITY FOR ANNEALED BAR AT ELEVATED TEMPERATURES (24)(25)

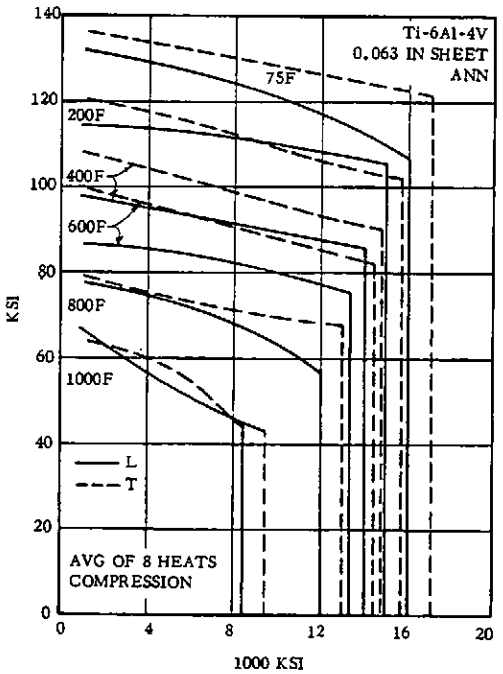


FIG. 3.0641 TANGENT MODULUS CURVES IN COMPRESSION AT ROOM AND ELEVATED TEMPERATURES FOR ANNEALED SHEET (3)

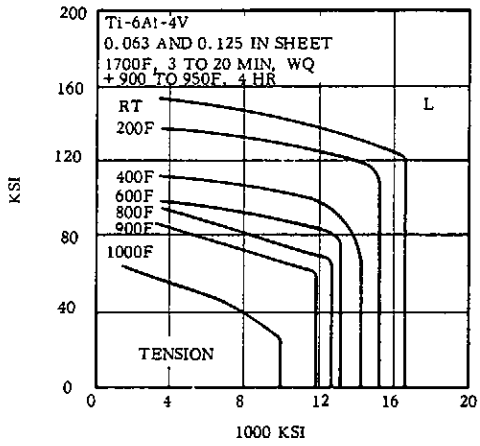
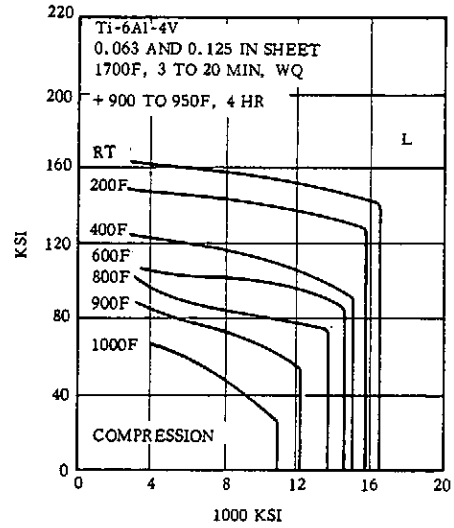


FIG. 3.0642 LONGITUDINAL TENSILE TANGENT MODULUS CURVES AT ELEVATED TEMPERATURES FOR AGED SHEET (42, p. 21, 22)



Ti
6 Al
4 V

Ti-6Al-4V

FIG. 3.0644 LONGITUDINAL COMPRESSION TANGENT MODULUS CURVES AT ELEVATED TEMPERATURES FOR AGED SHEET (42, p. 23, 24)

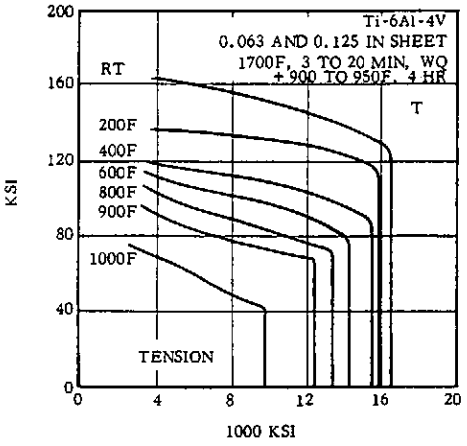


FIG. 3.0643 TRANSVERSE TENSILE TANGENT MODULUS CURVES AT ELEVATED TEMPERATURES FOR AGED SHEET (42, p. 21, 22)

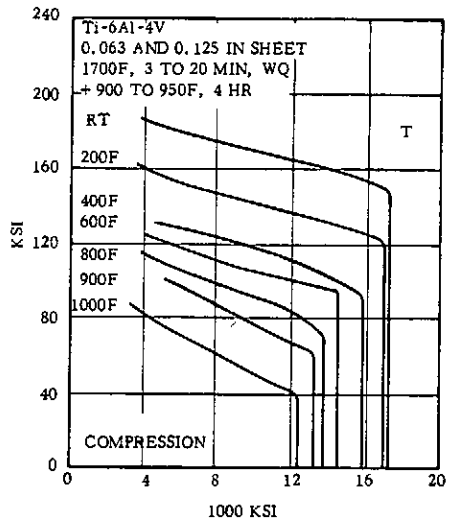


FIG. 3.0645 TRANSVERSE COMPRESSION TANGENT MODULUS CURVES AT ELEVATED TEMPERATURES FOR AGED SHEET (42, p. 23, 24)

Ti
6 Al
4 V

Ti-6Al-4V

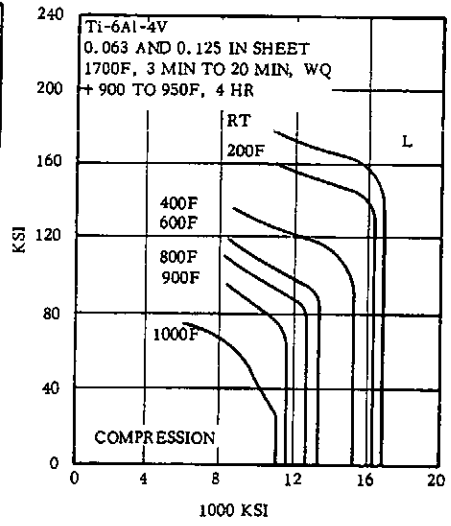


FIG. 3.0651 LONGITUDINAL COMPRESSION SECANT MODULUS CURVES AT ELEVATED TEMPERATURES FOR AGED SHEET (42, p. 25-26)

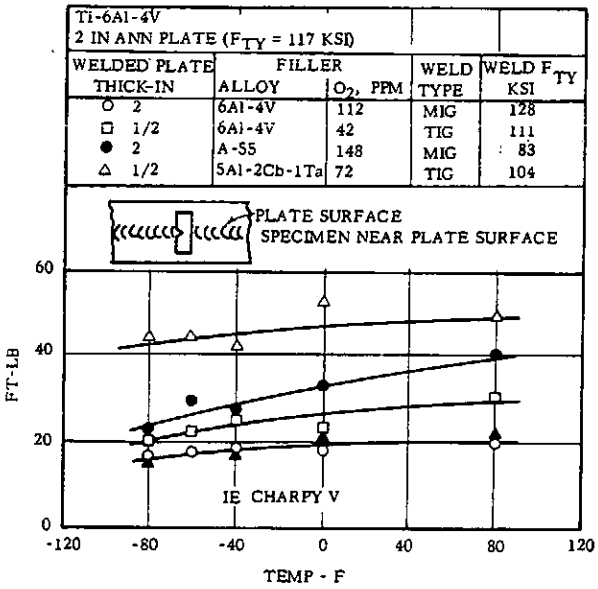


FIG. 4.034 EFFECT OF TEST TEMPERATURE ON THE IMPACT PROPERTIES OF PLATE WELDED WITH VARIOUS FILLERS (28, Figs. 10, 11)

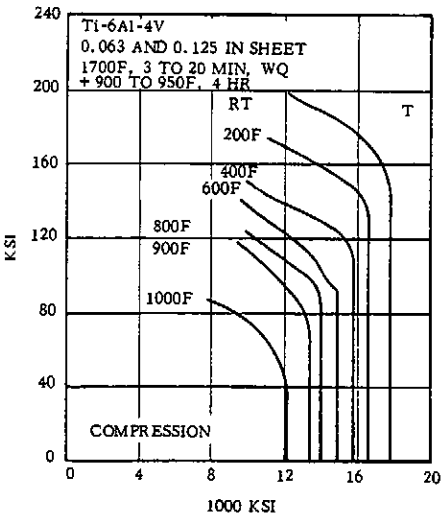


FIG. 3.0652 TRANSVERSE COMPRESSION SECANT MODULUS CURVES AT ELEVATED TEMPERATURES FOR AGED SHEET (42, p. 25, 26)

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Ti
6 Al
4 V

Ti-6Al-4V

Ti
6 Al
4 V

Ti-6Al-4V

A1. GENERAL

This alloy is the most widely used of all the alpha-beta titanium compositions. It may be heat treated to a range of strength levels and, in its fully aged condition, is successfully used in highly stressed welded structures. However, in the maximum strength conditions, careful attention must be given to the fracture toughness in a design of highly stressed parts. Hardenability is limited and sections over 1 inch thick may not develop full properties. The alloy has good strength and high stability up to 750 F. Very high strength is obtained at cryogenic temperatures, however, the fracture toughness below about -250 F is extremely poor for the fully heat treated conditions. Low temperature applications should employ the extra low interstitial (ELI) grades. The alloy exhibits some susceptibility to environment-assisted cracking in halide containing aqueous environments and in hydrogen. Properties also depend on the texture in rolled products. Improved properties are obtained by using the ELI grades and beta-processing. The alloy can be welded using special techniques. Forming requires special methods and elevated temperatures.

A1.01 Commercial Designation

6Al-4V Titanium Alloy.

A1.02 Alternate Designations

C 120AV, HA 6510, RS 120A, Ti-6Al-4V, Ti-6Al-4V ELI.

A1.03 Specifications

Table A1.03.

A1.04 Composition

A1.041 AMS specified composition for wrought product and weld wire, Table A1.041.

A1.042 AMS specified composition for powder and powder metallurgy products, Table A1.042.

A1.09 Special Considerations

This alloy is somewhat susceptible to environment assisted cracking in halide containing aqueous environments and in hydrogen under sustained loading and in fatigue. The susceptibility depends on heat treatment and mechanical processing (see A2.03).

A2. PHYSICAL AND CHEMICAL PROPERTIES

A2.03 Chemical Properties

This alloy is somewhat susceptible to environment assisted cracking in halide containing aqueous environments and in hydrogen under sustained load (stress corrosion cracking) and in fatigue (corrosion fatigue). The degree of susceptibility depends on the prior thermal and mechanical treatment, which is reduced by the use of ELI grades and beta-processing (A12, A13). Because recommended practices for obtaining stress-corrosion cracking data are not yet available, such data are not reported here. The reader should consult references (A12, A13) to obtain information on the influences of strength and microstructure on stress-corrosion cracking susceptibility.

A3. MECHANICAL PROPERTIES

A3.01 Specified Mechanical Properties

A3.011 AMS specified mechanical properties.

A3.0111 AMS specified mechanical perperties for sheet, strip, and plate, Table A3.0111.

A3.0112 AMS specified mechanical properties for bar, forging, and ring, Table A3.0112.

A3.0113 AMS specified mechanical properties for bar, and forging (rectangle), Table A3.0113.

A3.0114 AMS specified mechanical properties for extrusions, flash welded rings, and powder-metallurgy products, Table A3.0114.

A3.05 Fatigue Properties

A3.056 Influence of load ratio (R) on fatigue crack growth for mill annealed plate in air at room temperature, Figure A3.056.

A3.057 Influence of environment on fatigue crack growth for mill annealed plate at room temperature, Figure A3.057.

A3.058 Fatigue crack growth in dehumidified argon for mill annealed plate at different temperatures and K levels, Figure A3.058.

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A6. AMS 4934A (January 15, 1977).
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Ti
6 Al
4 V

Ti-6Al-4V

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Alloy	Ti-6Al-4V
AMS	Form
4906	Sheet, strip, and plate
4907C	
4911D	
4928H	Bars and forgings – annealed, 120 ksi yield
4967E	Bars, forgings, and rings – annealed, heat treatable
4934A	Extrusions and flash welded rings – solution heat treated and aged, and annealed
4954C	Welding wire
4956A	
4996	Powder-metallurgy products
4998	Powder

TABLE A1.03. SPECIFICATIONS

Alloy	Ti-6A1-4V			
Grade	Normal		ELI	
Composition	Percent		Percent	
	Min	Max	Min	Max
Al	5.50	6.75	5.50	6.50(a)
V	3.50	4.50	3.50	4.50
Fe	–	0.30	–	0.25(a)
O	–	0.20(b)	–	0.13(a)
C	–	0.10(b)(c)	–	0.08(a)
Ni	–	0.05(b) (500 ppm)	–	0.05(a) (500 ppm)
H	–	0.0125(b)(c) (125 ppm)	–	0.0125(a) (125 ppm)
Y	–	0.005 (50 ppm)	–	0.005 (50 ppm)
Residuals				
Each	–	0.10(d)	–	0.10(a)(d)
Total	–	0.40(d)	–	0.30(a)(d)
Ti	Remainder		Remainder	

(a) AMS 4956A specifies aluminum – 6.75 Max, iron – 0.15 Max, oxygen – 0.08 Max, carbon – 0.03 Max, nitrogen – 0.012 Max, hydrogen – 0.005 Max, residual elements – 0.03 Max each and 0.10 Max total.
(b) AMS 4954C specifies oxygen – 0.18 Max, carbon – 0.05 Max, nitrogen – 0.03 Max, hydrogen – 0.015 Max.
(c) AMS 4906 specifies carbon – 0.08 Max; AMS 4911D specifies carbon – 0.08 Max, hydrogen 0.015 Max.
(d) Determination not required for routine acceptance.

TABLE A1.041. AMS SPECIFIED COMPOSITION FOR WROUGHT PRODUCT AND WELD WIRE (A1,A2,A3,A4,A5, A6,A7,A8,A9)

Alloy	Ti-6A1-4V			
Composition	Percent		Percent	
	Min	Max	Min	Max
Al	5.50	6.75	5.50	6.75
V	3.50	4.50	3.50	4.50
O	0.13	0.19	0.13	0.18
Fe	–	0.30	–	0.30
C	–	0.10	–	0.10
Sn(a)	–	0.10	–	0.10
Mo(a)	–	0.10	–	0.10
Cu(a)	–	0.10	–	0.10
Mn(a)	–	0.10	–	0.10
Zr	–	0.10	–	0.10
Ni	–	0.04 (400 ppm)	–	0.04 (400 ppm)
H	–	0.0125 (125 ppm)	–	0.012 (120 ppm)
Y	–	0.001 (10 ppm)	–	0.001 (10 ppm)
Residuals, total(b)	–	0.20	–	0.20
Ti	Remainder		Remainder	

(a) Tin plus molybdenum plus copper plus manganese shall not exceed 0.20 Max.
(b) Determination not required for routine acceptance.

TABLE A1.042. AMS SPECIFIED COMPOSITION FOR POWDER AND POWDER METALLURGY PRODUCTS (A10,A11)

Alloy	Ti-6A1-4V								
Form	Sheet, Strip, and Plate (Normal Purity)					Sheet, Strip, and Plate(a) (ELI Grade)			
Condition	Annealed					Annealed			
Diameter or Thickness, in.	< 0.008	0.008 to 0.025	0.025 to 0.063	0.063 to 0.1875	0.1875 to 4.000	0.008 to 0.015	0.015 to 0.025	0.025 to 1.000	1.000 to 3.000
F_{tu}, ksi (Min)	134	134	134	134	130	130	130	130	130
F_{ty}, ksi (Min)	126	126	126	126	120	120	120	120	115
e(2 in. or 4D), percent (Min)	–	6	8	10	10	6	8	10	10

(a) Using specified tensile test specimens, product tested at –423 F shall maintain a notch/unnotched tensile ratio of not less than 0.75 (A2).

TABLE A3.0111. AMS SPECIFIED MECHANICAL PROPERTIES FOR SHEET, STRIP, AND PLATE (A2, A3)

Ti
6 Al
4 V
Ti-6Al-4V

Alloy	Ti-6Al-4V							
Form	Bar, Forging, and Ring							
Condition	Annealed							
Diameter or Distance Between Parallel Sides, in.	< 4.000	4.000 to 6.000	0.500	0.500 to 1.000	1.000 to 1.500	1.500 to 2.000	2.000 to 3.000	3.000 to 4.000
F_{tu}, ksi (Min)	130	130	165	160	155	150	135	130
F_{ty}, ksi (Min)	120	120	155	150	145	140	125	120
e(2 in. or 4D), percent (Min)								
Longitudinal	10	10	10	10	10	10	10	10
Transverse	10	10	–	–	–	–	8	6
Short transverse	10	8	–	–	–	–	–	–
RA, percent (Min)								
Longitudinal	25	20	20	20	20	20	20	20
Transverse	20	20	–	–	–	–	–	–
Short transverse	–	15	–	–	–	–	–	–

For AMS 4928H: Using specified notched specimens, product shall have 5-hour minimum rupture life at room temperature when loaded to 170 ksi.

For AMS 4967E: Using specified notched specimens, products up to 1-inch diameter or distance between parallel sides shall have 5-hour minimum rupture life at room temperature when loaded to 185 ksi.

TABLE A3.0112. AMS SPECIFIED MECHANICAL PROPERTIES FOR BAR, FORGING, AND RING (A4, A5)

Alloy	Ti-6Al-4V								
Form	Bar and Forging (Rectangles)								
Condition	Annealed								
Thickness, in.	< 0.500	0.500 to 1.000		1.000 to 1.500		1.500 to 2.000		2.000 to 3.000	3.000 to 4.000
Width, in.	0.500 to 8.000	1.000 to 4.000	4.000 to 8.000	1.500 to 4.000	4.000 to 8.000	2.000 to 4.000	4.000 to 8.000	3.000 to 8.000	4.000 to 8.000
F_{tu}, ksi (Min)	160	155	150	150	145	145	140	135	130
F_{ty}, ksi (Min)	150	145	140	140	135	135	130	125	120
e(2 in. or 4D), percent (Min)									
Longitudinal	10	10	10	10	10	10	10	10	10
Transverse	10	10	10	10	10	10	10	8	6
RA, percent (Min)									
Longitudinal	25	20	20	20	20	20	20	20	20

For AMS 4967E: Using specified notched specimens, products up to 1-inch distance between parallel sides shall have 5-hour minimum rupture life at room temperature when loaded to 185 ksi.

TABLE A3.0113. AMS SPECIFIED MECHANICAL PROPERTIES FOR BAR AND FORGING [RECTANGLES] (A5)

Alloy	Ti-6Al-4V							
Form	Extrusions and Flash Welded Rings						Billets or Preforms	Forged Coupons
Condition	Annealed							
Diameter or Distance Between Parallel Sides, in.	< 0.500	0.500 to 0.750	0.750 to 1.000	1.000 to 2.000	2.000 to 3.000	3.000		
F_{tu}, ksi (Min)	160	155	150	140	130	130	300	300
F_{ty}, ksi (Min)	150	146	140	130	120	120	120	120
e(2 in. or 4D), percent (Min)	6	6	6	6	6	10(L) 8(T)	5	10
RA, percent (Min)	12	12	12	12	12	20(L) 15(T)	10	20

For AMS 4934A: Using specified notched specimens, product shall have 5-hour minimum rupture life at room temperature when loaded to 185 ksi.

For AMS 4935D: Using specified notched specimens, product shall have 5-hour minimum rupture life at room temperature when loaded to 170 ksi.

TABLE A3.0114. AMS SPECIFIED MECHANICAL PROPERTIES FOR EXTRUSIONS, FLASH WELDED RINGS, AND POWDER METALLURGY PRODUCTS (A6,A7,A10)

Ti
6 Al
4 V
Ti-6Al-4V

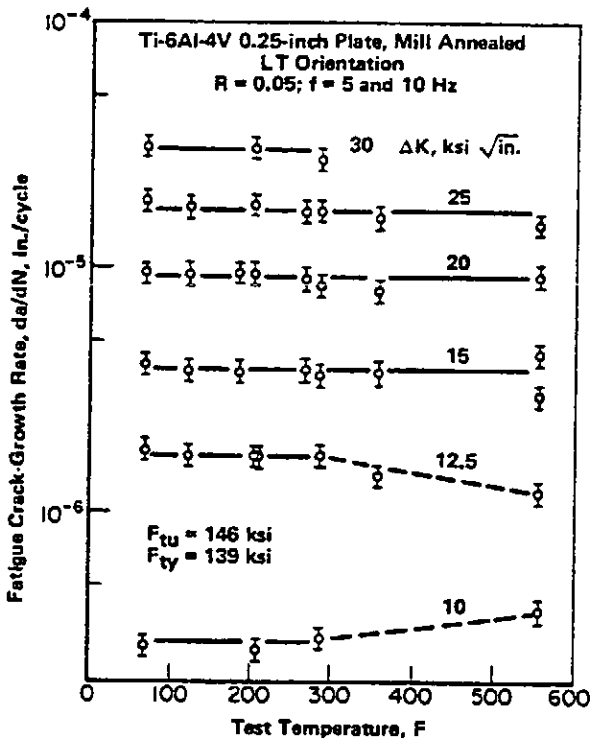


FIGURE A3.058. FATIGUE CRACK GROWTH IN DEHUMIDIFIED ARGON FOR MILL ANNEALED PLATE AT DIFFERENT TEMPERATURES AND K LEVELS (A16)

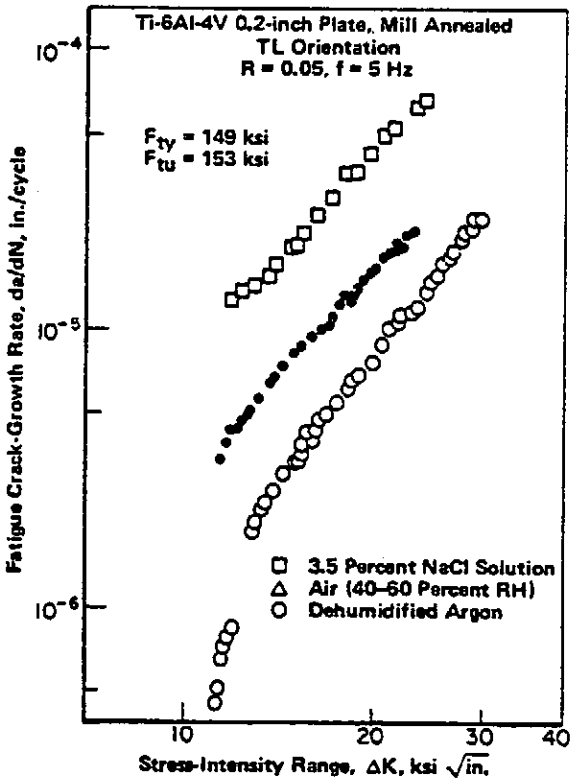


FIGURE A3.057. INFLUENCE OF ENVIRONMENT ON FATIGUE CRACK GROWTH FOR MILL ANNEALED PLATE AT ROOM TEMPERATURE (A15)

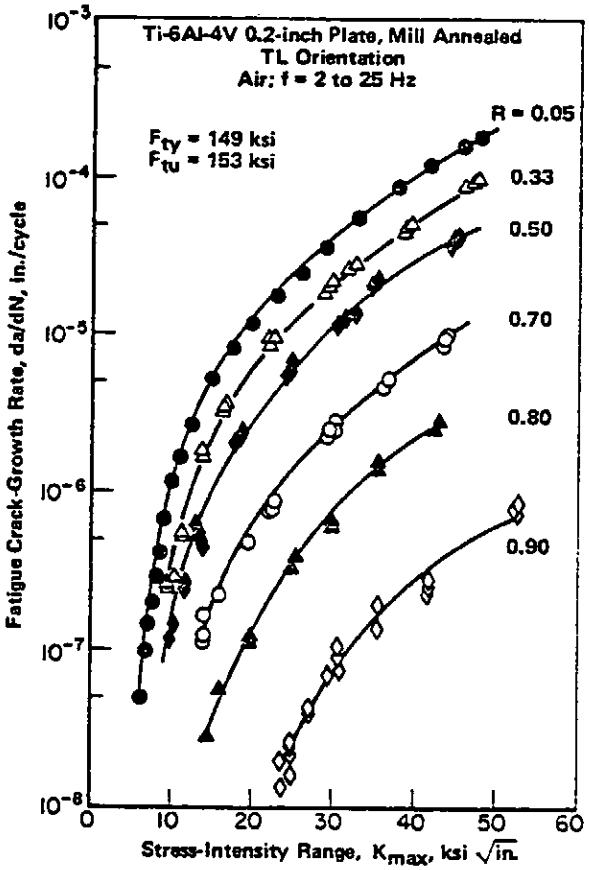


FIGURE A3.056. INFLUENCE OF LOAD RATIO (R) ON FATIGUE CRACK GROWTH FOR MILL ANNEALED PLATE IN AIR AT ROOM TEMPERATURE (A14)

Ti
7 Al
4 Mo

1. GENERAL

Ti-7Al-4Mo is a heat treatable alpha-beta type alloy. It is used primarily in the form of light and intermediate forgings and extrusions at temperatures up to 850F. Its strength is higher than that of Ti-6Al-4V by about 15 ksi in the annealed condition and about 25 ksi in the solution treated and aged condition. The depth of hardening of this alloy is essentially the same as that of Ti-6Al-4V. Welding of this alloy is not recommended.

1.01 Commercial Designation

7Al-4Mo Titanium Alloy.

1.02 Alternate Designations

C-135AMo, Ti(6 to 7)Al-(3 to 4)Mo, MST 7Al-4Mo, RS-135, RMI-7Al-4Mo, HA-7146.

1.03 Specifications

Table 1.03.

TABLE 1.03

Form	Condition	Specifications	
		AMS (1)	Company
Bar, forgings forging stock	Ann	-	General Electric Co. B50T52-53
	ST + aged	AMS 4970A	-

1.04 Composition

1.041 AMS specified composition, Table 1.041.

TABLE 1.041

Source	AMS (1)	
	Percent	
	Min	Max
Aluminum	6.50	7.30
Carbon	-	0.10
Hydrogen	-	0.013
Iron	-	0.30
Molybdenum	3.50	4.50
Nitrogen	-	0.05
Oxygen	-	0.20
Other elements Total*	-	0.40
Titanium	Balance	

* Need not be reported

1.042 Producer's specified composition, Table 1.042.

TABLE 1.042

Source	(2)(3)(4)	
	Percent	
	Min	Max
Aluminum	6.5	7.3
Carbon	-	0.08
Hydrogen	-	0.0125 **
Iron	-	0.25
Molybdenum	3.5	4.5
Nitrogen	-	0.05
Oxygen *	-	-
Titanium	Balance	

* Not specified

** Billet, 0.0100% maximum

1.043 Users' specified composition, Table 1.043.

TABLE 1.043

Source	(5)	
	Percent	
	Min	Max
Aluminum	6.5	7.3
Carbon	-	0.15
Hydrogen	-	0.0125
Iron *	-	-
Molybdenum	3.5	4.5
Nitrogen	-	0.07
Oxygen	-	0.20
Titanium	Balance	

* Not specified

1.05 Heat Treatment

1.051 Anneal.

1.0511 For maximum formability. 1450F, 1 hour, furnace cool at 300F per hour maximum to 1050F maximum, air cool.

1.0512 For maximum creep properties. 1450F, 1 hour, furnace cool at 300F per hour maximum to 1050F, air cool + 1050F, 24 hours, air cool.

1.052 Stress relief. 900 to 1300F, 1 to 8 hours, using highest temperature at which oxidation is no problem, air cool.

1.053 Solution treat. 1700 to 1800F, 30 minutes to 2 hours, water quench.

1.0531 Effect of solution treat temperature on room temperature tensile properties of unaged bar, Fig. 1.0531.

1.0532 Effect of solution treat temperature on room temperature tensile properties of aged bar, Fig. 1.0532.

1.054 Age. 1000F to 1200F, 2 to 8 hours, air cool. Aging response of bar, Fig. 1.054.

1.06 Hardness

In sections up to 4 inches, the hardenability of this alloy is essentially identical to that of Ti-6Al-4V. Its strength at full hardness, however, exceeds that of Ti-6Al-4V.

1.061 Effect of as-quenched section size on room temperature tensile properties of aged bar, Fig. 1.061.

1.062 Hardness. Typical. 32 to 38 RC.

1.07 Forms and Conditions Available

1.071 Alloy is available in the full commercial range of sizes for bar, forgings and extrusions.

1.072 Some of the special products which are available on a commercial basis are sheet, plate and wire.

1.073 All products are supplied in the annealed condition. Bar is additionally supplied in the heat treated condition, (9).

1.08 Melting and Casting Practice

1.081 Consumable electrode double vacuum melt, (1)(9).

1.09 Special Considerations

See Ti, Commercially Pure.

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range. Approximately 3000F.

2.012 Phase changes. This alloy transforms on cooling from beta to alpha plus beta at 1815F to 1865F, (3)(4).

2.013 Thermal conductivity, Fig. 2.013.

2.014 Thermal expansion, Fig. 2.014.

2.015 Instantaneous specific heat, Fig. 2.015.

2.016 Thermal diffusivity

2.02 Other Physical Properties

2.021 Density. 0.162 lb per cu in; 4.48 gr per cu cm, (3)(4)(10)(11)(12).

2.0211 Time-temperature-transformation diagrams

2.022 Electrical resistivity, Fig. 2.022.

Ti
7 Al
4 Mo

2.023 Magnetic properties. Alloy is nonmagnetic.
2.024 Emissivity
2.025 Damping capacity

2.03 Chemical Properties
See Ti, Commercially Pure.

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties
3.011 AMS specified mechanical properties, Table 3.011.

TABLE 3.011

Source	AMS (1)			
Alloy	Ti-7Al-4Mo			
Form	Bars and forgings			
Condition	1725F ± 25, 1 to 2 hr, WQ+ 1200F + 25F, 16 hr, AC			
Diameter or thickness - in	F_{tu}, ksi - min	F_{ty}, ksi - min	e(4D), % - min	RA, % - min
≤ 1.00	170	150	10	20
> 1.00 to 2.00	165	150	10	20
> 2.00 to 3.00	155	145	10	20

Hardness shall not be lower than RC 30
'See Reference(1) for stress rupture and creep stability specifications

3.012 Producer's guaranteed mechanical properties for annealed material, Table 3.012.

TABLE 3.012

Source	(13)	
Alloy	Ti-7Al-4Mo	
Form	Bar	
Condition	Ann	
Thickness - in	≤ 2	2 to 3
F_{tu}, min-ksi	145	140
F_{ty}, min-ksi	135	130
e, (4D) min-%	10	10
RA, min-%	20	20
Hardness, RC - max	38	38

3.013 Producer's guaranteed mechanical properties for material solution treated and aged, Table 3.013.

TABLE 3.013

Source	(10)(13)				
Alloy	Ti-7Al-4Mo				
Form	Bar				
Condition	HT				
Section size - in	F_{tu} - ksi	F_{ty} - ksi	RT e(1 in) - %	RA - %	Test Location
≤ 1 max	170	160	8	20	Center
>1 to 2 max	160	150	8	20	Mid-radius
> 2 to 4 max	150	140	8	20	Mid-radius
≤ 1 max	195	180	5	12	Center
> 1 to 2 max	175	160	5	12	Mid-radius
> 2 to 4 max	165	150	5	12	Mid-radius

3.02 Mechanical Properties at Room Temperature
See section 3.03 also.
3.021 Tension
3.0211 Stress-strain diagrams
3.0212 Tensile properties for bar.
3.02121 Effect of exposure to elevated temperatures with and without load on tensile properties of annealed bar, Table 3.02121.

TABLE 3.02121

Source	(10)(13)				
Alloy	Ti-7Al-4Mo				
Form	Bar				
Condition	1450F, 1hr, FC 300F per hr to 1050F, AC+1000F, 24hr				
1000 hr exposure at	Tested at RT				
Temp-F	Load, ksi	F_{tu}, ksi	F_{ty}, ksi	e(2 in) %	RA, %
RT	-	149	137	6	-
600	-	149	137	13 to 15	25 to 46
	80	146	141	16	46
800	-	149	137	13 to 15	25 to 46
	50	148	144	16	45
1000	15	152	148	14	54

Ti
7 Al
4 Mo

3.02122 Effect of exposure to elevated temperatures with load on tensile properties of annealed bar, Table 3.02122.

TABLE 3.02122

Source	(12)						
Alloy	Ti-7Al-4Mo						
Form	Bar						
Condition	Ann 1475F, 2 hr, FC to 1000F, AC						
Exposure conditions			% e at	Subsequent RT tensile properties			
Temp - F	Stress, ksi	Time - hr	temp - F	F_{tu}, ksi	F_{ty}, ksi	e(4D), %	RA, %
None	None	None	None	156	147	13	38
800	90	815	8.0	167	161	10	34
900	60	145	1.0	156	144	17	39
900	30	500	0.75	160	151	14	42
1000	30	145	1.0	157	149	16	41
1000	6	500	0.32	164	157	13	38

3.02123 Effect of exposure to elevated temperatures with load on tensile properties of solution treated and aged bar, Table 3.02123.

TABLE 3.02123

Source	(12)						
Alloy	Ti-7Al-4Mo						
Form	Bar						
Condition	ST 1700F, 4 hr, WQ + age 1100F, 6 hr, AC						
Exposure conditions			e% at	Subsequent RT tensile properties			
Temp - F	Stress-ksi	Time - hr	temp - F	F_{tu}, ksi	F_{ty}, ksi	e(4 D), %	RA, %
None	None	None	None	173	158	10	23
800	102	770	10.0	194	179	7	20
900	60	145	1.0	178	152	11	24
900	35	500	0.52	177	153	12	19
1000	30	145	3.0	175	157	10	30
1000	13	500	0.48	175	162	10	30

3.02124 Effect of extrusion temperature on tensile properties of as-extruded and extruded-plus-annealed bar, Fig. 3.02124.

3.0213 Tensile properties for forgings

3.02131 Effect of exposure to elevated temperatures with load on tensile properties of annealed upset press forgings, Table 3.02131.

TABLE 3.02131

Source	(14)						
Alloy	Ti-7Al-4Mo						
Form	Upset press forged						
Condition	Press forged 2 to 1 to 3/4 in from 1750F, AC + 1450F, 1 hr, FC to 1050F, AC						
Direction	150 hr exposure at		Total creep def,	Subsequent RT tensile properties			
	Temp - F	Stress - ksi	%	F_{tu}, ksi	F_{ty}, ksi	e(4D), %	RA, %
Rad	None	None	None	150	140	13	31
Tang	None	None	None	154	145	12	31
Rad	750	80	0.56	153	142	15	33
Tang	750	80	0.63	156	144	13	23
Rad	850	45	0.43	151	139	12	29
Tang	850	45	0.44	157	142	16	27
Rad	950	25	0.92	158	146	12	27
Tang	950	25	0.74	158	145	11	19

Ti
7 Al
4 Mo

3.02132 Effect of exposure to elevated temperatures with load on tensile properties of solution treated and aged upset press forging, Table 3.02132.

TABLE 3.02132

Source	(14)						
Alloy	Ti-7Al-4Mo						
Form	Upset press forged						
Condition	Press forged 2 to 1 to 3/4 in from 1750F, AC + 1750F, AC + 1750, 1hr, WQ + 1100F, 8 hr, AC						
Direction	150 hr exposure at		Total creep def, %	Subsequent RT tensile properties			
	Temp - F	Stress, ksi		F_{tu}, ksi	F_{ty}, ksi	e(4D), %	RA, %
Rad	None		None	179	161	8	12
Tang	None		None	179	162	9	13
Rad	750	80	0.25	178	162	5	10
Tang	750	80	*	186	167	9	14
Rad	850	45	0.27	181	163	8	10
Tang	850	45	*	175	154	8	18
Rad	950	25	0.39	183	165	6	9
Tang	950	25	*	177	162	5	12

* Not measured

3.02133 Effect of exposure to elevated temperature with load on tensile properties of annealed compressor blade forging, Table 3.02133.

TABLE 3.02133

Source	(6)					
Alloy	Ti-7Al-4Mo					
Form	Compressor blade forging					
Condition	Forge 1700-1750F + Ann 1450F, 1 hr argon, FC at 100F/hr max to 1050F, AC					
Exposure conditions			Subsequent RT tensile properties (Spec gage section 0.160 in dia x 0.650 in length			
Temp - F	Stress-ksi	Total elongation, %	F_{tu}, ksi	F_{ty}, ksi	e, %	RA, %
None			151	144	17	56
850	40	0.97% in 209 hr	156	146	22	53

3.02134 Effect of exposure to elevated temperatures with load on tensile properties of solution treated and aged compressor blade forgings, Table 3.02134.

TABLE 3.02134

Source	(6)					
Alloy	Ti-7Al-4Mo					
Form	Compression blade forgings					
Condition	Forge 1700 - 1750F + ST 1560F, 30 min argon, AC + age 1020F, 24 Hr, AC					
Exposure Conditions			SUBSEQUENT RT TENSILE PROPERTIES (Spec gage section 0.160 inch dia x 0.650 in length)			
Temp - F	Stress-ksi	Total Elongation, %	F_{tu}, ksi	F_{ty}, ksi	e, %	RA_n, %
None			162	156	17	53
850	40	0.71% in 120 hr	164	154	20	26
950	12	0.46% in 57 hr	164	-	18	46

3.02135 Effect of aging on short time tensile properties of upset forgings, Fig. 3.02135.
3.0214 Effect of extrusion temperature on as-extruded tensile properties of extrusions, Fig. 3.0214.
3.022 Compression
3.0221 Stress-strain diagrams
3.023 Impact. See 3.033.
3.024 Bending
3.025 Torsion and shear
3.0251 Shear properties, Table 3.0251.

TABLE 3.0251

Source	(10)(15)			
Alloy	Ti-7Al-4Mo			
Form	1/2 in bar			
Condition	Ann		1650F, WQ+ 1000F, 4 hr	
Pin dia-in	3/16	3/8	3/16	3/8
F_{su}, -ksi	104 to 115	104 to 105	117 to 120	114 to 118

3.026 Bearing
3.027 Stress concentration
3.0271 Notch properties
3.0272 Fracture toughness
3.028 Combined properties

3.03 Mechanical Properties at Various Temperatures
3.031 Tension
3.0311 Stress-strain diagrams
3.0312 Tensile properties for forgings

Ti
7 Al
4 Mo

3.03121 Typical room temperature and 572F short time tensile properties of annealed upset forgings, Table 3.03121.

TABLE 3.03121

Source	(10)		
Alloy	Ti-7Al-4Mo		
Form	Upset forging		
Condition	Forge 1750F +Ann 1450F, 1 1/2 hr, FC 300F/hr max to 1050F, AC		
Upset ratio	Test temp-F	F_{tu}, ksi	F_{ty}, ksi
3:2	RT	150	140
	572F	110	92
3:1	RT	153	144
	572F	114	94

3.03122 Average 572F short time tensile properties of upset forgings aged at two different temperatures, Table 3.03122.

3.03125 Effect of subzero and elevated temperature on short time tensile properties of 3:1 upset forging, Fig. 3.03125.

3.03126 Effect of test temperature on tensile properties of annealed and aged compressor wheel forgings, Fig. 3.03126.

3.03127 Effect of test temperature on tensile properties of annealed and aged compressor blade forgings, Fig. 3.03127.

3.0313 Tensile properties for bar

3.03131 Effect of elevated temperatures on tensile properties of annealed and heat treated bars, Fig. 3.03131.

3.03132 Effect of elevated temperatures on tensile properties of bar for two heat treatments, Fig. 3.03132.

3.03133 Influence of test temperature and forging history on tensile properties of heat treated bars, Fig. 3.03133.

3.0314 Effect of subzero temperatures on smooth and notch tensile properties of annealed sheet and bar from same heat, Fig. 3.0314.

3.0315 Effect of elevated temperatures on tensile properties of extrusions, Fig. 3.0315.

TABLE 3.03122

Source	(10)					
Alloy	Ti-7Al-4Mo					
Form	Upset forging					
Condition	Forge 1750F, + Ann 1450F, 1 1/2 hr, FC 300F/hr max to 1050F, AC + ST 1750F, 1 1/2 hr, WQ + age as indicated					
Age temp - F	Age time - hr	Upset ratio	Tested at 572F F_{tu}, ksi	F_{ty}, ksi	e, %	RA, %
1050	4	3:2	152	119	12	49
		3:1	149	116	14	54
1100	4	3:2	139	111	13	44
		3:1	141	110	13	54

3.03123 Effect of exposure at 850F, 45 ksi on 750F short time tensile properties of annealed compressor wheel forgings, Table 3.03123.

TABLE 3.03123

Source	(16)				
Alloy	Ti-7Al-4Mo				
Form	Compressor wheel forging				
Condition	Forge below beta transus + Ann 1450F, 1 hr, FC at 300F/hr max to 1050F, AC				
Exposure conditions: 850F, 45 ksi Exposure time, hr	Approximate plastic creep, %	Subsequent 750F properties F_{tu}, ksi	F_{ty}, ksi	e, %	RA, %
0	0	103	85	19	63
20	0.19	107	84	18	56
100	0.43	111	86	18	55
300	0.69	114	89	18	57

3.03124 Effect of exposure at 850F, 45 ksi on 750F short time tensile properties of heat treated compressor wheel forgings, Table 3.03124.

TABLE 3.03124

Source	(16)				
Alloy	Ti-7Al-4Mo				
Form	Compressor wheel forging				
Condition	Forge below beta transus + Ann 1450F, 1 hr, FC at 300F/hr max to 1050F, AC + ST 1560F, 30 min, AC + age 1020F, 24 hr, AC				
Exposure conditions: 850F, 45 ksi Exposure time, hr	Approximate plastic creep %	Subsequent 750F properties F_{tu}, ksi	F_{ty}, ksi	e, %	RA, %
0	0	110	87	16	51
20	0.15	111	86	18	57
100	0.27	115	89	19	57
300	0.42	116	89	19	53

Ti
7 Al
4 Mo

3.032 Compression
3.0321 Stress-strain diagrams
3.033 Impact
3.0331 Impact properties of bar at subzero and elevated temperatures, Fig. 3.0331.
3.034 Bending
3.035 Torsion and shear
3.036 Bearing
3.037 Stress concentration. See Fig. 3.0314.
3.0371 Notch properties
3.0372 Fracture toughness
3.038 Combined properties

3.04 Creep and Creep Rupture Properties
3.041 Creep and creep rupture properties for forgings
3.0411 Creep and creep stability properties of heat treated upset forgings, Table 3.0411.

TABLE 3.0411

Source	(10)						
Alloy	Ti-7Al-4Mo						
Form	Upset forging						
Condition	Forge 1750F + Ann 1450F, 1 1/2 hr, FC at 300F/hr max to 1050F, AC + ST 1750F, 1 1/2 hr, WQ + age 1120F, 4 hr, AC						
Heat	Creep test conditions: 850F, 45ksi Total creep in		Upset ratio	RT properties subsequent to 150 hr creep tests			
	30 hr, %	150 hr, %		F_{tu}, ksi	F_{ty}, ksi	e, %	RA, %
A	0.198	0.356	3:2	193	167	8	13
B	0.226	0.366		182	161	11	24
A	0.175	0.315	3:1	193	169	8	19
B	0.200	0.352		183	160	10	16

3.0412 Master curves for creep and creep rupture of annealed compressor blade forgings, Fig. 3.0412.
3.0413 Master curve for creep and creep rupture of aged compressor blade forgings, Fig. 3.0413.
3.0414 Master curves for creep and creep rupture of annealed and aged compressor wheel forgings, Fig. 3.0414.
3.0415 Master curves for creep in upset forgings, Fig. 3.0415.
3.042 Creep and creep rupture properties for bar
3.0421 Creep rupture curves for bar at 1020 and 1200F, Fig. 3.0421.
3.0422 Minimum creep rate curves for bar at 1020 and 1200F, Fig. 3.0422.
3.0423 Isochronous stress-strain curves in tension at 600 to 1000F for bar, Fig. 3.0423.
3.0424 Total strain curves at various temperatures for annealed bar, Fig. 3.0424.
3.0425 Total strain curves at various temperatures for solution treated and aged bar, Fig. 3.0425.

3.05 Fatigue Properties
3.051 Fatigue properties for smooth and notched bar, Table 3.051.

TABLE 3.051

Source	(10)(13)				
Form	1/2 to 3/4 in bar				
Condition	Ann				
Temp, F	Method	Stress Ratio		Stress Concentration	Fatigue strenght-ksi at cycles
		A	R		10^7
RT	Rot bend	∞	-1	$K_t = 1$	97
				$K_t = 3.9$	29

3.052 Stress range diagram for bar at room temperature to 900F, Fig. 3.052.
3.053 Overstress ratio versus cycles to failure at room temperature for both bending and torsion, Fig. 3.053.

3.06 Elastic Properties
3.061 Poisson's ratio
3.062 Modulus of elasticity
3.0621 Static modulus of elasticity at room and elevated temperatures, Fig. 3.0621.
3.0622 Dynamic modulus of elasticity at elevated temperatures, Fig. 3.0622.
3.063 Modulus of rigidity
3.0631 Modulus of rigidity at room and elevated temperatures, Fig. 3.0631.

4. FABRICATION

4.01 Formability
4.011 Forging. For best combination of strength and ductility; starting temperature 1850F maximum, finishing temperature 1500F minimum. Reduction of 25 to 40 percent should be performed in the alpha + beta range in the final forging operation. Subsequent reheating such as required for sizing operations, should not exceed a temperature of about 200F below the beta to alpha + beta transformation temperature, (8).
4.012 For best creep and creep rupture properties, at some sacrifice in ductility, forging in the beta region is effective, (8).
4.013 Casting this alloy is not done at the present time, (1966), (8).

4.02 Machining and Grinding
See Ti, Commercially Pure

4.03 Welding
4.031 General. Since this alloy is heat hardenable it is not generally recommended for welded assemblies, (6).

4.04 Heat Treatment
See Ti-6Al-4V.

4.05 Surface Treatment
See Ti, Commercially Pure

	Ti
7	Al
4	Mo

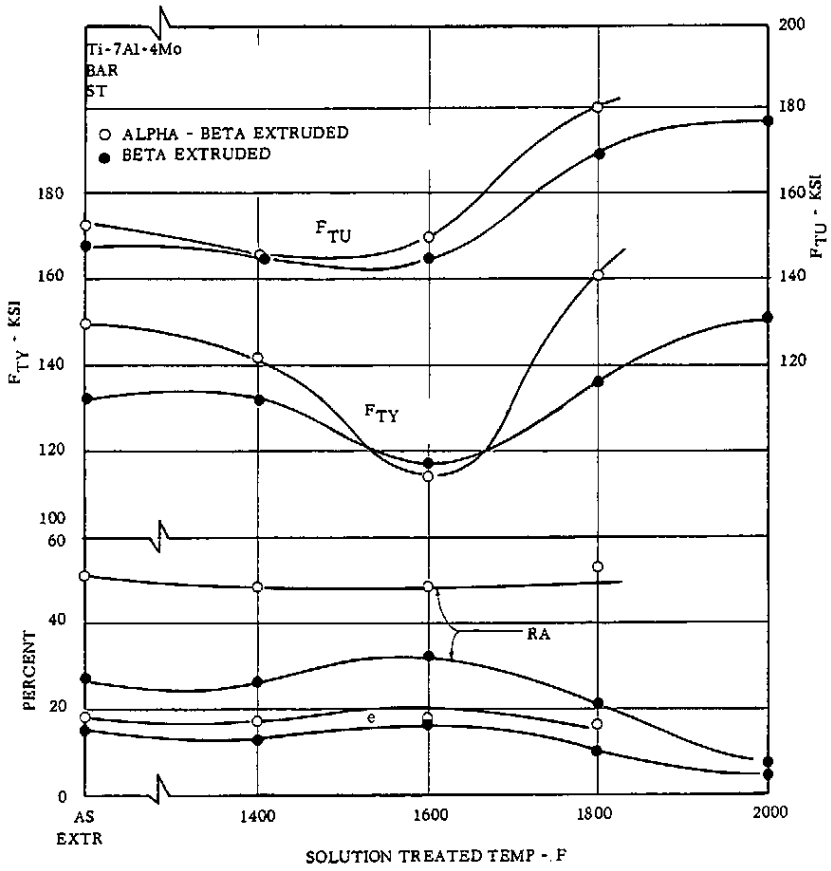


FIG. 1.0531 EFFECT OF SOLUTION TREAT TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF UNAGED BAR (7, p. 11, 12)

Ti
7 Al
4 Mo

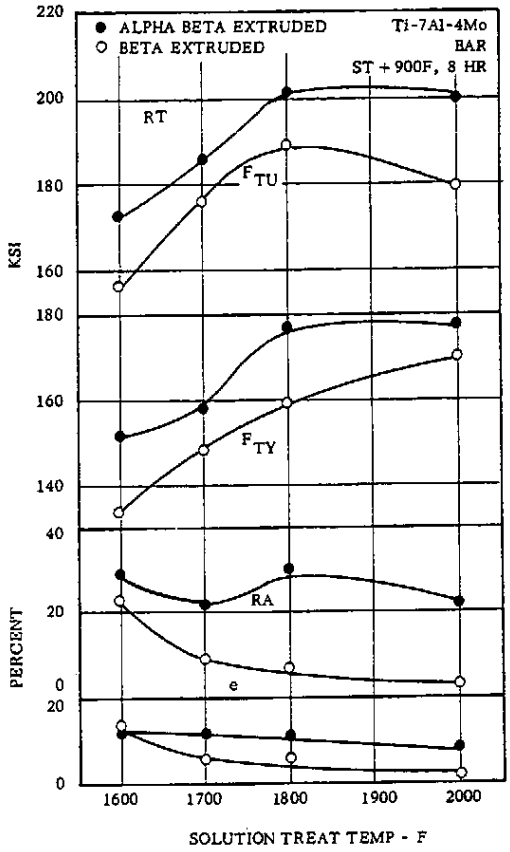


FIG. 1.0532 EFFECT OF SOLUTUION TREAT TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF AGED BAR (7, p.13)

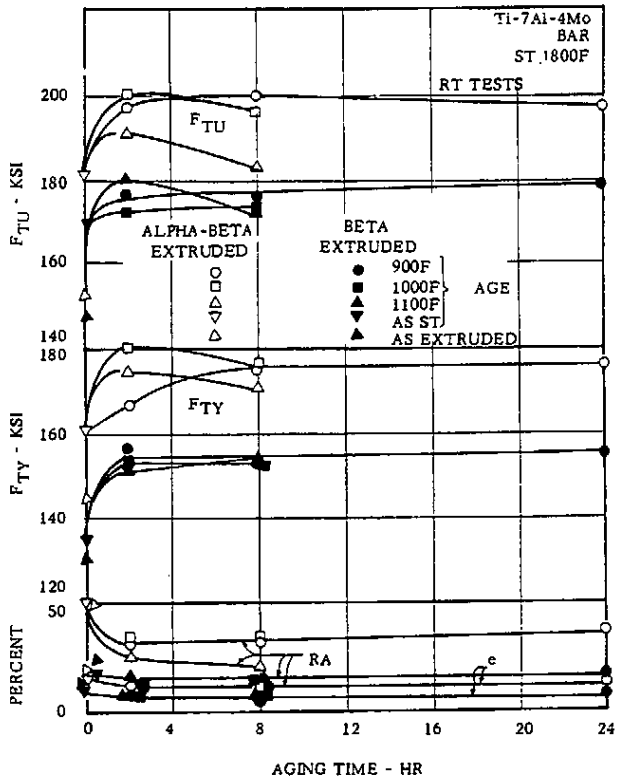


FIG. 1.054 AGING RESPONSE OF BAR (7, p.14, 15)

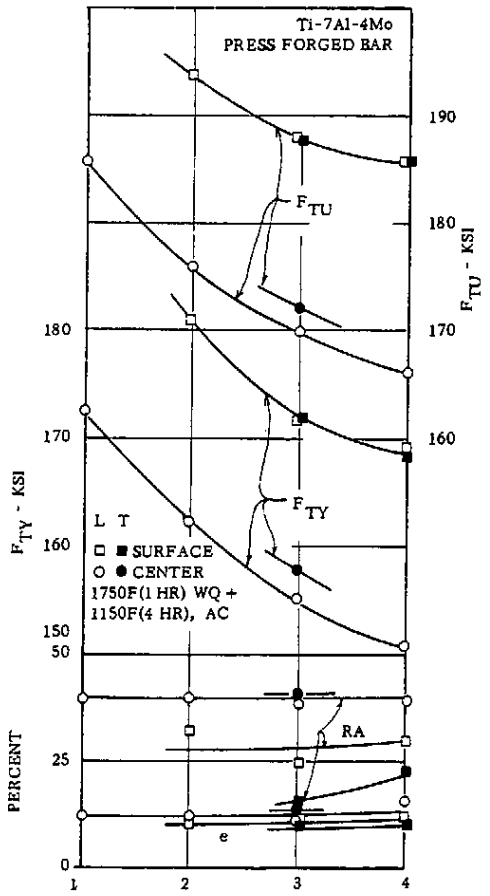
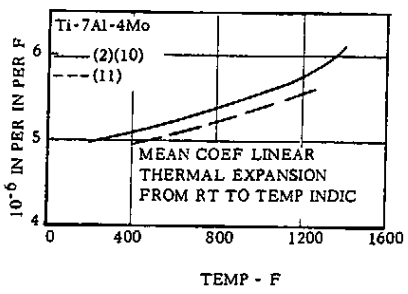


FIG. 1.061 EFFECT OF AS-QUENCHED SECTION SIZE ON ROOM TEMPERATURE TENSILE PROPERTIES OF AGED BAR (8, p. 7 to 11)



Ti
7 Al
4 Mo

FIG. 2.014 THERMAL EXPANSION (2 , p. 2)(11)(10, p. 3)

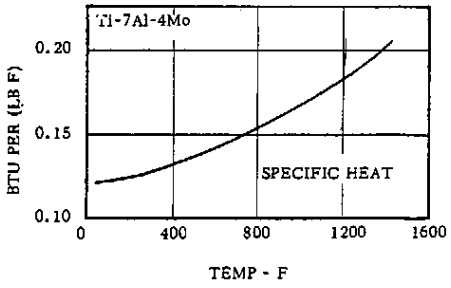


FIG. 2.015 INSTANTANEOUS SPECIFIC HEAT (2, p. 2)(10, p. 3)

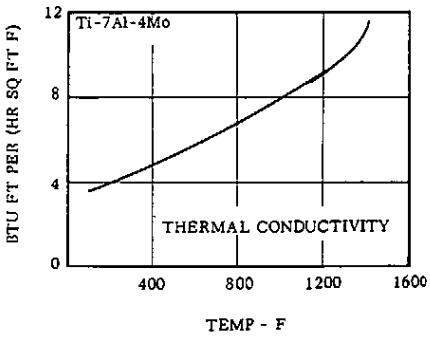


FIG. 2.013 THERMAL CONDUCTIVITY (2, p. 1)(10, p. 2, 3)

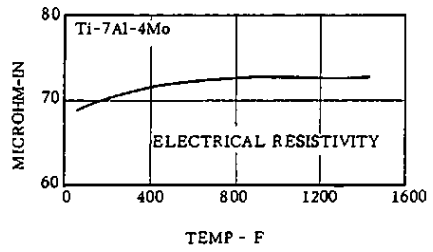


FIG. 2.022 ELECTRICAL RESISTIVITY (2, p. 2)(10, p. 4)

	Ti
7	Al
4	Mo

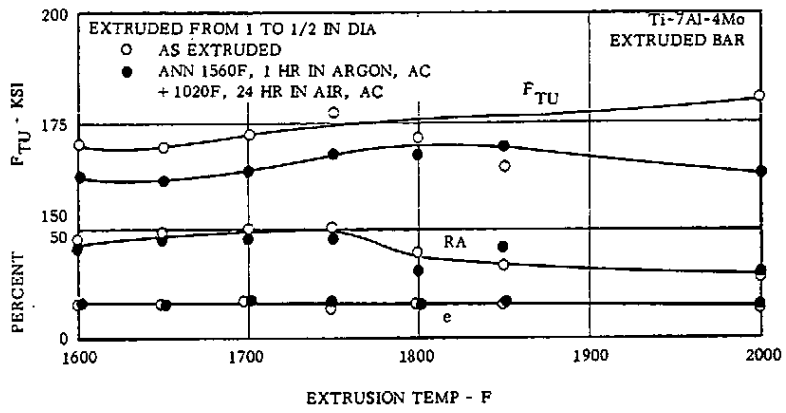


FIG. 3.02124 EFFECT OF EXTRUSION TEMPERATURE ON TENSILE PROPERTIES OF AS-EXTRUDED AND EXTRUDED -PLUS-ANNEALED BAR (7, p. 33)

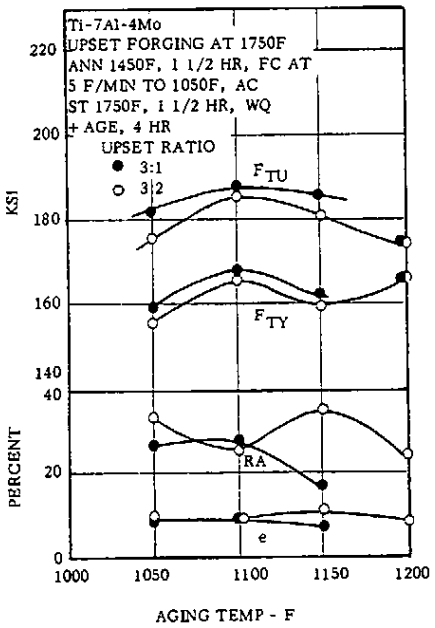


FIG. 3.02135 EFFECT OF AGING ON SHORT TIME TENSILE PROPERTIES OF UPSET FORGING (10, p. 7)

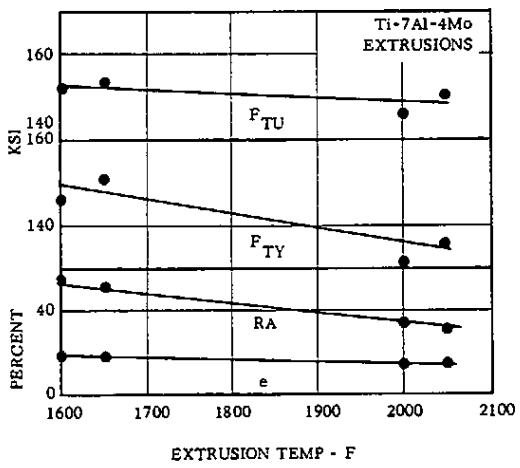


FIG. 3.0214 EFFECT OF EXTRUSION TEMPERATURE ON AS-EXTRUDED TENSILE PROPERTIES OF EXTRUSIONS (7, p. 26)

	Ti
7	Al
4	Mo

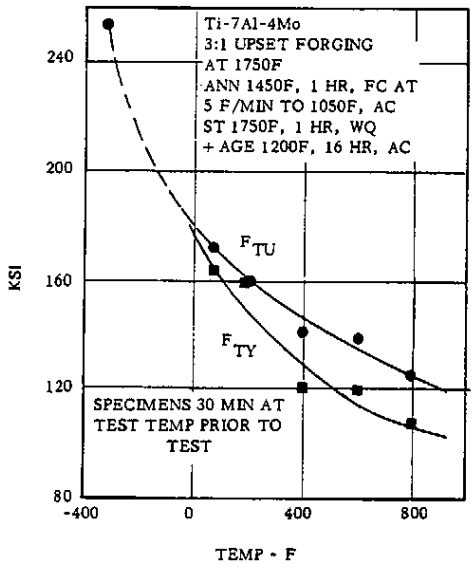


FIG. 3.03125 EFFECT OF SUBZERO AND ELEVATED TEMPERATURE ON SHORT TIME TENSILE PROPERTIES OF 3:1 UPSET FORGING
(10, p.8)

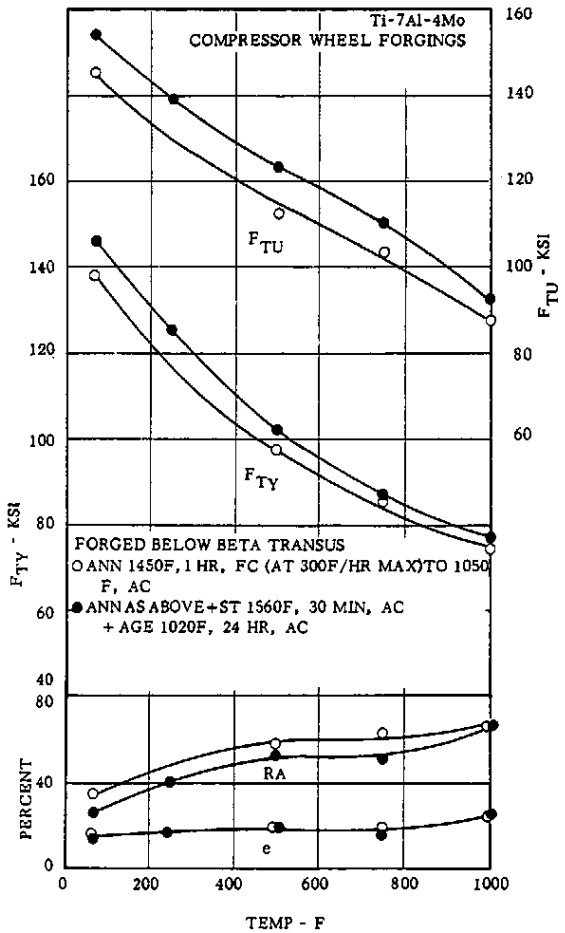


FIG. 3.03126 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED AND AGED COMPRESSOR WHEEL FORGINGS
(16, p.C.2.6.c 2.7)

Ti
7 Al
4 Mo

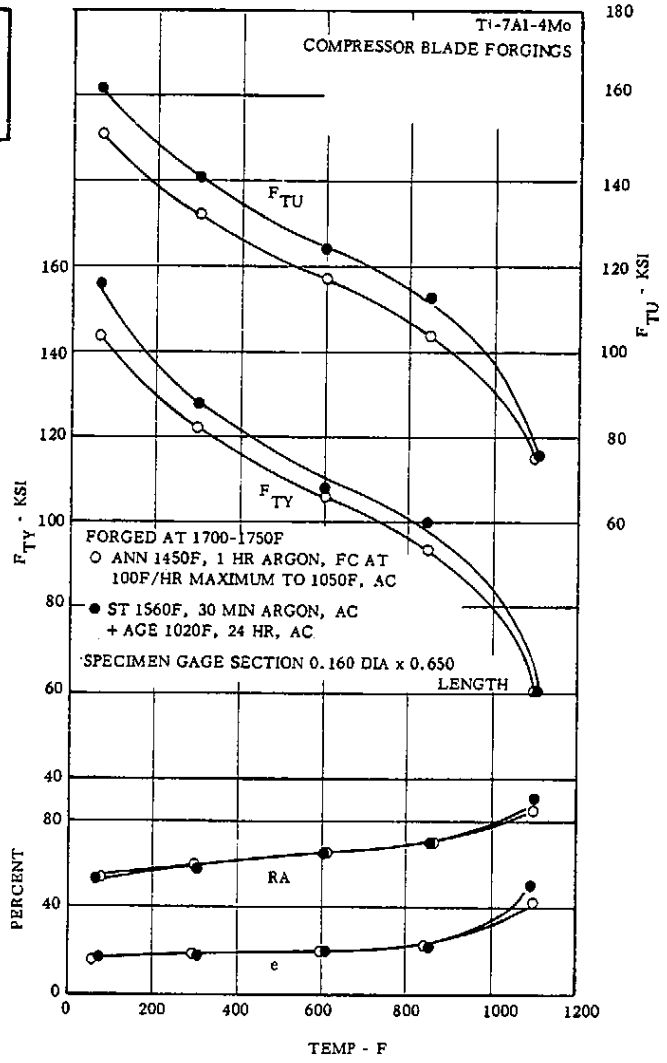


FIG. 3.03127 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED AND AGED COMPRESSOR BLADE FORGINGS
(6, p.c.19, c.1.10)

	Ti
7	Al
4	Mo

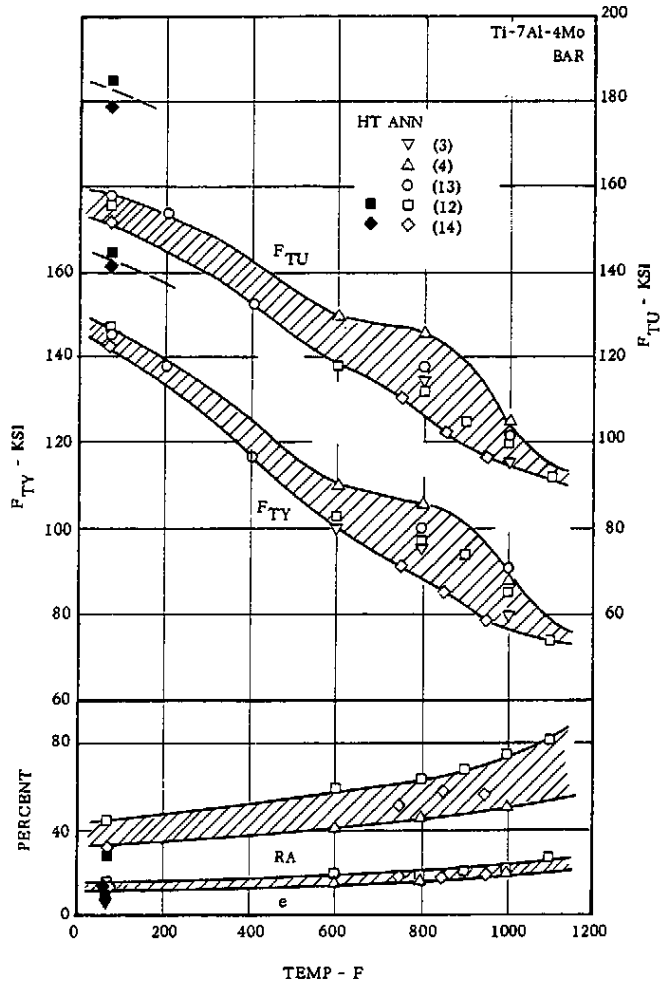


FIG. 3.03131 EFFECT OF ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED AND HEAT TREATED BAR

(3, p. 16)(4, p. 24)(12, p. 20)(13, p. 4)(14, p. 7)

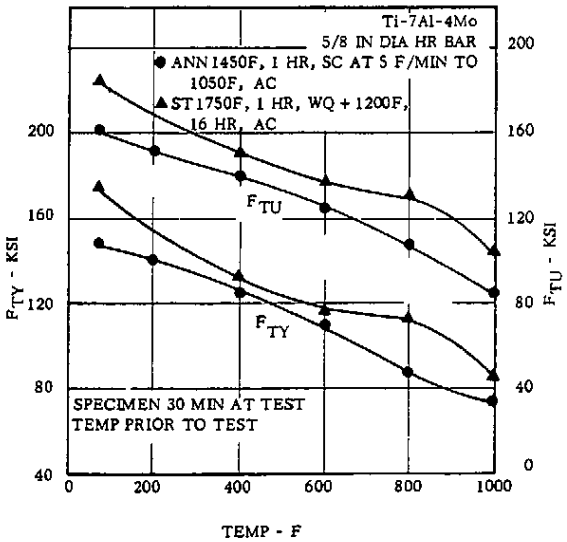


FIG. 3.03132 EFFECT OF ELEVATED TEMPERATURES ON TENSILE PROPERTIES OF BAR FOR TWO HEAT TREATMENTS (10, p. 5)

	Ti
7	Al
4	Mo

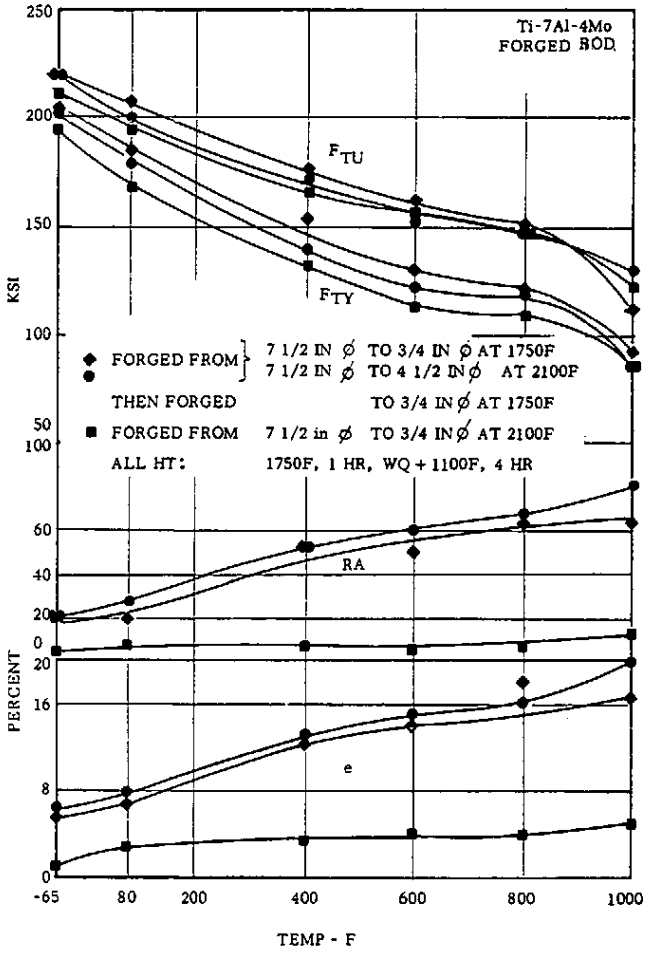


FIG. 3.03133 INFLUENCE OF TEST TEMPERATURE AND FORGING HISTORY ON TENSILE PROPERTIES OF HEAT TREATED BARS (17)

	Ti
7	Al
4	Mo

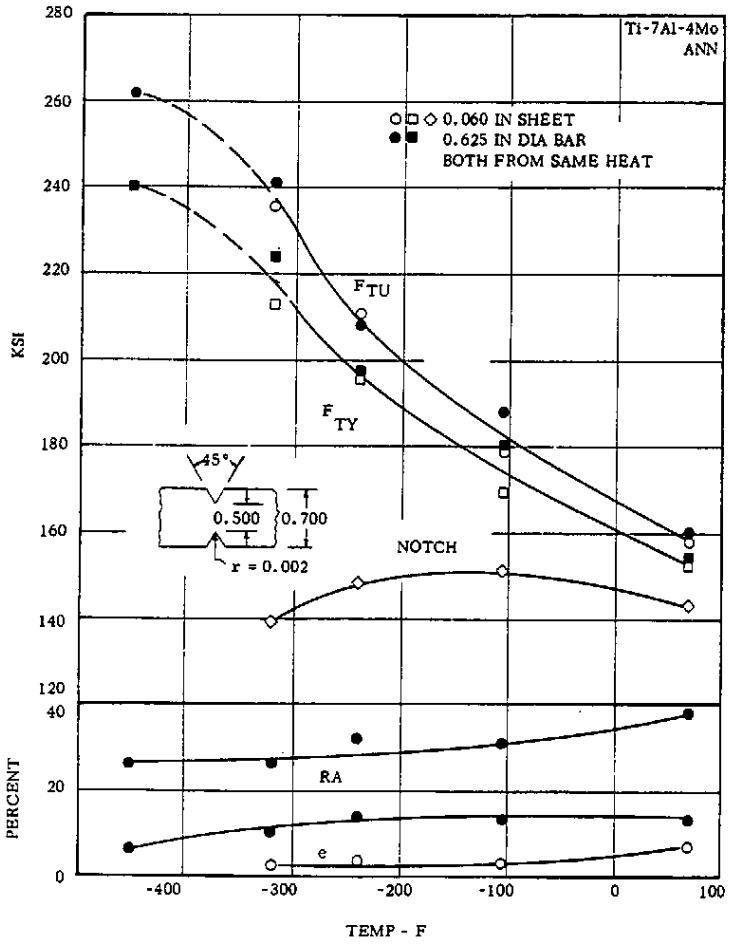


FIG. 3.0314 EFFECT OF SUBZERO TEMPERATURES ON SMOOTH AND NOTCH TENSILE PROPERTIES OF ANNEALED SHEET AND BAR FROM SAME HEAT (18, p. 4-5)

	Ti
7	Al
4	Mo

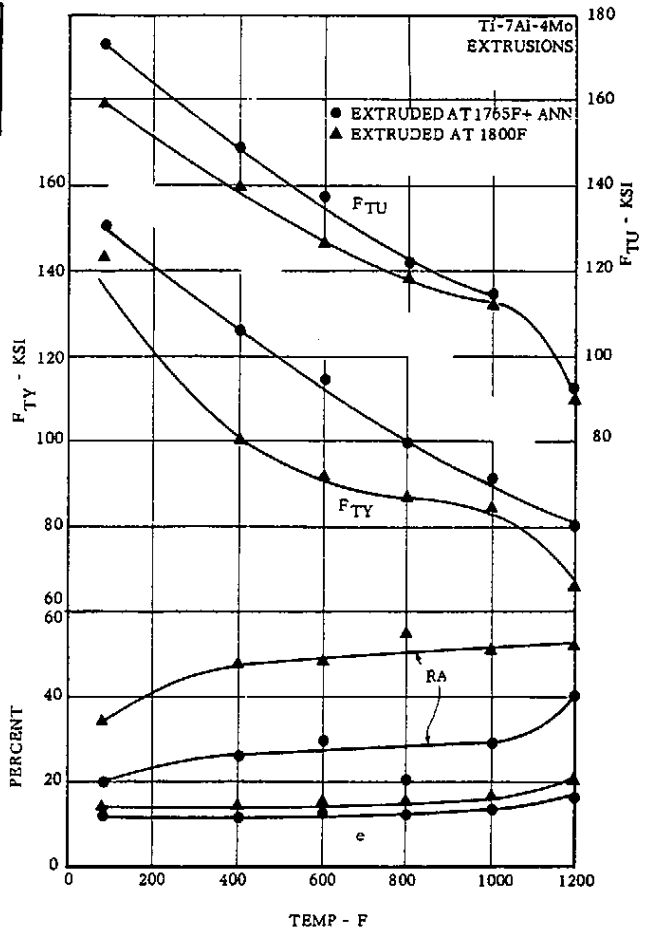


FIG. 3.0315 EFFECT OF ELEVATED TEMPERATURES ON TENSILE PROPERTIES OF EXTRUSIONS (7, p. 53, 54)

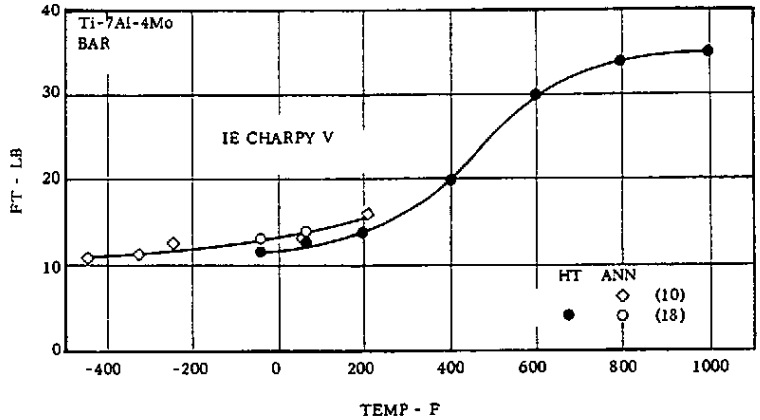


FIG. 3.0331 IMPACT PROPERTIES OF BAR AT SUBZERO AND ELEVATED TEMPERATURES (10, p. 13)(18, p. 4)

	Ti
7	Al
4	Mo

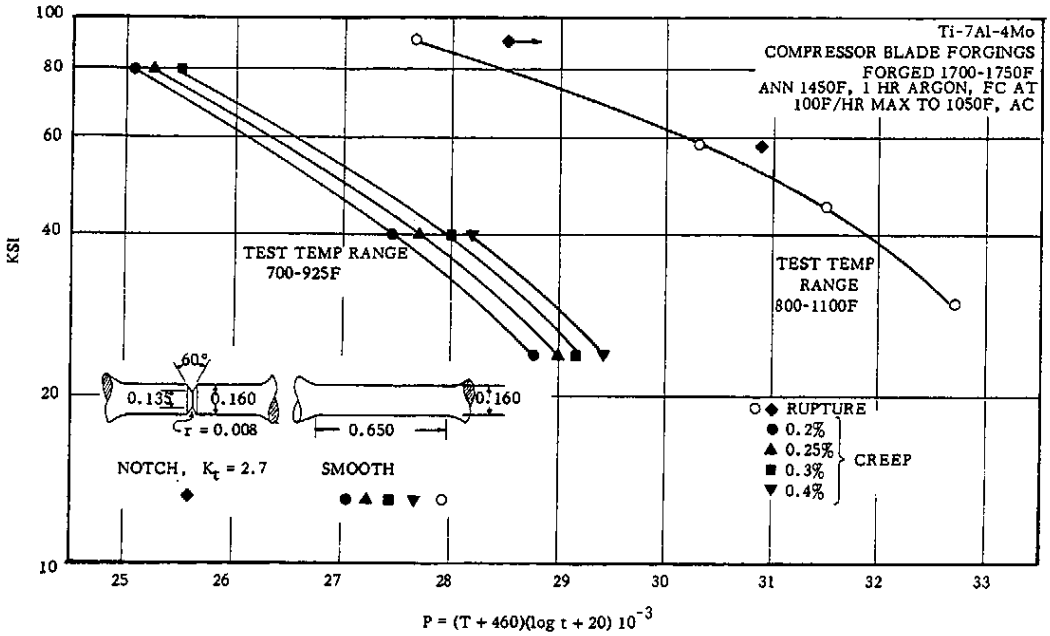


FIG. 3.0412 MASTER CURVES FOR CREEP AND CREEP RUPTURE OF ANNEALED COMPRESSOR BLADE FORGINGS

(6, p. c.1.11 and c.1.13)

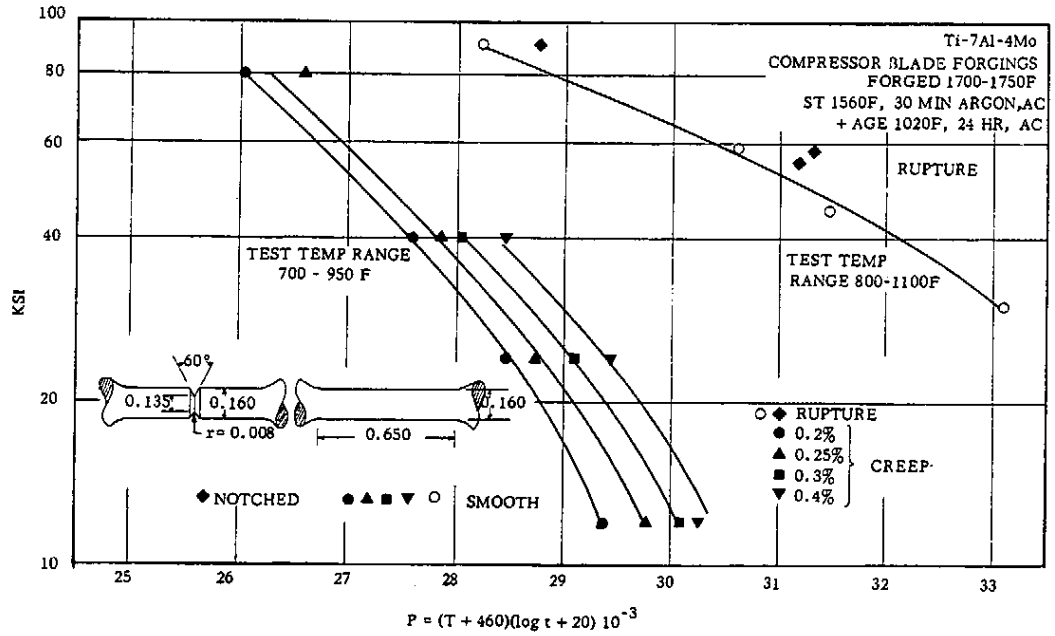


FIG. 3.0413 MASTER CURVE FOR CREEP AND CREEP RUPTURE OF AGED COMPRESSOR BLADE FORGINGS

(6, p. 6.1.12, c.L.14)

Ti
7 Al
4 Mo

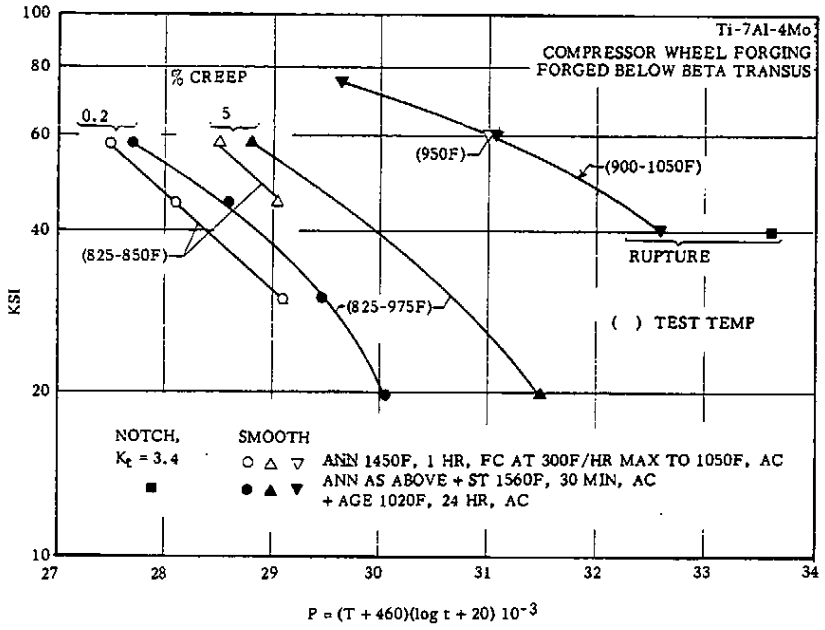


FIG. 3.0414 MASTER CURVES FOR CREEP AND CREEP RUPTURE OF ANNEALED AND AGED COMPRESSOR WHEEL FORGINGS (16, p. c. 2.11, c. 2.12, c. 2.19, c. 2.20)

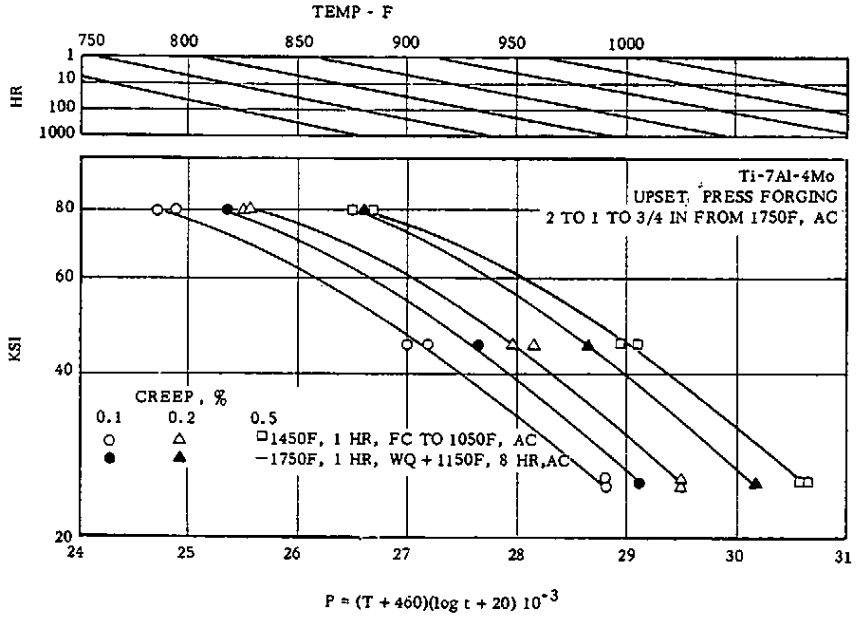


FIG. 3.0415 MASTER CURVES FOR CREEP IN UPSET FORGINGS (14)

	Ti
7	Al
4	Mo

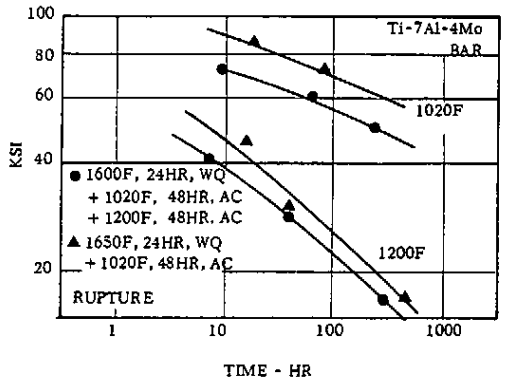


FIG. 3.0421 CREEP RUPTURE CURVES FOR BAR AT 1020 AND 1200F (15, p. 128)

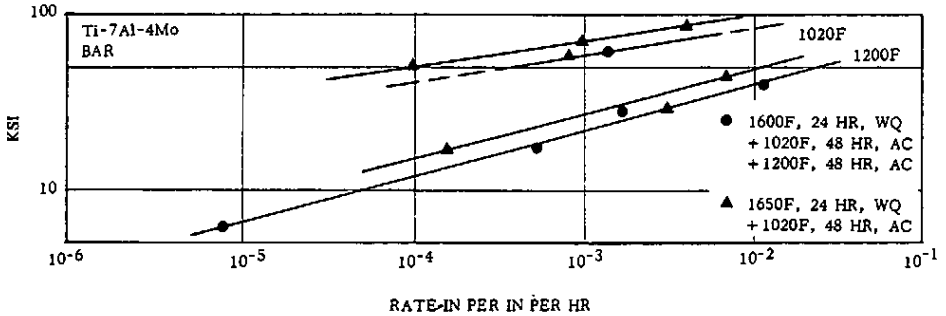


FIG. 3.0422 MINIMUM CREEP RATE CURVES FOR BAR AT 1020 AND 1200F (15, p. 129)

	Ti
7	Al
4	Mo

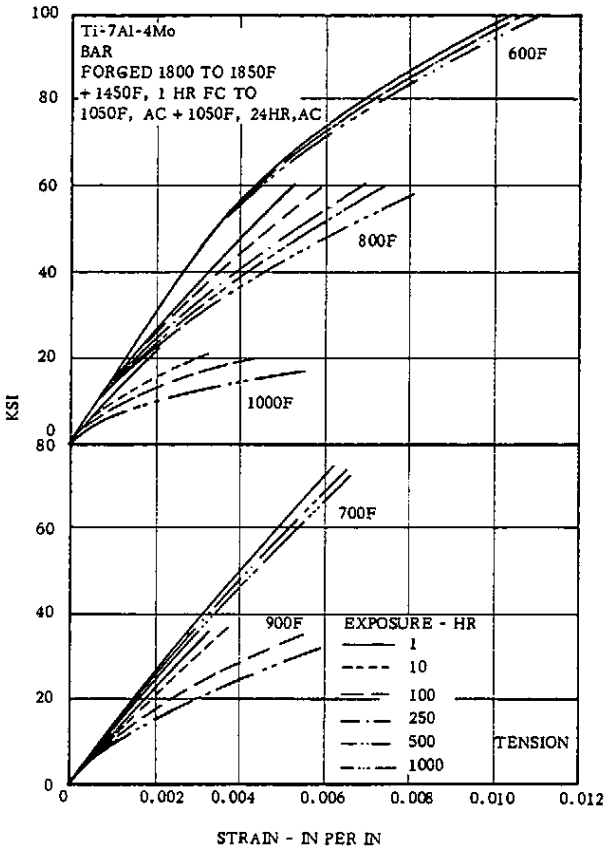


FIG. 3.0423 ISOCHRONOUS STRESS-STRAIN CURVES IN TENSION AT 600 TO 1000F FOR BAR (13, pp. 10-14)

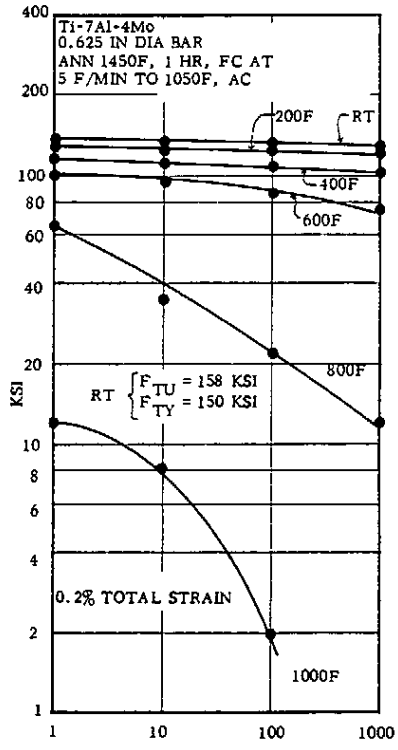


FIG. 3.0424 TOTAL STRAIN CURVES AT VARIOUS TEMPERATURES FOR ANNEALED BAR (10, p. 8-9)

	Ti
7	Al
4	Mo

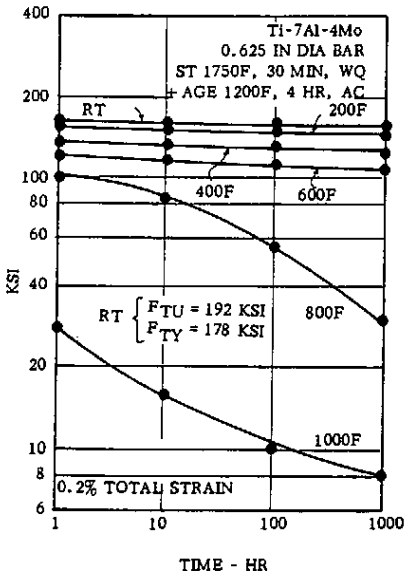


FIG. 3.0425 TOTAL STRAIN CURVES AT VARIOUS TEMPERATURES FOR SOLUTION TREATED AND AGED BAR (10, pp. 8, 9)

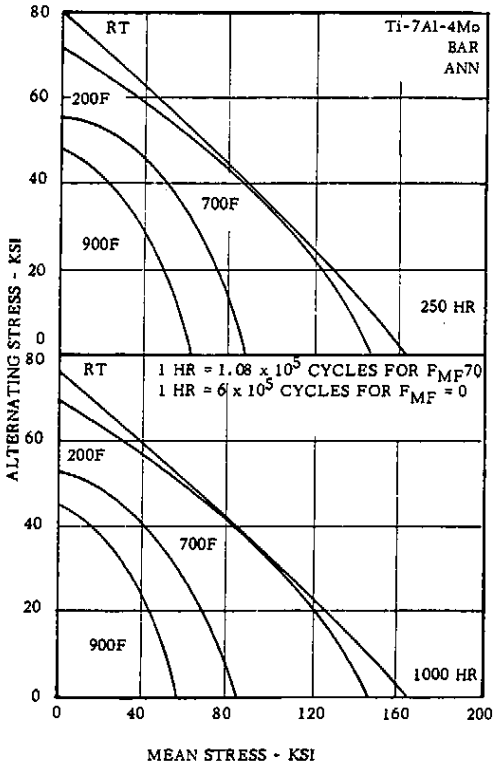


FIG. 3.052 STRESS RANGE DIAGRAMS FOR BAR AT ROOM TEMPERATURE TO 900F (11)

Ti
7 Al
4 Mo

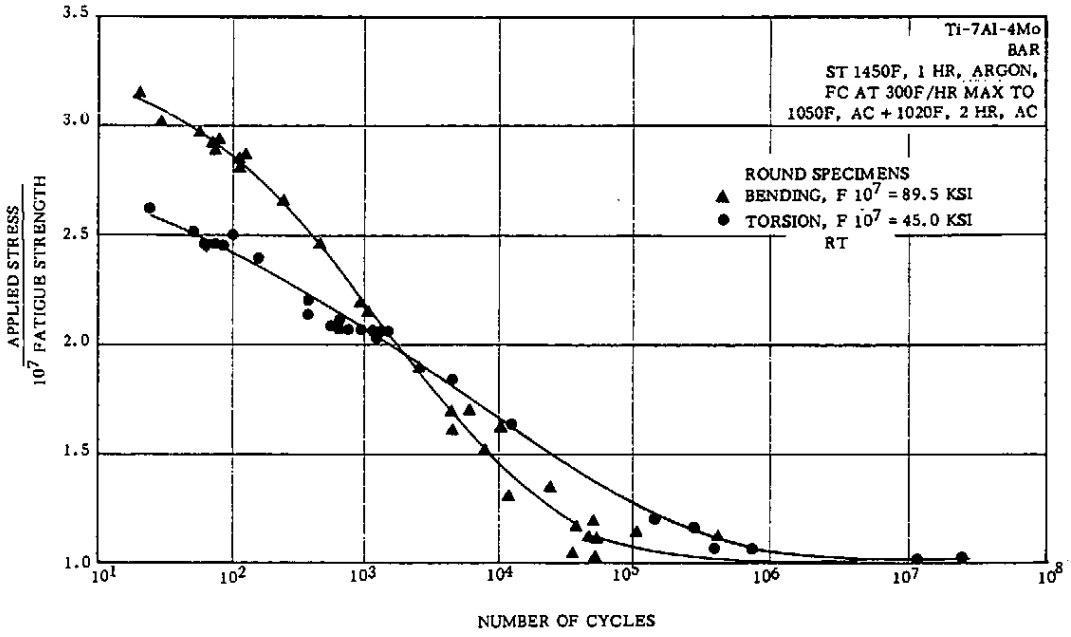


FIG. 3.053 OVERSTRESS RATIO VERSUS CYCLES TO FAILURE AT ROOM TEMPERATURE FOR BOTH BENDING AND TORSION (19)

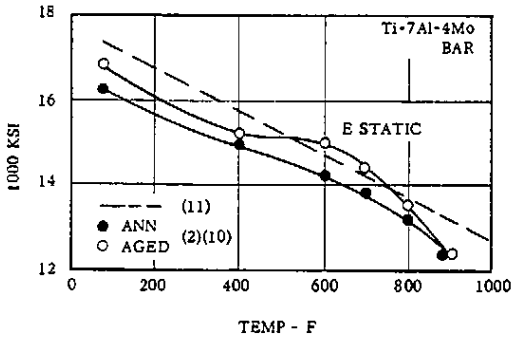


FIG. 3.0621 STATIC MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES (2, p. 3)(10, p. 2)(11)

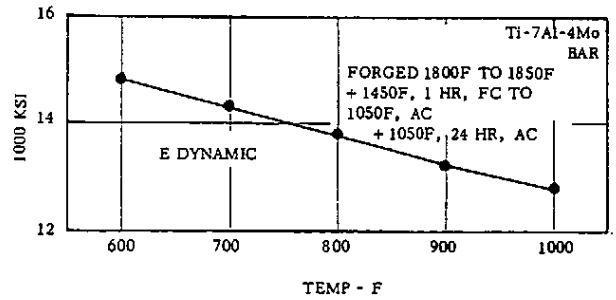


FIG. 3.0622 DYNAMIC MODULUS OF ELASTICITY AT ELEVATED TEMPERATURES (13, p. 10-14)

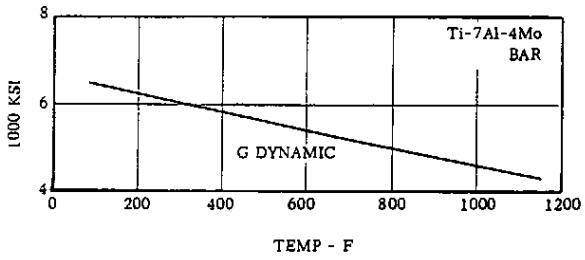


FIG. 3.0631 MODULUS OF RIGIDITY AT ROOM AND ELEVATED TEMPERATURES (11)

	Ti
7	Al
4	Mo

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2 Jones, J. P., "Personal Communciation", Crucible Steel Company, Specifications and Technical Information, (September 17, 1959)

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4 Reactive Metals, Incorporated, "Basic Design Facts About Titanium"

5 General Electric Company, "Materials Information Data Compilation - Part IV", (February 1963), ASD USAF Contract No. AF33(657)-8017, Material Specification 850T52-S3, (June 26, 1962)

6 General Electric Company, "Materials Information Data Compilation - Part IV", February 1963), ASD USAF Contract No. AF33(657)-8017, Technical Information Series No. R58AGT832, (October 31, 1958)

7 Titanium Metallurgical Laboratory, "Compilation of Available Information on the Ti-7Al-3 to 4Mo Alloy", TML Memorandum, (July 18, 1958)

8 Orr, D. L., "Heat Treatability of Low Temperature Press Forged Ti-7Al-4Mo, X7 Formulation Heat M-9692-B", Case Study 6-3, Titanium Metals Corporation of America, May 23, 1961)

9 Private Communication with R. Frank Malone, Associate Director of Metals Processing and Titanium Research, Crucible Steel Company of America, (1966)

10 Crucible Steel Company, "Crucible C-135AMo-Titanium Base Alloy 7% Aluminum - 4% Molybdenum", Preliminary Data Sheet, (November 1959)

11 General Electric Company, "Data Sheet", General Electric Company Specifications B50T52, C50T51, C50T56, (November 10, 1958)

12 Republic Steel Corporation, "Titanium - Grades and Properties", (1959)

13 Crucible Steel Company, "Tentative Data Sheet for: Crucible C-135AMo7Al-4Mo", (December 1, 1958)

14 Titanium Metals Corporation of America, "Room and Elevated Temperature Properties of Experimentally Forged Ti-6Al-4V and Ti-7Al-4Mo - Case Study 10-4", (October 26, 1964)

15 Garew, W. F., Crossley, F. A. and McPherson, D. J., "Titanium Alloys for Elevated Temperature Application", WADC TR 54-278, Pt. I, II, (July 1955)

16 General Electric Company, "Materials Information Data Compilation - Part IV", (February 1963), ASD USAF Contract No. AF 33(657)-8017, Technical Information Series No. R58AGT457, (June 17, 1958)

17 Hamer, J. E., Hendricks, P. L., Taylor, M. E., "The Effects of Processing on the Heat Treated Properties of C135Mo (Ti-7Al-4Mo)", Crucible Steel Company of America, Presented at New York University's Sixth Titanium Metallurgy Conference, (September 1960)

18 Hickey, C. F., Jr., "Mechanical Properties of Titanium and Aluminum Alloys at Cryogenic Temperatures", Proc. ASTM, (1962)

19 Danforth, C. E. and Starkey, W. L., "The Effects of High-Stress-Amplitude Fatigue Damage on the Endurance Properties of High-Performance Stainless-Steel and Titanium Alloys", ASME Paper No. 62-WA-230, (1962)

	Ti
8	Al
1	Mo
1	V

1. GENERAL

This alloy is designed primarily for use in elevated temperature applications and in the annealed condition. The room temperature tensile strength is about equal to 6Al-4V but at elevated temperatures the tensile strength and creep resistance are superior to other commonly available alpha or alpha + beta titanium alloys. Special duplex annealing treatments have been developed which yield high fracture toughness in sheet at temperatures as low as -200F. This alloy has the highest tensile modulus and lowest density of any commercial titanium alloy. Recent investigations have shown it to be more susceptible to elevated temperature solid salt corrosion than 6Al-4V or 4Al-3Mo-1V. Delayed failure of cracked specimens has been encountered in salt solutions and susceptibility to this effect increases with thickness.

1.01 Commercial Designation

8Al-1Mo-1V-Ti alloy.

1.02 Alternate Designation

None.

1.03 Specifications

1.031 AMS 4955, Welding wire, (50).

1.04 Composition

Table 1.04.

TABLE 1.04

Source	(1)(4)	
Alloy	Ti-8Al-1Mo-1V	
	Percent	
	Min	Max
Aluminum	7.5	8.5
Molybdenum	0.75	1.25
Vanadium	0.75	1.25
Iron	-	0.3
Carbon	-	0.08
Nitrogen	-	0.05
Oxygen*	-	0.10
Hydrogen	-	0.015
Titanium	Balance	

* Ref. 4

1.05 Heat Treatment

1.051 Alloy is used in annealed condition and solution treating and aging is not recommended. Either single anneal or duplex cycles are employed depending on the combination of properties desired. The duplex cycles follow normal mill annealing (furnace cool) and involve air cooling. Air cooling from the annealing temperature increases the toughness with some reduction in room temperature strength, (19). Special heat treating procedures are under development to improve the hot-salt stress corrosion resistance and to reduce the tendency to delayed failure in the presence of certain environments, (see 1.09 and 2.03).

1.052 Bar forgings and heavy sections. Duplex, 1650 to 1850, 1 hour, air cool + 1000 to 1100F, 8 to 24 hours, air cool. For minimum distortion 1650F, 1 hour, air cool + 1100F, 8 hours, air cool. For higher creep resistance 1850F, 1 hour, air cool + 1100F, 8 hours, air cool, (1).

1.053 Sheet

1.0531 Mill anneal. 1450F, 8 hour, furnace cool. Highest room temperature tensile strength. Good stability and creep strength to 700F.

1.0532 Duplex anneal. Mill anneal + 1450F, 15 minutes, air cool. Appears particularly suited to moderately elevated temperature applications and where high toughness is required. See Table 3.02712.

1.0533 Duplex anneal (also called Triplex). Mill anneal + 1850F, 5 minutes, air cool + 1375F, 15 minutes, air cool. For superior creep resistance combined with good toughness, (see Fig. 3.041) and Table 3.02712).

1.054 Stress relief

1.0541 Stress relief for mill annealed sheet, 1300F, 30 minutes, air cool.

1.0542 Stress relief for duplex annealed sheet 1350F to 1450F, 15 minutes, air cool, (5).

1.0543 Process anneal for sheet, 1450F, 15 to 30 minutes, air cool, (5).

1.06 Hardness

Alloy is used in annealed condition only.

1.07 Forms and Conditions Available

Alloy is available in all normal commercial forms except strip, (3).

1.08 Melting and Casting Practice

1.081 Melting. Double consumable electrode vacuum melt.

1.082 Casting. Alloys is not cast.

1.09 Special Considerations

This alloy is susceptible to hot salt corrosion at temperatures above about 400F and subject to delayed failure when tested with cracks in the presence of salt water, (see 2.03). Heating in or slow cooling through the temperature range from about 1000 to 1200F should be avoided, (see Fig. 3.02713) thus, slow cooling from the annealing temperature tends to decrease the toughness, (see Fig. 3.037110). Unfortunately the structure produced by air cooling from the annealing temperature is not stable if heated for long periods of time at moderately elevated temperatures and under the circumstances the yield strength increases and the toughness decreases, (see Figs. 3.03110, 3.0218 and 3.02714).

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range. Approximately 3100F, (3).

2.012 Phase changes. Alloy transforms on heating to all-beta at approximately 1900F. Slow cooling from above the beta transus results in a predominately alpha structure with approximately ten percent beta, (3).

2.0121 Time-temperature-transformation diagrams

2.013 Thermal conductivity, Fig. 2.013.

2.014 Thermal expansion, Fig. 2.014.

2.015 Specific heat

2.016 Thermal diffusivity

2.02 Other Physical Properties

2.021 Density. 0.156 lbs per cu in. 4.37 gr per cu cm.

2.022 Electrical resistivity, Fig. 2.022.

2.023 Magnetic properties

2.024 Emissivity

2.025 Damping capacity

2.03 Chemical Properties

See also 6Al-4V.

2.031 Corrosion resistance. General. Recent intensive investigations of several commercial titanium alloys including 8Al-1Mo-1V have served to characterize the elevated temperature solid salt stress corrosion behavior in considerable detail and have shown that delayed failure of cracked specimens may be encountered at room temperature in both air and aqueous environments. Only a brief summary of these investigations can be given here and the reader should refer to the references for further details. In general, the results indicated that this alloy in its conventionally processed and heat treated conditions is more susceptible to solid salt stress corrosion than is annealed 6Al-4V or 4Al-3Mo-1V but probably less so than 5Al-2.5Sn. It appears to be more susceptible to delayed failure in aqueous salt solutions than 6Al-4V. Preliminary results indicate that by special processing and heat treatment the delayed failure resistance of this alloy may be improved.

2.032 Solid salt corrosion. The rate of corrosion in the presence of salt is very rapid above 900F without stress while the rate at lower temperatures depends strongly on the stress. Sodium chloride coated sheet tensile

	Ti
8	Al
1	Mo
1	V

specimens stressed at 40 ksi exhibit losses in retained room temperature tensile strength after exposures of 5000 hours at 500F and 1000 hours at 500F, (31), (see Fig. 2.0321). Exposure at 650F and 10 ksi for 100 hours results in a large loss in tensile elongation, (44). Tension-tension fatigue tests (19) at 800F and 60 ksi show pronounced loss in the fatigue life of sheet specimens provided with a small hole (K_t = 2.3) while no effect on the fatigue life of these specimens was observed at 600F and below. The stress and temperature limits below which solid salt stress corrosion does not occur are not definitely established. As might be expected, the sensitivity of the test is a factor which must be considered when attempting to establish these limits, and different tests can have widely different sensitivities. For example a self stressed specimen (see Fig. 2.0321) has been developed (29) which appears to be more sensitive than the commonly used tensile specimen. The self stressed specimen is formed of a pair of oppositely bowed strips fastened at their ends to preserve the bow. The amount of bowing determines the exposure stress.

Following exposure the specimen is placed in longitudinal compression and the end deflection or shortening to fracture determined. On the basis of the data thus far available it would appear that at temperatures below 400F salt stress corrosion of this alloy would not be an important consideration for most applications.

A wide variety of halogen salts have been found to produce stress corrosion in this alloy at 650F and above, (32)(35). Pure sodium chloride appears to be among the most damaging and is more severe than ASTM artificial sea salt, (29)(32).

Stressed specimens (120 ksi) placed in a non-industrial atmosphere two miles from the sea for 18,000 hours showed appreciable stress corrosion when subsequently exposed 2,600 hours at 550F in air, (29) and tested using the self stressed specimen shown in Fig. 2.0321. Various metals used for bearing or for surface protection readily form chlorides in the presence of even a few ppm of chlorine at temperatures above 750F. These chloride coated metals, if in contact with a titanium alloy susceptible to salt stress corrosion, can produce premature failures of the titanium alloy, (33). Silver is a bad actor in this respect and precautions should be taken to avoid contact between silver and titanium if elevated temperatures are encountered in the service application. Other metals which may have a damaging effect include cadmium, lead and palladium, (33).

Reducing the thickness of sodium chloride coatings decreases the time at temperature necessary to initiate stress corrosion but does not appreciably affect the amount of damage produced by very long times at temperature, (30)(31).

The amount of stress corrosion produced by a given total time at elevated temperature during cyclic heating decreases the cycle dwell time at elevated temperature, (30)(31). In certain types of tests this beneficial effect of cycling begins to disappear as the cycle dwell time exceeds about 8 hours, (see Fig. 2.0322).

The mechanism of solid salt corrosion of titanium alloys is not clearly understood and appears to be complex, involving as yet unidentified intermediate reaction products. There is general agreement that oxygen in some form, (e.g. as a titanium oxide) must be present and that corrosion is more rapid in moist than in dry environments. The electrochemical nature of the reaction can be readily demonstrated, (38) and involves an oxygen differential cell with the cracks occurring at the cathode. Some investigators propose a gas reaction product is directly or indirectly involved in the cracking. Thus, it has been suggested chlorine could be formed from the intermediate corrosion products and cause cracking directly, (29)(35). Another suggested mechanism involves the production of HCl (from a reaction between NaCl and water) which then reacts with Ti, Al, and V to form chlorides and hydrogen. The hydrogen then diffuses into the titanium alloy to produce the observed cracking, (32). Experiments conducted using hot stage microscopy have been interpreted to show that a gas is not responsible for the cracks but that a solid state reaction occurs producing hydrogen ions that diffuse into and embrittle the metal, (37).

2.0321 Effect of exposure temperature and time on solid salt stress corrosion of duplex annealed sheet, Fig. 2.0321.

2.0322 Effect of cyclic heating on solid salt corrosion susceptibility of duplex annealed sheet, Fig. 2.0322.

2.033 Delayed failure. Titanium alloys are considered to be exceptionally resistant to attack by aqueous environments including most inorganic salt solutions. Recent investigations, however, have shown that cracked specimens of this and several other titanium alloys exhibit delayed failure in aqueous sodium chloride solutions and in certain cases also in distilled water, (36)(42)(43)(45). The mill annealed condition of this alloy appears to be considerably more susceptible to this than the duplex annealed condition, (see Fig. 2.0331). Sufficiently thin duplex annealed sheet exhibits essentially no susceptibility to delayed failure in the presence of a 3 1/2 percent sodium chloride solution while this alloy condition in the 0.045 inch gage shows large reductions in strength when tested in the same environment, (see Fig. 2.0331). Additional information is necessary to properly delineate this thickness effect and the influence of metallurgical structure. Preliminary results (36) indicate that significant improvement in the resistance to delayed failure may be obtained by producing microstructures having substantial amounts of transformed beta so that the primary alpha exists in the form of discontinuous islands. Suitable structure may be obtained by modified rolling techniques followed by 1850F, 5 minutes, AC + 1375F, 15 minutes, AC, heat treatment, (41). The possible influence of mill processing and heat treatment variables on solid salt stress corrosion of this or other titanium alloys has received little attention. There is some indication that rapid cooling from the 1450F annealing temperature appears to produce a less susceptible condition than a very slow cooling rate, (34). However, additional tests would be necessary to prove this. Investigations of protective coatings show that aluminum modified silicone provides useful protection from solid salt corrosion at 550F for 3000 hours, (39). Data for longer exposure times is not yet available . Preliminary results indicate that flame sprayed or zinc dipped coatings should be further investigated, (35).

2.0331 Delayed failure curves in 3 1/2 percent salt solution for mill and duplex annealed sheet, Fig. 2.0331.

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 AMS specifications. Welding wire; AMS 4955, (50).

3.012 Producer's guaranteed minimum tensile properties for annealed bar and forgings, Table 3.012.

TABLE 3.012

Source	(1)	
Alloy	Ti-8Al-1Mo-1V	
Form	Forgings[a]	Rolled Bar[a]
Condition	Single or Duplex anneal	
F_{tu}, min -ksi	130	130
F_{ty}, min -ksi	120	120
e(4D)min - percent	10	10
RA, min - percent	20	25

(a) Sections up to and including 4 sq in.

	Ti
8	Al
1	Mo
1	V

3.013 Producer's guaranteed minimum tensile properties for annealed sheet, Table 3.013.

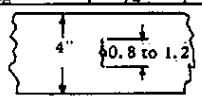
TABLE 3.013

Source	TMCA (20)		
Alloy	Ti-8Al-1Mo-1V		
Form	Sheet		
Condition	Mill ann, 1450F 8hr, FC	1450F 15 min, AC	1850F, 5 min, AC + 1375F, 15 min, AC
F_{tu} min-ksi	145	135	135
F_{ty} min-ksi	135	125	125
e(2in)-percent			
< 0.025 in	8	8	6
≥ 0.025 in	10	10	8

3.02 Mechanical Properties at Room Temperature
3.021 Tension. See also 3.03.
3.0211 Stress-strain diagrams. See 3.0311.
3.0212 Average and spread of longitudinal tensile properties for mill annealed sheet of various thicknesses, Fig. 3.0212.
3.0213 Average and spread of transverse tensile properties for mill annealed sheet of various thicknesses, Fig. 3.0213.
3.0214 Influence of various reannealing cycles on tensile properties of 1350F mill annealed sheet, Fig. 3.0214.
3.0215 Influence of various reannealing cycles on tensile properties of 1450F mill annealed sheet, Fig. 3.0215.
3.0216 Influence of aging temperature and solution treating temperature on tensile properties of sheet, Fig. 3.0216.
3.0217 Effect of elevated temperature air exposure on tensile properties of duplex annealed bar, Fig. 3.0217.
3.0218 Effect of elevated temperature exposure with and without stress on tensile properties of duplex annealed sheet, Fig. 3.0218.
3.022 Compression. See 3.0322.
3.0221 Stress-strain diagrams
3.023 Impact. See 3.033.
3.024 Bending
3.025 Torsion and shear
3.026 Bearing. See 3.036.
3.027 Stress concentration
3.0271 Notch properties. See also 3.0371.
3.02711 Sharp notch properties of mill annealed sheet, Table 3.02711.

TABLE 3.02711

Source	(4)			
Alloy	Ti-8Al-1Mo-1V			
Form	0.020 in Sheet			
Condition	Mill ann 1350 F, 8 hr		Mill ann 1425 F, 8 hr	
	L	T	L	T
F_{ty}, -ksi	157	153	142	140
Notch strength - ksi	72	54	96	71



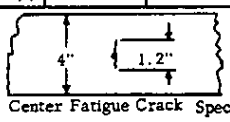
Fatigue center crack
Slow crack extension by ink stain
Anneal before cracking

3.02712 Sharp notch properties of mill and duplex annealed sheet, Table 3.02712.

TABLE 3.02712

Source	(5)					
Alloy	Ti-8Al-1Mo-1V					
Form	0.032 in sheet					
Condition	Mill ann 1450F, 8hr, FC		Lab ann 1850F, 5 min, AC + 1375F, 15min, AC		Mill ann 1850F, 5 min, AC + 1375F, 15 min AC	
Direction	L	T	L	T	L	T
F_{tu} - ksi	147	145	141	138	141	138
F_{ty} - ksi	139	137	130	127	130	127
e(2 in) - percent	15	15	10	10	10	10
Notch strength-ksi	79	74	125	123	132	123
K_c - ksi $\sqrt{in}$ (a)	138	137	> 225	> 225	> 225	> 225

(a) Nominal



Center Fatigue Crack Specimen

Slow Crack Extension Not Measured
Cracked after Anneal

3.02713 Effect of stress relief temperature and time on sharp notch properties of duplex annealed sheet, Fig. 3.02713.
3.02714 Effect of elevated temperature exposure on sharp notch properties of duplex annealed sheet, Fig. 3.02714.
3.0272 Fracture toughness. See 3.0327.
3.02721 Nominal fracture toughness of mill annealed and duplex annealed sheet, (see Table 3.02712).
3.028 Combined properties

3.03 Mechanical Properties at Various Temperatures
3.031 Tension
3.0311 Stress-strain diagrams
3.03111 Stress-strain curves for mill annealed sheet at elevated temperatures, Fig. 3.03111.
3.03112 Stress-strain curves at elevated temperature for duplex annealed sheet, Fig. 3.03112.
3.0312 Effect of test temperature on tensile properties of forgings annealed at two temperatures, Fig. 3.0312.
3.0313 Effect of test temperature and annealing temperature on tensile properties of duplex annealed bar stock, Fig. 3.0313.
3.0314 Effect of test temperature on tensile properties of 1450F mill annealed sheet, Fig. 3.0314
3.0315 Effect of test temperature on tensile properties of duplex annealed sheet from five heats, Fig. 3.0315.
3.0316 Effect of test temperature on two heats of triplex annealed sheet, Fig. 3.0316.
3.0317 Effect of low temperatures on tensile properties of 1350F mill annealed sheet, Fig. 3.0317.
3.0318 Effect of exposure and test temperature on tensile properties of 1450F mill annealed sheet, Fig. 3.0318.
3.0319 Effect of elevated temperature exposure time under stress on tensile properties and mill annealed sheet at room temperature and 550F, Fig. 3.03719.
3.03191 Effect of eleevated temperature exposure under stress on tensile properties of duplex annealed sheet at several temperatures, Fig. 3.03191.
3.032 Compression
3.0321 Stress-strain diagrams
3.0322 Effect of test temperature on compressive yield strength of mill annealed sheet, Fig. 3.0322.
3.033 Impact
3.0331 Effect of test temperature and hot rolling temperature on impact strength of hot rolled bar, Fig. 3.0331.
3.034 Bending
3.035 Torsion and shear
3.0351 Effect of test temperature on shear strength of bar duplex annealed at various temperatures, Fig. 3.0351.
3.036 Bearing
3.0361 Effect of test temperature on bearing properties of mill annealed sheet, Fig. 3.0361.
3.037 Stress concentration
3.0371 Notch properties
3.03711 Effect of test temperature and annealing temperature on notch properties of duplex annealed bar, Fig. 3.03711.
3.03712 Effect of test temperature on notch properties of 1350F mill annealed sheet, Fig. 3.03712.
3.03713 Effect of test temperature and sheet thickness on notch properties of 1850F duplex annealed sheet, Fig. 3.03713.
3.03714 Effect of low test temperature on notch properties of 1800F duplex annealed sheet, Fig. 3.03714.
3.03715 Effect of low test temperature on notch properties of quenched and aged sheet, Fig. 3.03715.

Ti
8 Al
1 Mo
1 V

3.03716 Effect of test temperature on sharp notch strength of duplex annealed sheet from three heats, Fig. 3.03716.

3.03717 Effect of test temperature on nominal fracture toughness of three heats of duplex annealed sheet, Fig. 3.03717.

3.03718 Effect of crack length on sharp notch properties of triplex annealed sheet at several temperatures, Fig. 3.03718.

3.03719 Effect of reannealing temperature on the -110F sharp notch properties of duplex annealed sheet, Fig. 3.03719.

3.037110 Effect of cooling rate from reannealing temperature on -110F sharp notch properties of duplex annealed sheet, Fig. 3.037110.

3.037111 Effect of exposure and test temperature on sharp notch properties of mill annealed sheet, Fig. 3.037111.

3.037112 Effect of exposure and test temperature on sharp notch properties of duplex annealed sheet, Fig. 3.037112.

3.037113 Effect of thickness and elevated temperature exposure on sharp notch strength of duplex annealed sheet, Fig. 3.037113.

3.037114 Effect of room temperature stretching on -110F sharp notch properties of duplex annealed sheet, Fig. 3.037114.

3.0372 Fracture toughness. The fracture toughness of annealed sheet is very high at room temperature and above. At subzero temperature the toughness of duplex annealed sheet is superior to that of mill annealed sheet (compare Figs. 3.037111 with Fig. 3.037112). In general rapid cooling from temperatures above about 1350F is necessary for development of optimum combinations of strength and toughness (eg. see Figs. 3.037110). However, the benefits of this rapid cooling are lost if the alloy is heated for long periods of time at elevated temperature. (See Fig. 3.02714). Room temperature stretching reduces the low temperature toughness of sheet (see Fig. 3.037114). Plane strain fracture toughness data is not yet available, (see also 1.09).

3.038 Combined properties

3.04 Creep and Creep Rupture Properties

3.041 Creep deformation curves for mill and duplex annealed sheet, Fig. 3.041.

3.042 0.1 percent creep deformation curves for duplex annealed sheet at 450 to 650F, Fig. 3.042.

3.043 Isochronous stress-strain curves for mill annealed sheet, Fig. 3.043.

3.044 Creep properties at various temperatures for mill and duplex annealed sheet, Table 3.044.

TABLE 3.044

Source	(4)(21)								
Alloy	Ti-8Al-1Mo-1V								
Form	0.056 to 0.080 in thick								
Condition	Mill Ann. 1450F, 8hr, FC					1850F, 5 min, AC + 1100F, 8hr, AC			
Creep Stress and Temp - F	550F 67 ksi	800F 65 ksi	900F 45 ksi	1000F 25 ksi	1100F 10 ksi	800F 65 ksi	900F 45 ksi	1000F 25 ksi	1100F 10 ksi
Total Deformation Percent in 150 hrs		0.36	0.92	2.48	4.82	0.14	0.28	0.52	2.18
1000 hrs	0.032								
12000 hrs	0.032								

3.045 Creep properties at various temperatures for duplex annealed bar, Table 3.045.

TABLE 3.045

Source	(1)								
Alloy	Ti-8Al-1Mo-1V								
Form	1/2 in dia bar								
Condition	1650F, 1hr, AC + 1100F, 8hr, AC			1800F, 1hr, AC + 1100F, 8hr, AC			1950F, 1hr, AC + 1100F, 8hr, AC		
	Stress - ksi at temp								
	850F	1000F	1100F	850F	1000F	1100F	850F	1000F	1100F
Total Def. in 150hr									
0.2 percent	50	15	-	50	(13)	4	(70)	25	(20)
0.5 percent	60	20	-	60	24	8	-	45	-
1.0 percent	-	28	-	-	30	12	-	-	-

() Value extrapolated.

3.046 Creep rupture properties for duplex annealed bar and forgings, Fig. 3.046.

3.047 Creep properties at two temperatures for compression forging, Table 3.047.

TABLE 3.047

Source	(14)							
Alloy	Ti-8Al-1Mo-1V							
Form	21 in dia x 1 1/2 in Compressor forging							
Direction	Radial							
Condition	1650F, 1 hr, AC + 1100F, 8 hr, AC		1850F, 1 hr, AC + 1100F, 8 hr, AC		1850F, 1 hr, WQ + 1100F, 8 hr, AC		1850F, 1 hr, WQ + 1375F, 30 min, AC	
Creep stress and temperature	900F 45 ksi	1000F 25 ksi	900F 45 ksi	1000F 25 ksi	900F 45 ksi	1000F 25 ksi	900F 45 ksi	1000F 25 ksi
Total deformation percent in 150 hr	0.39	0.18	0.29	0.20	0.31	0.16	0.28	0.15

	Ti
8	Al
1	Mo
1	V

3.05 Fatigue Properties

3.051 Axial load fatigue properties of duplex annealed sheet at low and elevated temperature, Fig. 3.051.

3.052 Axial load notch fatigue properties of duplex annealed sheet at low and elevated temperatures, Fig. 3.052.

3.053 Axial load sharp notch fatigue properties of duplex annealed sheet at room and elevated temperature, Fig. 3.053.

3.054 Rotating beam fatigue properties of mill and duplex annealed bar, Table 3.054.

TABLE 3.054

Source	(1)						
Alloy	Ti-8Al-1Mo-1V						
Form	Bar						
Condition	Method	Stress Ratio		Stress Conc	Fatigue strength - ksi, at cycles		
		A	R		10^5	10^6	10^7
Ann, 1400F, 24 hr, AC	Rot Beam		-1	Smooth $K_t = 1$	97	86	82
1800F, 4 hr, AC, 1000F, 24hr, AC					103	91	-

3.055 Axial load fatigue properties of duplex annealed sheet at elevated temperatures, Table 3.055.

TABLE 3.055

Source	(27)						
Alloy	Ti-8Al-1Mo-1V						
Form	0.050 in sheet						
Condition	1450F, 8 hr, FC + 1450F, 30 min, AC						
Temp - F	Method	Stress Ratio		Stress Conc	Fatigue strength - ksi at cycles		
		A	R		10^4	10^5	10^6	10^7
RT	Direct Stress		0.1	Notch K = 2 (a)	80	50	45	40
400					74	48	43	40
650					67	45	42	40
RT	Direct Stress		-0.5		58	40	34	28
400					50	39	34	28
650					45	38	34	28
RT	Direct Stress		0.1	Smooth K = 1	145	102	99	90
400					125	97	90	85
650					105	95	90	85
RT	Direct Stress		-0.5		120	83	75	72
400					94	70	65	63
650					87	70	60	58

(a) For specimen see Fig. 3.057

3.056 Effect of elevated temperature stress exposure on the 10^5 cycle fatigue strength of duplex annealed sheet at room and elevated temperatures, Fig. 3.056.

3.057 Effect of elevated temperature stress exposure on the 10^5 cycle notch fatigue strength of duplex annealed sheet at room and elevated temperatures, Fig. 3.057.

3.06 Elastic Properties

3.061 Poisson's ratio

3.062 Modulus of elasticity

3.0621 Tensile modulus of elasticity for duplex annealed sheet at low and elevated temperatures, Fig. 3.0621.

3.0622 Tensile modulus of elasticity at various temperatures for annealed bars and sheet, Fig. 3.0622.

3.0623 Compression modulus for mill annealed sheet at various temperatures, Fig. 3.0623.

3.063 Modulus of rigidity

3.064 Compressive tangent modulus at various temperatures for mill annealed sheet, Fig. 3.064.

3.065 Compressive secant modulus at various temperatures for mill annealed sheet, Fig. 3.065.

4. FABRICATION

4.01 Formability

4.011 General. Forming practices for this alloy are similar to those of other alpha rich titaniums. The beta transus of this alloy is higher than Ti-6Al-4V, and this permits higher hot work temperatures. Finish working temperatures above the beta transus (aproximately 1900F) produce coarser grain size than is characteristic of finishing below the beta transus. (See 1.09). Sheet forming is more difficult than in Ti-6Al-4V, and for severe operations forming temperatures between 1325F and 1375F are required, (3).

4.012 Hot sizing 1450F, (5).

4.013 Forging. Starting temperature 1950F maximum. Finishing temperature 1800F minimum and 1900F maximum, (1).

4.0131 Tensile properties for duplex annealed bar upset forged at 1850 to 1950F, Table 4.0131.

TABLE 4.0131

Source	(1)			
Alloy	Ti-8Al-1Mo-1V			
Form	3 in long quarter section of 9 1/2 in round axial upset to 3/4 in			
Upset temp	1850 F		1950 F	
Duplex anneal(a)	1650 F	1800 F	1650 F	1800 F
Radial and tang. Average of properties at center				
F_{tu} - ksi	151	141	138	142
F_{ty} - ksi	139	128	124	124
e(4D) - percent	16	17	12	15
RA - percent	24	34	21	31

(a) Indicated temp 1 hr, AC + 1100 F, 8 hr, AC.

4.014 Rolling. Finish rolling temperature for sheet is normally about 1800F, however, special rolling schedules may use a different temperature in order to improve stress corrosion resistance.

4.02 Machining and Grinding

Machines similar to Ti-6Al-4V but requires stress relief, (see 1.054), (3).

4.03 Welding

4.031 General. Sheet is readily welded by the TIG process using a parent alloy filler and the welds have high joint efficiencies, (4)(7). Resistance welding is readily accomplished providing care is taken to insure the facing surfaces are clean at the time of welding, (46). For thick sections the MIG process has been successfully employed, although experience with welding of thick sections of this alloy is very limited as yet, (47).

4.032 Stress relief. Stress relief heat treatments should not be carried out in the temperature range between 1000 and 1200F in order to avoid loss in fracture toughness as well as increased sensitization of the weld metal and parent metal to stress corrosion, see 1.054. In fusion welding of sheet a preheat of 500F has been found beneficial in reducing residual stress, (48).

4.033 Effect of test temperature and reannealing on tensile properties of welded sheet, Fig. 4.033.

4.04 Heat Treatment

See Ti, commercially pure.

4.05 Surface Treatment

See Ti-6Al-4V.

	Ti
8	Al
1	Mo
1	V

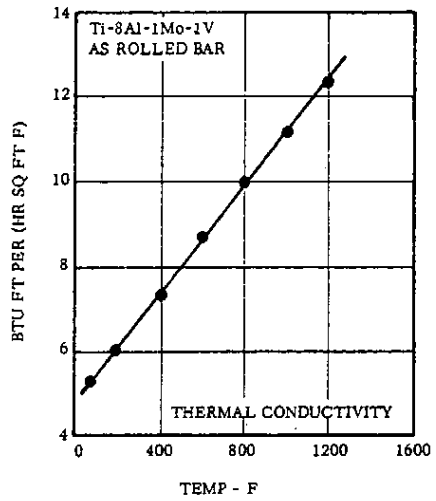


FIG. 2.013 THERMAL CONDUCTIVITY (1)

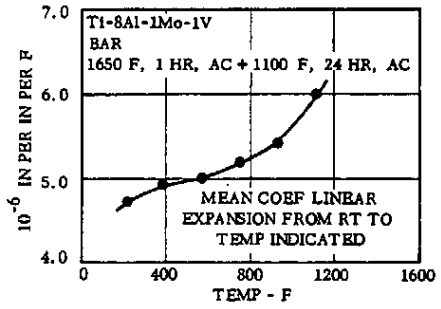


FIG. 2.014 THERMAL EXPANSION (1)

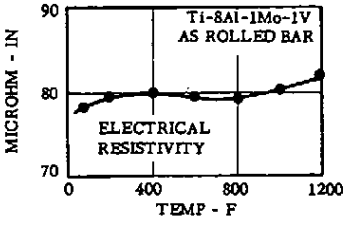


FIG. 2.022 ELECTRICAL RESISTIVITY (1)

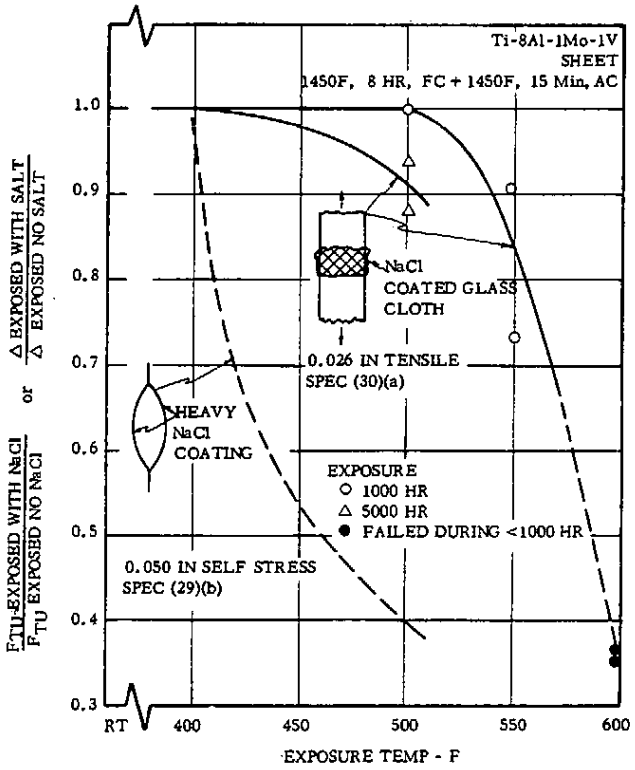


FIG. 2.0321 EFFECT OF EXPOSURE TEMPERATURE AND TIME ON SOLID SALT STRESS CORROSION OF DUPLEX ANNEALED SHEET (29)(30)

(a) Exposed 40 ksi plus room temperature tension to determine F_{tu}.
(b) Exposed 50 ksi 5000 hours plus room temperature compression to determine shortening Δ to failure.

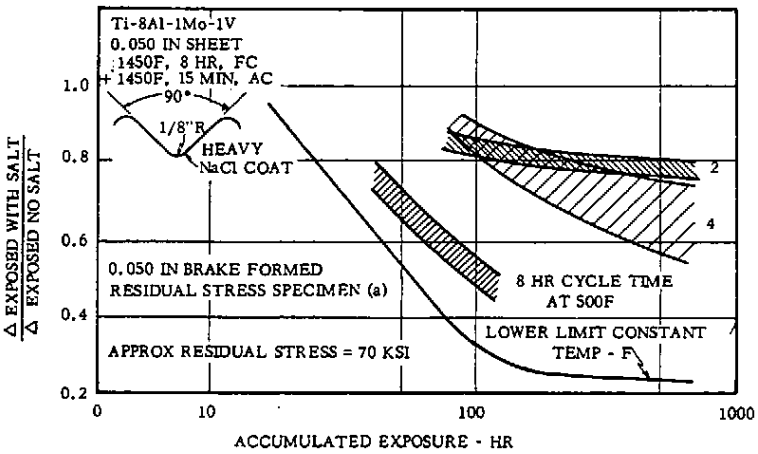


FIG. 2.0322 EFFECT OF CYCLIC HEATING ON SOLID SALT CORROSION SUSCEPTIBILITY OF DUPLEX ANNEALED SHEET (29)

(a) Exposed at 550F plus room temperature compression to determine shortening Δ to failure.

	Ti
8	Al
1	Mo
1	V

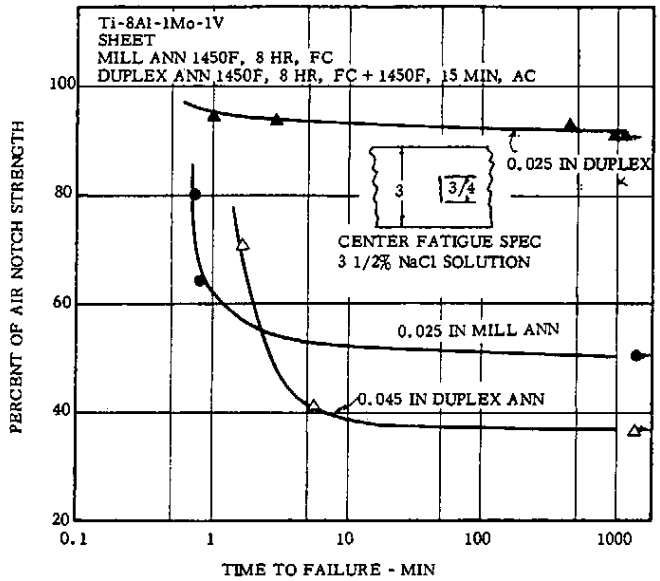


FIG. 2.0331 DELAYED FAILURE CURVES IN 3 1/2 PERCENT SALT SOLUTION FOR MILL AND DUPLEX ANNEALED SHEET (36)(41)

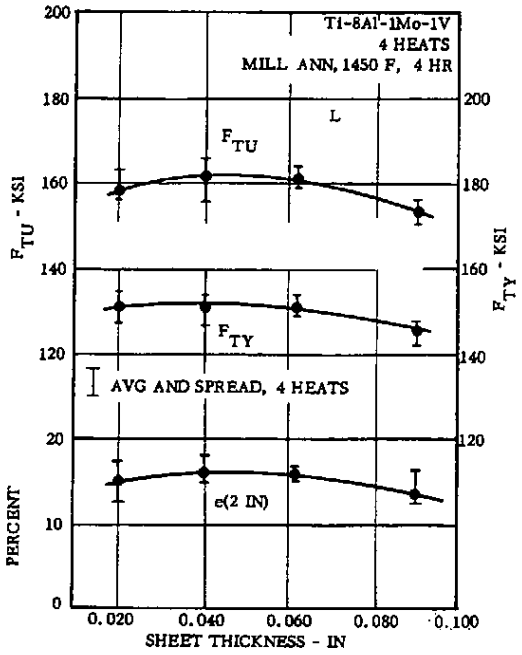


FIG. 3.0212 AVERAGE AND SPREAD OF LONGITUDINAL TENSILE PROPERTIES FOR MILL ANNEALED SHEET OF VARIOUS THICKNESSES (4)

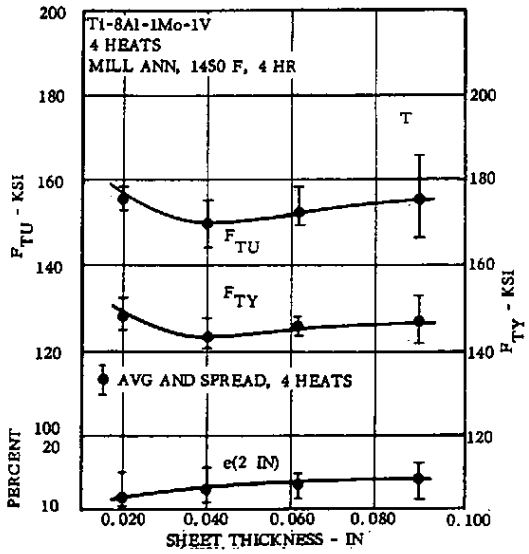


FIG. 3.0213 AVERAGE AND SPREAD OF TRANSVERSE TENSILE PROPERTIES FOR MILL ANNEALED SHEET OF VARIOUS THICKNESSES (4)

	Ti
8	Al
1	Mo
1	V

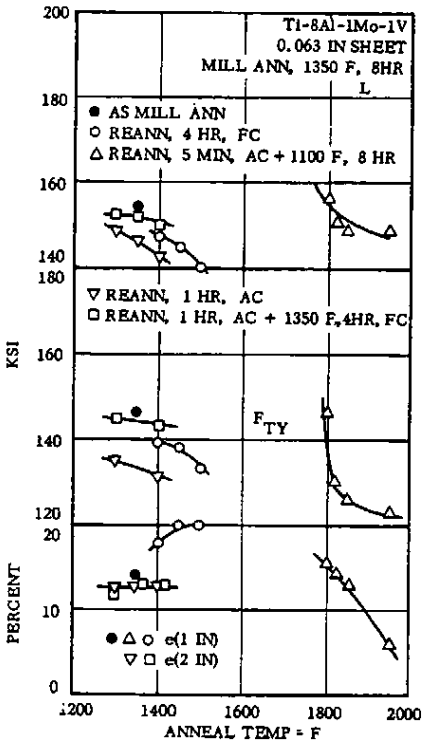


FIG. 3.0214 INFLUENCE OF VARIOUS REANNEALING CYCLES ON TENSILE PROPERTIES OF 1350 F MILL ANNEALED SHEET (8)(4)

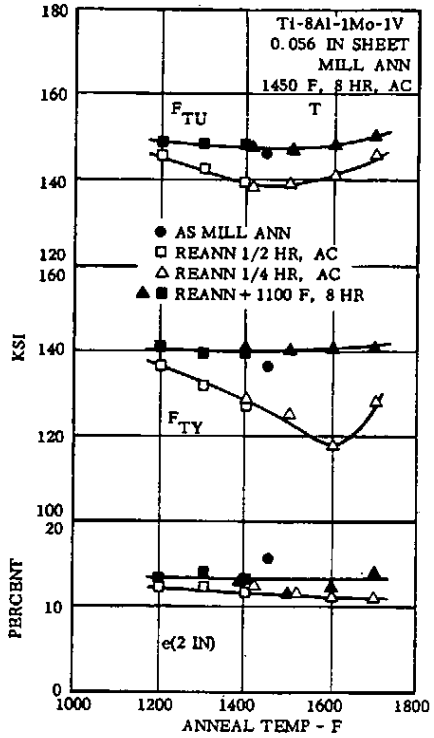


FIG. 3.0215 INFLUENCE OF VARIOUS REANNEALING CYCLES ON THE TENSILE PROPERTIES OF 1450 F MILL ANNEALED SHEET (4)

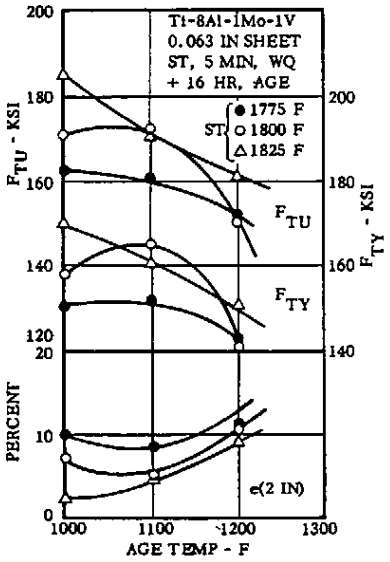


FIG. 3.0216 INFLUENCE OF AGING TEMPERATURE AND SOLUTION TREATING TEMPERATURE ON TENSILE PROPERTIES OF SHEET (4)

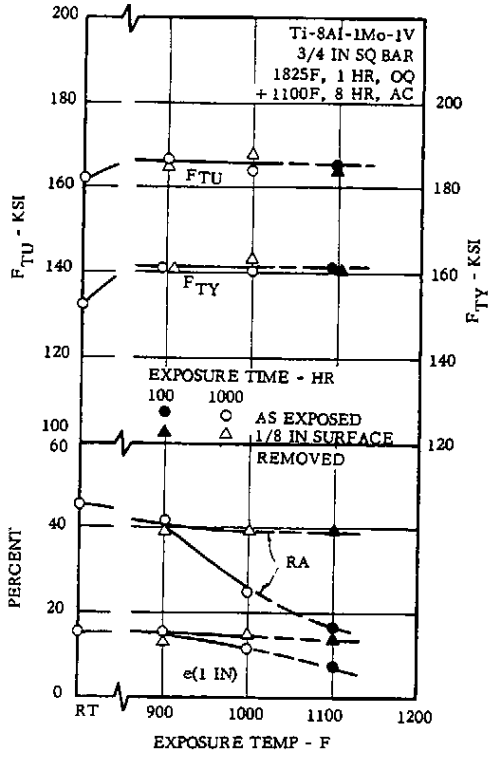
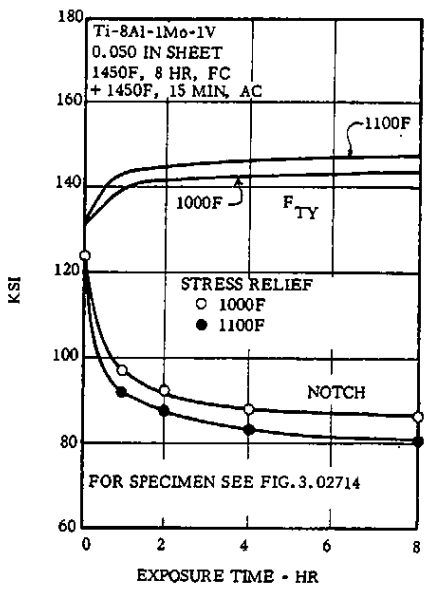


FIG. 3.0217 EFFECT OF ELEVATED TEMPERATURE AIR EXPOSURE ON TENSILE PROPERTIES OF DUPLEX ANNEALED BAR (31)



Ti
8 Al
1 Mo
1 V

FIG. 3.02713 EFFECT OF STRESS RELIEF TEMPERATURE AND TIME ON SHARP NOTCH PROPERTIES OF DUPLEX ANNEALED SHEET (40)

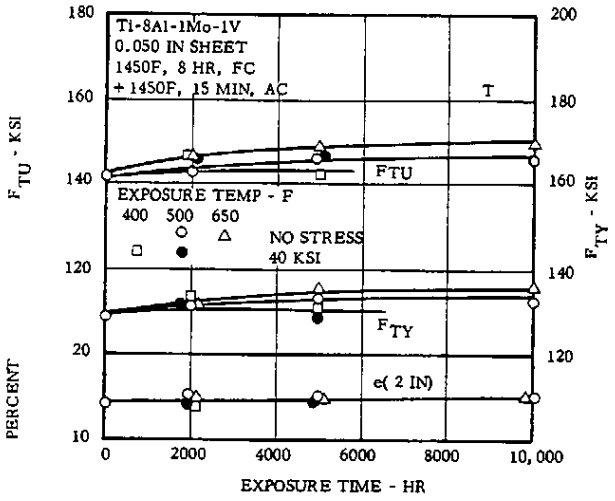


FIG. 3.0218 EFFECT OF ELEVATED TEMPERATURE EXPOSURE WITH AND WITHOUT STRESS ON TENSILE PROPERTIES OF DUPLEX ANNEALED SHEET (40)

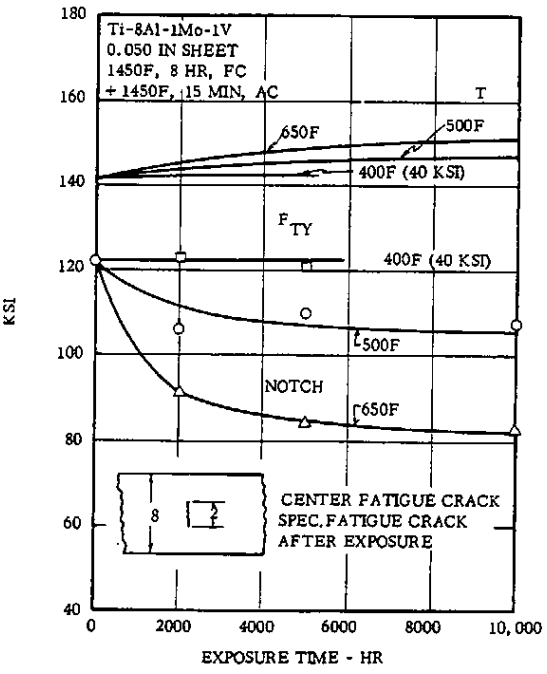


FIG. 3.02714 EFFECT OF ELEVATED TEMPERATURE EXPOSURE ON SHARP NOTCH PROPERTIES OF DUPLEX ANNEALED SHEET (40)

	Ti
8	Al
1	Mo
1	V

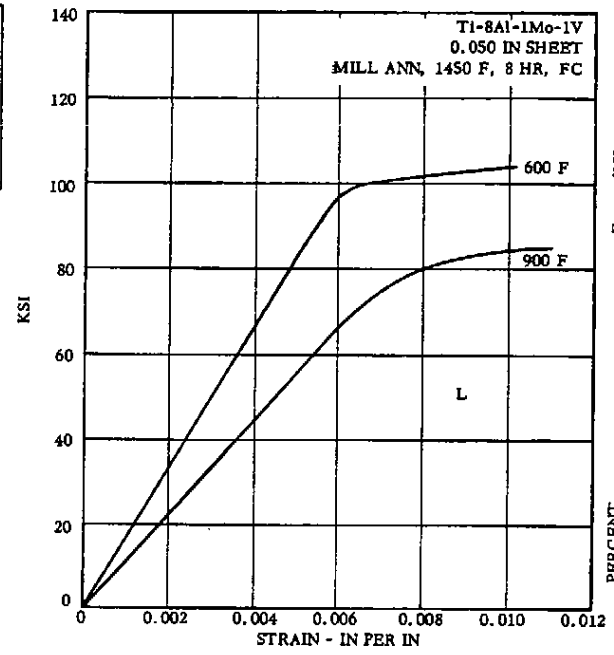


FIG. 3.03111 STRESS STRAIN CURVES FOR MILL ANNEALED SHEET AT ELEVATED TEMPERATURES (13)

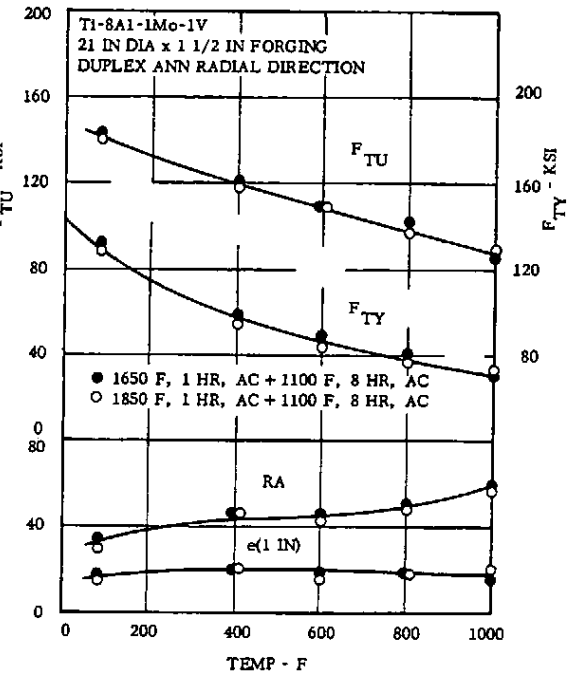


FIG. 3.0312 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF FORGINGS ANNEALED AT TWO TEMPERATURES (14)

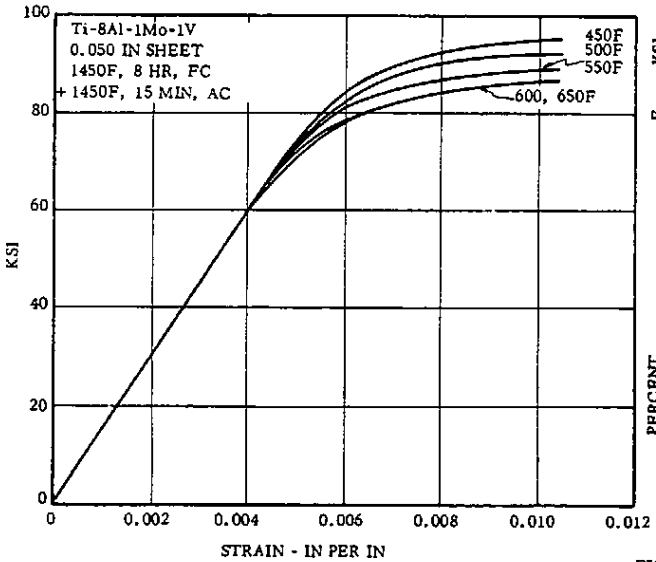


FIG. 3.03112 STRESS-STRAIN CURVES AT ELEVATED TEMPERATURE FOR DUPLEX ANNEALED SHEET (25)

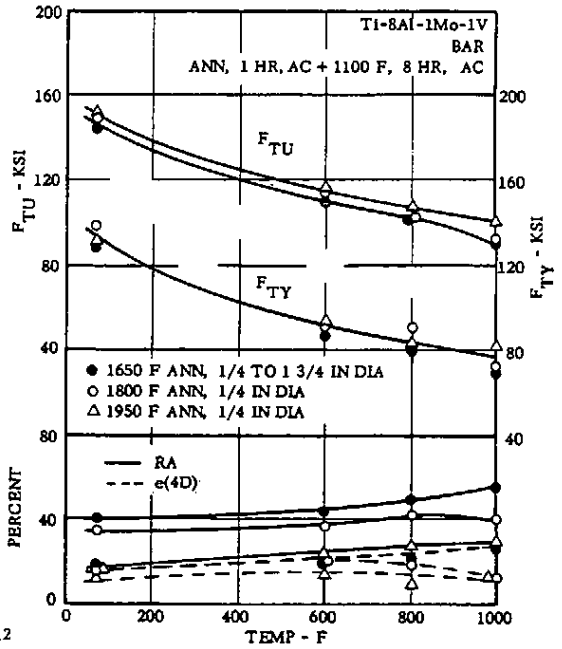


FIG. 3.0313 EFFECT OF TEST TEMPERATURE AND ANNEALING TEMPERATURE ON TENSILE PROPERTIES OF DUPLEX ANNEALED BAR STOCK (1)

	Ti
8	Al
1	Mo
1	V

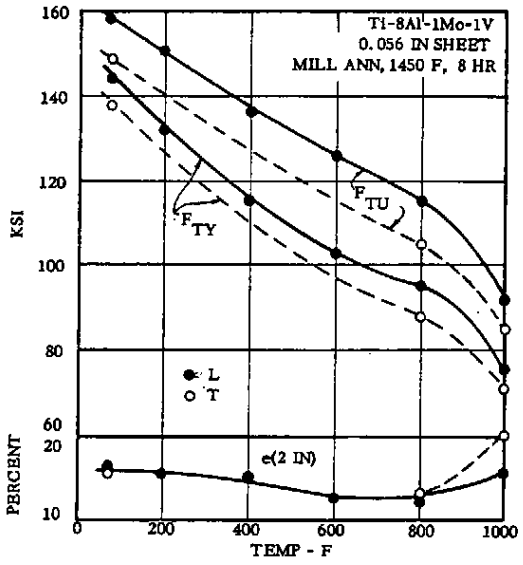


FIG. 3.0314 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF 1450F MILL ANNEALED SHEET (4)

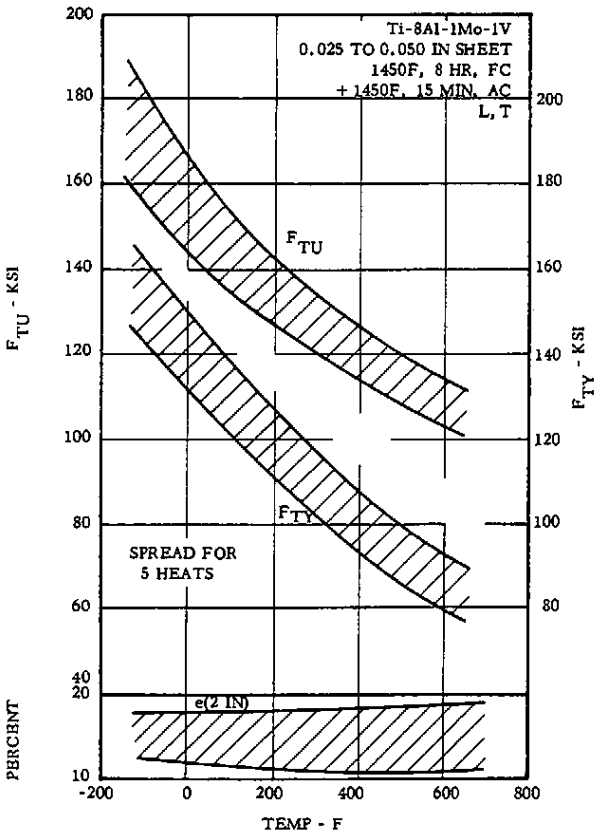


FIG. 3.0315 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF DUPLEX ANNEALED SHEET FROM FIVE HEATS (25)(26)

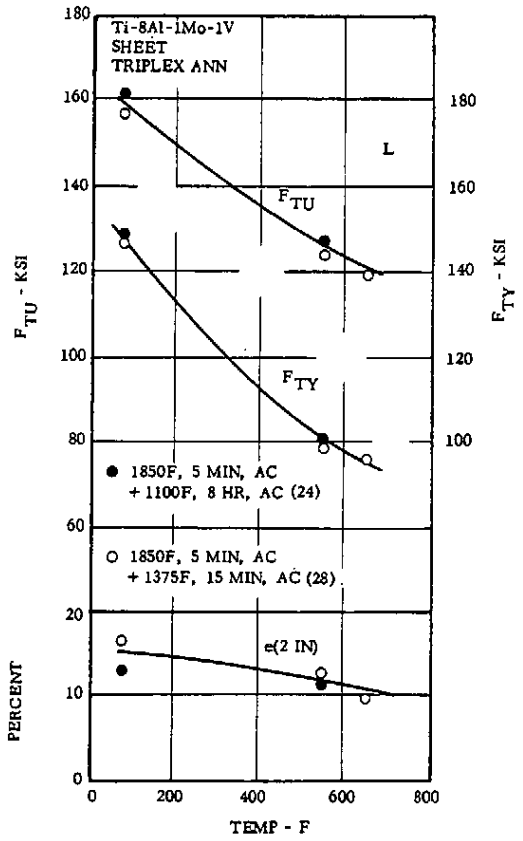


FIG. 3.0316 EFFECT OF TEST TEMPERATURE ON TWO HEATS OF TRIPLEX ANNEALED SHEET (24)(28)

	Ti
8	Al
1	Mo
1	V

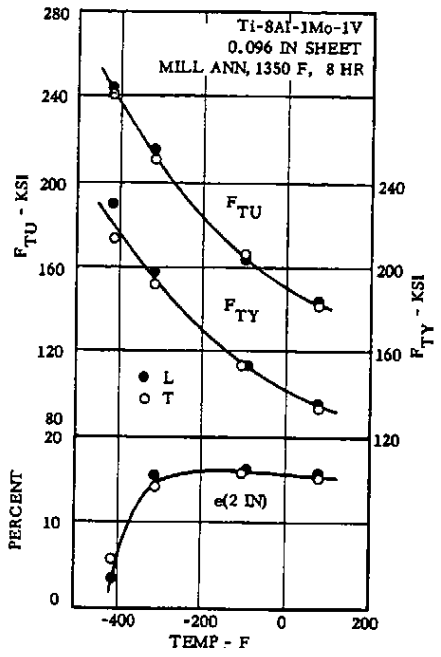


FIG. 3.0317 EFFECT OF LOW TEMPERATURES ON TENSILE PROPERTIES OF 1350 F MILL ANNEALED SHEET (9)

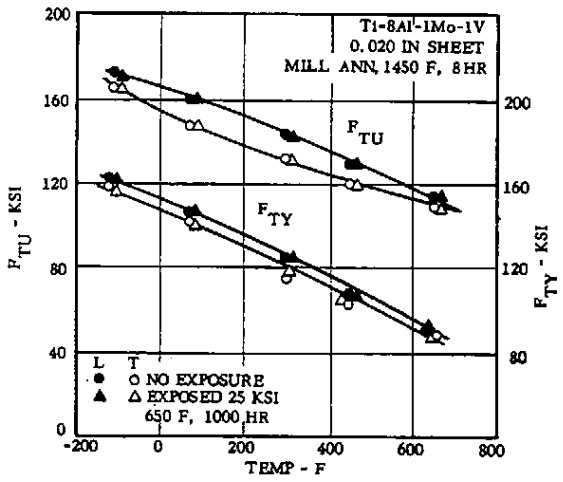


FIG. 3.0318 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON TENSILE PROPERTIES OF 1450 F MILL ANNEALED SHEET (10)

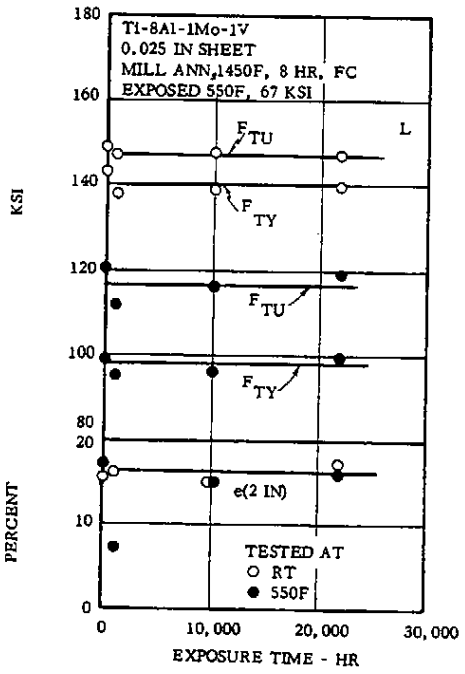


FIG. 3.0319 EFFECT OF ELEVATED TEMPERATURE AND EXPOSURE TIME UNDER STRESS ON TENSILE PROPERTIES OF MILL ANNEALED SHEET AT ROOM TEMPERATURE AND 550F (24)

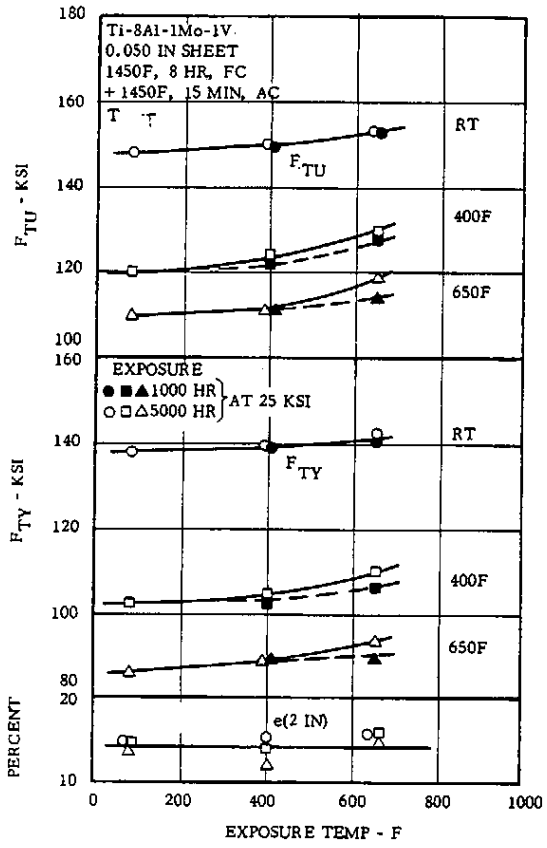
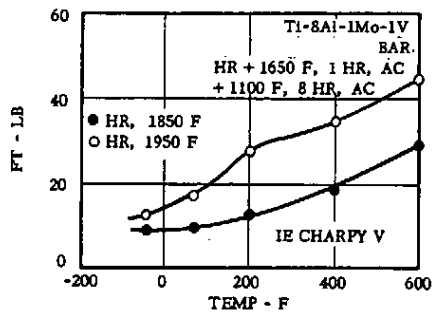


FIG. 3.03191 EFFECT OF ELEVATED TEMPERATURE EXPOSURE UNDER STRESS ON TENSILE PROPERTIES OF DUPLEX ANNEALED SHEET AT SEVERAL TEMPERATURES (27)



	Ti
8	Al
1	Mo
1	V

FIG. 3.0331 EFFECT OF TEST TEMPERATURE AND HOT ROLLING TEMPERATURE ON IMPACT STRENGTH OF HOT ROLLED BAR (1)

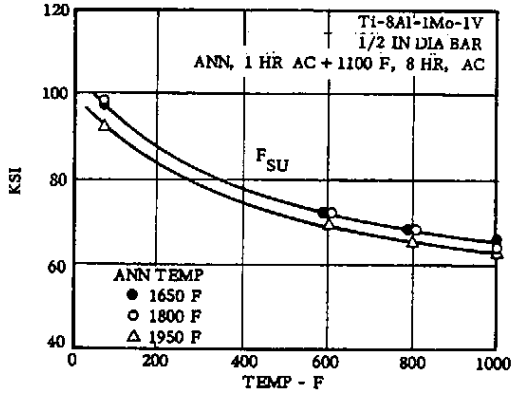


FIG. 3.0351 EFFECT OF TEST TEMPERATURE ON SHEAR STRENGTH OF BAR DUPLEX ANNEALED AT VARIOUS TEMPERATURES (1)

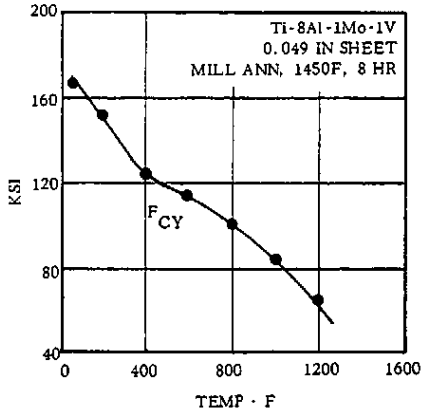


FIG. 3.0322 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF MILL ANNEALED SHEET (4)

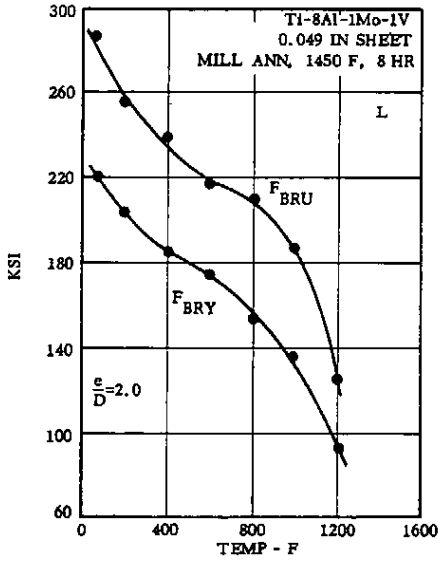


FIG. 3.0361 EFFECT OF TEST TEMPERATURE ON BEARING PROPERTIES OF MILL ANNEALED SHEET (4)

	Ti
8	Al
1	Mo
1	V

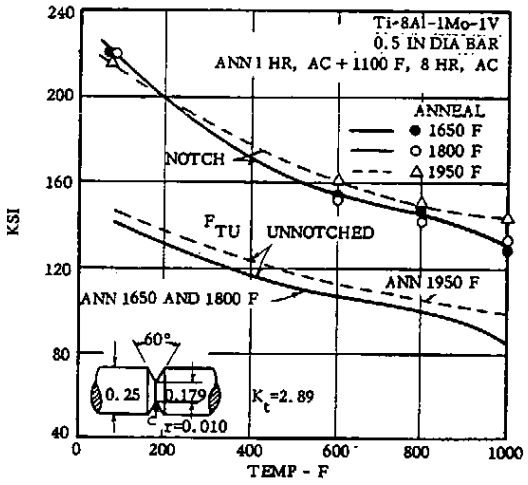


FIG. 3.03711 EFFECT OF TEST TEMPERATURE AND ANNEALING TEMPERATURE ON NOTCH PROPERTIES OF DUPLEX ANNEALED BAR (1)

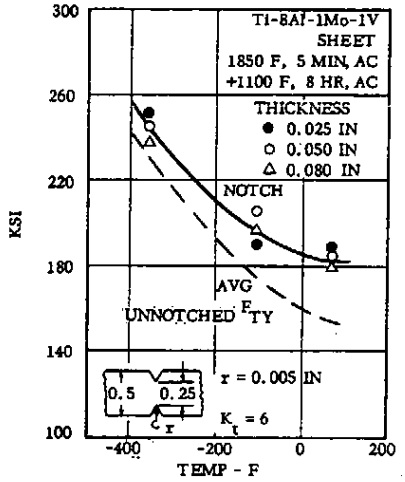


FIG. 3.03713 EFFECT OF TEST TEMPERATURE AND SHEET THICKNESS ON NOTCH PROPERTIES OF 1850 F DUPLEX ANNEALED SHEET (11)

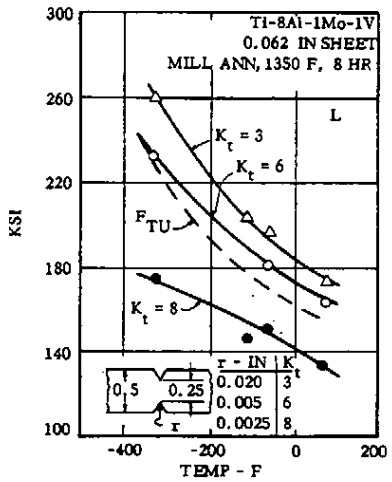


FIG. 3.03712 EFFECT OF TEST TEMPERATURE ON NOTCH PROPERTIES OF 1350 F MILL ANNEALED SHEET (4)

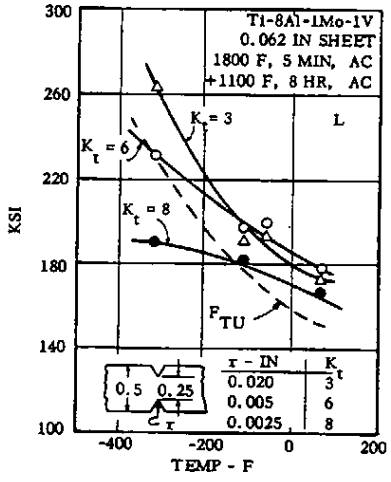


FIG. 3.03714 EFFECT OF LOW TEST TEMPERATURE ON NOTCH PROPERTIES OF 1800 F DUPLEX ANNEALED SHEET (4)(14)

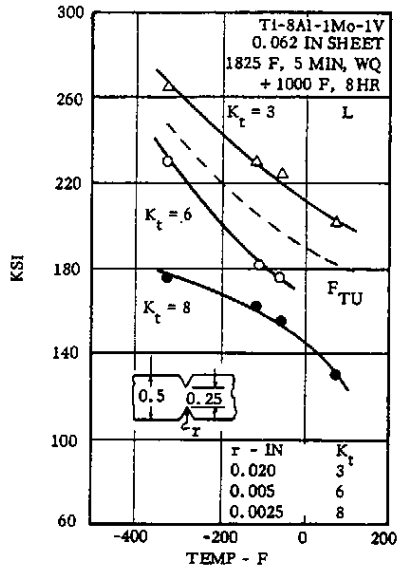
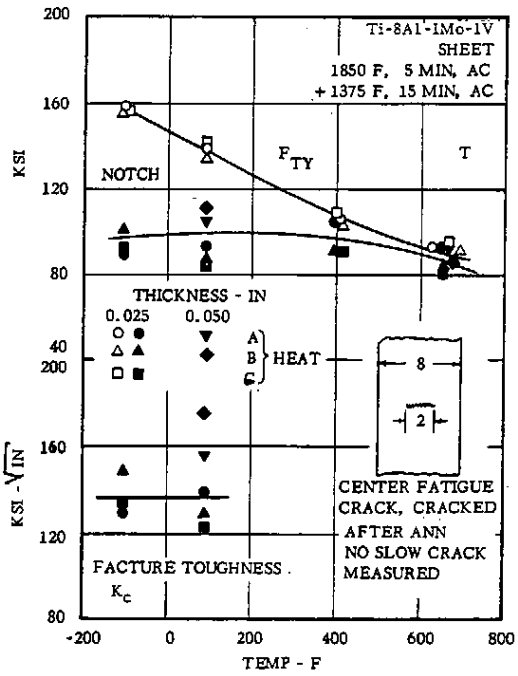


FIG. 3.03715 EFFECT OF LOW TEST TEMPERATURE ON NOTCH PROPERTIES OF QUENCHED AND AGED SHEET (4)(5)



	Ti
8	Al
1	Mo
1	V

FIG. 3.03717 EFFECT OF TEST TEMPERATURE ON NOMINAL FRACTURE TOUGHNESS OF THREE HEATS OF DUPLEX ANNEALED SHEET (16)

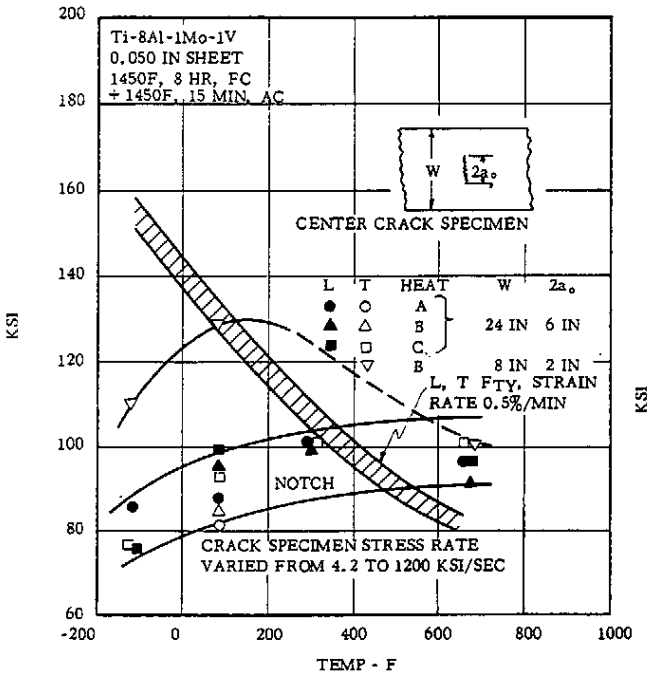


FIG. 3.03716 EFFECT OF TEST TEMPERATURE ON SHARP NOTCH STRENGTH OF DUPLEX ANNEALED SHEET FROM THREE HEATS (26)

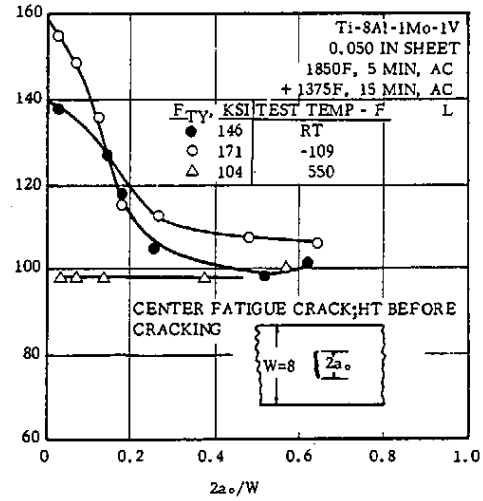


FIG. 3.03718 EFFECT OF CRACK LENGTH ON THE SHARP NOTCH PROPERTIES OF TRIPLEX ANNEALED SHEET AT SEVERAL TEMPERATURES (22)

	Ti
8	Al
1	Mo
1	V

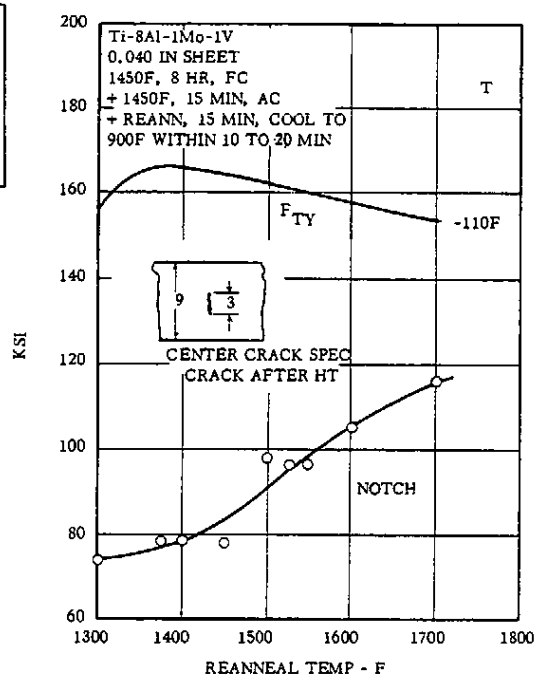


FIG. 3.03719 EFFECT OF REANNEALING TEMPERATURE ON THE -110F SHARP NOTCH PROPERTIES OF DUPLEX ANNEALED SHEET (40)

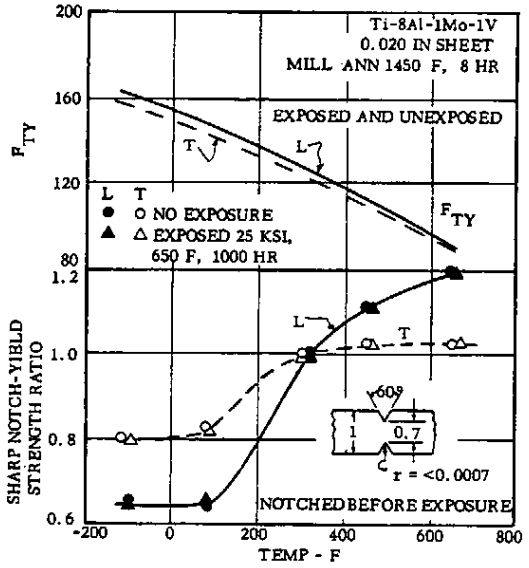


FIG. 3.037111 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON SHARP NOTCH PROPERTIES OF MILL ANNEALED SHEET (10)

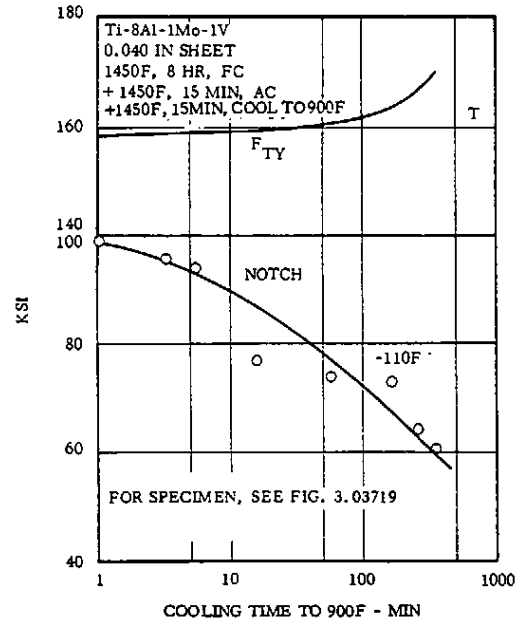


FIG. 3.037110 EFFECT OF COOLING RATE FROM REANNEALING TEMPERATURE ON THE -110F SHARP NOTCH PROPERTIES OF DUPLEX ANNEALED SHEET (40)

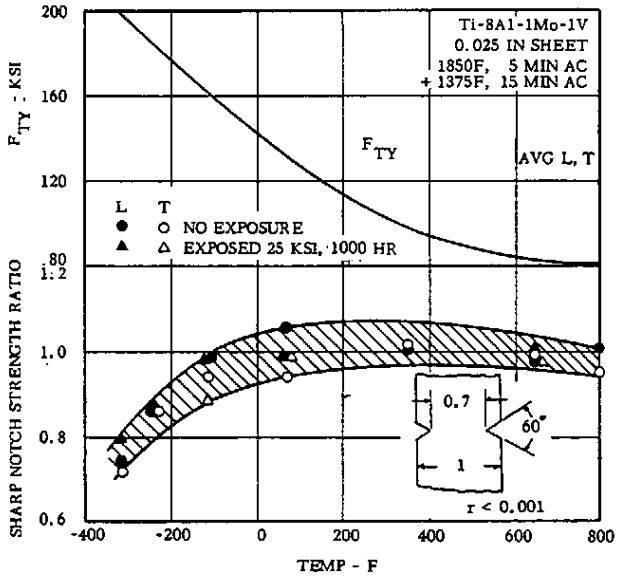


FIG. 3.037112 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON SHARP NOTCH PROPERTIES OF DUPLEX ANNEALED SHEET (17)(18)

	Ti
8	Al
1	Mo
1	V

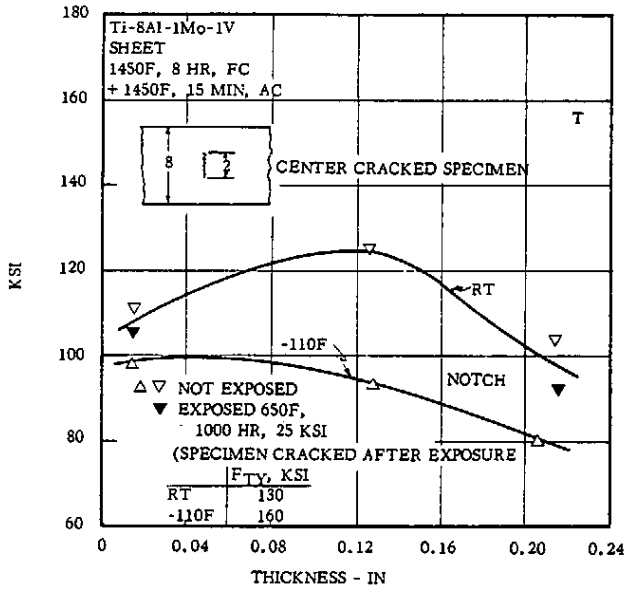


FIG. 3.037113 EFFECT OF THICKNESS AND ELEVATED TEMPERATURE EXPOSURE ON SHARP NOTCH STRENGTH OF DUPLEX ANNEALED SHEET (26)

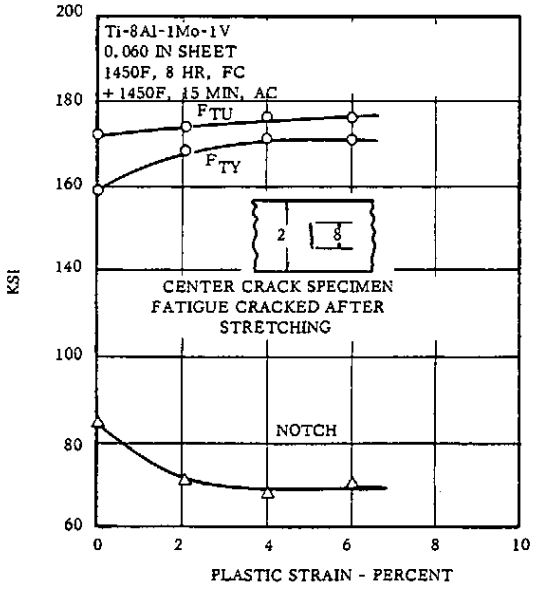


FIG. 3.037114 EFFECT OF ROOM TEMPERATURE STRETCHING ON -110F SHARP NOTCH PROPERTIES OF DUPLEX ANNEALED SHEET (49)

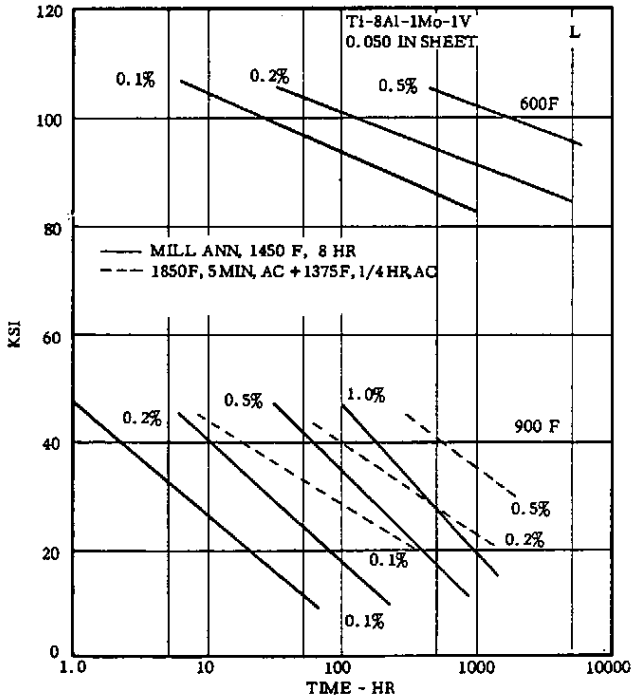


FIG. 3.041 CREEP DEFORMATION CURVES FOR MILL AND DUPLEX ANNEALED SHEET (13)

Ti
8 Al
1 Mo
1 V

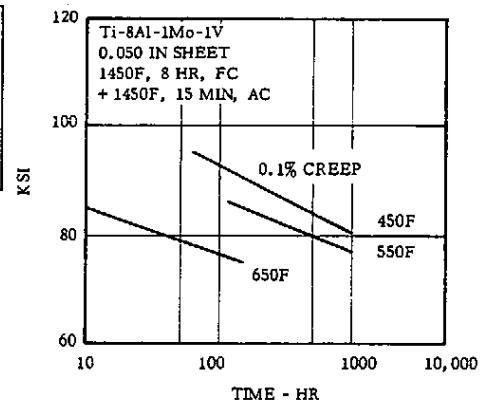


FIG. 3.042 0.1 PERCENT CREEP DEFORMATION CURVES FOR DUPLEX ANNEALED SHEET AT 450 TO 650F (25)

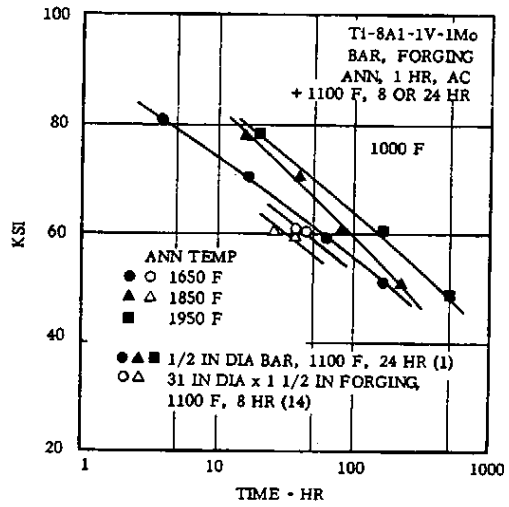


FIG. 3.046 CREEP RUPTURE PROPERTIES FOR DUPLEX ANNEALED BAR AND FORGING (1)(14)

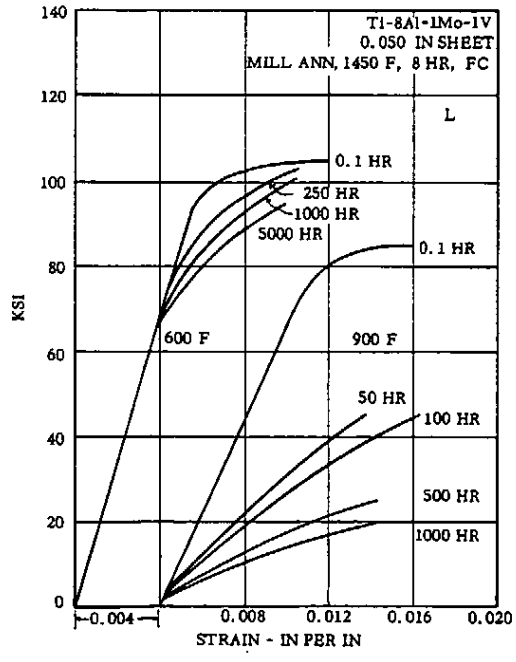


FIG. 3.043 ISOCHRONOUS STRESS STRAIN CURVES FOR MILL ANNEALED SHEET (13)

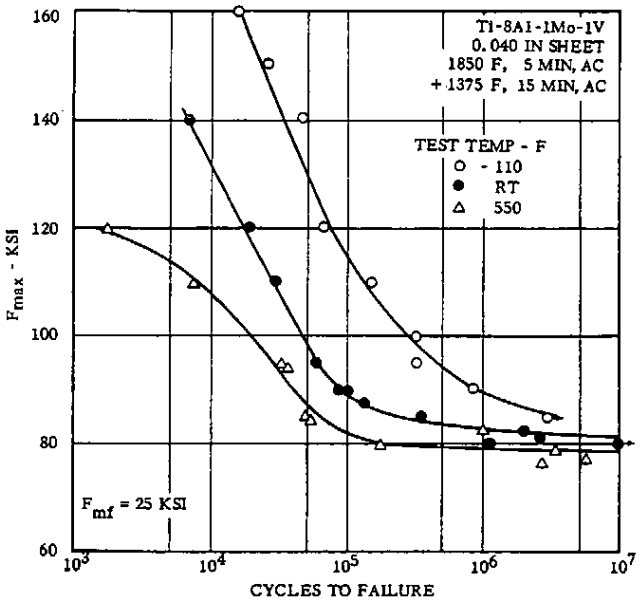


FIG. 3.051 AXIAL LOAD FATIGUE PROPERTIES OF DUPLEX ANNEALED SHEET AT LOW AND ELEVATED TEMPERATURES (15)

	Ti
8	Al
1	Mo
1	V

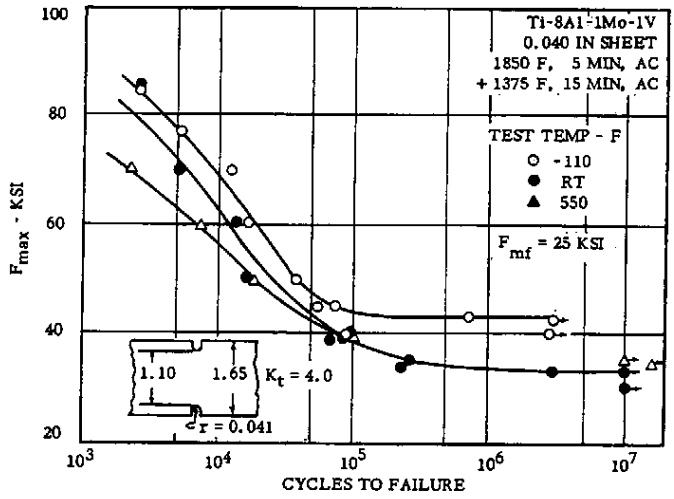


FIG. 3.052 AXIAL LOAD NOTCH FATIGUE PROPERTIES OF DUPLEX ANNEALED SHEET AT LOW AND ELEVATED TEMPERATURE (15)

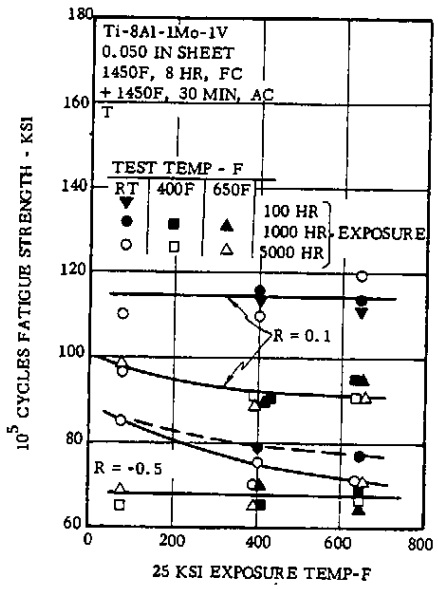


FIG. 3.056 EFFECT OF ELEVATED TEMPERATURE STRESS EXPOSURE ON THE 10^5 CYCLE FATIGUE STRENGTH OF DUPLEX ANNEALED SHEET AT ROOM AND ELEVATED TEMPERATURES (27)

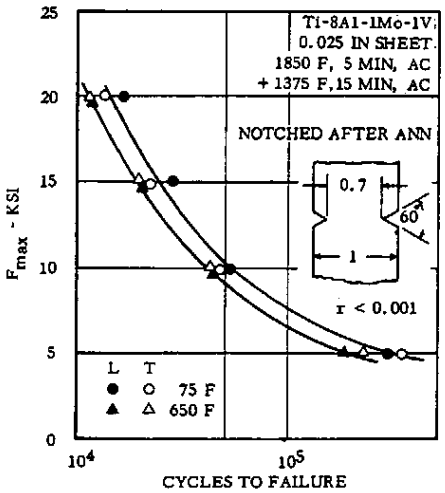


FIG. 3.053 AXIAL LOAD SHARP NOTCH FATIGUE PROPERTIES OF DUPLEX ANNEALED SHEET AT ROOM AND ELEVATED TEMPERATURE (17)

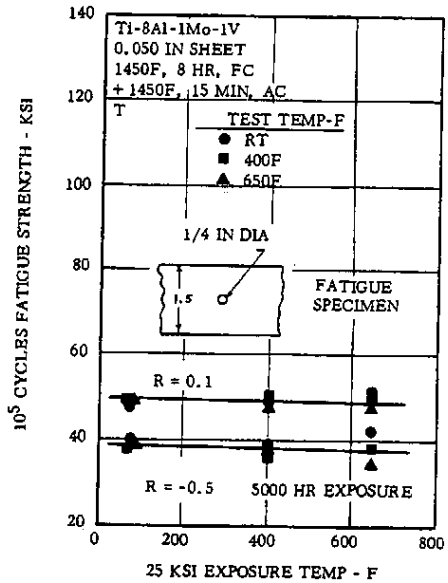


FIG. 3.057 EFFECT OF ELEVATED TEMPERATURE STRESS EXPOSURE ON THE 10^5 CYCLE NOTCHED FATIGUE STRENGTH OF DUPLEX ANNEALED SHEET AT ROOM AND ELEVATED TEMPERATURES (27)

Ti
8 Al
1 Mo
1 V

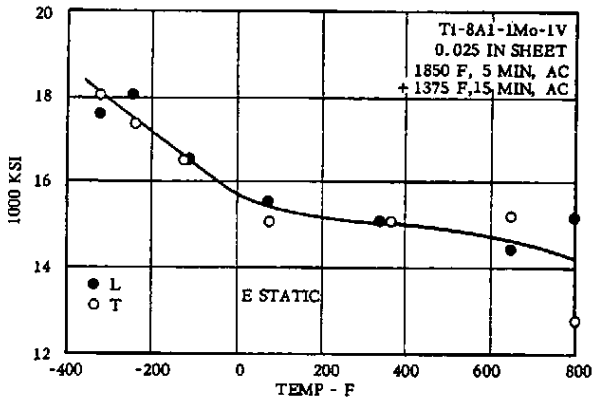


FIG. 3.0621 TENSILE MODULUS OF ELASTICITY FOR DUPLEX ANNEALED SHEET AT LOW AND ELEVATED TEMPERATURES (18)

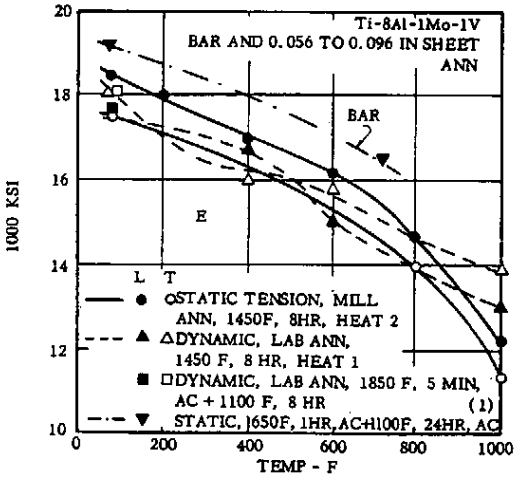


FIG. 3.0622 TENSILE MODULUS OF ELASTICITY AT VARIOUS TEMPERATURES FOR ANNEALED BAR AND SHEET (1)(4)

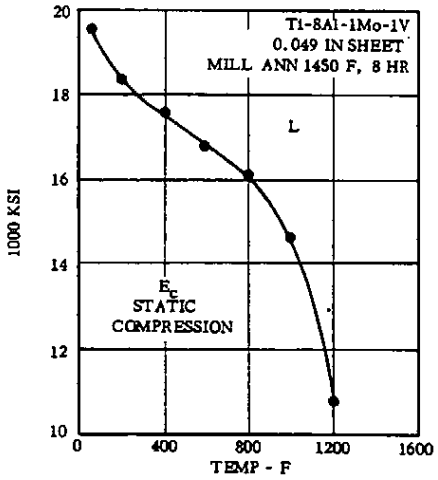


FIG. 3.0623 COMPRESSION MODULUS FOR MILL ANNEALED SHEET AT VARIOUS TEMPERATURES (4)

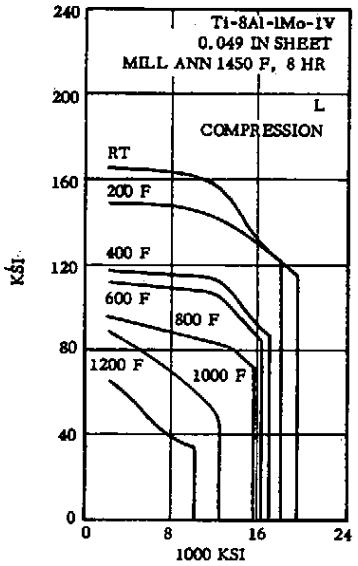


FIG. 3.064 COMPRESSIVE TANGENT MODULUS AT VARIOUS TEMPERATURES FOR MILL ANNEALED SHEET (4)

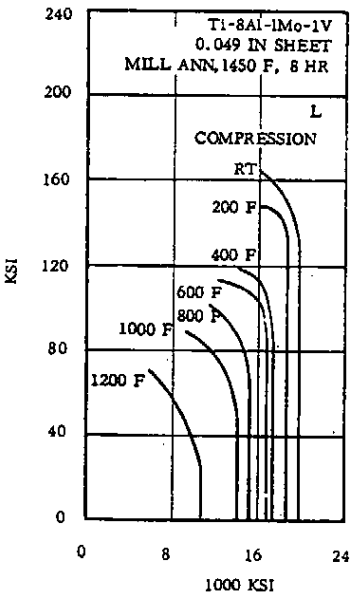


FIG. 3.065 COMPRESSIVE SECANT MODULUS AT VARIOUS TEMPERATURES FOR MILL ANNEALED SHEET (4)

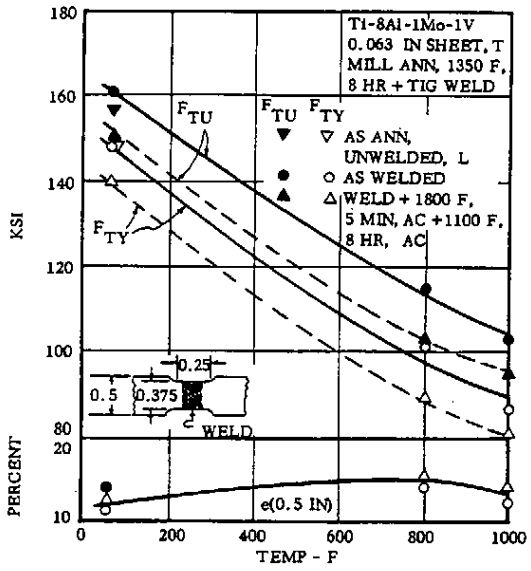


FIG. 4.033; EFFECT OF TEST TEMPERATURE AND REANNEALING ON TENSILE PROPERTIES OF WELDED SHEET (4)

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	Ti
8	Al
1	Mo
1	V

	Ti
8	Al
1	Mo
1	V

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RELEASED: DECEMBER 1970
AUTHOR: J. L. SHANNON, JR.

NONFERROUS ALLOYS

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

1. GENERAL

Ti-8Mo-8V-2Fe-3Al is an ageable, metastable beta alloy developed under U. S. Army Contract DA-30-069-ORD-3743. It was developed primarily as a high strength, formable sheet alloy but also possesses hardenability in 4 inch sections (possibly 6 inch sections (9)(10)) and potential as a fastener alloy. In common with its competitor, Ti-13V-11Cr-3Al (B 120 VCA), the alloy's body centered cubic phase (high temperature allotrope) is retained on cooling from solution temperatures to ambient temperature at relatively slow rates. The stability of the beta phase, however, is such that the alloy can be subsequently strengthened by reheating above 800F through the conventional precipitation of alpha phase (close packed hexagonal structure).

The alloy is superior to B 120 VCA in aging kinetics, requiring less aging time to achieve high strength levels. In addition, the alloy is claimed to surpass B 120 VCA in notch fatigue strength, modulus of elasticity, stability at 600F, and, in the annealed condition, salt water corrosion resistance (8)(9). The major disadvantages of this and other beta alloys compared to alpha-beta alloys are high density and relatively poor creep properties at elevated temperatures. This alloy does not appear to possess smooth fatigue resistance commensurate with its higher strength when compared to Ti-6Al-4V.

The alloy is a relatively new composition which, in some respects, is still in a state of development. Data presented in this chapter were obtained using laboratory heats (0.5, 10, and 30 pound ingots) and small commercial heats (500 and 1800 pound ingots). Current studies are being carried out on full commercial heats (28 inch diameter, 6000 to 7000 pound ingots). Since typical properties for this alloy have not yet been established, actual test values are reported in this chapter for a broader-than-usual range of material and test conditions. In all cases, the ingot size and processing are identified. Much of the data for sheet were developed for simulated hand mill product (hot cross rolled) and simulated mill strip (rolled unidirectionally and received some cold work). Data are also presented for forgings and fastener stock.

1.01 Commercial Designation

8Mo-8V-2Fe-3Al Titanium Alloy

1.02 Alternate Designations

Ti-8Mo-8V-2Fe-3Al

1.03 Specifications

None.

1.04 Composition

1.041 Producer's specified composition, Table 1.041.

TABLE 1.041

Source	(5)	
Element	Weight Percent	
	Minimum	Maximum
Molybdenum	7.5	8.5
Vanadium	7.5	8.5
Iron	1.75	2.25
Aluminum	2.5	3.5
Oxygen	0.10	0.18
Nitrogen	-	0.08
Carbon	-	0.05
Hydrogen	-	*
Other Elements: Each	-	0.10
Total	-	0.30
Titanium	Balance	

* Bar and billet, 0.015 maximum.
Sheet and wire, 0.02 maximum.

1.042 Compositional variations. General. The conventional tensile properties and hardness of this alloy are markedly affected by certain compositional variations. Studies have been conducted with 0.050 inch sheet to define the individual effect of iron content variations above and below the nominal value and extending slightly beyond the specified range. The influence of total alloy content variations has also been determined for the following limiting cases: normal minimum alloy content, normal maximum alloy content, composition corresponding to lowest alpha-beta ratio, and composition corresponding to highest alpha-beta ratio. The following two sections summarize the results of these investigations.

1.043 Iron Content. Increasing iron content produces an increase in elastic modulus for both the solution treated and the solution treated plus aged conditions (see Table 3.0621). The strength and ductility (elongation) rise with increasing iron content for the solution treated condition; strength drops and ductility is unaffected for the solution treated plus aged condition (see Table 3.0212). The aging response established by Vickers hardness measurements is greater for lower iron contents at aging temperatures from 800 to 950F and aging times up to 24 hours (see Figure 1.061).

1.044 Total alloy content. The influence of total alloy content variations on the elastic modulus and on strength and ductility are presented in Tables 3.0622 and 3.0213, respectively. For the solution treated condition, the normal maximum alloy content corresponds to the highest elastic modulus and the normal minimum alloy content the lowest. The modulus of compositions corresponding to both the lowest and highest alpha-beta ratios lie between these extremes. Solution treated strengths vary only slightly with total alloy content variations within the range investigated. Elongations of solution treated stock of normal maximum alloy content and highest alpha-beta ratio composition are equal and exceed those for the normal minimum alloy content and lowest alpha-beta ratio composition, the latter two also equal. In contrast the elongation values for all compositions studied are nearly equal and low for the solution treated plus aged condition while the strengths vary somewhat. Thus the strength of normal maximum alloy content material is least and that of the highest alpha-beta ratio composition greatest. The strength of normal minimum alloy content stock and stock of lowest alpha-beta ratio composition are equal and intermediate in value. The influence of total alloy variations on aging response is seen in Figures 1.062 through 1.065, where Vickers hardness values are presented as a function of aging time up to 24 hours at aging temperatures ranging from 800 to 950F. For these aging conditions, the highest achievable hardness and most rapid aging response characterizes the composition corresponding to the highest alpha-beta ratio and is followed, in descending order, by compositions of normal minimum alloy content, normal maximum alloy content, and of lowest alpha-beta ratio.

1.05 Heat Treatment

(see also 4.04)

1.051 Sheet and plate. Recommended heat treatment schedules for sheet and plate have not yet been established. However, some developmental results are available for simulated hand mill sheet and simulated mill strip 50 percent and 100 percent recrystallized (by selective solution treatments) and variously aged. A description of simulated hand mill sheet and mill strip and a discussion of recrystallization studies are given in Section 4.04.

Smooth tensile properties corresponding to a wide range of aging conditions are presented in Figures 3.0215 through 3.02110. These show that, for simulated hand mill product, 800-900F aged yield strengths range from 185 to 200 ksi with elongations as low as 1 percent. "Stabilized" yield strengths (1100F age) are around 140 ksi with elongations exceeding 8 percent. In general, the strength/ductility combinations of 50 percent recrystallized material are superior to those for fully recrystal-

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-
8V-2Fe-3Al

lized stock. Thus 1475F, 30 min, AC + 900F, 8 hr , AC is rated the best heat treatment to produce high strength, and 1475F, 30 min, AC + 1100F, 16 hr, AC is judged best to provide "stabilized" material (4).

Results for simulated mill strip show that 25 percent and 50 percent cold reductions have little if any effect on the strength and ductility of aged material compared with simulated hand mill product, independent of the degree of recrystallization. Thus 1450F, 10 min, AC + 900F, 8 hr, AC heat treatment representing 25 percent cold rolled, 50 percent recrystallized and aged material (see Figure 3.0217) was selected for additional mechanical property determinations so as to simplify comparisons with hand mill product.

In broadest terms, the hardness of material aged at 900F approaches or exceeds 400 Vickers points; aging curves for material stabilization aged at 1100F show a tendency to flatten out at or above 300 VHN. Aging curves established by Vickers hardness measurements are presented in Figures 1.066 through 1.0611.

The greater part of mechanical property data presented in this chapter was developed for material in the three aforementioned conditions; namely, hand mill product 50 percent recrystallized and aged at 900F or 1100F and 25 percent cold rolled mill strip 50 percent recrystallized and aged at 900F.

1.052 Bar, billet, and forgings. Solution treat and age: 1475F, 1 hr minimum (for sections greater than 2 inches), WQ (AC for sections less than 2 inches) + 1000F, 8 hr, AC.

1.053 Fastener stock. Solution treat: 1400F, 15 min, AC (as-received condition for bar or coil). This condition recommended for applications where severe cold heading is required and long term thermal exposure does not exceed 400F, 2000 hours. This is a condition of moderate strength.

Solution treat plus age: 1400F, 15 min, AC + 900F, 8 hr AC. This treatment recommended where high strength is required. Alloy cannot be cold worked in this condition.

Solution treat plus stabilization age: 1400F, 15 min, AC + 1200F, 8 hr, AC. This treatment recommended where long term thermal exposures exceed 400F but not 600F and where modest cold heading is required.

1.06 Hardness

1.061 Effect of aging time and temperature on hardness of solution treated sheet of two iron contents, Figure 1.061.

1.062 Effect of aging time and temperature on hardness of solution treated sheet of normal minimum alloy content, Figure 1.062.

1.063 Effect of aging time and temperature on hardness of solution treated sheet of normal maximum alloy content, Figure 1.063.

1.064 Effect of aging time and temperature on hardness of solution treated sheet of composition corresponding to lowest alpha-beta ratio, Figure 1.064.

1.065 Effect of aging time and temperature on hardness of solution treated sheet of composition corresponding to hightest alpha-beta ratio, Figure 1.065.

1.066 Effect of aging time and temperature on hardness of annealed sheet 50 percent recrystallized, Figure 1.066.

1.067 Effect of aging time and temperature on hardness of annealed sheet 100 percent recrystallized, Figure 1.067.

1.068 Effect of aging time and temperature on hardness of 25 percent cold rolled sheet 50 percent recrystallized, Figure 1.068.

1.069 Effect of aging time and temperature on hardness of 25 percent cold rolled sheet 100 percent recrystallized, Figure 1.069.

1.0610 Effect of aging time and temperature on hardness of 50 percent cold rolled sheet 50 percent recrystallized, Figure 1.0610.

1.0611 Effect of aging time and temperature on hardness of 50 percent cold rolled sheet 100 percent recrystallized, Figure 1.0611.

1.0612 Statistical relationship between hardness and strength for sheet, Figure 1.0612.

1.0613 Since hardness is, in general, related to alloy strength characteristics, the variation in strength properties with heat treated section size provides a useful measure of alloy hardenability. Figure 3.02113 shows the influence of heat treated section size on the solution treated and aged smooth tensile properties of forged sections up to 4 inches square. As expected, the highest strengths were obtained for the edge location, but were generally no more than about 10 ksi greater than the center location over the range of sizes investigated. Some strength directionality is observed, but this does not exceed the center-to-edge variation. On the other hand, a sizeable directionality is noted for the edge location reduction of area for the largest bar size investigated. It is implied that higher breakdown temperatures than those used in this study (see processing schedule in Table 4.012) would promote macrograin size refinement and lower finishing temperatures than those used (also shown in Table 4.012) would produce improved microstructural refinement, both of which would improve property uniformity (1). Table 3.02114 suggests that cross forging would also tend to improve property uniformity.

Unpublished results on 4 inch bar sandwiched between 1 inch plates to simulate the cooling rate expected in 6 inch sections suggest that through-hardening would be obtained in 6 inch sections (10).

1.07 Forms and Conditions Available

Sheet, strip, bar, billet, forging stock, and fastener stock. Alloy is not yet in full commercial production. However, the full range of commercial sizes in any form can be produced on request.

1.08 Melting and Casting Practice

Alloy is double consumable electrode vacuum melted. Alloy is not yet considered castable.

1.09 Special Considerations

1.091 Stability. The effect of exposure in air at 600F for times up to 500 hours at stresses up to 90 percent of the 600F yield strength on subsequent room temperature smooth tensile properties of sheet and strip is presented in Tables 3.02118 through 3.02121. Similar data for 150 hour exposure at temperatures up to 650F without load for fastener stock are illustrated in Figure 3.02122. The data are not consistent but do show that small elevations in strength and large reductions in elongation can obtain for hand mill sheet and mill strip aged at 900F and exposed at 600F with load (see Tables 3.02120 and 3.02121). Hand mill sheet stabilization aged at 1100F appears insensitive to the exposure conditions investigated (see Tables 3.02119 and 3.02120) while mill strip similarly aged and exposed can suffer serious losses in ductility (Table 3.02121).

Stabilization aged fastener stock exhibits large increases in strength and reductions in elongation for 650F exposure without load (see Figure 3.02122).

600F exposure with load has only a slight effect on the elastic modulus of hand mill sheet and mill strip (see Tables 3.06220 and 3.06221).

No data are available on the influence of exposure on other mechanical properties but should be determined for applications where metallurgical stability is an important design consideration.

1.092 Fatigue. R. R. Moore rotating beam fatigue tests were performed on smooth specimens from a small, aircraft type closed die forging (F_{ty} = 180 ksi) - results are presented in Figure 3.051. Although there is considerable scatter in the data, the 10^7 cycles fatigue strength appears to be 70 ksi or only slightly higher. This is approximately the same level as is observed in normally processed, annealed Ti-6Al-4V forgings (2). Apparently

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

the high strength achieved in Ti-8Mo-8V-2Fe-3Al is not accompanied by corresponding high fatigue strength.

1.093 Fastener application. For fastener application the alloy possesses acceptable cold upsettability, double shear strength and stability to 600F for 150 hours. No data are available for longer exposure times or the influence of exposure for any duration on other critical mechanical properties.

1.094 Low temperature embrittlement. Tables 3.0314 and 3.0315 show serious losses in elongation at -65F for hand mill product and mill strip aged at either 900F or 1100F.

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range.

2.012 Phase change. Alloy transforms on cooling from beta to alpha + beta at 1425 ± 25F, but the reaction is so sluggish that for all but extremely low cooling rates the beta phase is retained to room temperature (1)(6).

2.0121 Time-temperature-transformation diagrams.

2.013 Thermal conductivity.

2.014 Thermal expansion.

2.015 Specific heat.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density. 0.175 lb per cu in, 4.852 gr per cu cm (1)(3).

2.022 Electric properties.

2.023 Magnetic properties. Alloy is nonmagnetic.

2.024 Emissivity.

2.025 Damping capacity.

2.03 Chemical Properties

2.031 Corrosion resistance. General. In common with other titanium alloys, Ti-8Mo-8V-2Fe-3Al is susceptible to solid salt stress corrosion at elevated temperatures and exhibits delayed failure of cracked specimens at room temperature in aqueous salt environments. Since only limited data are available, a complete characterization of this alloy in terms of its corrosion behavior cannot be made at this time. In general, however, it appears that this alloy is slightly more susceptible to solid salt stress corrosion than Ti-13V-11Cr-3Al but less susceptible than Ti-8Al-1Mo-1V, Ti-5Al-2.5Sn, and Ti-6Al-4V (4). Delayed failure characteristics of this alloy in aqueous salt solutions are not sufficiently developed to permit much of a comparison with other alloys. It is claimed, however, that the salt water corrosion resistance of Ti-8Mo-8V-2Fe-3Al is superior to that of Ti-13V-11Cr-3Al for the annealed condition (8). No comparisons have been made for other heat treated conditions or other alloy compositions.

2.032 Solid salt stress corrosion. Solid salt stress corrosion bend tests were performed using 3 inch x 1/2 inch specimens of 0.050 inch sheet solution treated 1500F, 10 min, AC. Specimens were bent around a die to produce a free bend radius of 6t and coated with a saturated NaCl solution which was subsequently dried in air to produce a deposit of solid salt on all surfaces. After 2 hour exposure at 800F in still air, the specimens were washed with water, flattened and examined metallographically for cracking. No cracks were observed (3)(4).

Tension specimens coated with solid salt in the manner described above were exposed at 600, 800, and 1000F at various stress levels for 200 hours. Results shown in Figures 2.033 and 2.034 indicate that the maximum stress which can be tolerated at 600F is 50 ksi, and at 800F, 25 ksi. No evidence of stress corrosion was found on specimens exposed at 10-15 ksi at 1000F. These results appear to be independent of aging treatment.

Tables 2.035 through 2.038 show the influence of hot salt exposure with load on the subsequent room temperature tensile properties. As expected, the effect of exposure increases with increasing exposure stress and temperature.

2.033 Hot salt stress corrosion behavior of simulated mill strip solution treated (50 percent recrystallized) and aged, Figure 2.033.

2.034 Hot salt stress corrosion behavior of simulated mill strip solution treated (50 percent recrystallized) and stabilization aged, Figure 2.034.

2.035 Effect of hot salt exposure with load on subsequent room temperature tensile properties of simulated mill strip solution treated (50 percent recrystallized) and aged, Table 2.035.

TABLE 2.035

Source	(4)			
Alloy	Ti-8Mo-8V-2Fe-3Al			
Form	0.060 Inch Sheet (a)			
Condition	Cold Rolled 25 Percent (0.080 Inch to 0.060 Inch) (b) + 1450F, 10 Min, AC(c) + 900F, 8 Hr, AC			
200 Hr, Hot Salt Exposure		Subsequent RT Tensile Properties(d)		
Temperature F	Stress ksi	F_{tu} ksi	F_{ty} ksi	e(1 in) Percent
None		204	198	5.5
None		201	187	4.0
600	80	Broke on tensile test loading at 87 ksi(e)		
600	65	175	173	1.0(e)
600	50	195	185	2.0
600	40	202	185	4.0
800	45	(Failed at 31 hours)		
800	35	(Failed at 63.5 hours)		
800	30	Broke on tensile test loading (e)		
800	25	215	201	5.0
800	25	211	200	1.5
1000	10	155	151	1.0
1000	7.5	182	174	5.0
1000	5	169	163	1.0

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Representative of mill strip.
(c) 50 percent recrystallized.
(d) Transverse. Tested in as-exposed condition.
(e) Stress corrosion present.

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

2.036 Effect of hot salt exposure with load on subsequent room temperature tensile properties of simulated mill strip solution treated (50 percent recrystallized) and stabilization aged, Table 2.036.

TABLE 2.036

Source	(4)			
Alloy	Ti-8Mo-8V-2Fe-3Al			
Form	0.060 Inch Sheet (a)			
Condition	Cold Rolled 25 Percent (0.080 Inch to 0.060 Inch)(b) + 1450F, 10 Min, AC (c) + 1100F, 24 Hr, AC			
200 Hr, Hot Salt Exposure		Subsequent RT Tensile Properties (d)		
Temperature F	Stress ksi	F_{tu} ksi	F_{ty} ksi	e(1 in) Percent
None		148	137	14.0
None		149	139	18.5
600	85	135	131	5.0(e)
600	75	(Failed at 138 hours)		
600	60	131	125	1.0(e)
600	50	144	135	8.0
600	40	145	136	8.0
800	50	(Failed at 60.75 hours)		
800	40	(Failed at 79.5 hours)		
800	30	Broke on tensile test loading (e)		
800	25	136	-	(f)
800	25	162	150	13.0
800	20	162	150	14.0
1000	15	130	125	(f)
1000	10	118	-	(f)
1000	7.5	152	138	15.0

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Representative of mill strip.
(c) 50 percent recrystallized.
(d) Transverse. Tested in as-exposed condition.
(e) Stress corrosion present.
(f) Broke outside gage length.

2.037 Effect of hot salt exposure with load on room temperature elastic modulus of simulated mill strip solution treated (50 percent recrystallized) and aged, Table 2.037.

TABLE 2.037

Source	(4)	
Alloy	Ti-8Mo-8V-2Fe-3Al	
Form	0.060 Inch Sheet (a)	
Condition	Cold Rolled 25 Percent (0.080 Inch to 0.060 Inch)(b) + 1450F, 10 Min, AC(c) + 900F, 8 Hr, AC	
200 hr, Hot Salt Exposure		
Temperature - F	Stress - ksi	$E - 10^3$ ksi (d)
None		17.2
600	80	Not determined(e)
600	65	14.2(e)
600	50	15.1
600	40	15.5
800	45	(Failed at 31 hours)
800	35	(Failed at 63.5 hours)
800	30	Not determined(e)
800	25	16.2
800	25	15.9
1000	10	15.1
1000	7.5	15.9
1000	5	15.7

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Representative of mill strip.
(c) 50 percent recrystallized.
(d) Transverse. Tested in as-exposed condition. (see Table 2.035 for balance of tensile properties)
(e) Stress corrosion present.

2.038 Effect of hot salt exposure with load on room temperature elastic modulus of simulated mill strip solution treated (50 percent recrystallized) and stabilization aged, Table 2.038.

TABLE 2.038

Source	(4)	
Alloy	Ti-8Mo-8V-2Fe-3Al	
Form	0.060 Inch Sheet (a)	
Condition	Cold Rolled 25 Percent (0.080 Inch to 0.060 Inch) (b) + 1450F, 10 Min, AC (c) + 1100F, 24 Hr, AC	
200 Hr, Hot Salt Exposure		
Temperature - F	Stress - ksi	$E - 10^3$ ksi (d)
None		15.7
None		16.2
600	85	15.4(e)
600	75	(Failed at 138 hours)
600	60	14.3(e)
600	50	14.9
600	40	15.5
800	50	(Failed at 60.75 hours)
800	40	(Failed at 79.5 hours)
800	30	Not determined(e)
800	25	15.5
800	25	15.2
800	20	15.3
1000	15	17.3
1000	10	18.2
1000	7.5	16.4

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Representative of mill strip.
(c) 50 percent recrystallized.
(d) Transverse. Tested in as-exposed condition (see Table 2.036 for balance of tensile properties).
(e) Stress corrosion present.

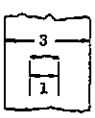
2.039 Delayed failure.

2.0310 Effect of salt water exposure with load on failure time of fatigue-cracked sheet specimens, Table 2.0310.

TABLE 2.0310

Source	(4)	
Alloy	Ti-8Mo-8V-2Fe-3Al	
Form	0.060 Inch Sheet **	
Condition	3.5 Percent NaCl Solution Exposure (pH = 7.5)	
	Net Stress - ksi	Time to Failure
Furnace Annealed:	105	1 min
1285F, 4 Hr, FC to 1000F,	100	1 min
AC	97.5	1 min
	95	3 hours*
Solution Treated:	110	3 hours*
1450F, 10 Min, AC	105	15 hours, 39 min*
	95	3 hours*
Solution Treated and Aged:	95	0
1450F, 10 Min, AC + 900F,	75	0
24 Hr, AC	50	0.5 min
	40	3 hours*

* Did not fail - test discontinued.
** Prepared from 500 pound ingot mill processed as described in Table 4.011.



Transverse Direction

ASTM Center Fatigue Crack Specimen

2.0311 Oxidation. Oxidation results are presented in Table 2.0312. The weight gains reported exceed those measured for beta alloy Ti-13V-11Cr-3Al for the same exposure conditions (4). Tables 2.0313 and 2.0314 show essentially no effect of superficial aging-treatment oxidation on the smooth tensile properties of sheet.

2.0312 Oxidation characteristics of sheet, Table 2.0312.

TABLE 2.0312

Source	(4)				
Alloy	Ti-8Mo-8V-2Fe-3Al				
Form	0.060 Inch Sheet (a)(b)				
Exposure Temperature F	Exposure Time hours	Unexposed Sample Weight gm	Exposed Sample Weight Gain gm	Exposed Sample Weight Gain Percent	Exposed Sample Weight Gain gm per sq cm of surface
1500	2	4.5131	0.0345	0.764	0.0027
1500	4	5.0055	0.1839	3.674	0.0142
1500	8	4.6346	0.5147	11.11	0.0399
1800	2	4.4362	0.5116	11.53	0.0396
1800	4	4.4241	1.0516	23.77	0.0815
1800	8	4.4398	2.7117	61.08	0.2101
1900	2	4.6497	0.5679	12.20	0.0440
1900	4	4.4410	1.3710	29.30	0.1062
1900	8	4.4628	2.7059	60.63	0.2097
2200	2	4.1004	0.9221	22.49	0.0714
2200	4	4.7734	1.9491	40.83	0.1518
2200	8	4.5793	2.6106	57.01	0.2023

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Samples 1 inch x 1 inch x 0.060 inch, exposed in air in open crucibles.

2.0313 Effect of superficial aging-treatment oxidation on room temperature tensile properties of solution treated and aged sheet, Table 2.0313.

TABLE 2.0313

Source	(4)		
Alloy	Ti-8Mo-8V-2Fe-3Al		
Form	0.050 Inch Sheet *		
Condition	F_{tu} ksi	F_{ty} ksi	e(2 In) Percent
1500 F, 10 Min, AC + 900 F, 24 Hr, AC; sandblast and pickle to remove 0.005 inch of gage, machine specimen and test. (No surfaces of specimen oxidized.)	199	189	6.5
1500 F, 10 Min, AC + Sandblast and pickle to remove 0.005 inch of gage, age 24 hr at 900 F, machine specimen and test. (Only sheet surfaces of test specimen oxidized.)	196	180	5.5
1500 F, 10 Min, AC, sandblast and pickle to remove 0.005 inch of gage, machine specimen, age 24 hrs at 900 F and test. (Sheet surfaces and edges of test specimen oxidized.)	204	188	5.8

* Prepared from 30 pound ingot as described in Table 3.0241. Transverse Direction.

2.0314 Effect of superficial aging-treatment oxidation on room temperature tensile elastic modulus of solution treated and aged sheet, Table 2.0314.

TABLE 2.0314

Source	(4)	
Alloy	Ti-8Mo-8V-2Fe-3Al	
Form	0.050 Inch Sheet *	
Condition		E - 10^3 ksi
1500 F, 10 Min, AC + 900 F, 24 hr, AC; sandblast and pickle to remove 0.005 inch of gage, machine specimen and test. (No surfaces of test specimen oxidized.)		16.2
1500 F, 10 Min, AC, sandblast and pickle to remove 0.005 inch of gage, age 24 hr at 900 F, machine specimen and test. (Only sheet surfaces of test specimen oxidized.)		16.4
1500 F, 10 Min, AC, sandblast and pickle to remove 0.005 inch of gage, machine specimen, age 24 hr at 900 F and test. (Sheet surfaces and edges of test specimen oxidized.)		16.1

* Prepared from 30 pound ingot as described in Table 3.0241. Transverse Direction. (see Table 2.0313 for balance of tensile properties)

2.04 Nuclear Properties

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties
None.

3.02 Mechanical Properties at Room Temperature
3.021 Tension.
3.0211 Stress-strain diagrams.
3.0212 Effect of variation in iron content on tensile properties of solution treated and solution treated plus aged sheet, Table 3.0212.

Ti	
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

TABLE 3.0212

Source	(3)					
Form	0.050 Inch Sheet (a)					
Condition	1500 F, 15 Min, WQ			1500 F, 15 Min, WQ + 900 F, 8 Hr, AC		
Alloy	F_{tu} ksi	F_{ty} ksi	e Percent	F_{tu} ksi	F_{ty} ksi	e Percent
Ti-8Mo-8V-1Fe-3Al(b)	123	116	16 (c)	197	181	5 (c)
Ti-8Mo-8V-2Fe-3Al(d)	124	119	17 (e)	198	181	5 (e)
Ti-8Mo-8V-3Fe-3Al(b)	126	124	26 (c)	174	162	6 (c)

(a) Transverse direction tested only.
(b) Prepared from 1/2 pound ingot as described in Figure 1.061.
(c) 1 inch gage length.
(d) Prepared from 30 pound ingot as described in Table 3.0241.
(e) 2 inch gage length.

3.0213 Effect of variation in total alloy composition on tensile properties of solution treated and solution treated plus aged sheet, Table 3.0213.

TABLE 3.0213

Source	(4)					
Form	0.050 Inch Sheet *					
Condition	1500 F, 15 Min, WQ			1500 F, 15 Min, WQ + 900 F, 8 Hr, AC		
Alloy	F_{tu} ksi	F_{ty} ksi	e(2 In) Percent	F_{tu} ksi	F_{ty} ksi	e(2 In) Percent
Ti-8.5Mo-8.5V-2.25Fe-3.5Al-0.18O (Normal Maximum Alloy Content)	134	132	25	186	170	6
Ti-7.5Mo-7.5V-1.75Fe-2.5Al-0.10O (Normal Minimum Alloy Content)	131	124	18	198	186	7
Ti-8.5Mo-8.5V-2.25Fe-2.5Al-0.10O (Composition corresponding to lowest alpha-beta ratio)	126	122	19	194	182	8
Ti-7.5Mo-7.5V-1.75Fe-3.5Al-0.18O (Composition corresponding to highest alpha-beta ratio)	131	126	24	218	204	6

* Prepared from 10 pound ingot in same manner as described in Table 3.0241 for 30 pound ingot.
Values average of duplicate tests. Transverse direction.

3.0214 Effect of aging time and temperature on tensile properties of solution treated sheet, Figure 3.0214.
3.0215 Effect of aging time at 900 and 1100 F on tensile properties of anncaled, simulated hand mill sheet 50 percent recrystallized, Figure 3.0215.
3.0216 Effect of aging time at 800, 900, and 1100 F on tensile properties of annealed, simulated hand mill sheet 100 percent recrystallized, Figure 3.0216.
3.0217 Effect of aging time at 800, 900, and 1100 F on tensile properties of 25 percent cold rolled, simulated mill strip 50 percent recrystallized, Figure 3.0217.
3.0218 Effect of aging time at 900, 1000, and 1100 F on tensile properties of 25 percent cold rolled, simulated mill strip 100 percent recrystallized, Figure 3.0218.

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

3.0219 Effect of aging time at 800, 900, 1100, and 1200F on tensile properties of 50 percent cold rolled, simulated mill strip 50 percent recrystallized, Figure 3.0219.

3.02110 Effect of aging time at 800, 900, 1100, and 1200F on tensile properties of 50 percent cold rolled, simulated mill strip 100 percent recrystallized, Figure 3.02110.

3.02111 Tensile properties of solution treated plate, Table 3.02111.

TABLE 3.02111

Source	(4)			
Alloy	Ti-8Mo-8V-2Fe-3Al			
Form	Plate (a)			
Condition	1500F, 10 Min, AC			
Plate Thickness Inches	Room Temperature Tensile Properties (b)(c)			
	F_{tu} ksi	F_{ty} ksi	RA Percent	e(1 In) Percent
1/2	116-119	114-118	48-53	24-29
2	111-115	108-114	31-42	18-23

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Range of values from three tests for 1/2 inch plate and from five tests for 2 inch plate.
(c) Center properties, longitudinal direction.

3.02112 Tensile properties of solution treated and aged plate, Table 3.02112.

TABLE 3.02112

Source	(4)			
Alloy	Ti-8Mo-8V-2Fe-3Al			
Form	Plate (a)			
Condition	1500F, 10 Min, AC + 900F, 16 Hr, AC			
Plate Thickness Inches	Room Temperature Tensile Properties (b)(c)			
	F_{tu} ksi	F_{ty} ksi	RA Percent	e(1 In) Percent
1/2	209-210	195-197	4.0-9.5	4-8
2	202-212	196-204	2.5-5.5	1-2

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Range of values from three tests for 1/2 inch plate and from five tests for 2 inch plate.
(c) Center properties, longitudinal direction.

3.02113 Effect of heat treated section size on tensile properties of unidirectionally forged bars, Figure 3.02113.

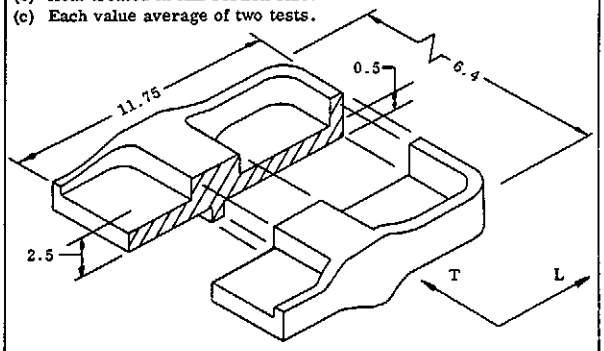
3.02114 Effect of cross forging on tensile properties of 3 inch and 4 inch solution treated and aged forged square bars, Table 3.02114.

3.02115 Tensile properties of solution treated and aged closed die forging, Table 3.02115.

TABLE 3.02115

Source	(2)					
Alloy	Ti-8Mo-8V-2Fe-3Al					
Form	Closed Die Forging (a)					
Condition	1475F, 1 Hr, WQ + 1000F, 8 Hr, AC (b)					
Direction	Section Size Inches	Location	Room Temperature Tensile Properties (c)			
			F_{tu} ksi	F_{ty} ksi	e(1 In) Percent	RA Percent
Longitudinal	0.5	Center	187.8	181.7	4.2	7.7
Transverse	0.5	Center	188.1	181.0	4.8	6.2
Transverse	2.5	Outside	183.4	177.8	3.0	7.2
Transverse	2.5	Center	184.0	177.5	4.5	11.3

(a) Forged in three steps (rough shaping on flat dies followed by blocker and finishing cycles), each at 1700F working temperature - starting section 4 in x 4 in x 12 in, processed from 1800 pound ingot as described in Table 4.012.
(b) Heat treated in full section size.
(c) Each value average of two tests.



Closed-Die Forging

TABLE 3.02114

Source		(1)											
Alloy		Ti-8Mo-8V-2Fe-3Al											
Form		Forged Bar											
Condition		1475F, 1 Hr, WQ + 1000F, 8 Hr, AC *											
		F_{tu} - ksi			F_{ty} - ksi			e(4D) - Percent			RA - Percent		
		(Four inch Square Forged Bar)**											
		(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
Long	Edge	170.7	179.5	179.4	159.3	170.7	174.3	10.0	5.5	5.0	24.1	9.4	13.1
	Mid-radius	173.7	177.6	173.6	166.9	170.5	169.9	8.0	5.0	5.0	14.6	11.2	14.6
	Center	171.5	173.7	172.1	168.3	170.8	170.2	9.0	7.0	5.0	16.6	14.2	16.6
Trans	Edge	177.3	181.7	187.3	168.5	172.0	177.2	5.0	6.0	3.0	5.0	13.4	4.0
	Mid-radius	179.9	179.8	181.2	170.6	175.4	177.8	6.5	-	5.0	11.7	10.2	12.3
	Center	179.1	174.9	177.2	169.6	170.5	176.2	7.0	7.0	6.0	10.9	14.7	20.4
		(Three inch Square Forged Bar)**											
		(d)	(e)		(d)	(e)		(d)	(e)		(d)	(e)	
Long	Edge	173.8	179.9		164.5	168.1		10.0	6.0		16.1	10.9	
	Mid-radius	168.5	174.6		166.3	171.4		9.5	5.0		15.3	13.1	
	Center	174.3	181.2		164.8	169.7		9.5	7.5		16.8	9.8	
Trans	Edge	180.3	184.6		169.5	174.8		5.0	5.0		10.2	10.9	
	Mid-radius	170.8	176.1		167.9	170.2		7.0	5.0		15.4	13.5	
	Center	178.6	182.4		169.5	175.0		4.5	5.0		5.5	13.8	

(a) 4 inch square bar unidirectionally forged 1650F (Beta + 225F).
(b) 4 inch square x 7 inch long upset 1600F to 4 inch thick, cross forged to 4 inch square x length.
(c) 4 inch square x 7 inch long upset 1700F to 4 inch thick, cross forged to 4 inch square x length.
(d) 3 inch square bar unidirectionally forged 1650F (Beta + 225F).
(e) 3 inch square x 5 inch long upset 1400F to 3 inch thick, cross forged to 3 inch square x length.
* Heat treated in full section size.
** Starting bars processed from 1800 pound ingot as described in Table 4.012.

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

3.02116 Effect of aging temperature on room temperature tensile properties of cold rolled plus solution treated and aged fastener stock, Figure 3.02116.

3.02117 Tensile properties of solution treated and solution treated plus stabilization aged fastener stock, Table 3.02117.

TABLE 3.02117

Source	(8)(11)			
Alloy	Ti-8Mo-8V-2Fe-3Al			
Form	0.256 Inch Diameter Wire (Fastener Stock)			
Condition	Cold Rolled 9 Percent + Heat Treat			
Heat Treatment	RT Tensile Properties			
	F_{tu} ksi	F_{ty} ksi	e Percent	RA Percent
1450F, 15 Min, AC	124	117	34.0	58.0
1450F, 15 Min, AC + 1200F, 8 Hr, AC	142	125	21.0	36.2

3.02118 Effect of exposure to elevated temperature with load on room temperature tensile properties of solution treated and aged sheet, Table 3.02118.

TABLE 3.02118

Source	(3)					
Alloy	Ti-8Mo-8V-2Fe-3Al					
Form	0.050 Inch Sheet (a)					
Condition	Solution Treated and Aged					
Exposure Conditions				Subsequent Room Temperature Tensile Properties (b)		
Temperature F	Stress ksi	Time hours	Permanent Deformation percent	F_{tu} ksi	F_{ty} ksi	e(1 in) percent
1500F, 15 Min, WQ + 900F, 8 Hr, AC						
	None			197	180	5(c)
600	128	150	0.320	203	196	6
600	128	150	0.264	204	197	6
600	128	150	0.276	201	194	5
600	128	500	0.429	206	200	4
600	128	500	0.367	205	200	4
600	128	500	0.382	204	198	4
1500F, 15 Min, WQ + 900F, 24 Hr, AC						
	None			204	191	5(c)
600	138	150	0.292	208	202	6
600	138	150	0.288	208	201	6
600	138	150	0.248	206	200	6
600	138	500	0.364	204	201	4
600	138	500	0.407	206	203	5
600	138	500	0.396	204	197	6

(a) Prepared from 30 pound ingot as described in Table 3.0241.
(b) Transverse direction. Tested in as-exposed condition.
(c) 2 inch gage length.

3.02119 Effect of exposure to elevated temperature with load on room temperature tensile properties of solution treated and stabilization aged sheet, Table 3.02119.

TABLE 3.02119

Source	(3)					
Alloy	Ti-8Mo-8V-2Fe-3Al					
Form	0.050 Inch Sheet (a)					
Condition	1500F, 10 Min, AC + 1100F, 8 Hr, AC					
Exposure Conditions				Subsequent Room Temperature Tensile Properties (b)		
Temperature F	Stress ksi	Time hours	Permanent Deformation percent	F_{tu} ksi	F_{ty} ksi	e(1 in) percent
	None(c)			149	139	14
600	93.5	150	0.098	152	143	18
600	93.5	150	0.141	150	140	18
600	93.5	150	0.116	151	142	16
600	93.5	500	0.160	157	142	16
600	93.5	500	0.193	156	147	17
600	93.5	500	0.244	156	143	14

(a) Prepared from 30 pound ingot as described in Table 3.0241.
(b) Transverse direction. Tested in as-exposed condition.
(c) Unexposed values average five tests. Elongation for 2 inch gage length.

3.02120 Effect of 500 hour, 600F exposure at 90 percent of 600F yield strength on room temperature tensile properties of annealed, simulated hand mill sheet solution treated (50 percent recrystallized) and aged, Table 3.02120.

TABLE 3.02120

Source	(4)				
Alloy	Ti-8Mo-8V-2Fe-3Al				
Form	0.060 Inch Sheet (a)				
Condition	Annealed 1285F, 4 Hr, FC to 1000F, AC (b)+ST+Age				
500 Hr, 600F Exposure		Subsequent Room Temperature Tensile Properties(c)			
Stress ksi	Permanent Deformation Percent	Direction	F_{tu} - ksi	F_{ty} - ksi	e(1 In) Percent
1475F, 1/2 Hr, AC (d) + 900F, 8 Hr, AC					
None		Longitudinal	200	187	5.5
None		Longitudinal	201	189	6.0
None		Transverse	195	(e)	(f)
None		Transverse	204	200	2.5
138	0.781	Longitudinal	179	(e)	0
138	0.710	Transverse	219	213	2.0
138	0.676	Transverse	197	(e)	0
1475F, 1/2 Hr, AC (d) + 1100F, 16 Hr, AC					
None		Longitudinal	155	140	16.0
None		Longitudinal	156	142	13.0
None		Transverse	160	149	12.0
None		Transverse	158	147	12.0
98	0.163	Longitudinal	156	149	11.0
98	0.410	Transverse	149	142	13.0
98	0.203	Transverse	153	149	12.0

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) This condition representative of hand mill sheet. Sheet descaled, ground and pickled after annealing.
(c) Tested in as-exposed condition.
(d) 50 percent recrystallized.
(e) Specimen broke before achieving 0.2 percent strain.
(f) Specimen broke outside gage length.

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

3.02121 Effect of 500 hour, 600F exposure at 90 percent of 600F yield strength on room temperature tensile properties of 25 percent cold rolled, simulated mill strip solution treated (50 percent recrystallized) and aged, Table 3.02121.

TABLE 3.02121

Source	(4)				
Alloy	Ti-8Mo-8V-2Fe-3Al				
Form	0.060 Inch Sheet (a)				
Condition	Cold Rolled 25 Percent (0.080 Inch to 0.060 Inch)(b) + ST + Age				
500 Hr, 600F Exposure		Subsequent Room Temperature Tensile Properties (c)			
Stress ksi	Permanent Deformation percent	Direction	F_{tu} - ksi	F_{ty} - ksi	e(1 in) percent
1450F, 10 Min, AC (d) + 900F, 8 Hr, AC					
None		Longitudinal	198	-	7.0
None		Longitudinal	194	183	8.5
None		Transverse	204	198	5.5
None		Transverse	201	187	4.0
125	1.654	Longitudinal	201	(e)	0
125	1.192	Transverse	219	203	(f)
125	1.189	Transverse	178	(e)	0
1450F, 10 Min, AC (d) + 1100F, 24 Hr, AC					
None		Longitudinal	142	135	16.0
None		Longitudinal	141	135	15.0
None		Transverse	148	137	14.0
None		Transverse	149	139	18.5
93	0.316	Longitudinal	148	138	17.0
93	0.360	Transverse	146	145	16.0
93	0.105	Transverse	164	159	4.0

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Representative of mill strip.
(c) Tested in as-exposed condition.
(d) 50 percent recrystallized.
(e) Specimen broke before achieving 0.2 percent strain.
(f) Specimen broke outside gage length.

3.02122 Effect of 150 hour exposure to elevated temperatures on room temperature tensile properties of cold rolled plus solution treated and aged fastener stock, Figure 3.02122.
3.022 Compression.
3.0221 Stress-strain diagrams.
3.023 Impact.
3.024 Bending.
3.025 Torsion and shear.
3.0251 Shear strength of solution treated and solution treated plus stabilization aged fastener stock, Table 3.0251.

TABLE 3.0251

Source	(8)(11)		
Alloy	Ti-8Mo-8V-2Fe-3Al		
Form	0.256 Inch Diameter Wire (Fastener Stock)		
Condition	Cold Rolled 9 Percent + Heat Treat		
Heat Treatment		F_{ty}-ksi (a)	F_{su}-ksi (b)
1450F, 15 Min, AC		117	90.8
1450F, 15 Min, AC + 1200F, 8 Hr, AC		125	99.4

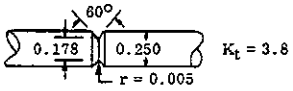
(a) See Table 3.02117 for balance of tensile properties.
(b) 0.200 inch diameter double shear specimen. Shear planes separated two diameters minimum. Shear testing clevis bushed to produce near zero clearance between specimen and holes and between adjacent surfaces of shear clevis.

3.026 Bearing.
3.027 Stress concentration.
3.0271 Notch properties.
3.02711 Mild notch tensile properties of solution treated and aged closed die forging, Table 3.02711.

TABLE 3.02711

Source	(2)			
Alloy	Ti-8Mo-8V-2Fe-3Al			
Form	Closed Die Forging (a)			
Condition	1475F, 1 Hr, WQ + 1000F, 8 Hr, AC (b)			
Direction	Section Size Inches	Location	F_{ty} (c) ksi	NTS(d) ksi
Longitudinal	0.5	Center	181.7	227.7
Transverse	0.5	Center	181.0	208.6
Longitudinal	2.5	Outside	177.8	131.8(e)
Longitudinal	2.5	Outside	177.8	226.9

(a) See Table 3.02115 for forging configuration and production details.
(b) Heat treated in full section size.
(c) Each value average two tests. See Table 3.02115 for balance of smooth tensile properties.
(d) Individual results.
(e) Considered by the investigator to be invalid in view of the other values obtained. However, visual and metallographic examination of broken specimen furnished no reason for this low value.



3.0272 Fracture toughness. (see Appendix C)
3.02721 Room temperature plane strain fracture toughness values of 50.4 and 54.7 ksi $\sqrt{in}$ were obtained using 3 point bend specimens from 3 inch square forged bars heat treated in full section to F_{ty} = 165 ksi (1475F, 1 hr, WQ + 1000F, 8 hr, AC)(1). Specimen orientation was RT (or RW, equivalent for symmetrical forgings) with the crack tips located at "mid-radius". Using the same specimen type, values ranging from 38.3 to 41.6 ksi $\sqrt{in}$ were obtained for 0.5 inch and 2.5 inch sections from a small, aircraft type forging heat treated in full section to F_{ty} = 177.5 to 181.0 ksi (same heat treatment as above). Specimen orientation was transverse to the long axis of the part (see drawing in Table 3.0211). These latter results are presented in Table 3.02722. For both studies the specimen, instrumentation and method of data analysis conformed in all respects to ASTM Tentative Method of Test E 399-70 T (5)(6)(7).
3.02722 Room temperature plane strain fracture toughness of solution treated and aged closed die forging, Table 3.02722.

TABLE 3.02722

Source	(2)			
Alloy	Ti-8Mo-8V-2Fe-3Al			
Form	Closed Die Forging (a)			
Condition	1475F, 1 Hr, WQ + 1000F, 8 Hr, AC (b)			
Direction	Section Size Inches	Location	F_{ty} (c) ksi	K_{Ic} (d)(e) ksi $\sqrt{in}$
Transverse	0.5	Center	181.0	38.3
Transverse	0.5	Center	181.0	41.6
Transverse	2.5	Center	177.5	41.1

(a) See Table 3.02115 for forging configuration and production details.
(b) Heat treated in full section size.
(c) Each value average two tests (see Table 3.02115 for balance of smooth tensile properties).
(d) Individual results.
(e) Specimens (three point bend), instrumentation and method of data analysis conformed in all respects to the ASTM Tentative Method of Test for Plane Strain Fracture Toughness of Metallic Materials (5)(6).

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

3.028 Combined properties.

3.03 Mechanical Properties at Various Temperatures

3.031 Tension.

3.0311 Stress-strain diagrams.

3.0312 Tensile properties of solution treated and aged sheet at room temperature and 600 F, Table 3.0312.

TABLE 3.0312

Source	(3)					
Alloy	Ti-8Mo-8V-2Fe-3Al					
Form	0.050 Inch Sheet (a)					
Condition	1500 F, 15 Min, WQ + 900 F, 8 Hr, AC			1500 F, 15 Min, WQ + 900 F, 24 Hr, AC		
Test Temperature - F	F_{tu} ksi	F_{ty} ksi	e percent	F_{tu} ksi	F_{ty} ksi	e percent
RT	198	181	4.5(b)	204	191	5.2(b)
600	168	142	4.2(c)	170	154	3.8(c)

(a) Prepared from 30 pound ingot as described in Table 3.0241. Transverse direction tested only. Each value average two tests minimum.
(b) 2 inch gage length.
(c) 1 inch gage length.

3.0313 Tensile properties of solution treated and stabilization aged sheet at room temperature and 600 F, Table 3.0313.

TABLE 3.0313

Source	(3)		
Alloy	Ti-8Mo-8V-2Fe-3Al		
Form	0.050 Inch Sheet (a)		
Condition	1500 F, 10 Min, AC + 1100 F, 8 Hr, AC		
Test Temperature - F	Tensile Properties (b)		
	F_{tu} - ksi	F_{ty} - ksi	e(2 In) - Percent
RT	149	139	14
600	122	104	9

(a) Prepared from 30 pound ingot as described in Table 3.0241.
(b) Each value average of five tests. Transverse direction.

3.0314 Tensile properties at -65 F, room temperature, and 600 F for annealed, simulated hand mill sheet solution treated (50 percent recrystallized) and aged. Table 3.0314.

TABLE 3.0314

Source	(4)					
Alloy	Ti-8Mo-8V-2Fe-3Al					
Form	0.060 Inch Sheet (a)(b)					
Condition	Annealed 1285 F, 4 Hr, FC to 1000 F, AC (c) + ST + Age					
Test Temperature F	1475 F, 1/2 Hr, AC(d) + 900 F, 8 Hr, AC			1475 F, 1/2 Hr, AC(d) + 1100 F, 16 Hr, AC		
	F_{tu} ksi	F_{ty} ksi	e(2 In) Percent	F_{tu} ksi	F_{ty} ksi	e(2 In) Percent
-65	204	(e)	(f)	168	148	5.0
-65	196	(e)	(f)	168	-	4.5
RT	195	(e)	(f)	160	149	12.0
RT	204	200	2.5	158	147	12.0
600	180	159	3.0	131	110	10.0
600	176	153	2.5	126	108	10.0
600	174	147	4.5	-	-	-

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Transverse direction.
(c) This condition representative of hand mill sheet. Sheet descaled, ground and pickled after annealing.
(d) 50 percent recrystallized.
(e) Specimen broke before achieving 0.2 percent strain.
(f) Specimen broke outside gage length.

3.0315 Tensile properties at -65 F, room temperature and 600 F for 25 percent cold rolled, simulated mill strip solution treated (50 percent recrystallized) and aged, Table 3.0315.

TABLE 3.0315

Source	(4)					
Alloy	Ti-8Mo-8V-2Fe-3Al					
Form	0.060 Inch Sheet (a)(b)					
Condition	Cold Rolled 25 Percent (0.080 Inch to 0.060 Inch)(c) + ST + Age					
Test Temperature F	1450 F, 10 Min, AC(d) + 900 F, 8 Hr, AC			1450 F, 10 Min, AC(d) + 1100 F, 24 Hr, AC		
	F_{tu} ksi	F_{ty} ksi	e(2 In) Percent	F_{tu} ksi	F_{ty} ksi	e(2 In) Percent
-65	214	(e)	(f)	172	164	8.0
-65	198	184	1.0	169	163	13.0
RT	204	198	5.5	148	137	14.0
RT	201	187	4.0	149	139	18.5
600	162	137	6.0	122	103	9.0
600	164	140	3.5	124	103	14.5

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Transverse direction.
(c) Representative of mill strip.
(d) 50 percent recrystallized.
(e) Specimen broke before achieving 0.2 percent strain.
(f) Specimen broke outside gage length.

3.0316 Room temperature and 600 F tensile properties of solution treated and aged plate, Table 3.0316.

TABLE 3.0316

Source	(4)				
Alloy	Ti-8Mo-8V-2Fe-3Al				
Form	Plate (a)				
Condition	1500 F, 10 Min, AC + 900 F, 16 Hr, AC				
Plate Thickness Inches	Test Temperature F	Tensile Properties (b)(c)			
		F_{tu} ksi	F_{ty} ksi	RA Percent	e(1 In) Percent
1/2	RT	209-210	195-197	4.0-9.5	4-8
1/2	600	161-181	143-159	16-54	4-7
2	RT	202-212	196-204	2.5-5.5	1-2
2	600	176-183	161-167	4.0-9.0	1-4

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Range of values from three tests for 1/2 inch plate and from five tests for 2 inch plate.
(c) Center properties, longitudinal direction.

3.0317 Tensile properties at room temperature and 600 F for solution treated and aged 1 inch square forged bar, Table 3.0317.

TABLE 3.0317

Source	(1)			
Alloy	Ti-8Mo-8V-2Fe-3Al			
Form	1 Inch Square Forged Bar*			
Condition	1475 F, 1 Hr, WQ + 1000 F, 8 Hr, AC			
Test Temperature - F	F_{tu} - ksi	F_{ty} - ksi	e(4D)-percent	RA - percent
RT	182.6	166.6	8.2	13.6
600	156.9	133.0	15.0	41.2

* Processed from 1800 pound ingot as described in Table 4.012.

	Ti
8	Mo
8	V
2	Fe
3	Al

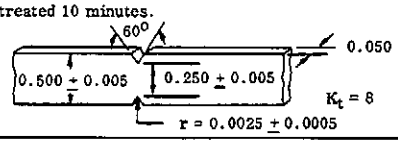
Ti - 8Mo-8V-2Fe-3Al

3.032 Compression.
3.0321 Stress-strain diagrams.
3.033 Impact.
3.034 Bending.
3.035 Torsion and shear.
3.036 Bearing.
3.037 Stress concentration.
3.0371 Notch properties.
3.03711 Mild notch tensile properties at room temperature and 600 F for solution treated and aged sheet, Table 3.03711.

TABLE 3.03711

Source	(3)			
Alloy	Ti-8Mo-8V-2Fe-3Al			
Form	0.050 Inch Sheet (a)			
Condition	1500 F, 10 to 15 Min (b), WQ + 900 F, 8 hr, AC		1500 F, 10 to 15 Min (b), WQ + 900 F, 24 hr, AC	
Test Temperature - F	F_{ty} - ksi	NTS - ksi	F_{ty} - ksi	NTS - ksi
RT	181	172	191	164
600	142	184	154	188

(a) Prepared from 30 pound ingot as described in Table 3.0241. Transverse direction tested only. Mild notch strength values average five tests. Yield strength values average two tests minimum.
(b) Sheet from which smooth specimens extracted solution treated 15 minutes. Sheet from which mild notch specimens extracted solution treated 10 minutes.

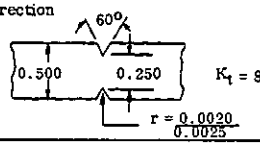


3.03712 Mild notch tensile properties at room temperature and 600 F for solution treated and stabilization aged sheet, Table 3.03712.

TABLE 3.03712

Source	(3)	
Alloy	Ti-8Mo-8V-2Fe-3Al	
Form	0.050 Inch Sheet (a)	
Condition	1500 F, 10 Min, AC + 1100 F, 8 Hr, AC	
Test Temperature F	F_{ty} - ksi (b)(d)	NTS - ksi (c)(d)
RT	139	174
600	104	136

(a) Prepared from 30 pound ingot as described in Table 3.0241.
(b) Balance of smooth tensile properties reported in Table 3.0313.
(c) Each value average of five tests.
(d) Transverse direction

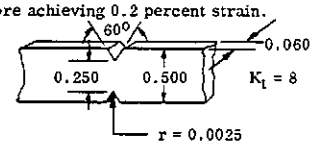


3.03713 Mild notch tensile properties at -65 F, room temperature and 600 F for annealed, simulated hand mill sheet solution treated (50 percent recrystallized) and aged, Table 3.03713.

TABLE 3.03713

Source	(4)				
Alloy	Ti-8Mo-8V-2Fe-3Al				
Form	0.060 Inch Sheet (a)				
Condition	Annealed 1235 F, 4 Hr, FC to 1000 F, AC(b)+ST+Age				
Test Temperature F	Direction	1475 F, 1/2 Hr, AC(c) + 900 F, 8 Hr, AC		1475 F, 1/2 Hr, AC(c) + 1100 F, 16 Hr, AC	
		F_{ty} - ksi	NTS - ksi	F_{ty} - ksi	NTS - ksi
-65	Transverse	(d)	137	148	175
-65	Transverse	(d)	144	148	165
RT	Longitudinal	188	140	141	162
RT	Longitudinal	188	135	141	168
RT	Transverse	200	154	148	169
RT	Transverse	200	151	148	170
600	Transverse	153	172	109	135
600	Transverse	153	172	109	134

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) This condition representative of hand mill sheet. Sheet descaled, ground and pickled after annealing.
(c) 50 percent recrystallized.
(d) Specimen broke before achieving 0.2 percent strain.

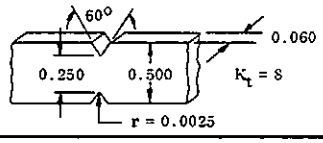


3.03714 Mild notch tensile properties at -65 F, room temperature and 600 F for 25 percent cold rolled, simulated mill strip solution treated (50 percent recrystallized) and aged, Table 3.03714.

TABLE 3.03714

Source	(4)				
Alloy	Ti-8Mo-8V-2Fe-3Al				
Form	0.060 Inch Sheet (a)				
Condition	Cold Rolled 25 Percent (0.080 Inch to 0.060 Inch)(b) + ST + Age				
Test Temperature F	Direction	1450 F, 10 Min, AC(c) + 900 F, 8 Hr, AC		1450 F, 10 Min, AC (c) + 1100 F, 24 Hr, AC	
		F_{ty} - ksi	NTS - ksi	F_{ty} - ksi	NTS - ksi
-65	Transverse	184	145	164	182
-65	Transverse	184	153	164	166
RT	Longitudinal	183	162	135	164
RT	Longitudinal	183	140	135	165
RT	Transverse	192	164	138	170
RT	Transverse	192	153	138	170
600	Transverse	138	175	103	134
600	Transverse	138	169	103	133

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Representative of mill strip.
(c) 50 percent recrystallized.



Ti	
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

3.03715 Mild notch tensile properties at room temperature and 600F for solution treated and aged plate, Table 3.03715.

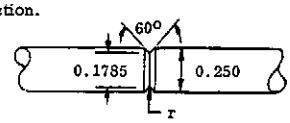
TABLE 3.03715

Source	(4)					
Alloy	Ti-8Mo-8V-2Fe-3Al					
Form	Plate*					
Condition	1500F, 10 Min, AC + Age					
Test Temperature - F			RT		600	
Plate Thickness Inches	K_t	Age Treatment	F_{ty}-ksi	NTS-ksi	F_{ty}-ksi	NTS-ksi
2	2.8	900F, 16 Hr, AC	200	216	162	230
1/2	2.8	900F, 16 Hr, AC	196	263	153	241
1/2	8.0	900F, 8 Hr, AC	-	226	-	230
1/2	8.0	900F, 16 Hr, AC	196	229	153	235

* Prepared from 500 pound ingot mill processed as described in Table 4.011.

All values average three tests minimum. Center properties, longitudinal direction.

r	K_t
0.010	2.8
0.001	8.2



3.042 500 hour, 600F creep behavior of 25 percent cold rolled, simulated mill strip solution treated (50 percent recrystallized) and aged, Table 3.042.

TABLE 3.042

Source	(4)		
Alloy	Ti-8Mo-8V-2Fe-3Al		
Form	0.060 Inch Sheet (a)		
Condition	Cold Rolled 25 Percent (0.080 Inch to 0.060 Inch) (b) + ST + Age		
	500 hr Deformation at 600F		
Stress (c) ksi	Initial Deformation Percent	Creep Deformation Percent	Total Deformation Percent
1450F, 10 Min, AC (d) + 900F, 8 Hr, AC			
125	1.234	1.301	2.535
125	1.041	1.012	2.053
125	1.496	0.942	2.438
1450F, 10 Min, AC (d) + 1100F, 24 Hr, AC			
93	0.646	0.128	0.774
93	0.743	0.342	1.085
93	0.878	0.238	1.116

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Representative of mill strip.
(c) 90 percent of 600F yield strength.
(d) 50 percent recrystallized.

3.0372 Fracture toughness. (see Appendix C)
3.038 Combined properties.

3.04 Creep and Creep Rupture Properties

3.041 500 hour, 600F creep behavior of annealed, simulated hand mill sheet solution treated (50 percent recrystallized) and aged, Table 3.041.

TABLE 3.041

Source	(4)		
Alloy	Ti-8Mo-8V-2Fe-3Al		
Form	0.060 Inch Sheet (a)		
Condition	Annealed 1285F, 4 Hr, FC to 1000F, AC (b) + ST + Age		
	500 Hr Deformation at 600F		
Stress (c) ksi	Initial Deformation Percent	Creep Deformation Percent	Total Deformation Percent
1475F, 30 Min, AC (d) + 900F, 8 Hr, AC			
138	1.033	0.662	1.695
138	0.964	0.531	1.495
138	1.068	0.645	1.713
1475F, 30 Min, AC (d) + 1100F, 16 Hr, AC			
98	0.670	0.135	0.805
98	0.954	0.221	1.175
98	0.797	0.122	0.919

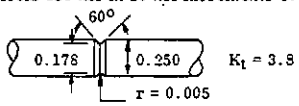
(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) This condition representative of hand mill sheet. Sheet descaled, ground and pickled after annealing.
(c) 90 percent of 600F yield strength.
(d) 50 percent recrystallized.

3.043 Room temperature mild notch stress rupture properties of solution treated and aged closed die forging, Table 3.043.

TABLE 3.043

Source	(2)			
Alloy	Ti-8Mo-8V-2Fe-3Al			
Form	Closed Die Forging (a)			
Condition	1475F, 1 Hr, WQ + 1000F, 8 Hr, AC (b)			
			RT Mild Notch Stress Rupture Properties (c)	
Direction	Section Size Inches	Location	Stress at Failure ksi	Time to Failure min
Longitudinal	2.5	Outside	220	0
Longitudinal	2.5	Outside	200	10

(a) See Table 3.02115 for forging configuration and production details and corresponding smooth tensile properties.
(b) Heat treated in full section size.
(c) Stress increased from 150 ksi in 10 ksi increments every 5 hours.



3.05 Fatigue Properties

3.051 Room temperature rotating beam fatigue strength of solution treated and aged closed die forging, Figure 3.051.

3.052 Room temperature mild notch fatigue strength of 25 percent cold rolled, simulated mill strip solution treated (50 percent recrystallized) and aged, Figure 3.052.

Ti
8 Mo
8 V
2 Fe
3 Al

Ti - 8Mo-8V-2Fe-3Al

3.06 Elastic Properties

3.061 Poisson's ratio.

3.062 Modulus of elasticity.

3.0621 Effect of variation in iron content on room temperature tensile elastic modulus of solution treated and solution treated plus aged sheet, Table 3.0621.

TABLE 3.0621

Source	(3)	
Form	0.050 Inch Sheet (a)	
Condition	1500 F, 15 Min, WQ	1500 F, 15 Min, WQ + 900 F, 8 Hr, AC
Alloy	E - 10^3 ksi	E - 10^3 ksi
Ti-3Mo-8V-1Fe-3Al (b)	9.43	14.35
Ti-3Mo-8V-2Fe-3Al (c)	10.15	15.0
Ti-3Mo-8V-3Fe-3Al (b)	11.05	15.0

(a) Transverse Direction.
(b) Prepared from 1/2 pound ingot as described in Figure 1.061.
(c) Prepared from 30 pound ingot as described in Table 3.0241.
(see Table 3.0212 for balance of tensile properties)

3.0622 Effect of variation in total alloy composition on room temperature tensile elastic modulus of solution treated and solution treated plus aged sheet, Table 3.0622.

TABLE 3.0622

Source	(4)	
Form	0.050 Inch Sheet*	
Condition	1500 F, 15Min, WQ	1500 F, 15 Min, WQ+900 F, 8 Hr, AC
Alloy	E - 10^3 ksi	E - 10^3 ksi
Ti-8.5Mo-8.5V-2.25Fe-3.5Al-0.18O (Normal maximum alloy content)	11.4	14.2
Ti-7.5Mo-7.5V-1.75Fe-2.5Al-0.10O (Normal minimum alloy content)	9.4	15.4
Ti-8.5Mo-8.5V-2.25Fe-2.5Al-0.10O (Composition corresponding to lowest alpha-beta ratio)	10.7	15.3
Ti-7.5Mo-7.5V-1.75Fe-3.5Al-0.18O (Composition corresponding to highest alpha-beta ratio)	9.8	15.7

* Prepared from 10 pound ingot in same manner as described in Table 3.0241 for 30 pound ingot.
Values average of duplicate tests. Transverse Direction.
(see Table 3.0213 for balance of tensile properties.

3.0623 Effect of aging time and temperature on room temperature tensile elastic modulus of solution treated sheet, Figure 3.0623.

3.0624 Effect of aging time at 900 and 1100 F on room temperature tensile elastic modulus of annealed, simulated hand mill sheet 50 percent recrystallized, Figure 3.0624.

3.0625 Effect of aging time at 800, 900, and 1100 F on room temperature tensile elastic modulus of 25 percent cold rolled, simulated mill strip 50 percent recrystallized, Figure 3.0625.

3.0626 Room temperature tensile elastic modulus of solution treated and solution treated plus aged plate, Table 3.0626.

TABLE 3.0626

Source	(4)	
Alloy	Ti-8Mo-8V-2Fe-3Al	
Form	Plate (a)	
Condition	1500 F, 10 Min, AC	1500 F, 10 Min, AC + 900 F, 16 Hr, AC
Plate Thickness Inches	E - 10^3 ksi (b)(c)(d)	
1/2	12.2-14.1	16.0-16.3
2	12.2-13.2	15.6-16.1

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Range of values from three tests for 1/2 inch plate and from five tests for 2 inch plate.
(c) Center location, longitudinal direction.
(d) For balance of tensile properties, see Tables 3.02111 and 3.02112.

3.0627 Effect of heat treated section size on room temperature tensile elastic modulus of forged bars, Figure 3.0627.

3.0628 Tensile elastic modulus at -65 F, room temperature and 600 F for annealed, simulated hand mill sheet solution treated (50 percent recrystallized) and aged, Table 3.0628.

TABLE 3.0628

Source	(4)	
Alloy	Ti-8Mo-8V-2Fe-3Al	
Form	0.060 Inch Sheet (a)(b)	
Condition	Annealed 1285 F, 4 Hr, FC to 1000 F, AC (c) + ST + Age	
Test Temperature- F	1475 F, 1/2 Hr, AC (d) + 900 F, 8 Hr, AC	1475 F, 1/2 Hr, AC (d) + 1100 F, 16 Hr, AC
	E - 10^3 ksi (e)	
-65	16.3	14.8
-65	15.2	15.1
RT	16.9	16.6
RT	-	15.9
600	15.8	14.1
600	15.1	15.6
600	16.5	-

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Transverse direction.
(c) This condition representative of hand mill sheet. Sheet descaled, ground and pickled after annealing.
(d) 50 percent recrystallized.
(e) See Table 3.0314 for balance of tensile properties.

3.0629 Tensile elastic modulus at -65 F, room temperature and 600 F for 25 percent cold rolled, simulated mill strip solution treated (50 percent recrystallized) and aged, Table 3.0629.

TABLE 3.0629

Source	(4)	
Alloy	Ti-8Mo-8V-2Fe-3Al	
Form	0.060 Inch Sheet (a)(b)	
Condition	Cold Rolled 25 Percent (0.080 Inch to 0.060 Inch) (c) + ST + Age	
Test Temperature- F	1450 F, 10 Min, AC (d) + 900 F, 8 Hr, AC	1450 F, 10 Min, AC (d) + 1100 F, 24 Hr, AC
	E - 10^3 ksi (e)	
-65	15.0	15.9
-65	15.6	15.5
RT	17.2	15.7
RT	-	16.2
600	14.7	13.0
600	13.6	14.6

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Transverse direction.
(c) Representative of mill strip.
(d) 50 percent recrystallized.
(e) See Table 3.0315 for balance of tensile properties.

3.06210 Effect of 500 hour, 600 F exposure at 90 percent of 600 F yield strength on room temperature tensile elastic modulus of annealed, simulated hand mill sheet solution treated (50 percent recrystallized) and aged, Table 3.06210.

TABLE 3.06210

Source	(4)		
Alloy	Ti-8Mo-8V-2Fe-3Al		
Form	0.060 Inch Sheet (a)		
Condition	Annealed 1285 F, 4 Hr, FC to 1000 F, AC (b) + ST + Age		
500 Hr, 600 F Exposure		Subsequent RT Elastic Modulus	
Stress ksi	Deformation Percent	Direction	E (c) 10^3 ksi
1475 F, 1/2 Hr, AC (d) + 900 F, 8 Hr, AC			
None		Longitudinal	16.3
None		Longitudinal	16.0
None		Transverse	16.9
138	0.781	Longitudinal	16.0
138	0.710	Transverse	16.0
138	0.676	Transverse	15.9
1475 F, 1/2 Hr, AC (d) + 1100 F, 16 Hr, AC			
None		Longitudinal	16.3
None		Longitudinal	18.0
None		Transverse	15.7
None		Transverse	16.8
98	0.163	Longitudinal	15.3
98	0.410	Transverse	15.0
98	0.203	Transverse	15.6

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) This condition representative of hand mill sheet. Sheet descaled, ground and pickled after annealing.
(c) Tested in as-exposed condition.
(d) 50 percent recrystallized.
(see Table 3.02120 for corresponding tensile properties)

3.06211 Effect of 500 hour, 600 F exposure at 90 percent of 600 F yield strength on room temperature tensile elastic modulus of 25 percent cold rolled, simulated mill strip solution treated (50 percent recrystallized) and aged, Table 3.06211.

TABLE 3.06211

Source	(4)		
Alloy	Ti-8Mo-8V-2Fe-3Al		
Form	0.060 Inch Sheet (a)		
Condition	Cold Rolled 25 Percent (0.080 Inch to 0.060 Inch)(b) +ST + Age		
500 Hr, 600 F Exposure		Subsequent RT Elastic Modulus	
Stress ksi	Deformation Percent	Direction	E (c) 10^3 ksi
1450 F, 10 Min, AC (d) + 900 F, 8 Hr, AC			
None		Longitudinal	16.7
None		Transverse	17.2
125	1.654	Longitudinal	15.3
125	1.192	Transverse	15.2
125	1.189	Transverse	15.1
1450 F, 10 Min, AC (d) + 1100 F, 24 Hr, AC			
None		Longitudinal	16.0
None		Longitudinal	15.9
None		Transverse	15.7
None		Transverse	16.2
93	0.316	Longitudinal	14.5
93	0.360	Transverse	15.1
93	0.105	Transverse	14.6

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Representative of mill strip.
(c) Tested in as-exposed condition.
(d) 50 percent recrystallized.
(see Table 3.02121 for corresponding tensile properties)

3.063 Modulus of rigidity.

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

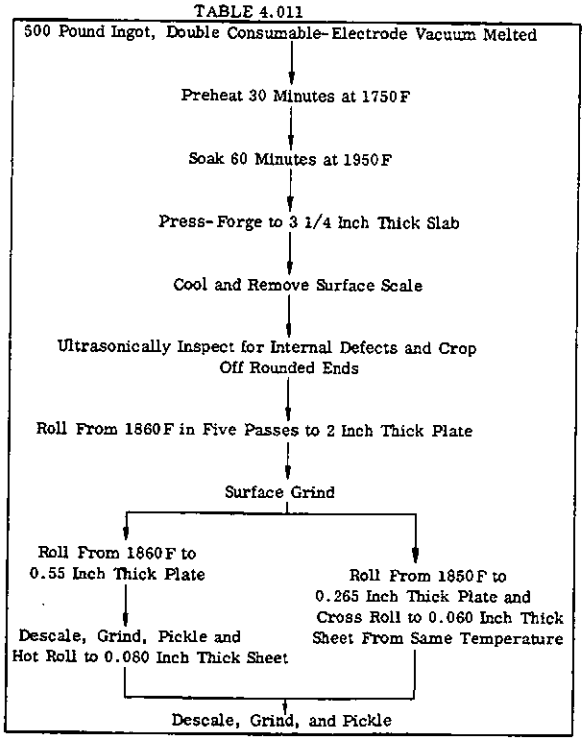
4. FABRICATION

4.01 Formability

General. As a class of alloys, the metastable beta compositions are considerably more formable than alpha + beta types, primarily because of the very high ductility of the body centered cubic beta phase (8). The data reported in this chapter were obtained on product forms processed from ingots ranging from 1/2 pound laboratory size to small commercial ingots of 500 pound and 1800 pound. No difficulties were encountered in scaling up from the smallest to largest ingot sizes. Forging and hot rolling characteristics of this alloy are judged similar to those of Ti-13V-11Cr-3Al; these include ease of deformation and surface condition after processing (4). Commercial processing schedules are outlined for the production of plate and sheet in Table 4.011, for forged bars in Table 4.012, and for a typical, small closed die aircraft type forging in Table 3.02115.

4.011 Processing of plate and sheet from 500 pound ingot, Table 4.011.

TABLE 4.011

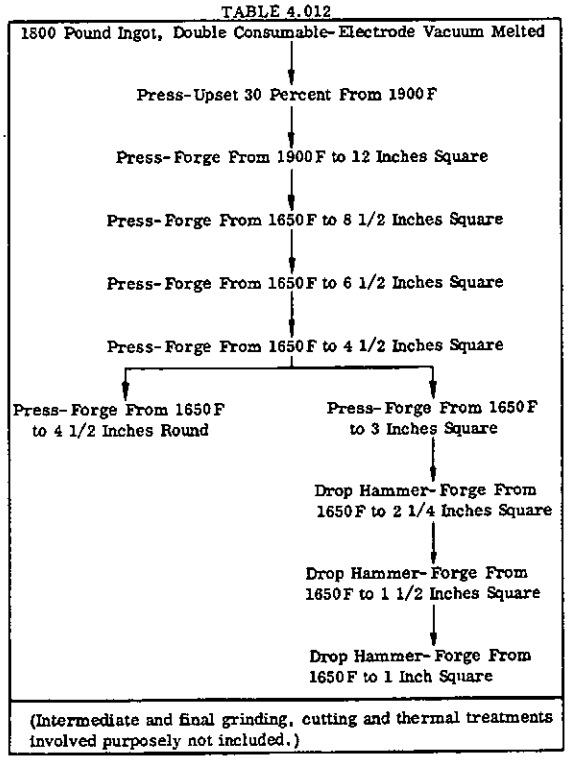


	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

4.012 Processing of forged bar from 1800 pound ingot, Table 4.012.

TABLE 4.012



(Intermediate and final grinding, cutting and thermal treatments involved purposely not included.)

4.013 Forging. The processing of bar from an 1800 pound ingot described in Table 4.012 involved initial pressing and forging at beta + 475F and finish forging at beta + 225F. The investigators were apparently dissatisfied with the ductility of these forged bars and suggested that beta grain size refinement be sought by using higher breakdown temperatures and lower finishing temperatures (1). Cross forging may not raise the level of ductility but can lessen directionality of elongation and reduction of area values as shown in Table 3.02114. Surprisingly this beneficial effect does not appear to depend on whether the cross forging temperature was either 1700F or 1400F.

The Wyman-Gordon Company produced a small, airframe-type closed die forging as a vehicle for evaluating the tensile (see Table 3.02115), fatigue (see Figure 3.051), notch stress rupture (see Table 3.043) and notch toughness (see Tables 3.02711 and 3.02722) of a typical forged part. All forging was done at 1700F as described in Table 3.02115. The part was given the same heat treatment as the bars produced in the foregoing study. Similar to the bars, the closed die forging possessed relatively low ductility (see Table 3.02115) even though the fracture toughness (see Table 3.02722) was quite high. The investigators state that additional evaluation of the alloy will undoubtedly suggest modifying processing cycles or heat treatments to produce improved strength ductility combinations.

4.014 Hot rolling. The production of hot rolled plate from a 500 pound ingot is described in Table 4.011. The first half of processing part of a 2 inch slab to 0.265 inch gage was performed at 1850F, or 40F lower than that normally used for reduction of Ti-13V-11Cr-3Al employing similar rolling pressures. Ti-8Mo-8V-2Fe-3Al may thus be slightly easier to roll than Ti-13V-11Cr-3Al.

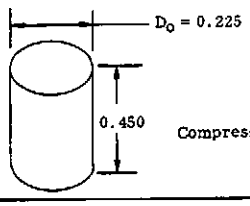
4.015 Cold upsettability. To be suitable for rivet stock, an alloy must be cold upsettable. Some consider a D_f/D_o of 1.7 when driven an acceptable minimum (8). This alloy meets this criterion in the solution treated condition.

4.016 Room temperature compressibility of solution treated and solution treated plus stabilization aged fastener stock, Table 4.016.

TABLE 4.016

Source	(8)(11)			
Alloy	Ti-8Mo-8Fe-2Fe-3Al			
Form	0.256 Inch Diameter Wire (Fastener Stock)			
Condition	Cold Rolled 9 Percent + Heat Treat			
Heat Treatment	F_{ty}-ksi(a)	Cold Upsettability D_f/D_o		
		Passed	Failed	
1450F, 15 Min, AC	117	1.96	2.13	
1450F, 15 Min, AC + 1200F, 8 Hr, AC	125	1.41	1.70	

(a) See Table 3.02117 for balance of tensile properties.
(b) After compression, puck inspected for cracks at 10x magnification: "Passed" - no cracks, "Failed" - cracked.



4.02 Machining and Grinding

4.03 Welding

This alloy is more weldable than Ti-13V-11Cr-3Al(10).

4.031 Room temperature tensile properties of welded sheet, Table 4.031.

TABLE 4.031

Source	(3)			
Alloy	Ti-8Mo-8Fe-2Fe-3Al			
Form	Welded 0.060 Inch Sheet			
Condition	1500F, 10 Min, AC + 900F, 16 Hr, AC + Weld (a)			
RT Tensile Properties	F_{tu} - ksi(c)	F_{ty} - ksi (c)	e(1/2 in) Percent(c)	e(2 in) Percent(c)
Range (b)	121-129	121-127	2-18	0.4-4.5
Average (b)	126	124	14.5	3.5

(a) Machine weld, without filler, using 3/32 inch diameter 2 percent thoriated tungsten electrode. Welded at 20 in/min in argon atmosphere. Welding current was 100-150 amps at 9 volts.
(b) Eight tests.
(c) Weld bead approximately 0.2 inch wide, perpendicular to specimen axis and ground flush with specimen surface. Gage length symmetrical about weld bead centerline.

4.032 Room temperature tensile elastic modulus of welded sheet, Table 4.032.

TABLE 4.032

Source	(3)
Alloy	Ti-8Mo-8V-2Fe-3Al
Form	Welded 0.060 Inch Sheet
Condition	1500F, 10 Min, AC + 900F, 16 Hr, AC + Weld (a)
E - 10^3 ksi	
Range (b)(c)	Average (b)(c)
14.2-15.7	15.0

(a) Machine weld, without filler, using 3/32 inch diameter 2 percent thoriated tungsten electrode. Welded at 20 in/min in argon atmosphere. Welding current was 100-150 amps at 9 volts.
(b) Eight tests.
(c) Weld bead approximately 0.2 inch wide, perpendicular to specimen axis and ground flush with specimen surface. Gage length symmetrical about weld bead centerline.
(see Table 4.031 for balance of tensile properties)

4.033 Room temperature tensile properties of welded simulated hand mill sheet, Table 4.033.

TABLE 4.033

Source	(4)
Alloy	Ti-8Mo-8V-2Fe-3Al
Form	0.060 Inch Sheet (a)(b)
Condition	Annealed 1285F, 4 Hr, FC to 1000F, AC (c) + Heat Treat/Weld

Heat Treat/Weld Sequence	No. of Tests	Room Temperature Tensile Properties (d) (Range of Values) Ftu ksi	Fty (e) ksi	e(2 in)(f) percent	e(1/2 in)(f) percent
1475F, 30 Min, AC + Weld	3	124-126	123-124	2.0-5.0	8.0-18.0
1475F, 30 Min, AC + 900F, 8Hr, AC + Weld	3	118-124	116-122	3.0-3.5	10.0-14.0
1475F, 30 Min, AC + Weld + 900F, 8 Hr, AC	2(g)	201	191 and 198	0.5 and 1.5	2.0 and 4.0
1475F, 30 Min, AC + 1100F, 16 Hr, AC + Weld	3	126-129	122-127	2.0-3.0	8.0
1475F, 30 Min, AC + Weld + 1100F, 16 Hr, AC	3	152-156	145-149	1.25	5.0
1475F, 30 Min, AC + 900F, 8 Hr, AC + Weld + 900F, 3 Hr, AC	6	185-193	180-188	2.0-3.0	2.0-4.0
1475F, 30 Min, AC + 900F, 8 Hr, AC + Weld (h) + 900F, 2 Hr, AC	10	126-153	125-151	1.0-2.0	4.0-6.0

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) GTA welded, without filler, using automatic welding machine (except where noted) with 3/32 inch diameter, 2 percent thoriated tungsten electrode and argon shielding, at 20 inches per minute with 100-150 amp current at 9 volts. Weld bead ground flush with base metal surfaces.
(c) Simulated hand mill product. Sheet descaled, ground and pickled after annealing.
(d) All specimens broke in weld.
(e) 2 inch gage length.
(f) Weld bead width, 0.2 inch; width of weld bead plus heat affected zone, 0.5 inch.
(g) One specimen, result for which not included, broke without yielding.
(h) Hand welded.

4.034 Room temperature tensile elastic modulus of welded simulated hand mill sheet, Table 4.034.

TABLE 4.034

Source	(4)
Alloy	Ti-8Mo-8V-2Fe-3Al
Form	0.060 Inch Sheet (a)(b)
Condition	Annealed 1285F, 4 Hr, FC to 1000F, AC (c) + Heat Treat/Weld

Heat Treat/Weld Sequence	Number of Tests	E (d) (Range) 10^3 ksi
1475F, 30 Min, AC + Weld	3	13.1-13.5
1475F, 30 Min, AC + 900F, 8 Hr, AC + Weld	3	14.5-15.3
1475F, 30 Min, AC + Weld + 900F, 8 Hr, AC	2(e)	15.4 and 16.0
1475F, 30 Min, AC + 1100F, 16 Hr, AC + Weld	3	15.3-15.9
1475F, 30 Min, AC + Weld + 1100F, 16 Hr, AC	3	14.9-15.3
1475F, 30 Min, AC + 900F, 8 Hr, AC + Weld + 900F, 3 Hr, AC	6	14.7-15.5
1475F, 30 Min, AC + 900F, 8 Hr, AC + Weld (f) + 900F, Hr, AC	10	13.2-15.7

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) GTA welded, without filler, using automatic welding machine (except where noted) with 3/32 inch diameter, 2 percent thoriated tungsten electrode and argon shielding, at 20 inches per minute with 100-150 amp current at 9 volts. Weld bead ground flush with base metal surfaces.
(c) Simulated hand mill product. Sheet descaled, ground and pickled after annealing.
(d) 2 inch gage length. Weld bead width, 0.2 inch; width of weld bead plus heat affected zone, 0.5 inch.
(e) One specimen, the result for which is not included, broke before yielding and had an elastic modulus of 13.9 x 10^3 ksi.
(f) Hand welded.
(see Table 4.033 for balance of tensile properties)

Ti
8 Mo
8 V
2 Fe
3 Al

Ti - 8Mo-8V-2Fe-3Al

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

4.035 600 F tensile properties of welded simulated hand mill sheet, Table 4.035.

TABLE 4.035

Source	(4)					
Alloy	Ti-8Mo-8V-2Fe-3Al					
Form	0.060 Inch Sheet (a)(b)					
Condition	Annealed 1285 F, 4 Hr, FC to 1000 F, AC (c) + Heat Treat/Weld					
Heat Treat/Weld Sequence		No. of Tests	600 F Tensile Properties (d) F_{tu} ksi	F_{ty}(e) ksi	e(2 in)(f) percent	e(1/2 in)(f) percent
1475 F, 30 Min, AC + 900 F, 8 Hr, AC + Weld		3	86-88	84-87	1.5-5.0	12.0-18.0
1475 F, 30 Min, AC + Weld + 900 F, 8 Hr, AC		3	182-185	173(g)	1.0-2.0	2.0-6.0
1475 F, 30 Min, AC + 1100 F, 16 Hr, AC + Weld		3	86-89	84-87	4.0-5.5	10.0-16.0
1475 F, 30 Min, AC + Weld + 1100 F, 16 Hr, AC		3	118-123	98-116	3.5-4.5	2.5-8.5
1475 F, 30 Min, AC + 900 F, 8 Hr, AC + Weld + 900 F, 3 Hr, AC		6	159-167	147-157	2.0-3.0	2.5-4.0

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) GTA welded, without filler, using automatic welding machine with 3/32 inch diameter, 2 percent thoriated tungsten electrode and argon shielding, at 20 inches per minute with 100-150 amp current at 9 volts. Weld bead ground flush with base metal surfaces.
(c) Simulated hand mill product. Sheet descaled, ground and pickled after annealing.
(d) All specimens broke in weld.
(e) 2 inch gage length.
(f) Weld bead width, 0.2 inch; width of weld bead plus heat affected zone, 0.5 inch.
(g) Two specimens, the results for which are not included, broke without yielding.
(see Table 4.033 for corresponding room temperature properties)

4.036 600 F tensile elastic modulus of welded simulated hand mill sheet, Table 4.036.

TABLE 4.036

Source	(4)		
Alloy	Ti-8Mo-8V-2Fe-3Al		
Form	0.060 Inch Sheet (a)(b)		
Condition	Annealed 1285 F, 4 Hr, FC to 1000 F, AC (c) + Heat Treat/Weld		
Heat Treat/Weld Sequence		Number of Tests	Elastic Modulus at 600 F E(d) (Range) 10^3 ksi
1475 F, 30 Min, AC + 900 F, 8 Hr, AC + Weld		3	14.7-15.4
1475 F, 30 Min, AC + Weld + 900 F, 8 Hr, AC		3	15.2-17.0
1475 F, 30 Min, AC + 1100 F, 16 Hr, AC + Weld		3	10.0-15.1
1475 F, 30 Min, AC + Weld + 1100 F, 16 Hr, AC		3	13.1-14.8
1475 F, 30 Min, AC + 900 F, 8 Hr, AC + Weld + 900 F, 3 Hr, AC		6	13.7-15.9

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) GTA welded, without filler, using automatic welding machine with 3/32 inch diameter, 2 percent thoriated tungsten electrode and argon shielding, at 20 inches per minute with 100-150 amp current at 9 volts. Weld bead ground flush with base metal surfaces.
(c) Simulated hand mill product. Sheet descaled, ground and pickled after annealing.
(d) 2 inch gage length. Weld bead width, 0.2 inch; weld bead plus heat affected zone width, 0.5 inch.
(see Table 4.035 for balance of tensile properties)

4.037 Effect of exposure to elevated temperature without load on room temperature tensile properties of welded simulated hand mill sheet, Table 4.037.

TABLE 4.037

Source	(4)				
Alloy	Ti-8Mo-8V-2Fe-3Al				
Form	0.060 Inch Sheet (a)(b)				
Condition	Annealed 1285 F, 4 Hr, FC to 1000 F, AC(c) + Heat Treat/Weld				
Exposure Conditions		Subsequent RT Tensile Properties (d)			
Temperature F	Time Hours	F_{tu} ksi	F_{ty}(e) ksi	e(2 In)(f) Percent	e(1/2 In)(f) Percent
1475 F, 30 Min, AC + Weld + 900 F, 8 Hr, AC					
None		(g)	(g)	0	2.0
None		201	191	1.5	4.0
None		201	198	0.5	2.0
650	500	189	180	2.0	2.0
650	500	193	187	2.0	2.0
1475 F, 30 Min, AC + Weld + 1100 F, 16 Hr, AC					
None		156	149	2.0	5.0
None		153	146	2.0	5.0
None		152	145	3.5	5.0
650	500	146	139	2.0	4.0
650	500	151	145	2.0	4.0

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) GTA welded, without filler, using automatic welding machine with 3/32 inch diameter, 2 percent thoriated tungsten electrode and argon shielding, at 20 inches per minute with 100-150 amp current at 9 volts. Weld bead ground flush with base metal surfaces.
(c) Simulated hand mill product. Sheet descaled, ground and pickled after annealing.
(d) All specimens broke in weld. Specimens tested in as-exposed condition.
(e) 2 inch gage length.
(f) Weld bead width, 0.2 inch; weld bead plus heat affected zone width, 0.5 inch.
(g) Specimen broke before yielding.

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

4.038 Effect of exposure to elevated temperature without load on room temperature tensile elastic modulus of welded simulated hand mill sheet, Table 4.038.

TABLE 4.038

Source	(4)	
Alloy	Ti-8Mo-8V-2Fe-3Al	
Form	0.060 Inch Sheet (a)(b)	
Condition	Annealed 1285F, 4 Hr, FC to 1000F, AC (c) + Heat Treat/Weld	
Exposure Conditions		Subsequent RT Elastic Modulus(d)
Temperature F	Time Hours	E 10^3 ksi
1475F, 30 Min, AC + Weld + 900F, 8 Hr, AC		
	None	13.9(e)
	None	15.4
	None	16.0
650	500	14.4
650	500	15.2
1475F, 30 Min, AC + Weld + 1100F, 16 Hr, AC		
	None	15.2
	None	14.9
	None	15.3
650	500	15.5
650	500	15.8

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) GTA welded without filler, using automatic welding machine with 3/32 inch diameter, 2 percent thoriated tungsten electrode and argon shielding, at 20 inches per minute with 100-150 amp current at 9 volts. Weld bead ground flush with base metal surfaces.
(c) Simulated hand mill product. Sheet descaled, ground and pickled after annealing.
(d) Specimens tested in as-exposed condition. 2 inch gage length. Weld bead width, 0.2 inch; width of weld bead plus heat affected zone, 0.5 inch.
(e) Specimen broke before yielding.
(see Table 4.037 for balance of tensile properties.

4.039 Effect of temperature on bend properties of welded simulated hand mill sheet, Table 4.039.

TABLE 4.039

Source	(4)			
Alloy	Ti-8Mo-8V-2Fe-3Al			
Form	0.060 Inch Sheet (a)(b)			
Condition	Annealed 1285F, 4 Hr, FC to 1000F, AC (c) + Heat Treat/Weld			
Heat Treat/Weld Sequence	Test Temperature F	Orientation of Weld Bead to Bend Axis	Bend Radius	
			Passed	Failed
1475F, 30 Min, AC + Weld	RT	No weld	2.2t	1.8t
1475F, 30 Min, AC + Weld	RT	Transverse	2.1t	1.8t
1475F, 30 Min, AC + Weld	RT	Parallel	3.0t	2.4t
1475F, 30 Min, AC + 900F, 8 Hr, AC + Weld	RT	No weld	7.4t	6.6t
1475F, 30 Min, AC + 900F, 8 Hr, AC + Weld	RT	Transverse	2.4t	2.1t
1475F, 30 Min, AC + 900F, 8 Hr, AC + Weld	RT	Parallel	2.5t	2.4t
1475F, 30 Min, AC + Weld + 900F, 8 Hr, AC	RT	No weld	9.1t	8.0t
1475F, 30 Min, AC + Weld + 900F, 8 Hr, AC	RT	Transverse	-	≥9.5t
1475F, 30 Min, AC + Weld + 900F, 8 Hr, AC	RT	Parallel	-	≥8.3t
1475F, 30 Min, AC + 1100F, 16 Hr, AC + Weld	RT	No weld	4.2t	3.6t
1475F, 30 Min, AC + 1100F, 16 Hr, AC + Weld	RT	Transverse	2.3t	2.0t
1475F, 30 Min, AC + 1100F, 16 Hr, AC + Weld	RT	Parallel	1.6t	1.0t
1475F, 30 Min, AC + Weld + 1100F, 16 Hr, AC	RT	No weld	4.1t	3.6t
1475F, 30 Min, AC + Weld + 1100F, 16 Hr, AC	RT	Transverse	4.3t	3.7t
1475F, 30 Min, AC + Weld + 1100F, 16 Hr, AC	RT	Parallel	11.9t	11.0t
1475F, 30 Min, AC + 900F, 8 Hr, AC + Weld	400	Transverse	0.9t	-
1475F, 30 Min, AC + 900F, 8 Hr, AC + Weld	400	Parallel	2.0t	1.5t
1475F, 30 Min, AC + Weld + 900F, 8 Hr, AC	400	Transverse	-	≥6.5t
1475F, 30 Min, AC + 1100F, 16 Hr, AC + Weld	400	Transverse	2.6t	1.6t
1475F, 30 Min, AC + 1100F, 16 Hr, AC + Weld	400	Parallel	3.0t	2.5t
1475F, 30 Min, AC + Weld + 1100F, 16 Hr, AC	400	Transverse	3.0t	2.5t
1475F, 30 Min, AC + Weld + 1100F, 16 Hr, AC	400	Parallel	7.8t	7.3t
1475F, 30 Min, AC + Weld + 1100F, 16 Hr, AC	1100	Transverse	-	≥2.0t
1475F, 30 Min, AC + Weld + 1100F, 16 Hr, AC	1100	Parallel	-	≥8.0t

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) GTA welded, without filler, using automatic welding machine with 3/32 inch diameter, 2 percent thoriated tungsten electrode and argon shielding, at 20 inches per minute with 100-150 amp current at 9 volts. Weld bead ground flush with base metal surfaces.
(c) Simulated hand mill product. Sheet descaled, ground and pickled after annealing.

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

4.04 Heat Treatment

Recrystallization. Recrystallization parameters were determined for sheet in three conditions: 0.060 inch gage annealed 1285F, 4 hr, FC to 1000F (simulated hand mill product), hot rolled sheet cold rolled 25 percent from 0.080 inch to 0.060 inch gage (simulates mill strip), and hot rolled sheet cold rolled 50 percent from 0.080 inch to 0.040 inch gage (also simulated mill strip). Samples from each condition were solution treated at temperatures ranging from 1350F to 1525F in 25F increments for 15, 30 and 60 minutes. Ten minute solution times were also used where required. After solution treatment, all samples were partially aged for 4 hours at 900F to permit metallographic distinction between recrystallized and uncrystallized material (when partially aged, recrystallized grains are darker etching). Following this, aging response was determined for both 50 percent and 100 percent recrystallized material. Aging temperatures ranged from 800F to 1200F in 100F increments for times ranging from 2 to 24 hours. Aging was most pronounced at 900F for 8 hours or more and partially recrystallized material aged faster than fully recrystallized material. The aging curves established by Vickers hardness measurements are presented in Figures 1.066 through 1.0611.

4.041 Recrystallization characteristics of annealed sheet (simulated hand mill product), Table 4.041.

TABLE 4.041

Source	(4)		
Alloy	Ti-8Mo-8V-2Fe-3Al		
Form	0.060 Inch Sheet (a)		
Condition	Annealed 1285F, 4 Hr, FC to 1000F, AC(b)		
Solution Temperature F	Solution Time		
	15 Minutes	30 Minutes	1 Hour
	Percent	Percent	Percent
1350	0	0	0
1375	0	0	0
1400	0	0	0
1425	0	T(c)	T(c)
1450	5	50	75
1475	10	50	90
1500	30	80	100
1525	50	100(d)	100(d)

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) This condition representative of hand mill sheet. Sheet descaled, ground and pickled after annealing.
(c) Traces of recrystallization.
(d) Few small scattered areas of unrecrystallized material.

4.042 Recrystallization characteristics of 25 percent cold rolled sheet (simulated mill strip), Table 4.042.

TABLE 4.042

Source	(4)		
Alloy	Ti-8Mo-8V-2Fe-3Al		
Form and Condition	Hot Rolled 0.080 Inch Sheet(a) Cold Rolled 25 Percent to 0.060 Inch Sheet (b)		
Solution Temperature F	Solution Time		
	15 Minutes	30 Minutes	1 Hour
	Percent	Percent	Percent
1350	0	0	0
1375	10	10	20
1400	40	75	95
1425	70	90	100
1450	70	100	100
1475	70	100	100
1500	100	100	100 with grain growth
1525	100	100	100 with grain growth

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Representative of mill strip. Sheet descaled, ground and pickled after cold rolling.

4.043 Recrystallization characteristics of 50 percent cold rolled sheet (simulated mill strip), Table 4.043.

TABLE 4.043

Source	(4)		
Alloy	Ti-8Mo-8V-2Fe-3Al		
Form and Condition	Hot Rolled 0.080 Inch Sheet (a) Cold Rolled 50 Percent to 0.040 Inch Sheet (b)		
Solution Temperature F	Solution Time		
	15 Minutes	30 Minutes	1 Hour
	Percent	Percent	Percent
1350	0	0	0
1375	T(c)	20	80
1400	85	90	100
1425	100	100	100
1450	100	100	100
1475	100	100	100 with grain growth
1500	100	100	100 with grain growth
1525	100	100 with grain growth	100 with grain growth

(a) Prepared from 500 pound ingot mill processed as described in Table 4.011.
(b) Representative of mill strip. Sheet descaled, ground and pickled after cold rolling.
(c) Traces of recrystallization.

4.044 Oxidation (see 2.0313 and 2.0314).

4.045 Cooling rate. Cooling rate from the solution temperature ranging from water quenching to plate cooling has no measurable influence on the room temperature smooth tensile properties of this alloy.

4.046 Effect of cooling rate from the solution temperature on room temperature tensile properties of solution treated and aged sheet, Table 4.046.

TABLE 4.046

Source	(4)		
Alloy	Ti-8Mo-8V-2Fe-3Al		
Form	0.050 Inch Sheet (a)		
Condition	F_{tu} ksi	F_{ty} ksi	e(2 in) Percent
1500F, 10 Min, WQ + 900F, 16 Hr, AC	204	192	5.0
1500F, 10 Min, AC + 900F, 16 Hr, AC	202	193	6.2
1500F, 10 Min, Plate Cool (b)+900F, 16 Hr, AC	203	193	5.2

(a) Prepared from 30 pound ingot as described in Table 3.0241. Transverse direction.
(b) Specimen blanks held between two 1 inch thick titanium plates; assemblage removed from furnace and allowed to cool in still air. Specimen blanks cooled to 700F in about 20 minutes, simulating the cooling rate expected in the production of 2 inch plate.

4.047 Effect of cooling rate from the solution temperature on room temperature tensile elastic modulus of solution treated and aged sheet, Table 4.047.

TABLE 4.047

Source	(4)	
Alloy	Ti-8Mo-8V-2Fe-3Al	
Form	0.050 Inch Sheet (a)	
Condition		E - 10^3 ksi
1500F, 10 Min, WQ + 900F, 16 Hr, AC		15.1
1500F, 10 Min, AC + 900F, 16 Hr, AC		15.3
1500F, 10 Min, Plate Cool (b), + 900F, 16 Hr, AC		15.7

(a) Prepared from 30 pound ingot as described in Table 3.0241. Transverse direction.
(b) Specimen blanks held between two 1 inch thick titanium plates; assemblage removed from furnace and allowed to cool in still air. Specimen blanks cooled to 700F in about 20 minutes, simulating the cooling rate expected in the production of 2 inch plate.
(see Table 4.046 for balance of tensile properties)

4.05 Surface Treatment

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

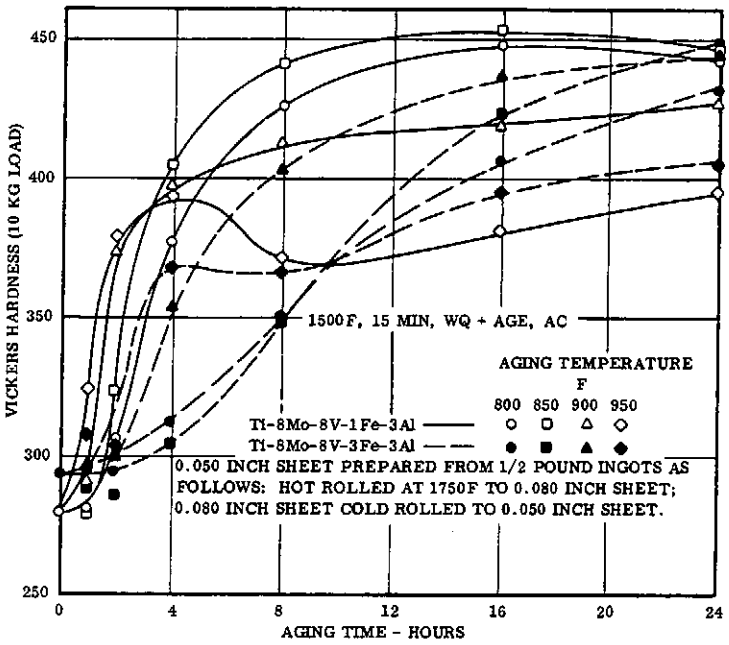


FIG. 1.061 EFFECT OF AGING TIME AND TEMPERATURE ON HARDNESS OF SOLUTION TREATED SHEET OF TWO IRON CONTENTS. (3)

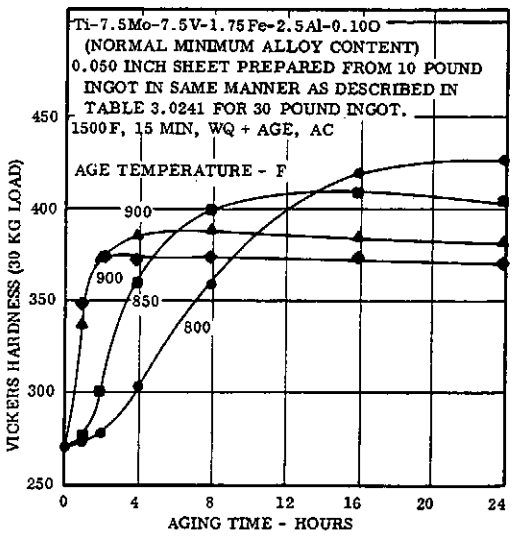


FIG. 1.062 EFFECT OF AGING TIME AND TEMPERATURE ON HARDNESS OF SOLUTION TREATED SHEET OF NORMAL MINIMUM ALLOY CONTENT. (4)

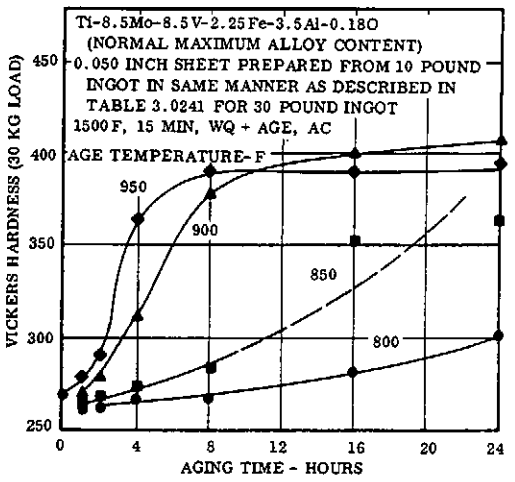


FIG. 1.063 EFFECT OF AGING TIME AND TEMPERATURE ON HARDNESS OF SOLUTION TREATED SHEET OF NORMAL MAXIMUM ALLOY CONTENT. (4)

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

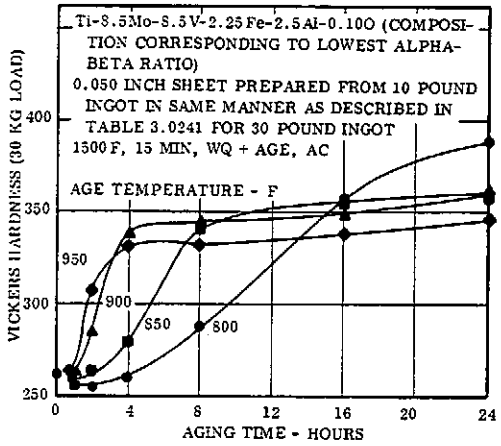


FIG. 1.064 EFFECT OF AGING TIME AND TEMPERATURE ON HARDNESS OF SOLUTION TREATED SHEET OF COMPOSITION CORRESPONDING TO LOWEST ALPHA-BETA RATIO. (4)

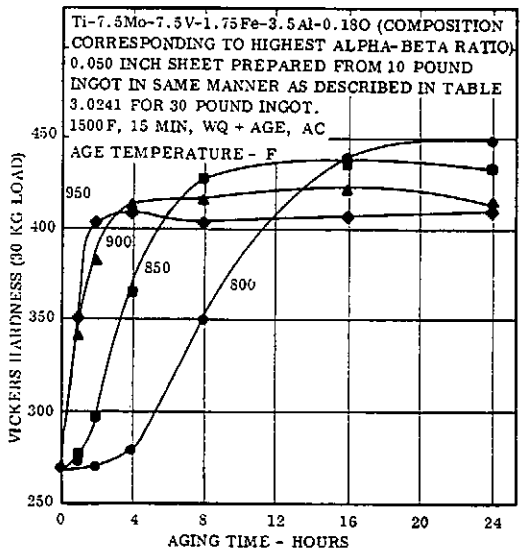


FIG. 1.065 EFFECT OF AGING TIME AND TEMPERATURE ON HARDNESS OF SOLUTION TREATED SHEET OF COMPOSITION CORRESPONDING TO HIGHEST ALPHA-BETA RATIO. (4)

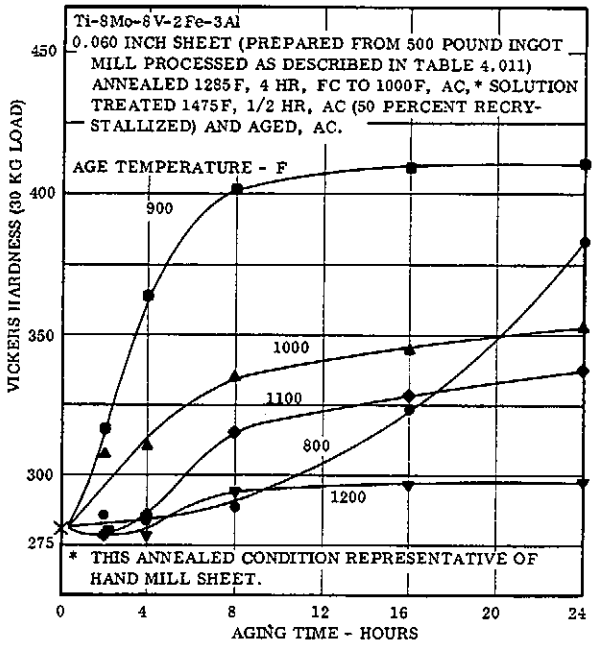


FIG. 1.066 EFFECT OF AGING TIME AND TEMPERATURE ON HARDNESS OF ANNEALED SHEET 50 PERCENT RECRYSTALLIZED. (4)

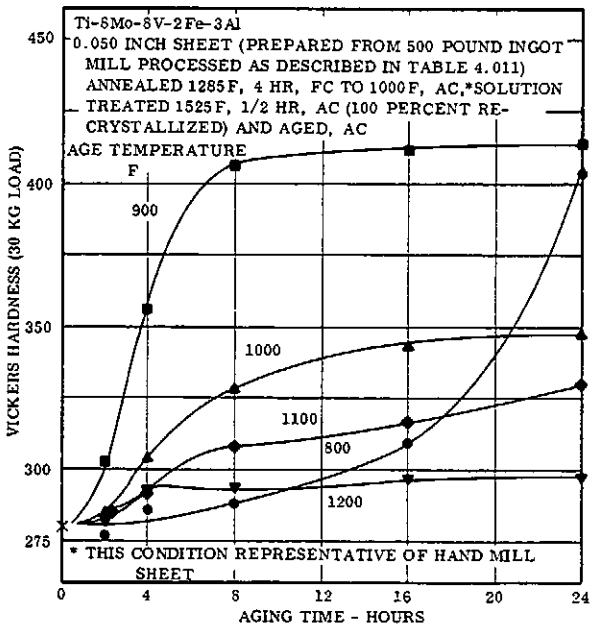


FIG. 1.067 EFFECT OF AGING TIME AND TEMPERATURE ON HARDNESS OF ANNEALED SHEET 100 PERCENT RECRYSTALLIZED. (4)

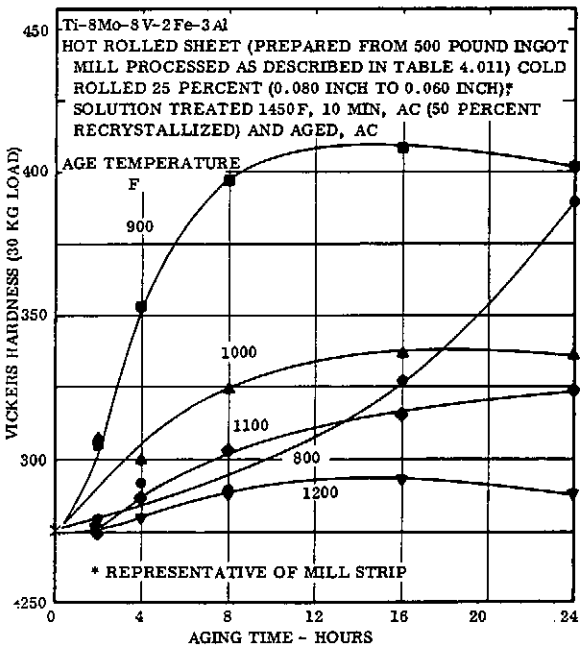


FIG. 1.068 EFFECT OF AGING TIME AND TEMPERATURE ON HARDNESS OF 25 PERCENT COLD ROLLED SHEET 50 PERCENT RECRYSTALLIZED. (4)

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

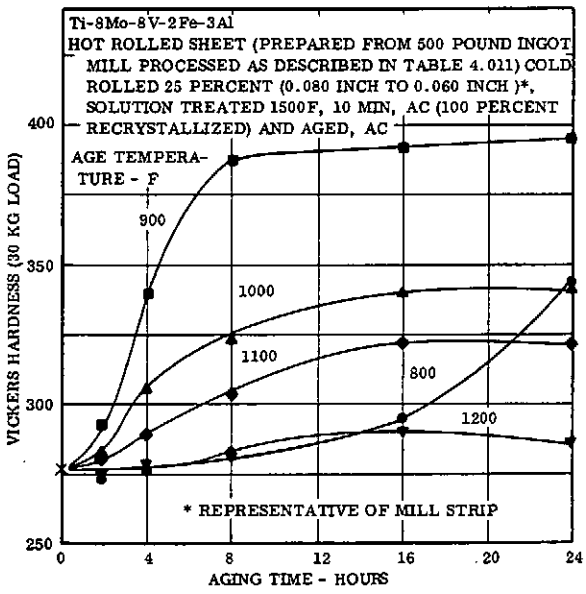


FIG. 1.069 EFFECT OF AGING TIME AND TEMPERATURE ON HARDNESS OF 25 PERCENT COLD ROLLED SHEET 100 PERCENT RECRYSTALLIZED. (4)

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

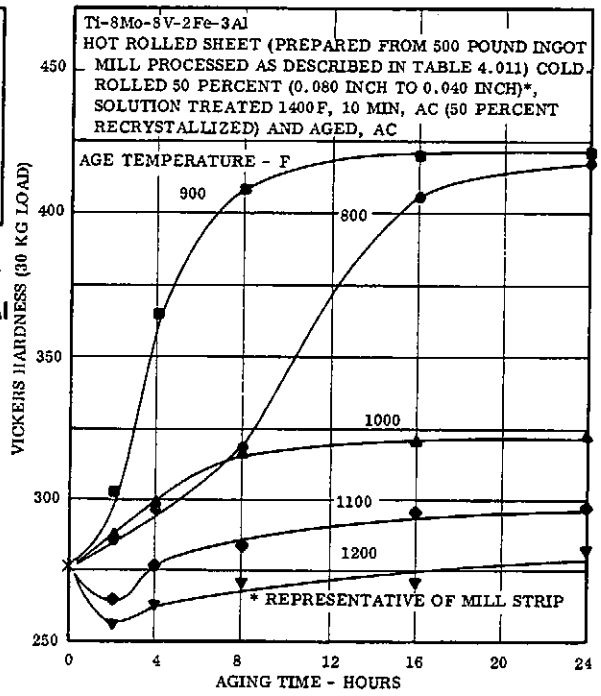


FIG. 1.0610 EFFECT OF AGING TIME AND TEMPERATURE ON HARDNESS OF 50 PERCENT COLD ROLLED SHEET 50 PERCENT RECRYSTALLIZED. (4)

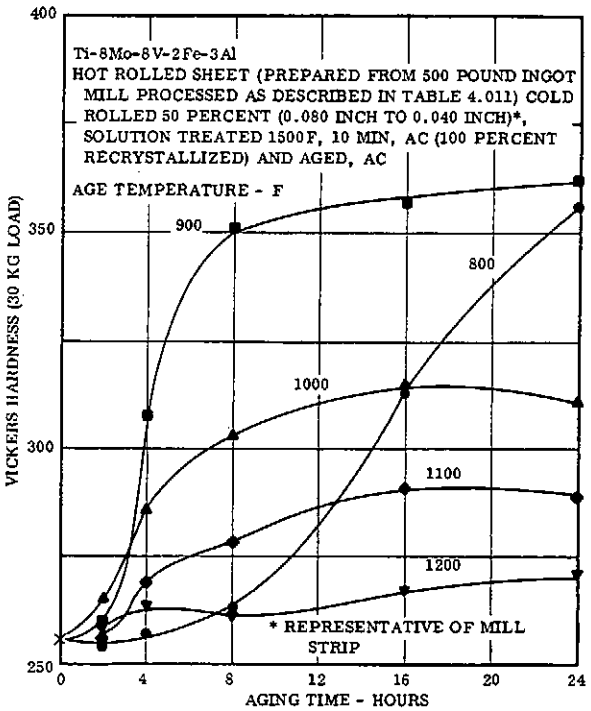


FIG. 1.0611 EFFECT OF AGING TIME AND TEMPERATURE ON HARDNESS OF 50 PERCENT COLD ROLLED SHEET 100 PERCENT RECRYSTALLIZED. (4)

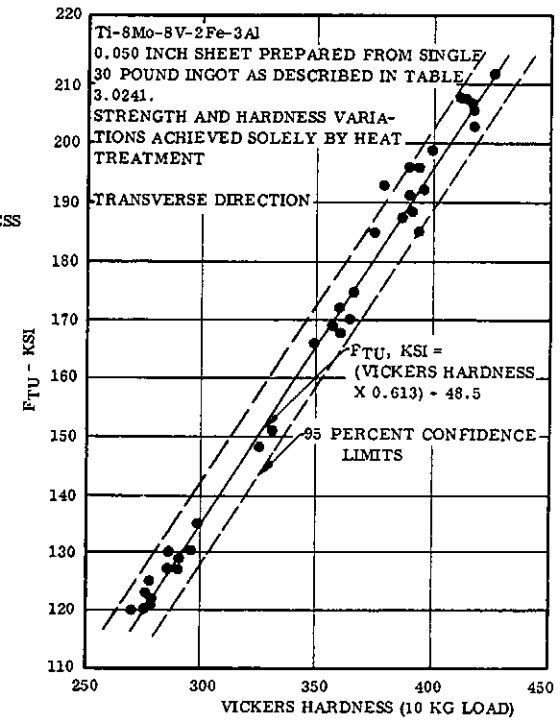


FIG. 1.0612 STATISTICAL RELATIONSHIP BETWEEN HARDNESS AND STRENGTH FOR SHEET. (3)

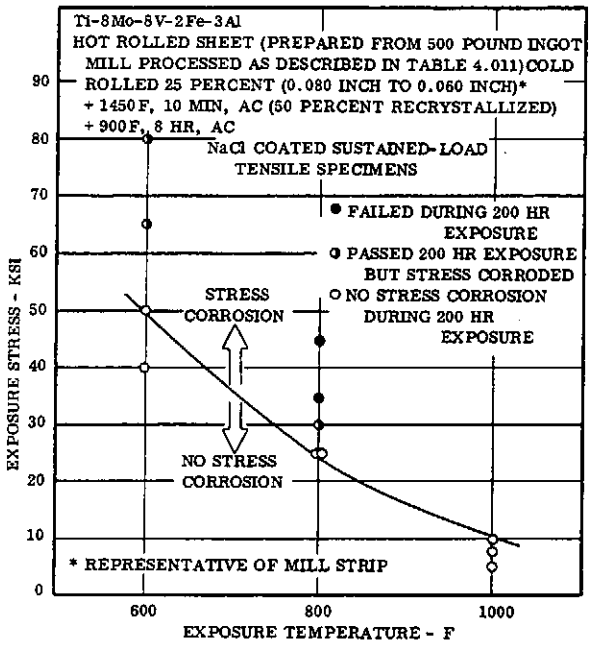


FIG. 2.033 HOT SALT STRESS CORROSION BEHAVIOR OF SIMULATED MILL STRIP SOLUTION TREATED (50 PERCENT RECRYSTALLIZED) AND AGED. (4)

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

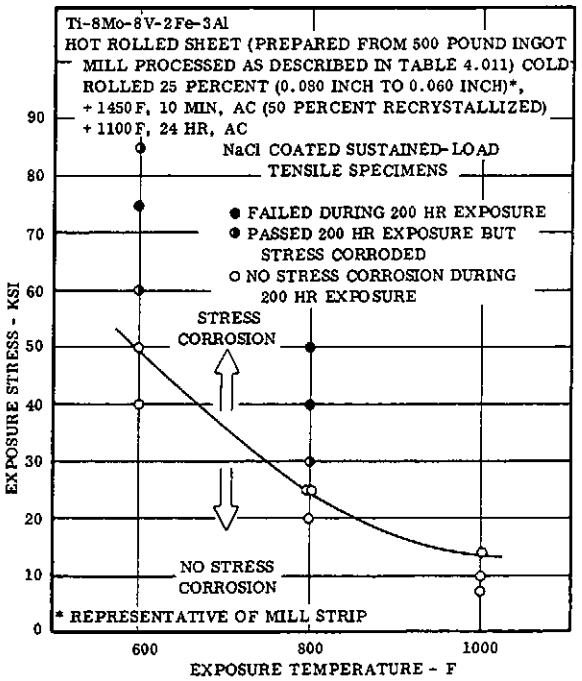


FIG. 2.034 HOT SALT STRESS CORROSION BEHAVIOR OF SIMULATED MILL STRIP SOLUTION TREATED (50 PERCENT RECRYSTALLIZED) AND STABILIZATION AGED. (4)

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-
8V-2Fe-3Al

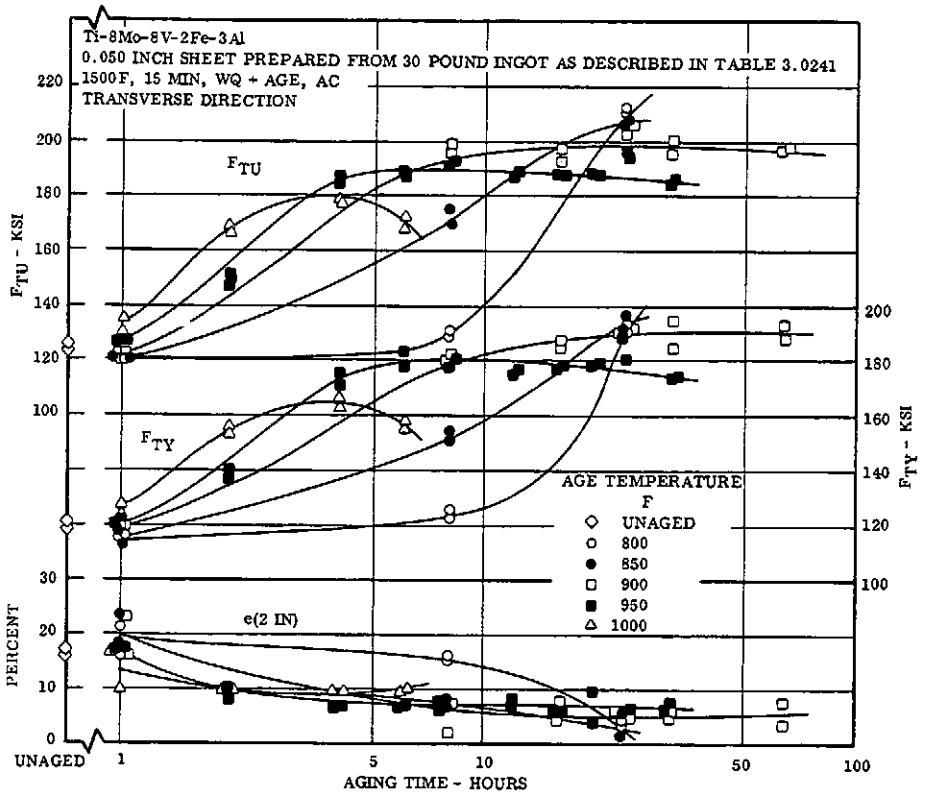


FIG. 3.0214 EFFECT OF AGING TIME AND TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION TREATED SHEET. (3)

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

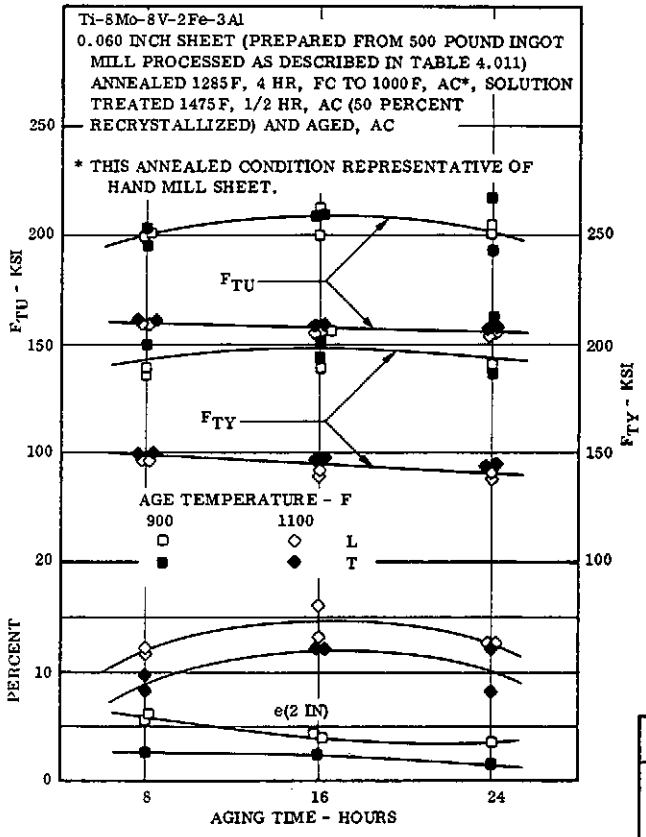


FIG. 3.0215 EFFECT OF AGING TIME AT 900 AND 1100F ON TENSILE PROPERTIES OF ANNEALED, SIMULATED HAND MILL SHEET 50 PERCENT RECRYSTALLIZED. (4)

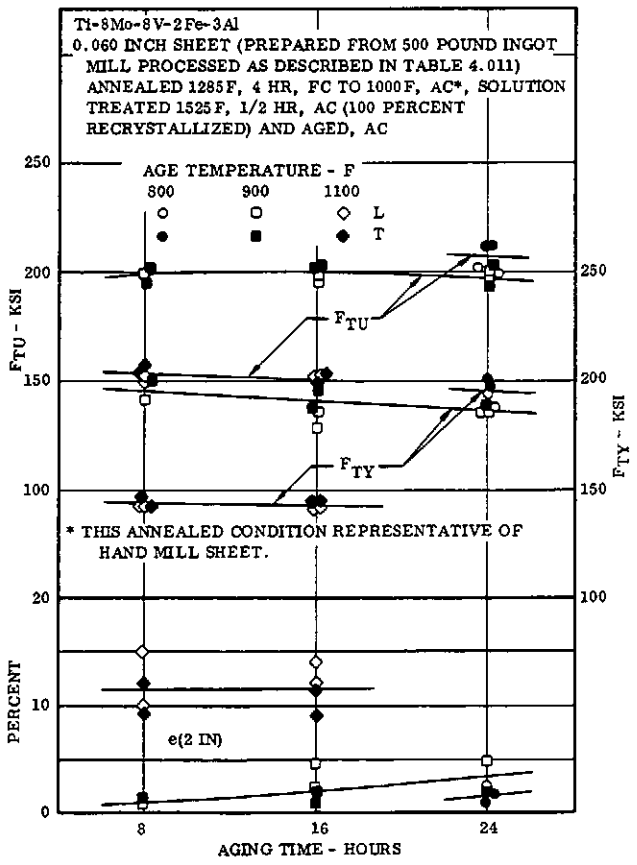


FIG. 3.0216 EFFECT OF AGING TIME AT 800, 900, AND 1100F ON TENSILE PROPERTIES OF ANNEALED, SIMULATED HAND MILL SHEET 100 PERCENT RECRYSTALLIZED. (4)

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

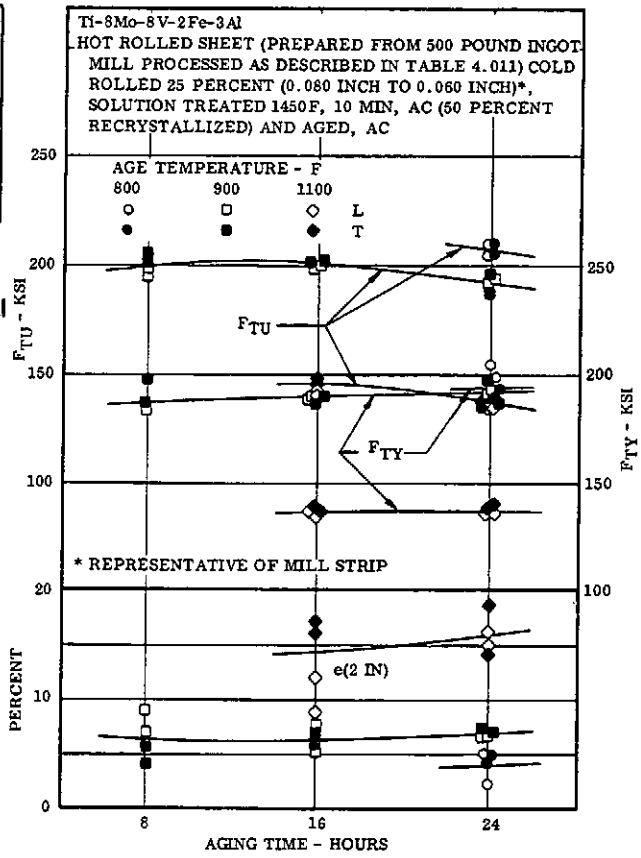


FIG. 3.0217 EFFECT OF AGING TIME AT 800, 900, AND 1100F ON TENSILE PROPERTIES OF 25 PERCENT COLD ROLLED, SIMULATED MILL STRIP 50 PERCENT RECRYSTALLIZED. (4)

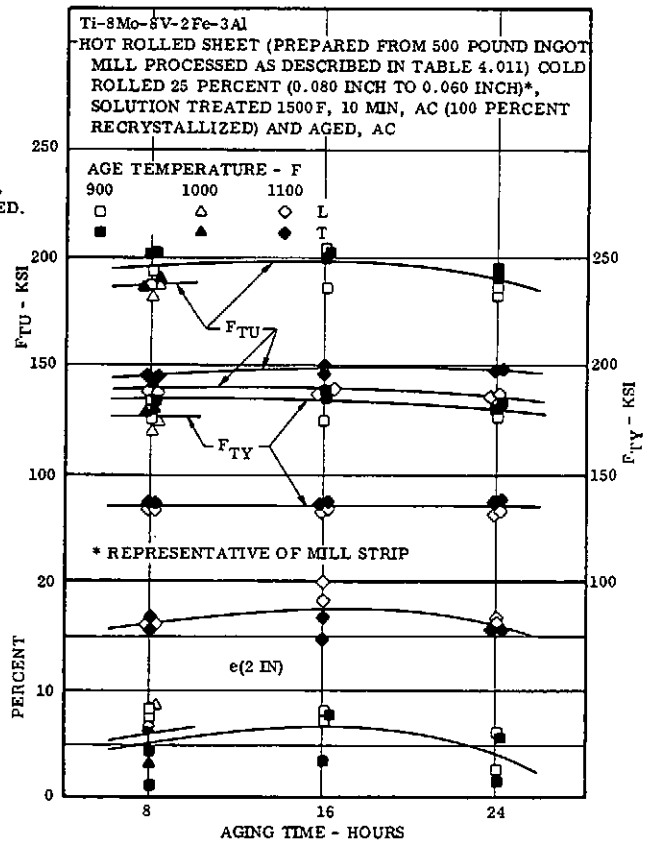


FIG. 3.0218 EFFECT OF AGING TIME AT 900, 1000, AND 1100F ON TENSILE PROPERTIES OF 25 PERCENT COLD ROLLED, SIMULATED MILL STRIP 100 PERCENT RECRYSTALLIZED. (4)

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

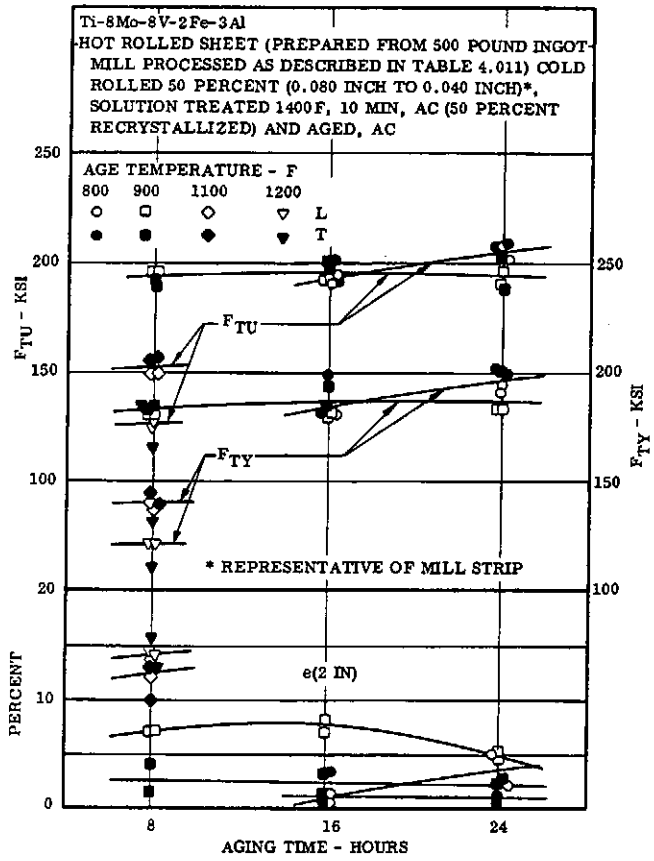


FIG. 3.0219 EFFECT OF AGING TIME AT 800, 900, 1100, AND 1200F ON TENSILE PROPERTIES OF 50 PERCENT COLD ROLLED, SIMULATED MILL STRIP 50 PERCENT RECRYSTALLIZED. (4)

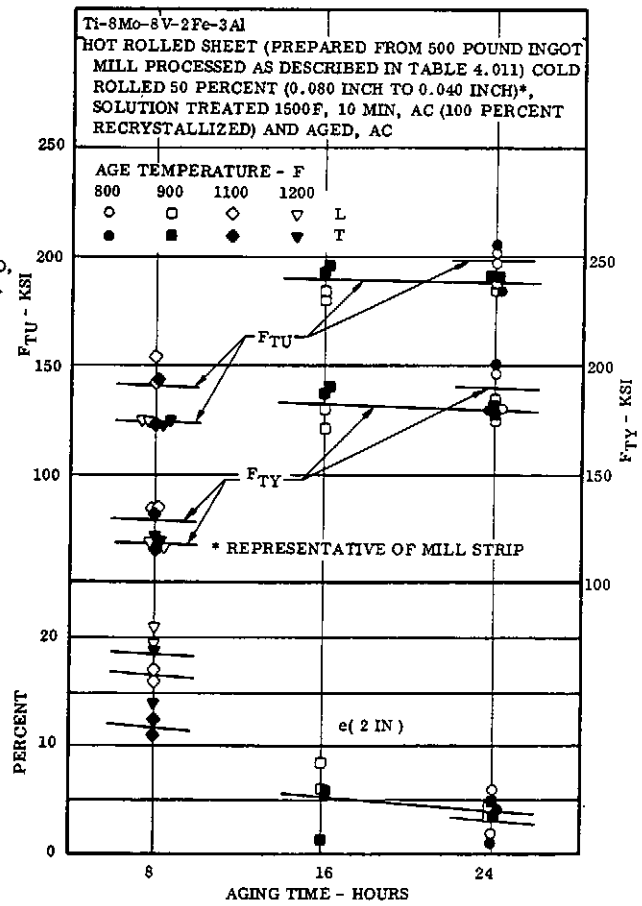


FIG. 3.02110 EFFECT OF AGING TIME AT 800, 900, 1100, AND 1200F ON TENSILE PROPERTIES OF 50 PERCENT COLD ROLLED, SIMULATED MILL STRIP 100 PERCENT RECRYSTALLIZED. (4)

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

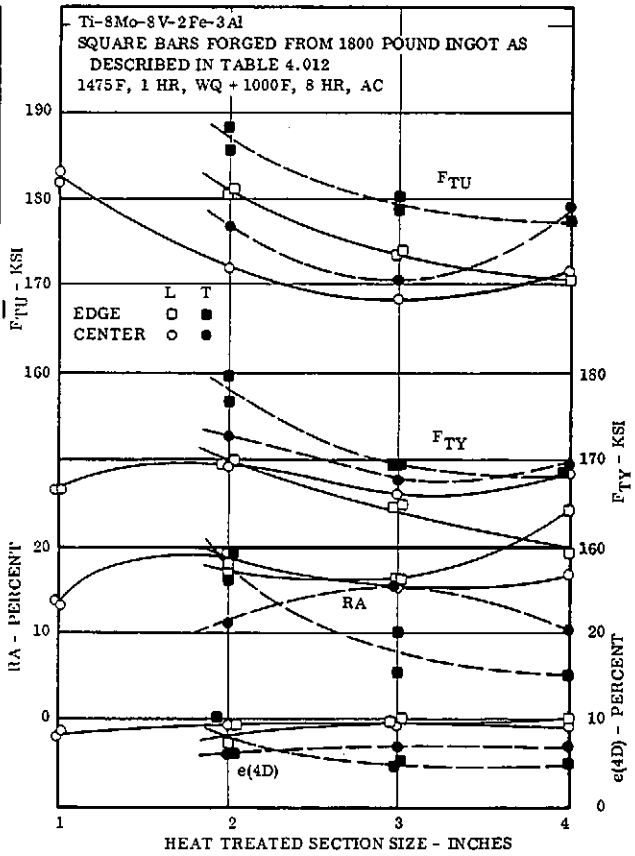


FIG. 3.02113 EFFECT OF HEAT TREATED SECTION SIZE ON TENSILE PROPERTIES OF UNDIRECTIONALLY FORGED BARS. (1)

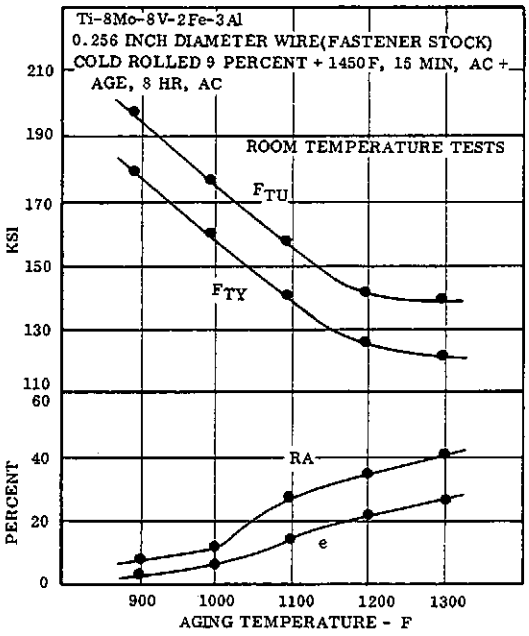


FIG. 3.02116 EFFECT OF AGING TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF COLD ROLLED PLUS SOLUTION TREATED AND AGED FASTENER STOCK. (8)

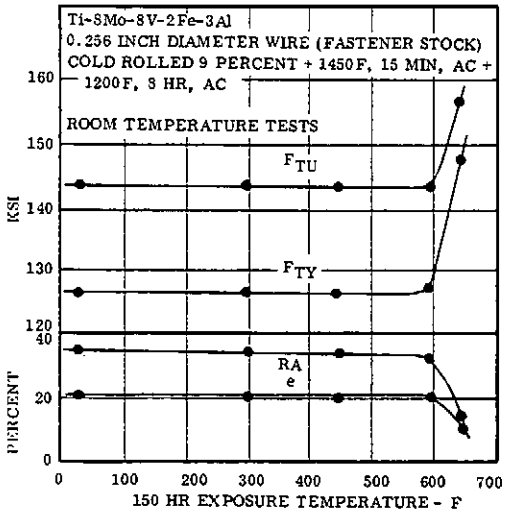


FIG. 3.02122 EFFECT OF 150 HOUR EXPOSURE TO ELEVATED TEMPERATURES ON ROOM TEMPERATURE TENSILE PROPERTIES OF COLD ROLLED PLUS SOLUTION TREATED AND AGED FASTENER STOCK. (8)

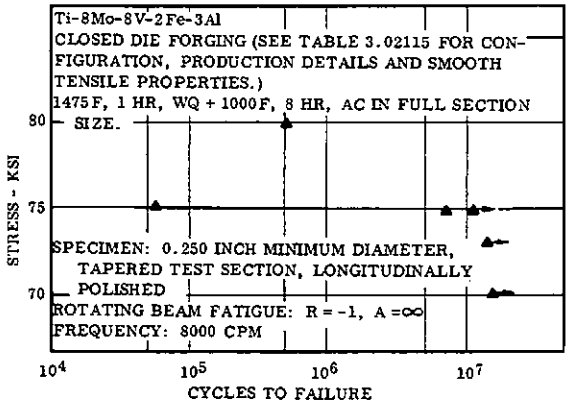


FIG. 3.051 ROOM TEMPERATURE ROTATING BEAM FATIGUE STRENGTH OF SOLUTION TREATED AND AGED CLOSED DIE FORGING. (2)

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-8V-2Fe-3Al

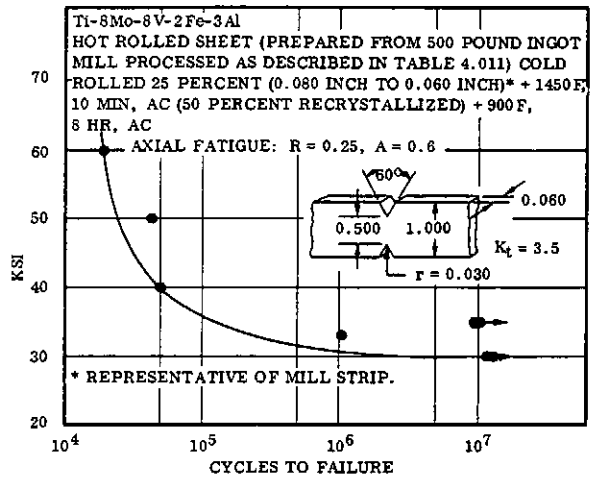


FIG. 3.052 ROOM TEMPERATURE MILD NOTCH FATIGUE STRENGTH OF 25 PERCENT COLD ROLLED, SIMULATED MILL STRIP SOLUTION TREATED (50 PERCENT RECRYSTALLIZED) AND AGED. (4)

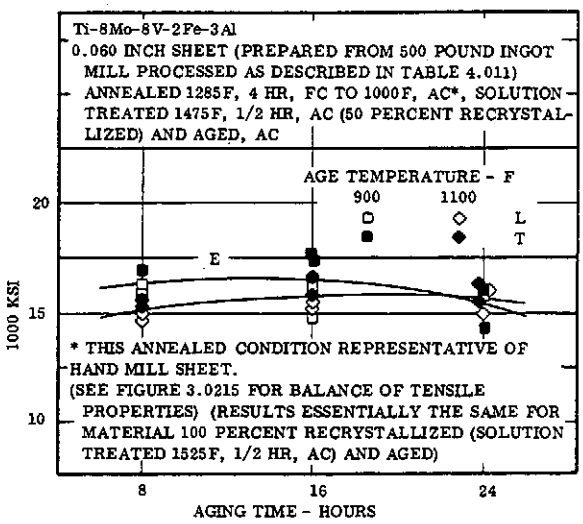


FIG. 3.0624 EFFECT OF AGING TIME AT 900 AND 1100F ON ROOM TEMPERATURE TENSILE ELASTIC MODULUS OF ANNEALED, SIMULATED HAND MILL SHEET 50 PERCENT RECRYSTALLIZED. (4)

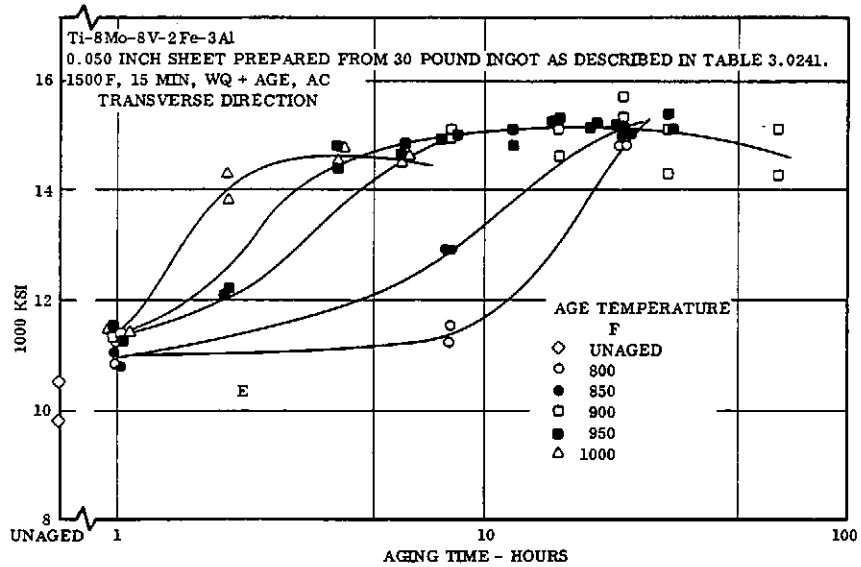


FIG. 3.0623 EFFECT OF AGING TIME AND TEMPERATURE ON ROOM TEMPERATURE TENSILE ELASTIC MODULUS OF SOLUTION TREATED SHEET. (3)

	Ti
8	Mo
8	V
2	Fe
3	Al

Ti - 8Mo-
8V-2Fe-3Al

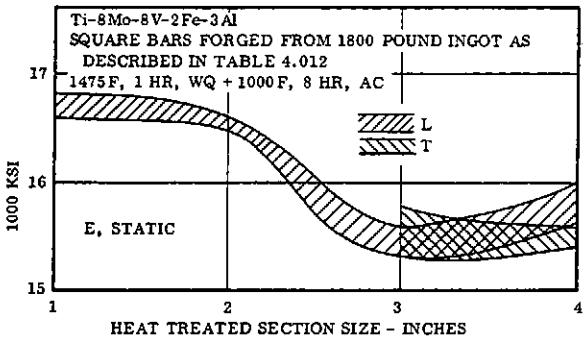


FIG. 3.0627 EFFECT OF HEAT TREATED SECTION SIZE ON ROOM TEMPERATURE TENSILE ELASTIC MODULUS OF FORGED BARS. (1)

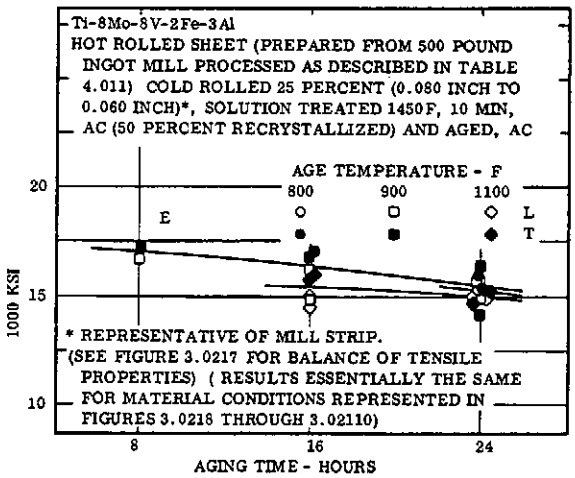


FIG. 3.0625 EFFECT OF AGING TIME AT 800, 900, AND 1100F ON ROOM TEMPERATURE TENSILE ELASTIC MODULUS OF 25 PERCENT COLD ROLLED, SIMULATED MILL STRIP 50 PERCENT RECRYSTALLIZED. (4)

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1 GENERAL

This is a near-beta alloy in which the high temperature beta-phase is stabilized by nominal alloying additions of 2 weight percent iron and 10 weight percent vanadium. The 3 weight percent aluminum is a natural ingredient in the master alloy and acts as a solid solution strengthener for the low temperature precipitating alpha-phase. The alloy exhibits excellent hot die isothermal forgeability above its beta transus temperature of about 1460 F. Net or near-net forged shapes are produced at lower temperatures and pressures than required for Ti-6Al-4V alloy, a significant cost saving feature which lowers die material cost and extends die life, reduces energy consumption, simplifies handling, and minimizes forging cleanup. Properties of the alloy can vary with section thickness, and from center to surface of a given sized section. However, guaranteed property minimums can be met in sections up to 5 inch, with a wide range of strengths and corresponding toughness achievable through the appropriate selection of forging parameters and heat treatment. The alloy is used principally in nonfatigue airframe structural component applications.

The alloy is available as billet, bar, plate, and forgings and is covered by United States Patent No. 3,802,877, dated April 9, 1974.

1.01 Commercial Designation

Ti-10V-2Fe-3Al Alloy.

1.02 Alternate Designation

Ti-10-2-3.

1.03 Specifications

Boeing Material Specification BMS-7-260 (6-18-79).

1.04 Composition

1.041 Producer's specified composition, Table 1.041.

1.042 User's specified composition, Table 1.042.

1.043 Oxygen content. The guaranteed maximum oxygen content is set at 0.13 weight percent in order to ensure high toughness. The effect of oxygen content on room temperature strength and toughness is given in Table 3.02728.

1.044 Iron segregation, see 1.092.

1.05 Heat Treatment

1.051 Solution treat + age (high strength condition): 1400 F, 1 hr, WQ + 950 F, 8 hr, AC.

1.052 Solution treat + overage (intermediate strength condition): 1350 to 1400 F, 1 hr, AC or faster + 1075 F, 8 hr, AC.

1.053 For enhanced fracture toughness it is recommended that finish forging or rolling be done above the beta transus temperature (at approximately 1500 to 1550 F). For enhanced ductility (reduction in area and elongation) in the aged condition, finish forging or rolling below the beta transus temperature is recommended. In general, heat treatment is accomplished by subtransus solution treatment (1350 to 1400 F), followed by aging at 950 F for the high strength condition, or by overaging at 1050 to 1150 F for the intermediate strength condition. The latter overaging cycle is found to be compatible with plate fabrication and results in higher fracture toughness. Solution temperature and quench rate, and aging temperature and heat up rate all affect aging response. Aged strength is increased by increasing solution temperature, by rapid (water) quenching, and by decreasing aging temperature and aging heat up rate. Solution time has only a minor effect compared to thickness (cooling rate) and aging parameters. For thin sections in the high strength condition, approximately half of the yield strength is derived from aging.

Aging of this alloy is rapid, and overaging is recommended for enhanced fracture toughness and reduced property scatter. Aging at 900 F or higher also provides insurance against the formation of omega-phase.

1.054 An intensive study of the effects of heat treated microstructure on tensile properties and fatigue crack-growth rates has been made by Terlinde, Duerig, and Williams (16)(17)(18). Some of their results are presented in Figures 3.02110, 3.02127, 3.02144, and 3.0511 through 3.0516 and Table 3.02150. Their general findings are that for a constant volume fraction of primary alpha-phase it is possible to vary the yield strength over a wide range. It is also possible to reach comparable yield levels for different volume fractions of primary alpha-phase by an appropriate choice of aging temperatures and times as well as heat up rates to the aging temperature. Increasing the volume fraction of primary alpha-phase reduces ductility at comparable yield strengths for the alpha-aged condition. Only the beta solution treated conditions with no primary alpha-phase are an exception. They have lower ductilities than alpha + beta solution treated conditions. Heat treating to produce omega-aged microstructures results in the lowest ductilities at comparable yield strength levels. The differences between the alpha + beta solution treated and alpha-aged, the beta solution treated and alpha-aged, and the omega-aged microstructures are qualitatively related to different fracture modes. Microstructures from forgings with elongated primary alpha-phase structures exhibit lower ductilities than those with globular primary alpha-phase microstructures. Fatigue crack-growth characteristics are unaffected by the alpha-aged microstructure, but are far different from the omega-aged microstructures (see Figures 3.0511 through 3.0516).

No such study has been made of the fracture toughness characteristics for varying microstructures, though generally it would be expected that those producing high ductility would suffer reduced fracture toughness.

Ti
10 V
2 Fe
3 Al

Ti-10-2-3

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

1.06 Hardness

1.061 The hardening response of beta solution treated and quenched hot-rolled plate aged in molten salt is presented in Figure 1.062. The observed trends are explained (18) in terms of the precipitation reactions that occur at the aging temperature (refer to 2.01213 on heat treat phase transformations). At 392 F, the only precipitating phase is isothermal omega-phase; no overaging is observed within the time range shown. At 573 F, a transition from isothermal omega-phase to uniform alpha-phase gradually occurs during hardening, but the transition is incomplete within the time span shown and peak hardness is not achieved. At 752 F, isothermal omega-phase is replaced by uniform alpha-phase plus patchy sympathetic alpha-phase at an early time. The transition is nearly complete after 10 minutes, but still no overaging is observed. At 932 F, the hardening phase is entirely sympathetic alpha-phase; hardening is rapid and overaging occurs in about 10 minutes. The hardening response for plate alpha + beta solution treated at various temperatures and then aged in molten salt at 932 F is shown in Figure 1.063. Peak hardness decreases with decreasing solution treat temperature as the time to achieve peak hardness increases.
The hardening response of the same hot-rolled plate directly aged in molten salt or beta solution treated and then aged in molten salt, are compared in Figure 1.064. The directly aged material achieves notably lower peak hardness and at slightly longer aging times.
The hardness of isothermally forged pancakes is shown in Figure 1.065 for beta solution treatment prior to molten salt aging, and in Figure 1.066 for alpha + beta solution treatment prior to molten salt aging. For the forging schedules used, only small effects are observed for the beta solution treated material (Figure 1.065), but appreciable differences in hardness are observed for the alpha + beta solution treated material (Figure 1.066).

1.062 Effect of aging time on hardness of hot-rolled plate, beta solution treated and aged at several temperatures, Figure 1.062.

1.063 Effect of 500 F aging time on hardness of hot-rolled plate, alpha + beta solution treated and aged at 932 F, Figure 1.063.

1.064 Effect of 932 F aging time on hardness of hot-rolled plate either directly aged or beta solution treated and then aged, Figure 1.064.

1.065 Effect of 932 F aging time on hardness of beta solution treated isothermally forged pancakes, Figure 1.065.

1.066 Effect of 932 F aging time on hardness of alpha + beta solution treated isothermally forged pancakes, Figure 1.066.

1.067 Effect of solution temperature and cooling rate on aged hardness of 1-inch cubes, Table 1.067.

1.07 Forms and Conditions Available

Billet, bar, plate, and forgings (23). Forging billet and bar are supplied as hot worked or in an annealed condition suitable for further forging (1). Plate is normally supplied in the annealed, descaled and pickled condition (1).

1.08 Melting and Casting Practice

Consumable-electrode vacuum-arc melted.

1.09 Special Considerations

1.091 Stability. Retained room temperature tensile properties following creep exposure at 600 F, 100 ksi, for 100 hr are shown in Tables 3.045 and 3.046. Some instability under this exposure condition is indicated by changes in strength and ductility measured after exposure.

1.092 Iron segregation. Inhomogeneity, principally in in the form of iron segregation on both a micro and macroscale, has been observed in billets from large (28 inch) ingots (12). Variations in iron content as large as 0.5 weight percent have been reported (12) with a corresponding variation in beta transus temperature of 75 F. The center of the billet generally exhibits the highest iron content and the mid-radius position the lowest. Depression of the beta transus temperature in the iron-rich areas produces zones void of, or lean in alpha-phase, known as beta flecks. The resultant variation in structure can produce substantial variations in mechanical properties. Refinements in melting procedures have reportedly disposed of this problem (1)(12)(24).

1.093 Deformation assisted martensite. Because this is a "lean" modestly stabilized beta alloy, martensitic decomposition of the beta-phase can be accomplished by externally stressing the solution treated and quenched material (15). The temperature below which deformation assisted martensite is formed is designated M_d, and for this alloy M_d lies above room temperature. As a result, stress assisted martensite (orthorhombic α'') can be produced at room temperature.
The production of α'' causes an inflection in the tensile stress-strain curves of Figure 3.0211. The stress needed to initiate the α'' reaction corresponds to the onset of the inflection (premature departure from linearity) and is dependent on the solution treatment temperature. In the beta solution treated condition (1562 F, WQ), a stress of only 35 ksi is required to produce a deviation from linearity in the stress-strain curve. In the alpha + beta solution treated and quenched conditions, the beta matrix contains retained primary alpha-phase. Although the primary alpha-phase is too coarse to directly affect strength, it does increase the chemical stability of the surrounding beta matrix because of solute partitioning between the alpha and beta phases. Thus, as the solution temperature is reduced, the amount of primary alpha-phase is increased, the M_s temperature is further suppressed and M_d approaches room temperature. A greater stress is needed to initiate the α'' distortion, and the stress level of the inflection in the stress-strain curves rises. Finally, when the beta composition is rich enough in Fe and V to depress M_d below

room temperature, the material deforms by slip, no α'' is formed, and the stress-strain curve has no inflection. While the production of α'' is evidenced by its effect on the flow curves of Figure 3.0211, no results are available regarding its effect on other mechanical properties.
Strain induced martensite has been observed at the surfaces of solution treated and quenched products, but it is local and believed to be due to quenching stresses. Surface microstructure of solution treated and quenched products cannot therefore, be considered typical of the general product.

1.094 Aging heat up rate. Heat up rate to the aging temperature will affect the transformed structure and mechanical properties of this alloy as discussed in sections 1.054 and 2.01213 and illustrated by the results in Figure 3.02127 and Table 3.02146.

2 PHYSICAL PROPERTIES AND ENVIRONMENTAL EFFECTS

2.01 Thermal Properties

2.011 Melting range.

2.012 Phase changes. Beta transus, approximately 1460 F (1).

2.0121 Time-temperature-transformation diagrams.

2.01211 Schematic time-temperature-transformation (TTT) diagram for Ti-10V-2Fe-3Al beta solution treated, quenched, and rapidly heated to the aging temperature, Figure 2.01211.

2.01212 Dependence of primary alpha volume fraction on solution treatment temperature, Figure 2.01212.

2.01213 Heat treat phase transformations. Solution treatment establishes beta-phase composition and stability after quenching. Solution treatment above the beta transus temperature dissolves all primary alpha-phase and leads to a strong propensity for decomposition both during and after quenching. Full recrystallization of the beta matrix is rapid, but grain growth is very slow. Solution treatment in the alpha + beta field enriches the beta-phase in Fe and V (thereby stabilizing the beta-phase) and equilibrates the volume fraction of primary alpha-phase to a value characteristic of the solution temperature. Recrystallization of the beta matrix and subsequent grain growth are sluggish, but adjustment of primary alpha-phase is rapid. Propensity for decomposition decreases with decreasing alpha + beta solution temperature.
On quenching from the solution treatment temperature, no athermal martensite (neither hexagonal α' nor orthorhombic α'') is produced, indicating the M_S temperature of this alloy is below room temperature. Strain-induced martensite forms at the quenched surfaces, but is local and only the result of quenching strains. The only general transformation that takes place on quenching is that of athermal omega-phase which appears as coherent, uniformly distributed, nondescript, extremely fine particles. Material solution treated above the beta transus temperature will, after quenching, consist of recrystallized beta-phase with a fine distribution of athermal omega-phase. Alpha + beta solution treated and quenched material will consist of coarse globular primary alpha-phase surrounded by a metastable beta-phase-plus-athermal omega-phase matrix.
Isothermal aging reactions are schematically illustrated in Figure 2.01211 for material, beta solution treated, quenched, and rapidly heated to the aging temperature. At aging temperatures below about 500 F, isothermal omega-phase is uniformly developed. The reaction is anomalously rapid, seemingly too rapid to be a diffusion controlled process, though it apparently is. Above about 500 F, three regimes of alpha-phase precipitation exist. At low aging temperatures (500 F to 700 F), isothermal omega-phase particles are uniformly precipitated in short times, but continued aging of the beta + omega dispersion leads to a uniform alpha-phase precipitation. Although not proven, it would appear that the uniform alpha-phase is nucleated upon the isothermal omega-phase particles. At high aging temperatures (above about 850 F), alpha-phase is precipitated as very long and flat (lenticular) plates nonuniformly distributed at grain boundaries, subgrain boundaries, other alpha + beta interfaces, etc. Growth rates at these high temperatures are high, and therefore the number of nucleation sites is low. The particles tend to be coarse and adopt a preferred or free growth morphology consisting of high aspect ratio plates or laths. These precipitates are referred to as sympathetic, or auto-catalytic alpha-phase, such terms referring to any precipitation process which is locally enhanced by extant, or preexisting precipitation products. In this case, the presence of a first alpha plate locally enhances or encourages the nucleation of others. In the intermediate temperature regime from 700 F to 850 F (dubbed the transition region), both uniform and sympathetic alpha-phase are precipitated. The sympathetic alpha-phase appears as patches, or islands of plates within the beta matrix which is dispersed with uniform alpha-phase. Increasing the aging temperature within this regime increases the frequency of the patches. The patchy microstructure is apparently quite stable and persists to rather long aging times. To reiterate, aging in the transition region begins with isothermal omega-phase precipitation. The isothermal omega-phase then transforms to uniform alpha-phase at a constant but rather slow rate. Competing with this, however, is a nonuniform sympathetic alpha-phase plate reaction which bears no relation to the preceding beta-phase-plus-isothermal omega-phase dispersion. Although the initial nucleation may be

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

slow, once a plate is nucleated, subsequent nucleation occurs quickly and a rapidly grown patch is formed. In zones where this second reaction occurs, the isothermal omega-phase-to-uniform alpha-phase reaction is suppressed. In zones where the sympathetic alpha-phase reaction is slow to get started, the isothermal omega-phase-to-uniform alpha-phase reaction proceeds and quickly stabilizes the zone. Thus is the competition. As the aging temperature is increased, the statistics become biased in favor of the sympathetic alpha-phase reaction. In the high temperature, or sympathetic alpha-phase regime, a grain boundary alpha-phase reaction occurs, which becomes more pronounced as the aging temperature approaches the beta transus temperature. During the early stages of aging, the reaction is discontinuous; but after longer times a continuous grain boundary alpha-phase layer is developed, and this layer thickens as the temperature is increased. The intragranular alpha-phase particles likewise become coarser and fewer in number as the temperature is increased. As the grain boundary alpha-phase layer thickens, a Ti-depleted, alpha-phase free zone surrounding the alpha-phase layer develops. It is not unusual to observe inclusions in the alpha-phase layer, these inclusions having a statistical preference for the grain boundaries.

These transformation reactions have been observed for beta solution treated and quenched material brought rapidly to the aging temperature in molten salt. During slow heating to the aging temperature, as in air aging, more time is spent in the low temperature regime before the aging temperature is reached. The result is that the uniform alpha-phase reaction is favored. Thus at a given aging temperature, uniform alpha-phase will be produced on air aging where molten salt aging would produce sympathetic alpha-phase. Although grain boundary alpha-phase is developed upon aging in air or salt, salt aging produces a much more pronounced and continuous layer.

Solution treating in the alpha + beta field affects the beta-phase composition (as a function of the volume percent primary alpha-phase). Subsequent aging trends are generally the same as those described above for beta solution treated and quenched material, however, the temperature regimes are shifted. The omega-phase and uniform alpha-phase reactions are suppressed in favor of sympathetic alpha-phase by increasing the primary alpha-phase content, thereby forming a more solute rich beta-phase. For example, at temperatures where only uniform alpha-phase would be produced in beta solution treated and quenched material, only sympathetic alpha-phase will be developed in a matrix of beta-phase plus primary alpha-phase for alpha + beta solution treated and quenched material. Similarly, where only isothermal omega-phase is produced in beta solution treated and quenched material, isothermal omega-phase plus uniform alpha-phase will be produced in a matrix of beta-phase plus primary alpha-phase of the alpha + beta solution treated and quenched product. Triplex heat treatments (double solution treating prior to aging, or solution treating plus double aging) have been used in an attempt to adjust the alpha-phase morphology in such a way as to balance the ductility and fracture toughness response. It is believed this can be accomplished with the proper mix of globular (for improved ductility) and platelet (for improved fracture toughness) primary alpha-phase structures. Results for double solution treating plus aging in Table 3.02727 show no improvement over conventional solution treating plus aging (for example, compare the results of Table 3.02727 with the 1400 F, 1/2 hr, AC + 950 F, 8 hr, AC condition in Table 3.02723).

2.013 Thermal conductivity.

2.014 Thermal expansion. Almost all solids expand on heating and contract on cooling. Although the thermal expansion of metals depends largely on the basic modulus of the metal, the thermal expansion may vary in a complex manner with the alloy chemistry, the structural change, and transformation characteristics of the alloy. The tendency for titanium-base alloys to expand on heating may be nullified by its contraction due to phase changes as the temperature approaches the alpha-beta transus. Consequently, the thermal expansion coefficients of titanium-base alloys cannot simply be extrapolated from low temperature results (6).

The average coefficient of thermal expansion for plate from room temperature to 800 F is 5.4×10^{-5} in./in./F. For forgings, the average value above the 800 F to 2100 F range is about 4.8×10^{-5} in./in./F. This alloy is quite similar to other titanium alloys (1).

2.0141 Thermal expansion of beta processed forging, Figure 2.0141.

2.015 Specific heat.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density, 0.168 lb/in.3. The density of this alloy is approximately 5 percent greater than Ti-6Al-4V but about 4 percent less than the beta alloys Ti-13V-11Cr-3Al and Ti-8Mo-8V-2Fe-3Al.

2.022 Electrical properties.

2.023 Magnetic properties.

2.024 Emittance.

2.025 Damping capacity.

2.03 Chemical Environments

The behavior of this alloy in aggressive chemical environments has essentially not been investigated, presumably because its intended use is in benign environments. The reader, nevertheless, should refer to the discussion of chemical environmental effects on

titanium alloys in section 2.03 of alloy chapter 3725. A single finding shows essentially no effect of 3.5 percent NaCl solution on fatigue crack-growth rates above 2 x 10^{-6} in./cycle at R = 0.05 at frequencies ranging from 1 to 30 Hz for an airframe structural forging (Compare Figure 3.0510 with Figure 3.059).

2.04 Nuclear Environments

3 MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 Producer's guaranteed minimum mechanical properties, Table 3.011.

3.012 User's specified minimum mechanical properties, Table 3.012.

3.02 Mechanical Properties at Room Temperature

3.021 Tension – Stress-strain diagrams – Tension properties, see also 3.031, 3.06, and 4.01.

3.0211 Room temperature true stress-true strain curves for hot-rolled plate water quenched from several solution temperatures, Figure 3.0211.

3.0212 Room temperature true stress-true strain behavior of hot-rolled plate solution treated plus aged to three microstructural conditions, Figure 3.0212.

3.0213 Room temperature tensile properties of directly aged hot-rolled plate, Table 3.0213.

3.0214 Room temperature tensile properties of duplex aged hot-rolled plate, Table 3.0214.

3.0215 Comparison of directionality of room temperature tensile properties of hot-rolled plate beta solution treated plus aged and alpha + beta solution treated plus aged to fixed yield strength levels, Table 3.0215.

3.0216 Room temperature tensile properties of as-forged and heat treated hot die, alpha-beta forged pancake forging, Table 3.0216.

3.0217 Statistical variation of room temperature tensile properties of hot die press forged pancakes, Table 3.0217.

3.0218 Room temperature tensile properties of as-forged and heat treated hot die, beta forged airframe structural forgings, Table 3.0218.

3.0219 Effect of solution treatment temperature on room temperature tensile properties of 1-inch thick hot-rolled plate solution treated plus aged at 932 F in air or liquid salt, Figure 3.0219.

3.02110 Effect of solution treatment temperature on room temperature tensile yield strength, true fracture stress and true fracture strain of hot-rolled plate solution treated (primary alpha contents from 30 percent to 0 percent) and aged to maximum strength attainable at 932 F, Figure 3.02110.

3.02111 Effect of supratransus solution anneal temperature on room temperature tensile properties of pressed 1-inch square, beta-forged plus solution treated and aged, Figure 3.02111.

3.02112 Effect of subtransus solution anneal temperature on room temperature tensile properties of pressed 3-inch square, beta forged plus solution treated and aged, Figure 3.02112.

3.02113 Effect of solution treatment time on room temperature tensile properties of 1-inch thick hot-rolled plate solution treated and aged, Figure 3.02113.

3.02114 Effect of solution anneal time and aging temperature on room temperature tensile properties of 1/4-inch and 1-inch plate, Table 3.02114.

3.02115 Effect of solution treatment time and quench rate and of aging temperature on room temperature tensile properties of alpha-beta forged bar solution treated at 1400 F and aged, Figure 3.02115.

3.02116 Effect of solution treatment quench rate and of aging temperature on room temperature tensile properties of alpha-beta forged bar solution treated at 1350 F and aged (low center ductility of water quenched product due to high level of segregated iron at bar center), Figure 3.02116.

3.02117 Effect of aging temperature and test direction on room temperature tensile properties of forged bar, Figure 3.02117.

3.02118 Effect of aging temperature and test direction on room temperature tensile properties of forged bar, Figure 3.02118.

3.02119 Effect of aging temperature on room temperature tensile properties of alpha-beta forged bar solution treated and aged (low center ductility due to high level of segregated iron at bar center), Figure 3.02119.

3.02120 Effect aging temperature on room temperature tensile properties of alpha-beta forged bar solution treated and aged (low center ductility due to high level of segregated iron at bar center), Figure 3.02120.

3.02121 Effect of aging temperature on room temperature tensile properties of alpha-beta forged bar solution treated and aged, Figure 3.02121.

3.02122 Effect of aging temperature on room temperature tensile properties of alpha-beta forged bar double solution treated and aged, Figure 3.02122.

3.02123 Effect of aging temperature on room temperature tensile properties of solution treated and aged 3-inch round forged bar beta processed with final reduction below the beta transus, Figure 3.02123.

3.02124 Effect of aging temperature on room temperature tensile properties of solution treated and aged 3-inch round forged bar beta processed, Figure 3.02124.

3.02125 Effect of aging time on room temperature tensile properties of 1-inch thick hot-rolled plate beta solution treated at 1562 F and aged in salt at 932 F, Figure 3.02125.

3.02126 Effect of aging time on room temperature tensile properties of 1-inch thick hot-rolled plate alpha + beta solution treated at 1328 F and aged in salt at 698 F, Figure 3.02126.

3.02127 Effect of 932 F age time on room temperature yield strength and true fracture strain of hot-rolled plate containing 10 percent constant primary alpha content, heated at two rates to the aging temperature, Figure 3.02127.

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

3.02128 Effect of aging time on room temperature tensile properties of 1-inch thick hot-rolled plate alpha + beta solution treated at 1436 F and aged in air at 932 F, Figure 3.02128.

3.02129 Effect of aging time on room temperature tensile properties of 1-inch thick hot-rolled plate alpha + beta solution treated at 1436 F and aged in salt at 932 F, Figure 3.02129.

3.02130 Effect of aging time on room temperature ultimate tensile strength of plate of two thicknessses, Figure 3.02130.

3.02131 Effect of aging time on room temperature tensile properties of pressed 5-inch square, beta forged plus directly aged at 950 F, Figure 3.02131.

3.02132 Effect of aging time on room temperature tensile properties of pressed 5-inch square, beta forged plus directly aged at 1000 F, Figure 3.02132.

3.02133 Effect of aging time on room temperature tensile properties of pressed 5-inch square, beta forged plus solution treated and aged at 950 F, Figure 3.02133.

3.02134 Effect of aging time on room temperature tensile properties of pressed 5-inch square, beta forged plus solution treated and aged at 1000 F, Figure 3.02134.

3.02135 Effect of section thickness on room temperature tensile properties of pressed squares, as-beta forged, Figure 3.02135.

3.02136 Effect of section thickness on room temperature transverse tensile properties of pressed squares, beta forged plus directly aged at 1000 F, Figure 3.02136.

3.02137 Effect of section thickness on room temperature longitudinal tensile properties of pressed squares, beta forged plus directly aged at 1000 F, Figure 3.02137.

3.02138 Effect of section thickness on room temperature tensile properties of pressed squares, beta forged plus solution treated, Figure 3.02138.

3.02139 Effect of section thickness on room temperature tensile properties of pressed squares, beta forged plus solution treated and aged at 900 F, Figure 3.02139.

3.02140 Effect of section thickness on room temperature longitudinal tensile properties of pressed squares, beta forged plus solution treated and aged at 950 F, Figure 3.02140.

3.02141 Effect of section thickness on room temperature transverse tensile properties of pressed squares, beta forged plus solution treated and aged at 950 F, Figure 3.02141.

3.02142 Effect of section thickness on room temperature tensile properties of pressed squares, beta forged plus solution treated and aged at 1000 F, Figure 3.02142.

3.02143 Effect of section thickness on room temperature transverse tensile properties of pressed squares, beta forged plus solution treated and aged at 1000 F, Figure 3.02143.

3.02144 Relation between tensile yield strength and true fracture strain or reduction in area for various microstructures, Figure 3.02144.

3.02145 Room temperature tensile properties for selected microstructures, Table 3.02145.

3.02146 Room temperature strength, elongation, and true fracture strain for selected microstructures, Table 3.02146.

3.02147 Effect of microstructure on room temperature tensile properties of hot-rolled plate solution treated and aged to an approximate common yield strength level, Table 3.02147.

3.02148 Loss in room temperature ductility arising from a continuous grain boundary alpha layer in the microstructure of an isothermally forged pancake, Table 3.02148.

3.02149 Room temperature tensile properties of three solution treated and aged isothermally forged pancakes, Table 3.02149.

3.02150 Room temperature tensile properties of isothermally forged pancake solution treated or duplex solution treated prior to aging to nearly equal yield strength level, Table 3.02150.

3.022 Compression–Stress-strain diagrams–Compression properties, see 3.032.

3.023 Impact.

3.0231 Room temperature Charpy V impact energy of heat treated bar, Table 3.0231.

3.024 Bending.

3.025 Torsion and shear, see 3.035.

3.026 Bearing, see 3.036.

3.027 Stress concentration.

3.0271 Notch properties.

3.02711 Room temperature smooth and mild-notch tensile strengths for heat treated bar, Table 3.02711.

3.0272 Fracture toughness, see also Figures 4.0132 and 4.0135 and Table 4.031.

A wide range of strength/toughness combinations can be achieved in this alloy depending on the composition, processing, and heat treated condition of the product, as illustrated in Figure 3.02721. Some specific effects are represented in Figures and Tables 3.02722 through 3.02728. Superior fracture toughness accrues from beta processing with limited alpha/beta work and oxygen content limited to 0.13 weight percent.

3.02721 Summary representation of room temperature plane strain fracture toughness as a function of tensile yield strength for all products and conditions reported in the reference literature, Figure 3.02721.

3.02722 Room temperature plane strain fracture toughness of heat treated bar, Table 3.02722.

3.02723 Room temperature tensile properties and plane strain fracture toughness of 5/16-inch hot-rolled plate after various heat treatments, Table 3.02723.

3.02724 Effect of section thickness and heat treatment on room temperature tensile yield strength and plane strain fracture toughness of beta forged pressed squares, Figure 3.02724.

3.02725 Effect of die temperature on room temperature strength and toughness of forging, beta forged plus directly aged, Figure 3.02725.

3.02726 Room temperature plane strain fracture toughness of as-forged and heat treated hot die, beta forged airframe structural forgings, Table 3.02726.

3.02727 Room temperature conventional tensile properties and plane strain fracture toughness of heat

	treated airframe structural forging, Table 3.02727.
3.02728	Effect of oxygen content on room temperature ultimate tensile strength and plane strain fracture toughness of rolled plate, Table 3.02728.
3.028	Combined properties.
3.03	Mechanical Properties at Various Temperatures
3.031	Tension–Stress-strain diagrams–Tension properties, see also 3.021, 3.06, and 4.01.
3.0311	Typical tensile stress-strain curves at room temperature, 400 F, and 800 F for heat treated bar, Figure 3.0311.
3.0312	Effect of test temperature on tensile properties of heat treated bar, Figure 3.0312.
3.0313	Room temperature and 600 F tensile properties of pressed squares, beta forged after various heat treatments, Table 3.0313.
3.0314	Effect of test temperature on tensile properties of as-forged and heat treated hot die, beta forged airframe structural forgings, Figure 3.0314.
3.0315	Effect of very high test temperatures on tensile properties at two strain rates for beta cogged bar, Figure 3.0315.
3.0316	Comparison of strain rate and test temperature effects on tensile yield strength of Ti-10V-2Fe-3Al and Ti-6Al-4V alloys, Figure 3.0316.
3.032	Compression–Stress-strain diagrams–Compression properties.
3.0321	Typical compressive stress-strain curves at room temperature, 400 F, and 800 F for heat treated bar, Figure 3.0321.
3.0322	Effect of test temperature on compressive yield strength of heat treated bar, Figure 3.0322.
3.033	Impact.
3.034	Bending.
3.035	Torsion and shear.
3.0351	Effect of test temperature on shear ultimate strength of heat treated bar, Figure 3.0351.
3.036	Bearing.
3.0361	Effect of test temperature on bearing strength of heat treated bar, Figure 3.0361.
3.037	Stress concentration.
3.0371	Notch properties.
3.0372	Fracture toughness.
3.038	Combined properties.
3.04	Creep and Creep-Rupture Properties
3.041	Creep curves at 600 F, 100 ksi for heat treated hot die, beta forged airframe structural forgings, Figure 3.041.
3.042	Creep deformation and rupture curves at 700 F for heat treated bar, Figure 3.042.
3.043	Creep deformation and rupture curves at 900 F for heat treated bar, Figure 3.043.
3.044	Room temperature step-loaded mild-notch creep rupture properties of pressed squares, beta forged after various heat treatments, Table 3.044.
3.045	Effect of 600 F, 100 ksi, 100 hr creep exposure on subsequent room temperature tensile properties of pressed squares, beta forged after various heat treatments, Table 3.045.
3.046	Effect of 600 F, 100 ksi creep exposure on subsequent room temperature tensile properties of hot die, beta forged airframe structural forgings after various heat treatments, Table 3.046.
3.05	Fatigue Properties
3.051	Room temperature smooth and notch axial load fatigue properties of heat treated bar, Figure 3.051.
3.052	Smooth and notch axial load fatigue properties at 400 F of heat treated bar, Figure 3.052.
3.053	Smooth and notch axial load fatigue properties at 800 F of heat treated bar, Figure 3.053.
3.054	Room temperature smooth and notch axial load fatigue properties of heat treated forging, Figure 3.054.
3.055	Room temperature smooth fatigue properties of heat treated beta forged airframe structural forging, Figure 3.055.
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3.057	Room temperature single-hole specimen fatigue properties of heat treated beta forged airframe structural forging, Figure 3.057.
3.058	Room temperature double-hole specimen fatigue properties of heat treated beta forged airframe structural forging, Figure 3.058.
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3.0510	Room temperature fatigue crack-growth in 3.5 percent NaCl solution for airframe structural forging, Figure 3.0510.
3.0511	Room temperature fatigue crack-growth rates for hot-rolled plate solution treated and alpha-aged to five different microstructural conditions, all at approximately the same yield strength level, Figure 3.0511.
3.0512	Room temperature fatigue crack-growth rates for hot-rolled plate solution treated and either alpha-aged or omega-aged to a common yield strength level, Figure 3.0512.
3.0513	Effect of test direction on room temperature fatigue crack-growth rate for hot-rolled plate solution treated and alpha-aged, Figure 3.0513.
3.0514	Room temperature fatigue crack-growth rates for solution treated and aged isothermally forged pancakes, Figure 3.0514.
3.0515	Room temperature fatigue crack-growth rates for isothermally forged pancake solution treated or duplex solution treated prior to aging to nearly equal yield strength levels, Figure 3.0515.
3.0516	Room temperature fatigue crack-growth rates for isothermally forged pancake solution treated and aged (elongated primary alpha) or duplex solution treated and aged (continuous grain boundary alpha-layer), Figure 3.0516.

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

3.06 Elastic Properties
3.061 Poisson's ratio.
3.062 Modulus of elasticity.
3.0621 Room temperature ultimate strength and elastic modulus for plate of various thicknesses, beta-rolled and directly aged, Figure 3.0621.
3.0622 Effect of test temperature on tensile elastic modulus of heat treated bar, Figure 3.0622.
3.0623 Room temperature and 600 F tensile elastic modulus for heat treated forging, Table 3.0623.
3.0624 Effect of test temperature on compressive elastic modulus of heat treated bar, Figure 3.0624.
3.0625 Room temperature strength, elastic modulus, and plane strain fracture toughness of electron beam welded plate, Table 4.031.
3.063 Modulus of rigidity.
3.064 Tangent modulus.
3.0641 Typical compressive tangent modulus curves at room temperature, 400 F, and 800 F for heat treated bar, Figure 3.0641.
3.065 Secant modulus.

4 FABRICATION

4.01 Forming
4.011 Hot flow properties. The beta transus of this alloy is only about 1460 F, making it amenable to hot die beta forging at a stock temperature of 1500 to 1550 F with a die temperature at or below 1550 F. Required forge pressure under a forge temperature of 1550 F and a die temperature of 1400 F is comparable to that for Ti-6Al-4V alloy at a forge temperature of 1750 F and a die temperature of 1650 F (see Figures 4.0111 and 4.0112). This advantage derives from the favorable comparison of hot flow stress-strain rate characteristics of this alloy as compared with those for Ti-6Al-4V, as shown in Figure 4.0113.
This alloy is well suited to isothermal forging as indicated by the results in Table 4.0114 and Figures 4.0115 and 4.0116. A strong chill factor is evident from the data in Table 4.0114 Nevertheless, the results in Figures 4.0115 and 4.0116 suggest a much larger plan area for isothermal forging is possible with this alloy compared to Ti-6Al-4V. The slope of the log true stress/log true strain curve for this alloy at 1500 F is not linear as indicated in Figure 4.0117, suggesting this alloy exhibits a mild tendency toward superplasticity. This alloy is very resistant to cracking and good as-forged surfaces generally result from isothermal forging. Use of Acheson and TRW coatings provide excellent surface finishes in most cases.
4.0111 Variation of forge pressure with web thickness for Ti-10V-2Fe-3Al experimental rib-and-web forgings, Figure 4.0111.
4.0112 Variation of forge pressure with web thickness for Ti-6Al-4V and Ti-10V-2Fe-3Al experimental structural shape forgings, Figure 4.0112.
4.0113 Hot flow stress Ti-10V-2Fe-3Al compared to that of Ti-6Al-4V, Figure 4.0113.
4.0114 Results of hot compression tests, Table 4.0114.
4.0115 Temperature dependence of tensile yield strength for Ti-10V-2Fe-3Al and Ti-6Al-4V alloys, Figure 4.0115.
4.0116 Hot compression test results, Figure 4.0116.
4.0117 Strain rate sensitivity of Ti-10V-2Fe-3Al at 1500 F, Figure 4.0117.
4.012 Heat transfer. Table 4.0121 gives the cooling rate in air for various section thicknessses of this alloy in a flat monolithic forging, indicating achievable properties are limited by the quench. Immediate quenching out of the furnace becomes important as section size decreases. Depending on forging section variations, quench delays can be used to provide property uniformity throughout the forging.
4.0121 Heat transfer in flat monolithic forging during air cool, Table 4.0121.
4.013 Forging procedures and effects on properties. The properties of this alloy are strongly dependent on the forging practice employed. In this regard, beta forging is essential for the low strength, high toughness condition.
To balance ductility and toughness in the high strength condition, beta blocking with some alpha/beta finishing is required. The amount of alpha/beta finishing required will depend on the die and forging designs, whether a press or hammer is used, and the metal flow pattern. Experience (1) with billet has indicated that whereas 30 percent alpha/beta reduction provides ductility without seriously affecting K_{Ic}, 60 percent reduction degrades K_{Ic} significantly. That experience holds also in a general way for high strength hand or die forgings. Alpha/beta reduction, therefore, should be limited in the interest of both ductility and toughness. In press forged parts, alpha/beta finishing should be limited to 10 to 25 percent. During alpha/beta hammer forging, adiabatic heating should be avoided or controlled so that local regions do not exceed the desired working temperature.
4.0131 Effect of forging temperature and percent reduction on room temperature tensile properties of forged pancakes, Figure 4.0131.
4.0132 Effect of forging temperature on room temperature tensile yield strength and plane strain fracture toughness of heat treated 1-inch thick upset forgings, Figure 4.0132.
4.0133 Effect of upset forging temperature on room temperature tensile properties of heat treated 1-inch thick upset forgings, Figure 4.0133.
4.0134 Effect of upset forging temperature on room temperature tensile properties of forged plus directly aged 1-inch thick upset forgings, Figure 4.0134.
4.0135 Effect of forging temperature on room temperature tensile yield strength and plane strain fracture toughness of forged plus directly aged 1-inch thick upset forgings, Figure 4.0135.
4.0136 Effect of upset temperature on room temperature tensile properties of 1-inch thick forged upsets, Table 4.0136.
4.0137 Effect of isothermal forging conditions on room temperature tensile properties of solution treated and aged forged pancakes, Table 4.0137.
4.0138 Conversion schedule for 3-inch diameter bar isothermally forged to 0.5-inch thick flat plate for use in processing and heat treatment study reported upon in Tables 4.0139 through 4.01311, Figure 4.0138.

4.0139	Room temperature tensile properties of supratransus processed 3-inch round bar conventionally and isothermally subtransus forged to 0.5-inch thick flat plate and variously heat treated, Table 4.0139.
4.01310	Room temperature tensile properties of supratransus processed 3-inch round bar conventionally and isothermally supratransus forged to 0.5-inch flat plate and variously heat treated, Table 4.01310.
4.01311	Room temperature tensile properties of subtransus processed 3-inch round bar conventionally and isothermally subtransus forged to 0.5-inch thick flat plate and variously heat treated, Table 4.01311.
4.01312	Room temperature tensile and cold deformability properties of hot-rolled bar variously heat treated, Table 4.01312.

4.02 **Machining and Grinding**

This alloy is somewhat more difficult to machine than Ti-6Al-4V but less difficult than all beta titanium alloys (1). When water quenching is used during heat treatment there can be distortion during machining resulting from locked-in quenching stresses, but because of the alloy's low creep strength at the aging temperature, distortion is not excessive.

4.03 **Joining**

The weldability of this alloy is judged (7) to be comparable to that for Ti-6Al-4V. It can be electron beam welded using parameters similar to those for Ti-6Al-4V. Data are presented in Table 4.031 for two heat treated conditions. As expected, variations in heat treatment produce significant differences in mechanical properties, but weld properties are generally comparable to those of the base metal.

4.031	Room temperature strength, elastic modulus, and plane strain fracture toughness of electron beam welded plate, Table 4.031.

4.04 **Surface Treating**

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2 Fe
3 Al

Ti-10-2-3

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

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Alloy	Ti-10V-2Fe-3Al	
Form	Billet, Bar, Plate, and Forgings	
	Weight Percent	
Composition	Min	Max
Al	2.6	3.4
V	9.0	11.0
Fe	1.7	2.2
O		0.13
C		0.05
N		0.05
H		0.015
Other, Each		0.10
Other, Total		0.30
Ti	Balance	

TABLE 1.041. PRODUCER'S SPECIFIED COMPOSITION (1)

Alloy	Ti-10V-2Fe-3Al	
Form	Forgings	
	Weight Percent[a]	
Composition	Min	Max
Al	2.6	3.4
V	9.0	11.0
Fe	1.7	2.2
O		0.13
C		0.05
N		0.05
H		0.015[b]
Y		0.005
Other, Each		0.10
Other, Total		0.30
Ti	Balance	

(a) Check analysis shall be in accordance with AMS 2249.
(b) Hydrogen shall be determined on each lot of the product as shipped.

TABLE 1.042. USER'S SPECIFIED COMPOSITION (22)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al					
Form	1-inch Cubes					
Solution Temperature	1300 F		1350 F		1375 F	
Cooling Rate from Solution Temp[a]	VC	WQ	VC	WQ	VC	WQ
Aging Treatment	Hardness, R_C[b]					
None	30.3	29.6	35.8	32.4	35.5	30.3
900 F, 8 hr, AC	36.1	38.1	35.0	40.3	35.4	41.2
925 F, 8 hr, AC	33.1	32.8	35.5	38.8	33.2	36.5
950 F, 8 hr, AC	32.7	34.5	35.4	37.0	34.8	37.7

(a) VC = Cool from solution temperature under vermiculate; WQ = Water quench.
(b) Average of eight measurements.

TABLE 1.067. EFFECT OF SOLUTION TEMPERATURE AND COOLING RATE ON AGED HARDNESS OF 1-INCH CUBES (1)

Alloy	Ti-10V-2Fe-3Al									
Form	Forgings and Plate									
				e, percent			RA, percent			
Heat Treatment	Section Size, inch	F_{ty}, ksi	F_{tu}, ksi	L	T	ST	L	T	ST	
Solution Treat + Age	≤1	170	180	10	10	–	20	20	–	
1400-1425 F, 1 hr, WQ	>1-2	160	170	10	10	–	20	20	–	
+ 900-950 F, 8 hr, AC	>2-4	150	160	8	8	8	15	15	12	
	>4-5	145	155	8	8	8	15	15	12	
Solution Treat + Overage[a]										
1350-1400 F, 1 hr, AC or Faster	≤3	130	140	10	10	–	20	20	–	
+1075 F, 8 hr, AC	>3-5	125	135	10	10	8	20	20	15	

(a) Higher solution treat + overage strengths can be obtained by using lower overaging temperatures.

TABLE 3.011. PRODUCER'S GUARANTEED MINIMUM MECHANICAL PROPERTIES (1) (22)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al
Form	Forgings
Condition	Optional Duplex Solution Treat Plus Age < $T_{\beta(Min)}$[a], 1/2 hr Min, FC or AC + Standard Solution Treat Standard Solution Treat Plus Age 1350 F Min but < $T_{\beta(Min)}$[a], 1/2 hr Min, WQ + 900 F Min, 8 hr Min, AC
F_{tu}, ksi	180
F_{ty}, ksi	160
e (4D), percent	4
RA, percent	Report for Information Only.
K_{Ic}, ksi$\sqrt{in.}$	40

(a) Minimum beta transus temperature for the lot of forgings.

TABLE 3.012. USER'S SPECIFIED MINIMUM MECHANICAL PROPERTIES (22)

Alloy	Ti-10V-2Fe-3Al			
Form	1-inch Thick Hot-Rolled Plate, Beta Processed With Final 50% Reduction in Alpha-Beta Field Starting From 1292 F			
Direct Aging Treatment	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
None	132	136	7.8	51
932 F, 1.7 hr in Liquid Nitrate Salt	145	154	15.7	53
752 F, 16.7 hr in Liquid Nitrate Salt	158	174	13.5	44
392 F, 166.7 hr in Liquid Nitrate Salt	148	149	16.0	47

TABEL 3.0213. ROOM TEMPERATURE TENSILE PROPERTIES (LONGITUDINAL) OF DIRECTLY AGED HOT-ROLLED PLATE (18)

Alloy	Ti-10V-2Fe-3Al			
Form	1-inch Thick Hot-Rolled Plate, Beta Processed With Final 50% Reduction in Alpha-Beta Field Starting From 1292 F			
Condition	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
1346 F, 11.7 hr, WQ + 572 F, 5 hr in Liquid Nitrate Salt + 932 F, 76 hr in Liquid Nitrate Salt	148	150	4.4	15.4
1562 F, 2 hr, WQ + 572 F, 2.5 hr in Liquid Nitrate Salt + 932 F, 0.33 hr in Liquid Nitrate Salt	Brittle Fracture	--	--	--
1562 F, 2 hr, WQ + 572 F, 3 hr in Liquid Nitrate Salt + 932 F, 80 hr in Liquid Nitrate Salt	210	211	0.67	3.1

TABLE 3.0214. ROOM TEMPERATURE TENSILE PROPERTIES (LONGITUDINAL) OF DUPLEX AGED HOT-ROLLED PLATE (18)

Alloy	Ti-10V-2Fe-3Al				
Form	1-inch Thick Hot-Rolled Plate, Beta Processed With Final 50% Reduction in Alpha-Beta Field Starting From 1292 F				
Condition	Test Direction	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
Beta Solution Treated, WQ + 932 F, 0.1 hr in Liquid Nitrate Salt	L	192	200	5.5	28.0
Beta Solution Treated, WQ + 932 F, 4 hr in Liquid Nitrate Salt	T	192	203	7.5	4.1
1328 F, 0.83 hr, WQ + 698 F, 16.7 hr in Liquid Nitrate Salt	L	187	206	5.0	11.0
1328 F, 1.7 hr, WQ + 698 F, 13.3 hr in Liquid Nitrate Salt	T	187	213	5.0	10.0

TABLE 3.0215. COMPARISON OF DIRECTIONALITY OF ROOM TEMPERATURE TENSILE PROPERTIES OF HOT-ROLLED PLATE BETA SOLUTION TREATED PLUS AGED AND ALPHA + BETA SOLUTION TREATED PLUS AGED TO FIXED YIELD STRENGTH LEVELS (18)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al				
Form	Hot Die, Alpha-Beta Forged Pancake Forging				
		RT Tensile Properties			
Condition	Specimen Location	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
As Forged 1425 F, AC (Die Temp 1425 F)	RT1	139.0	153.0	9.5	20.2
	RT2	140.0	152.2	9.5	21.2
	TT6	142.0	156.0	8.8	12.0
	TT5	140.0	154.4	9.5	21.2
	TT4	141.6	155.6	8.1	16.1
	TT3	144.0	157.6	9.5	21.2
	TT2	142.4	155.6	7.4	19.0
	TT1	140.4	153.0	10.2	22.4
1400 F, 1 hr, WQ	RT1	96.8	122.0	34.8	41.4
	RT2	98.0	122.0	30.5	38.5
	TT5	94.0	122.0	34.8	42.3
	TT4	92.8	121.6	33.3	39.7
	TT3	94.0	121.6	32.0	38.8
	TT2	94.0	119.2	30.5	38.8
	TT1	94.0	119.2	30.5	38.8
1400 F, 1 hr, WQ + 950 F, 8 hr, AC	RT2	180.8	190.8	8.1	18.2
	TT6	188.4	197.8	8.1	17.2
	TT5	189.0	197.8	8.1	13.0
	TT4	185.0	194.0	8.1	17.2
	TT3	187.2	196.0	6.7	14.8
	TT2	185.6	193.6	8.1	18.2
	TT1	186.4	196.0	8.1	15.1

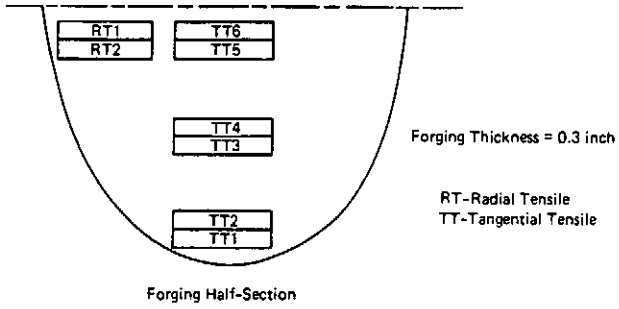


TABLE 3.0216. ROOM TEMPERATURE TENSILE PROPERTIES OF AS-FORGED AND HEAT TREATED HOT DIE, ALPHA-BETA FORGED PANCAKE FORGING (2)

Alloy	Ti-10V-2Fe-3Al			
Form	Hot Die Press Forged Pancakes Upset From 1.72 inch to 0.29 inch			
Condition	RT Tensile Properties	Mean, $\bar{X}$	Std Dev, S	Number of Samples, N
As Forged 1425 F, AC	F_{tu}, ksi	155	1.9	8
	F_{ty}, ksi	141	1.6	8
	e, percent	9.1	0.9	8
	RA, percent	19.2	3.5	8
As Forged + 1400 F, 1 hr, WQ	F_{tu}, ksi	121	1.3	7
	F_{ty}, ksi	95	1.9	7
	e, percent	32.3	2.0	7
	RA, percent	39.8	1.5	7
As Forged + 1400 F, 1 hr, WQ + 950 F, 8 hr, AC	F_{tu}, ksi	195	2.5	7
	F_{ty}, ksi	186	2.8	7
	e, percent	7.9	0.5	7
	RA, percent	16.2	2.0	7

TABLE 3.0217. STATISTICAL VARIATION OF ROOM TEMPERATURE TENSILE PROPERTIES OF HOT DIE PRESS FORGED PANCAKES (9)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al						
Form	Hot Die, Beta Forged Airframe Structural Forgings						
				RT Tensile Properties			
Condition	Specimen Location	Test Direction	Section Thickness, inch	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
As Forged 1550 F, AC	TR1 (Rib)	L	0.3	174.8	188.4	8.1	20.2
(Die Temp 1550 F)	TR2 (Rib)	L	0.3	176.0	189.6	9.5	26.1
	TR3 (Rib)	ST	1.2	159.6	174.4	9.5	38.8
	TW1 (Web)	L	0.6	162.8	178.4	9.5	20.2
	TW2 (Web)	L	0.6	166.0	183.0	6.7	10.9
	TW3 (Web)	T	0.6	160.8	177.2	8.8	17.2
	TW4 (Web)	T	0.6	167.0	180.8	8.7	22.3
1400 F, 1 hr, WQ +	TR1 (Rib)	L	0.3	174.0	185.0	9.5	19.0
950 F, 8 hr, AC	TR2 (Rib)	L	0.3	174.0	185.2	10.9	31.7
	TR3 (Rib)	ST	1.2	174.0	186.4	8.1	21.2
	TR4 (Rib)	T	1.2	172.6	184.5	6.7	33.0
	TW1 (Web)	L	0.6	166.0	176.0	11.6	24.6
	TW2 (Web)	L	0.6	174.0	183.8	8.1	16.1
	TW3 (Web)	T	0.6	174.4	183.0	8.8	19.0
	TW4 (Web)	T	0.6	179.0	185.2	9.3	26.0
1350 F, 1 hr, AC +	TR1 (Rib)	L	0.3	136.8	144.0	22.8	55.5
1075 F, 8 hr, AC	TR2 (Rib)	L	0.3	135.6	142.0	20.7	57.0
	TR3 (Rib)	ST	1.2	128.8	138.0	19.3	54.8
	TR4 (Rib)	T	1.2	131.6	140.8	20.7	56.2
	TW2 (Web)	L	0.6	134.0	141.6	22.1	56.2
	TW3 (Web)	T	0.6	130.0	138.4	22.1	57.0
	TW4 (Web)	T	0.6	129.6	138.4	20.7	55.5
	TW5 (Web)	T	0.6	131.2	140.8	20.0	54.0
	TW6 (Web)	T	0.6	134.8	144.2	20.0	53.6

All forgings produced from a single starting bar.

See Figure 3.0314 for elevated temperature tensile properties, Table 3.02726 for fracture toughness results, Figure 3.041 for creep curves, and Table 3.046 for effect of exposure to elevated temperature with load on RT tensile properties, all from these same forgings.

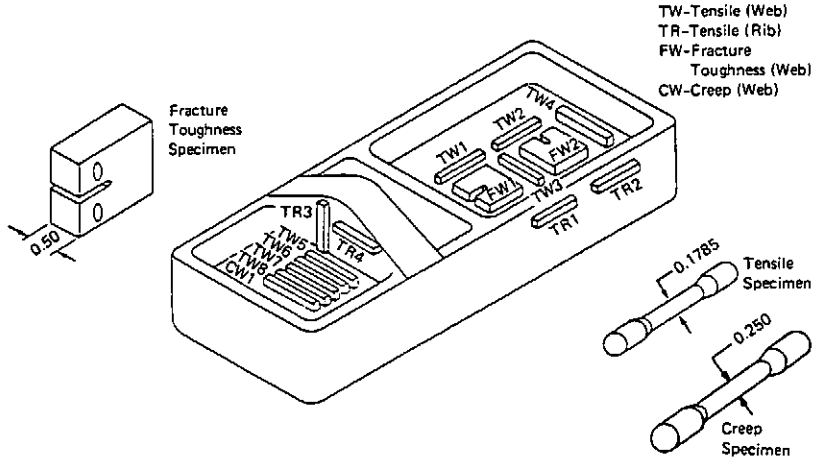


TABLE 3.0218. ROOM TEMPERATURE TENSILE PROPERTIES OF AS-FORGED AND HEAT TREATED HOT DIE, BETA FORGED AIRFRAME STRUCTURAL FORGINGS (2) (1)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al			
Form	Plate			
	RT Tensile Properties			
Condition	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
1/4-inch Plate				
1400 F, 1/2 hr, AC	144	158	6	11
1400 F, 1/2 hr, AC + 950 F, 8 hr, AC	183	192	8	19
1400 F, 1 hr, AC + 950 F, 8 hr, AC	185	194	8	21
1400 F, 2 hr, AC + 950 F, 8 hr, AC	182	193	9	19
1400 F, 1/2 hr, AC + 1050 F, 8 hr, AC	154	163	14	40
1400 F, 2 hr, AC + 1050 F, 8 hr, AC	161	169	9	27
1-inch Plate				
1400 F, 1/2 hr, AC	150	166	6	13
1400 F, 1/2 hr, AC + 950 F, 8 hr, AC	155	170	12	31
1400 F, 1 hr, AC + 950 F, 8 hr, AC	160	177	10	20
1400 F, 2 hr, AC + 1050 F, 8 hr, AC	162	177	7	16
1400 F, 1/2 hr, AC + 1050 F, 8 hr, AC	141	150	16	50
1400 F, 2 hr, AC + 1050 F, 8 hr, AC	146	157	14	38

Beta transus temperature = approx. 1467 F.

TABLE 3.02114. EFFECT OF SOLUTION ANNEAL TIME AND AGING TEMPERATURE TENSILE PROPERTIES OF 1/4-INCH AND 1-INCH PLATE (9)

Alloy	Ti-10V-2Fe-3Al					
Form	1.75-inch x 7-inch Cross Section Forged Plate Hot-Rolled From 1346 to 1-inch x 4.5-inch Cross Section Plate					
Heat Treatment	Microstructure	F_{ty}, ksi	F_{tu}, ksi	Uniform Elongation, percent	e, percent	RA, percent
1346 F, 48 hr, WQ	20% Primary $\alpha + \beta$ + Athermal ω	107.5	125.1	9.7	18.6	35.0
1562 F, 2 hr, WQ	β + Athermal ω	38.0	127.4	15.7	21.8	32.0
1292 F, 5 hr, WQ + 482 F, 100 hr	$\alpha + \beta$ + Isothermal ω	176.8	182.7	0.26	0.58	2.25
1562 F, 2 hr, WQ + 482 F, 166.7 hr	β + Isothermal ω	Brittle-No Yield	–	0	0	0
1328 F, 1.7 hr, WQ + 698 F, 16.7 hr	20% Primary $\alpha + \beta$ + Uniform α	180.0	207.4	2.7	8.9	16.0
1562 F, 1.7 hr, WQ + 698 F, 16.7 hr	β + Uniform α	Brittle-No Yield	–	0	0	0
1346 F, 12 hr, WQ + 932 F, 1 hr	20% Primary $\alpha + \beta$ + Sympathetic α	154.3	160.5	4.6	17.5	58.0
1562 F, 1.7 hr, WQ + 932 F, 4 hr	β + Sympathetic α	177.8	180.4	2.3	8.7	14.0

TABLE 3.02145. ROOM TEMPERATURE TENSILE PROPERTIES FOR SELECTED MICROSTRUCTURES (17)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al					
Form	Hot-Rolled Plate and Forged Pancakes					
Condition	Heat Treatment	Microstructure	F_{ty}, ksi	F_{tu}, ksi	e, percent	True Fracture Strain
Hot-Rolled Plate, Beta Processed With Final Working Step in Alpha + Beta Field Starting From 1346 F (Globular Primary α)						
I	1337 F, 20 hr, WQ + 932 F, 1 hr (Salt)	30% Primary α + "Large" Secondary α	154.3	160.5	17.7	0.99
II	1337 F, 1.7 hr, WQ + 698 F, 16.7 hr (Air)	30% Primary α + "Small" Secondary α	180.8	206.0	7.6	0.19
III	1436 F, 3 hr, WQ + 932 F, 1 hr (Salt)	10% Primary α + "Large" Secondary α	174.4	181.0	10.3	0.63
IV	1436 F, 3 hr, WQ + 932 F, 1 hr (Air)	10% Primary α + "Small" Secondary α	209.7	224.1	2.4	0.09
V	1562 F, 2 hr, WQ + 932 F, 4 hr (Salt)	0% Primary α + Grain Boundary α + "Large" Secondary α	181.4	189.8	3.9	0.16
Forged Pancakes, Beta Processed With Finish Upset in Alpha + Beta Field (1425 F) (Elongated Primary α)						
VI	1292 F, 8 hr, WQ + 392, 113.6 hr (Air)	35% Primary α + ω	176.8	183.7	0.5	0.02
VII	1562 F, 2 hr, WQ + 932 F, 4 hr (Salt)	0% Primary α + "Large" Secondary α + Grain Boundary α	171.6	183.6	3.8	0.17
VIII	1400 F, 1.25 hr, WQ + 932 F, 1 hr (Salt)	~ 10% Primary α + "Large" Secondary α	188.4	200.4	4.6	0.23
IX	1292 F, 1.25 hr, WQ + 662 F, 16.7 hr (Air)	~ 30% Primary α + "Small" Secondary α	179.8	202.5	3.9	0.11

TABLE 3.02146. ROOM TEMPERATURE STRENGTH, ELONGATION, AND TRUE FRACTURE STRAIN FOR SELECTED MICROSTRUCTURES (16)

Alloy	Ti-10V-2Fe-3Al						
Form	1-inch Thick Hot-Rolled Plate, Beta Processed With Final 50% Reduction in Alpha + Beta Field[a] Starting From 1292 F						
				Room Temperature Tensile Properties			
Condition	Heat Treatment	Microstructure	Test Direction	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
1	1562 F, 2.5 hr, WQ + 932 F, 0.1 hr (Salt)[b]	100% Recrystallized, 0% Primary α, and Coarse Underaged Sympathetic α	L	179	197	4.0	11.0
			T	190	204	3.0	6.0
2	1472 F, 0.5 hr, WQ + 932 F, 4 hr (Salt)[b]	80% Recrystallized, 5% Primary α, and Coarse Sympathetic α Plates	L	178	191	8.7	13.8
			T	192	203	4.1	7.5
3	1436 F, 5.5 hr, WQ + 932 F, 1 hr (Salt)[b]	40% Recrystallized, 10% Primary α, and Coarse Peak Aged Sympathetic α	L	178	183	9.8	43.9
			T	183	191	5.5	24.6
4	1400 F, 1.7 hr, WQ + 932 F, 24 hr (Air)	0% Recrystallized, 15% Primary α, and Fine Overaged Uniform α	L	177	181	10.0	39.0
			T	188	193	5.8	28.5
5	1328 F, 1.7 hr, WQ + 698 F, 13.3 hr (Salt)[b]	0% Recrystallized, 25% Primary α, and Fine Peak Aged Sympathetic α + Uniform α	L	181	208	9.0	11.0
			T	187	213	5.0	10.0
6	1292 F, 3 hr, WQ + 500 F, 113.3 hr (Salt)[b]	0% Recrystallized, 30% Primary α, and Very Fine Isothermal ω	L	177	178	0.6	2.3
			T	205	208	1.0	1.0
	1292 F, 3 hr, WQ + 500 F, 33.3 hr (Salt)[b]		T	182	191	2.8	13.2

(a) Beta transus temperature = 1481 F.
(b) Liquid nitrate salt.

TABLE 3.02147. EFFECT OF MICROSTRUCTURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF HOT-ROLLED PLATE SOLUTION TREATED AND AGED TO AN APPROXIMATE COMMON YIELD STRENGTH LEVEL (18)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al			
Form	Isothermally Forged Pancake, Prefinished Upset 50% at 1550 F + Finish Upset 15% at 1425 F			
	Room Temperature Tensile Properties			
Heat Treatment and Microstructure	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
1364 F, 5 hr, WQ + 932 F, 2 hr in Air (Discontinuous Grain Boundary α)	178	199	4.3	12.5
1562 F, 2 hr, WQ + 1364 F, 48 hr, WQ + 932 F, 2 hr in Air (Continuous α Layer on Recrystallized β Grains)	175	181	1.3	2.0

TABLE 3.02148. LOSS IN ROOM TEMPERATURE DUCTILITY ARISING FROM A CONTINUOUS GRAIN BOUNDARY ALPHA LAYER IN THE MICROSTRUCTURE OF AN ISOTHERMALLY FORGED PANCAKE (18)

Alloy	Ti-10V-2Fe-3Al					
Form	Isothermally Forged Pancakes					
Forging Conditions						
	Prefinish Upset		Finish Upset			
Forging	Temp, F	Reduction, percent	Temp, F	Reduction, percent		
1	1550	50	1425	15		
2	1250	50	1300	15		
3	1400	50	1425	15		
Heat Treatment, Microstructure and Room Temperature Tensile Properties						
			Room Temperature Tensile Properties			
Forging	Heat Treatment	Microstructure	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
1	1364 F, 5 hr, WQ + 932 F, 24 hr (Air)	Unrecrystallized, Elongated Primary α	174	183	2.0	16.0
3	1364 F, 5 hr, WQ + 932 F, 2 hr (Air)	Recrystallized, Equiaxed Primary α	187	199	4.3	12.5
1	1364 F, 5 hr, WQ + 932 F, 2 hr (Air)	Unrecrystallized, Equiaxed Primary α	186	201	4.4	5.9

TABLE 3.02149. ROOM TEMPERATURE TENSILE PROPERTIES OF THREE SOLUTION TREATED AND AGED ISOTHERMALLY FORGED PANCAKES (18)

Alloy	Ti-10V-2Fe-3Al				
Form	Isothermally Forged Pancake, Prefinish Upset 50% at 1550 F + Finish Upset 15% at 1425 F				
		Room Temperature Tensile Properties			
Heat Treatment	Microstructure	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
1364 F, 5 hr, WQ + 932 F, 24 hr (Air)	Unrecrystallized, Elongated Primary α	174	183	2.0	16.0
1425 F, 2 hr, AC + 1400 F, 2 hr, WQ + 950 F, 8 hr (Air)	Unrecrystallized, Elongated Primary α	181	191	3.1	9.2

TABLE 3.02150. ROOM TEMPERATURE TENSILE PROPERTIES OF ISOTHERMALLY FORGED PANCAKE SOLUTION TREATED OR DUPLEX SOLUTION TREATED PRIOR TO AGING TO NEARLY EQUAL YIELD STRENGTH LEVEL (18)

Alloy	Ti-10V-2Fe-3Al	
Form	3-inch diam Bar	
Condition	1400 F, 1 hr, FC + 1050 F, 8 hr, AC	
Specimen No.	Test Direction	IE Charpy V, ft-lb
1	L	26.5
2	L	30.0
3	L	30.0
4	T	20.5
5	T	19.5
6	T	17.0

(See Figure 3.0312 for conventional tensile properties)

TABLE 3.0231. ROOM TEMPERATURE CHARPY V IMPACT ENERGY OF HEAT TREATED BAR (4)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al				
Form	0.5-inch diam Round Bar				
Heat Treatment	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent	NTS(a), ksi
1400 F, 1/2 hr, AC + 950 F, 4 hr, AC	179	188	13	39	203
	173	180	16	39	234

(a) $K_t = 8.0$.

TABLE 3.02711. ROOM TEMPERATURE SMOOTH AND MILD-NOTCH TENSILE STRENGTHS FOR HEAT TREATED BAR (1)

Alloy	Ti-10V-2Fe-3Al
Form	3-inch diam Bar
Condition	1400 F, 1 hr, FC + 1050 F, 8 hr, AC
Specimen No.	K_{Ic}, ksi$\sqrt{in.}$
1	73.9
2	74.9
3	80.3
4	80.7

L-T Crack Plane Orientation; Standard Compact Specimens, B = 1.25 inch. (See ASTM Standard E-399) (See Figure 3.0312 for conventional tensile properties)

TABLE 3.02722. ROOM TEMPERATURE PLANE STRAIN FRACTURE TOUGHNESS OF HEAT TREATED BAR (4)

Alloy	Ti-10V-2Fe-3Al			
Form	5/16-inch Hot-Rolled Plate			
Condition	F_{ty}, ksi	F_{tu}, ksi	e (1 inch), percent	K_{Ic}, ksi$\sqrt{in.}$
900 F, 2 hr, AC	181	191	9	31
900 F, 4 hr, AC	179	189	7	32
900 F, 8 hr, AC	179	189	9	29
950 F, 4 hr, AC	170	183	10	50
1400 F, 1/2 hr, AC + 950 F, 4 hr, AC	187	193	6	44
1400 F, 1/2 hr, AC + 950 F, 8 hr, AC	172	179	7	52
1400 F, 1/2 hr, AC + 1000 F, 1 hr, AC	171	185	6	49
1400 F, 1/2 hr, AC + 1000 F, 2 hr, AC	170	177	9	55

TABLE 3.02723. ROOM TEMPERATURE TENSILE PROPERTIES AND PLANE STRAIN FACTURE TOUGHNESS OF 5/16-INCH HOT-ROLLED PLATE AFTER VARIOUS HEAT TREATMENTS (13)

Alloy	Ti-10V-2Fe-3Al			
Form	Hot Die, Beta Forged Airframe Structural Forgings Forge Temp 1550 F, Die Temp 1550 F			
Condition	Specimen(a)	Crack Plane Orientation	F_{ty}, ksi	K_{Ic},(b) ksi$\sqrt{in.}$
As Forged, 1550 F, AC	FW1	T-L	163.9(c)	54.26
	FW2	L-T	164.4(d)	54.97
1400 F, 1 hr, WQ +	FW1	T-L	176.7(c)	49.24
950 F, 8 hr, AC	FW2	L-T	170.0(d)	48.35
1350 F, 1 hr, AC +	FW1	T-L	131.4(e)	> 92.65(f)
1075 F, 8 hr, AC	FW2	L-T	134.0(g)	> 92.42(f)

(a) See Table 3.0218 for specimen locations and orientations.
(b) Tests performed according to ASTM Standard Method E-399-72, using 0.5-inch thick standard compact specimens.
(c) Average of values from specimens TW3 and TW4 of Table 3.0218.
(d) Average of values from specimens TW1 and TW2 of Table 3.0218.
(e) Average of values from specimens TW3 through TW6 of Table 3.0218.
(f) Specimen thickness insufficient; therefore values is underestimate of K_{Ic}.
(g) Value from specimen TW2 of Table 3.0218.

TABLE 3.02726. ROOM TEMPERATURE PLANE STRAIN FRACTURE TOUGHNESS OF AS-FORGED AND HEAT TREATED HOT DIE, BETA FORGED AIRFRAME STRUCTURAL FORGINGS (2)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al						
Form	Boeing 747 Lower Link Fitting, Beta Forged with Alpha-Beta (≤ 20%) Finish						
Condition	1435 F, 2 hr, AC + 1425 F, 2 hr, WQ + 950 F, 8 hr, AC						
Section Thickness, inch	Conventional RT Tensile Properties					RT Plane Strain Fracture Toughness	
	Test Direction	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent	Crack Plane Orientation	K_{Ic}, ksi$\sqrt{in.}$
1-1.5	L	184.6	195.4	5.0	11.6	L-T	46.3
	T	180.0	189.6	4.5	10.0	T-L	46.0
	ST	174.9	185.0	4.0	9.3	–	–
1.5-2.0	L	177.4	186.9	5.5	16.0	L-T	48.8
	T	176.4	185.2	5.5	10.8	T-L	47.9
	ST	173.8	186.1	6.0	12.2	–	–
2.0-3.25	L	177.1	186.8	6.0	13.7	L-T	54.8
	T	170.0	180.0	5.0	10.8	T-L	48.0
	ST	175.2	185.4	5.5	9.3	T-S	50.7

TABLE 3.02727. ROOM TEMPERATURE CONVENTIONAL TENSILE PROPERTIES AND PLANE STRAIN FRACTURE TOUGHNESS OF HEAT TREATED AIRFRAME STRUCTURAL FORGING (8) (11)

Alloy	Ti-10V-2Fe-3Al		
Form	Rolled Plate		
F_{tu}, ksi	180	190	200
Oxygen Content, percent	K_{Ic}, ksi$\sqrt{in.}$(a)		
0.09	55	50	45
0.11	52	47	42
0.13	49	44	39

(a) Values taken from least squares best fit line for data spanning 0.11-0.17 percent oxygen at 175-200 ksi. Standard error of estimate is 2.8 ksi.$\sqrt{in.}$

TABLE 3.02728. EFFECT OF OXYGEN CONTENT ON ROOM TEMPERATURE ULTIMATE TENSILE STRENGTH AND PLANE STRAIN FRACTURE TOUGHNESS OF ROLLED PLATE (1)

Alloy	Ti-10V-2Fe-3Al							
Form	Pressed Squares, Beta Forged 1500 F Longitudinal, Mid-Radius Tensile Properties							
Pressed Section Size, $in.^2$	Condition	RT				600 F			
		F_{ty}, ksi	F_{tu}, ksi	e(4D), percent	RA, percent	F_{ty}, ksi	F_{tu}, ksi	e(4D), percent	RA, percent
5	As Forged, AC + 1000 F, 8 hr, AC	135.1	142.4	18.0	46.7	91.1	106.4	22.0	69.9
	1400 F, 1 hr, WQ + 950 F, 8 hr, AC	154.6	164.6	13.0	32.2	99.0	126.0	18.0	67.0
	1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	149.1	159.6	14.0	41.6	94.2	125.4	16.0	58.6
4	As Fogred, AC + 1000 F, 8 hr, AC	142.2	148.2	17.5	49.3	96.7	110.3	21.0	67.9
	1400 F, 1 hr, WQ + 950 F, 8 hr, AC	157.9	167.0	14.5	33.4	100.5	130.9	15.0	51.9
	1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	152.9	162.3	12.5	31.6	105.5	131.3	16.0	57.2
3	As Forged, AC + 1000 F, 8 hr, AC	145.5	151.3	16.3	45.7	102.6	115.4	19.0	70.2
	1400 F, 1 hr, WQ + 950 F, 8 hr, AC	161.5	168.3	16.7	44.2	109.8	134.5	18.0	68.0
	1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	160.0	168.6	13.0	35.3	107.5	131.9	19.0	69.7

TABLE 3.0313. ROOM TEMPERATURE AND 600 F TENSILE PROPERTIES OF PRESSED SQUARES, BETA FORGED AFTER VARIOUS HEAT TREATMENTS (5)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al							
Form	Pressed Squares, Beta Forged 1500 F							
					RT Mild-Notch Creep Rupture Properties			
					No Failure		Failure	
Pressed Section Size, in.^{2}	Test Direction	Location	Condition	F_{tu}, ksi	Stress, ksi	Time, hr	Stress, ksi	Time, hr
5	T	Mid-Radius	As Forged, AC	145.8	190	5	200	1.0
			As Forged, AC + 950 F, 2 hr, AC	155.5	190	5	200	2.5
			As Forged, AC + 950 F, 4 hr, AC	149.6	210	5	220	BOL(a)
			As Forged, AC + 950 F, 8 hr, AC	145.4	210	5	220	BOL
			As Forged, AC + 950 F, 24 hr, AC	145.0	200	5	210	0.25
			As Forged, AC + 1000 F, 2 hr, AC	144.8	200	5	210	0.25
			As Forged, AC + 1000 F, 4 hr, AC	151.3	200	5	210	BOL
			As Forged, AC + 1000 F, 8 hr, AC	151.2	200	5	210	BOL
			As Forged, AC + 1000 F, 24 hr, AC	140.2	210	5	220	BOL
			1400 F, 1 hr, WQ	149.1	180	5	190	1.0
			1400 F, 1 hr, WQ + 950 F, 2 hr, AC	184.4	210	5	220	BOL
			1400 F, 1 hr, WQ + 950 F, 4 hr, AC	178.2	200	5	210	0.1
			1400 F, 1 hr, WQ + 950 F, 8 hr, AC	176.2	210	5	220	BOL
			1400 F, 1 hr, WQ + 950 F, 24 hr, AC	168.2	200	5	210	3.8
			1400 F, 1 hr, WQ + 1000 F, 2 hr, AC	171.0	210	5	220	BOL
			1400 F, 1 hr, WQ + 1000 F, 4 hr, AC	167.2	200	5	210	0.25
			1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	161.0	190	5	200	1.1
			1400 F, 1 hr, WQ + 1000 F, 24 hr, AC	156.8	210	5	220	BOL
	L	Mid-Radius	As Forged, AC + 1000 F, 8 hr, AC	142.5	190	5	200	0.3
			1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	160.6	200	5	210	BOL
4	T	Mid-Radius	As Forged, AC	–	210	5	220	0.25
			As Forged, AC + 1000 F, 8 hr, AC	152.9	210	5	220	0.25
			1400 F, 1 hr, WQ	150.2	180	5	190	BOL
			1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	167.0	210	5	220	0.25
	L	Mid-Radius	As Forged, AC + 1000 F, 8 hr, AC	149.7	210	5	220	0.25
			1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	164.6	210	5	220	0.25
3	T	Mid-Radius	As Forged	151.9	210	5	220	BOL
			As Forged, AC + 1000 F, 8 hr, AC	155.2	210	5	220	0.33
			1400 F, 1 hr, WQ	138.9	180	5	190	0.1
			1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	166.3	210	5	220	0.33
	L	Mid-Radius	As Forged, AC + 1000 F, 8 hr, AC	150.5	210	5	220	0.51
			1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	162.8	210	5	220	0.33
2	T	Mid-Radius	As Forged, AC	159.1	210	5	220	BOL
			As Forged, AC + 1000 F, 8 hr, AC	156.8	230	5	240	BOL
			1400 F, 1 hr, WQ	136.0	190	5	200	BOL
			1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	170.5	210	5	220	1.1
	L	Mid-Radius	As Forged, AC + 1000 F, 8 hr, AC	157.5	210	5	220	0.33
			1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	166.5	210	5	220	0.33
5	T	Mid-Radius	1400 F, 1 hr, WQ + 950 F, 8 hr, AC	166.8	220	5	230	BOL
	L	Mid-Radius	1400 F, 1 hr, WQ + 950 F, 8 hr, AC	166.0	210	5	220	0.5
4	T	Mid-Radius	1400 F, 1 hr, WQ + 950 F, 8 hr, AC	170.1	220	5	230	BOL
	L	Mid-Radius	1400 F, 1 hr, WQ + 950 F, 8 hr, AC	163.5	220	5	230	BOL
3	T	Mid-Radius	1400 F, 1 hr, WQ + 950 F, 8 hr, AC	171.0	220	5	230	BOL
	L	Mid-Radius	1400 F, 1 hr, WQ + 950 F, 8 hr, AC	165.1	220	5	230	BOL

(a) Broke on loading.

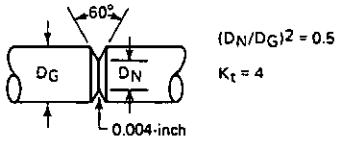


TABLE 3.044. ROOM TEMPERATURE STEP-LOADED MILD-NOTCH CREEP-RUPTURE PROPERTIES OF PRESSED SQUARES, BETA FORGED AFTER VARIOUS HEAT TREATMENTS (5)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al					
Form	Pressed Squares, Beta Forged 1500 F					
Section Size, in.^{2}	Condition	600 F, 100 ksi, 100 hr Creep Deformation, percent	Subsequent RT Tensile Properties[a]			
			F_{ty}, ksi	F_{tu}, ksi	(4D), percent	RA, percent
5	As Forged, AC + 1000 F, 8 hr, AC	Unexposed	135.1	142.4	18.0	46.6
		0.96	149.3	151.0	16.0	51.9
	1400 F, 1 hr, WQ + 950 F, 8 hr, AC	Unexposed	154.6	164.6	13.0	32.2
		0.83	164.5	167.0	10.0	24.9
	1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	Unexposed	149.0	159.6	14.0	41.6
		0.66	166.2	170.9	10.0	23.1
4	As Forged, AC + 1000 F, 8 hr, AC	Unexposed	142.2	148.2	17.5	49.3
		0.48	152.4	155.1	14.0	45.9
	1400 F, 1 hr, WQ + 950 F, 8 hr, AC	Unexposed	157.8	167.0	13.5	33.4
		0.49	168.9	174.6	8.0	18.8
	1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	Unexposed	142.2	148.2	17.5	49.3
		0.56	170.9	175.3	10.0	28.7
3	As Forged, AC + 1000 F, 8 hr, AC	Unexposed	145.5	151.3	16.3	45.7
		0.38	155.1	158.3	14.0	39.9
	1400 F, 1 hr, WQ + 950 F, 8 hr, AC	Unexposed	161.5	168.3	16.7	44.2
		0.21	170.6	174.0	11.0	42.0
	1400 F, 1 hr, WQ + 1000 F, 8 hr, AC	Unexposed	160.0	168.6	13.0	35.3
		0.43	173.5	178.2	12.0	37.0

(a) Longitudinal, mid-radius (except for 3 in.^{2} sections for which values shown are average of edge and center locations).

TABLE 3.045. EFFECT OF 600 F, 100 KSI, 100 HR, CREEP EXPOSURE ON SUBSEQUENT ROOM TEMPERATURE TENSILE PROPERTIES OF PRESSED SQUARES, BETA FORGED AFTER VARIOUS HEAT TREATMENTS (5)

Alloy	Ti-10V-2Fe-3Al						
Form	Hot Die, Beta Forged Airframe Structural Forgings, Forge Temp 1550 F, Die Temp 1550 F						
		600 F, 100 ksi Exposure		Subsequent RT Tensile Properties			
Condition	Specimen[a]	Time, hr	Deformation, percent	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
1400 F, 1 hr, WQ + 950 F, 8 hr, AC	TW3	Unexposed		174.4	183.0	8.8	19.0
	TW4	Unexposed		179.0	185.2	9.3	26.0
	CW1	117.4	0.44	182.2	190.2	7.0	26.4
1350 F, 1 hr, AC + 1075 F, 8 hr, AC	TW3	Unexposed		130.0	138.4	22.1	57.0
	TW4	Unexposed		129.6	138.4	20.7	55.5
	TW5	Unexposed		131.2	140.8	20.0	54.0
	TW6	Unexposed		134.8	144.2	20.0	53.6
	CW1	100.0	1.10	158.5	165.4	12.0	35.6

(a) See Table 3.0218 for specimen configuration, locations, and test directions.

TABLE 3.046. EFFECT OF 600 F, 100 KSI CREEP EXPOSURE ON SUBSEQUENT ROOM TEMPERATURE TENSILE PROPERTIES OF HOT DIE, BETA FORGED AIRFRAME STRUCTURAL FORGINGS AFTER VARIOUS HEAT TREATMENTS (2)

Alloy	Ti-10V-2Fe-3Al
Form	Forging
Condition	1400 F, 1 hr, WQ + 950 F, 8 hr, AC
Test Temp, F	E, 10^3 ksi
RT	16.2
600	13.8

See Figure 3.0314 for forging description and tensile properties.

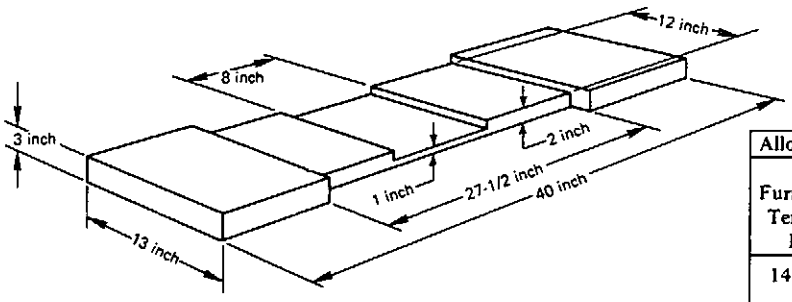
TABLE 3.0623. ROOM TEMPERATURE AND 600 F TENSILE ELASTIC MODULUS FOR HEAT TREATED FORGING (1)

Alloy	Ti-10V-2Fe-3Al	
Form	2-inch diam x 2-inch High Test Specimens	
Die Temp,[a] F	Final Thickness,[b] inch	Reduction,[c] percent
600	0.840	58
600	0.825	59
900	0.695	65
900	0.625	69
1200	0.475	76
1500	0.330	84
1500	0.335	83

(a) Stock temperature 1500 F.
(b) Stall load 100 tons (91 metric tons) in all cases.
(c) Metal deformation completed within 20-30 seconds after loading.

TABLE 4.0114. RESULTS OF HOT COMPRESSION TESTS (1)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3



Alloy	Ti-10V-2Fe-3Al			
Form	1-inch Thick Forged Upset [Upset From 3-inch Thickness(a)]			
Condition	1400 F, 1 hr, Fan Cool + 1050 F, 8 hr, AC			
		Room Temperature Tensile Properties		
Upset Temp, F	Test Direction	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
1500	Radial	149	156	14	49
	Tangential	148	154	19	61
1400	Radial	149	153	16	60
	Tangential	149	154	18	58

(a) Starting material sliced from 3-inch round forged bar which was beta processed with final 44 percent reduction from same starting temperature as subsequent upset temperature.

TABLE 4.0136. EFFECT OF UPSET TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF 1-INCH THICK FORGED UPSETS (19)

Alloy	Ti-10V-2Fe-3Al			
Form	Isothermally Forged Pancakes			
	Forging Conditions			
	Prefinish Upset(a)		Finish Upset(b)	
Forging	Temp, F	Reduction, percent	Temp, F	Reduction, percent
1	1550	50	1425	15
2	1250	50	1300	15
3	1400	50	1425	15

Room Temperature Tensile Properties					
Forging	Heat Treatment	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
1	1562 F, 2 hr, WQ + 932 F, 4 hr in Liquid Nitrate Salt	172	184	3.8	15.0
2		170	184	4.5	17.0
3		174	186	4.0	15.0
1	1400 F, 1.25 hr, WQ + 932 F, 1 hr in Liquid Nitrate Salt	188	201	4.8	15.0
2		177	187	7.0	39.0
3		178	184	7.6	33.0
1	1364 F, 5 hr, WQ + 932 F, 2 hr in Air	186	201	4.4	5.9
2		183	204	5.5	30.3
3		187	199	4.3	12.5
1	1292 F, 1.25 hr, WQ + 662 F, 16.7 hr in Liquid Nitrate Salt	180	202	3.9	11.0
2		171	186	9.0	38.0
3		179	200	3.3	17.0

(a) 1.5 in./min constant ram velocity.
(b) 0.75 in./min constant ram velocity.

TABLE 4.0137. EFFECT OF ISOTHERMAL FORGING CONDITIONS ON ROOM TEMPERATURE TENSILE PROPERTIES OF SOLUTION TREATED AND AGED FORGED PANCAKES (18)

Alloy	Ti-10V-2Fe-3Al			
Furnace Temp, F	Delay Time, sec	Center Temp, F, at Various Section Thickness, inch		
		1	2	3
1425	10	1421	1425	1425
	20	1406	1424	1425
	30	1387	1422	1424
1415	10	1411	1415	1415
	20	1396	1414	1415
	30	1378	1412	1414
1400	10	1396	1400	1400
	20	1382	1399	1400
	30	1364	1397	1399

TABLE 4.0121. HEAT TRANSFER IN FLAT MONOLITHIC FORGING DURING AIR COOL (1)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al					
Form	0.5-inch Thick Flat Plate Conventionally or Isothermally Subtransus Forged From 3-inch diam Supratransus Processed Round Bar					
			Room Temperature Tensile Properties			
Forging Condition(a)	Heat Treatment	Test Direction	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
AC	1350 F, 1 hr, AC + 1100 F, 8 hr, AC	L	137.3	138.2	23.5	55.6
		L	136.3	137.5	24.5	58.7
		T	132.0	135.2	24.0	53.0
		T	132.0	135.2	23.5	57.3
AC	1350 F, 1 hr, AC + 1150 F, 2 hr, AC	L	137.2	143.3	21.0	58.3
		L	133.7	137.9	21.0	55.9
		T	133.0	140.4	21.5	55.7
		T	132.0	137.4	22.0	57.8
AC	1000 F, 8 hr, AC + 1100 F, 2 hr, AC	L	148.4	151.8	19.0	53.9
		L	147.4	150.8	20.5	60.3
		T	148.2	151.6	20.0	58.7
		T	147.5	151.0	18.5	58.0
AC	1375 F, 1 hr, AC + 1050 F, 8 hr, AC	L	143.5	145.1	20.5	55.0
		L	143.5	145.1	22.0	59.0
		T	140.9	145.3	22.0	55.7
		T	141.7	144.3	22.0	59.2
AC	1400 F, 1 hr, AC + 1050 F, 8 hr, AC	L	146.3	150.8	21.0	57.3
		L	144.3	152.8	20.0	55.9
		T	143.5	149.4	20.0	58.0
		T	141.9	148.6	20.5	58.2
AI	1350 F, 1 hr, AC + 1100 F, 8 hr, AC	L	134.9	137.2	21.5	54.5
		L	134.8	138.9	24.0	58.0
		T	132.2	135.7	23.0	54.9
		T	131.7	136.5	23.0	56.6
AI	1350 F, 1 hr, AC + 1150 F, 2 hr, AC	L	135.2	140.8	22.0	59.8
		L	133.4	137.3	21.0	58.5
		T	130.9	135.3	23.0	56.6
		T	133.6	135.8	21.0	57.3
AI	1350 F, 1 hr, AC + 1250 F, 1 hr, AC + 1100 F, 8 hr, AC	L	129.8	132.0	23.5	57.5
		L	129.1	132.1	22.5	55.0
		T	127.8	131.8	22.0	56.3
		T	128.0	131.4	24.0	58.3
AI	1425 F, 1 hr, AC + 1050 F, 8 hr, AC	L	150.2	156.0	20.0	57.0
		L	148.0	154.4	20.0	58.7
		T	147.2	154.6	21.0	57.7
		T	148.6	155.4	20.5	55.2
AI	1400 F, 1 hr, AC + 1000 F, 8 hr, AC	L	152.6	156.7	19.0	55.4
		L	152.0	156.6	18.0	55.9
		T	149.8	155.0	18.0	47.8
		T	148.6	152.8	17.5	60.8

(a) See Figure 4.0138 for conversion schedule.

TABLE 4.0139. ROOM TEMPERATURE TENSILE PROPERTIES OF SUPRATRANSUS PROCESSED 3-INCH ROUND BAR CONVENTIONALLY AND ISOTHERMALLY SUBTRANSUS FORGED TO 0.5-INCH THICK FLAT PLATE AND VARIOUSLY HEAT TREATED (20)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al					
Form	0.5-inch Thick Flat Plate Conventionally or Isothermally Supratransus Forged From 3-inch diam Supratransus Processed Round Bar					
			Room Temperature Tensile Properties			
Forging Condition[a]	Heat Treatment	Test Direction	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
BC	1350 F, 1 hr, AC + 1100 F, 8 hr, AC	L	129.8	136.6	22.0	56.8
		L	128.8	136.5	22.0	55.4
		T	126.7	134.3	22.0	53.8
		T	127.9	134.7	22.0	53.9
BC	1400 F, 1 hr, AC + 1050 F, 8 hr, AC	L	131.6	137.7	21.5	53.1
		L	132.0	138.1	22.5	55.9
		T	132.1	139.1	23.5	51.0
		T	131.5	138.5	22.5	52.3
BC	1400 F, 1 hr, AC + 1000 F, 8 hr, AC	L	130.9	137.3	22.0	52.9
		L	130.0	136.8	22.0	49.8
		T	131.7	139.0	21.5	55.0
		T	131.6	138.4	20.5	54.1
BC	1530 F, 1 hr, AC + 1150 F, 8 hr, AC	L	139.2	149.4	12.5	18.9
		L	138.6	148.9	14.0	21.1
		T	134.1	143.5	13.5	25.2
		T	134.5	144.5	13.5	25.6
BC	1530 F, 1 hr, AC + 1350 F, 1 hr, AC + 1100 F, 8 hr, AC	L	126.4	134.5	19.0	38.6
		L	126.2	134.5	18.5	39.3
		T	124.2	132.8	17.5	42.8
		T	123.7	132.7	22.0	41.8
BC	1400 F, 1 hr, AC + 950 F, 8 hr, AC	L	149.4	161.1	14.5	39.4
		L	148.0	159.2	15.0	44.3
		T	147.7	160.3	17.5	42.2
		T	149.4	160.8	13.0	38.6
BC	1425 F, 1 hr, AC + 950 F, 8 hr, AC	L	143.3	155.2	15.5	40.7
		L	145.4	155.8	15.0	45.7
		T	146.3	158.2	15.5	39.0
		T	148.4	161.8	15.5	39.5
BC	1425 F, 1/2 hr, Fan Cool + 1375 F, 1 hr, Fan Cool + 950 F, 8 hr Fan Cool	L	148.7	157.1	16.0	41.9
		L	148.3	158.0	17.0	42.9
		T	149.8	155.8	17.0	43.7
		T	146.7	155.4	16.5	41.1
BC	1425 F, 1/2 hr, Fan Cool + 1400 F, 1 hr, Fan Cool, + 950 F, 8 hr Fan Cool	L	155.0	170.9	11.5	29.7
		L	155.8	168.3	13.0	35.5
		T	158.4	168.9	14.0	36.1
		T	156.5	167.8	13.0	35.6
BI	1350 F, 1 hr, AC + 1000 F, 8 hr, AC	L	143.3	147.4	20.0	52.9
		L	141.1	148.6	22.5	56.6
		T	141.7	148.1	20.0	54.3
		T	141.2	147.4	22.0	57.8
BI	1350 F, 1 hr, AC + 1100 F, 8 hr, AC	L	126.3	134.0	20.5	56.3
		L	130.0	137.2	23.0	51.7
		T	128.8	135.7	21.5	53.8
		T	128.0	135.0	23.5	55.2
BI	1400 F, 1 hr, AC + 1075 F, 2 hr, AC	L	131.1	137.9	22.5	55.4
		L	132.0	138.9	21.5	54.3
		T	130.1	138.3	22.0	57.7
		T	131.4	139.6	20.0	57.3
BI	1530 F, 1 hr, AC + 1150 F, 8 hr, AC	L	137.5	147.9	12.5	22.1
		L	137.1	146.7	10.5	19.3
		T	136.2	146.1	12.5	22.9
		T	137.3	145.7	12.0	26.9
BI	1100 F, 8 hr, AC	L	147.6	155.6	17.5	47.1
		L	148.6	157.0	17.0	50.7
		T	148.6	157.0	17.5	45.5
		T	148.4	156.4	15.5	40.4
BI	1425 F, 1/2 hr, Fan Cool + 1350 F, 1 hr, Fan Cool + 950 F, 8 hr, Fan Cool	L	150.4	161.6	16.5	41.1
		L	149.0	160.0	15.5	40.7
		T	150.0	159.4	16.5	41.7
		T	149.4	160.9	16.0	37.1
BI	1425 F, 1/2 hr, Fan Cool + 1375 F, 1 hr, Fan Cool + 900 F, 8 hr, Fan Cool	L	156.5	170.1	13.0	27.7
		L	157.4	170.1	11.5	22.8
		T	155.8	166.7	14.5	35.5
		T	154.8	168.8	11.5	29.1

TABLE 4.01310. (Continued)

Forging Condition(a)	Heat Treatment	Test Direction	Room Temperature Tensile Properties			
			F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
BI	1425 F, 1/2 hr, Fan Cool + 1375 F, 1 hr, Fan Cool + 900 F, 16 hr, Fan Cool	L	157.0	165.7	12.5	30.9
		L	156.4	167.1	12.5	28.0
		T	156.2	166.2	14.5	36.4
		T	155.0	166.0	15.0	38.9
BI	1530 F, 1/3 hr, Fan Cool + 1425 F, 1/2 hr, Fan Cool + 950 F, 8 hr, Fan Cool	L	158.4	169.8	16.5	45.1
		L	157.4	170.8	16.0	40.1
		T	156.7	167.5	12.5	27.8
		T	158.5	170.8	11.0	24.4

(a) See Figure 4.0138 for conversion schedule.

TABLE 4.01310. ROOM TEMPERATURE TENSILE PROPERTIES OF SUPRATRANSUS PROCESSED 3-INCH ROUND BAR CONVENTIONALLY AND ISOTHERMALLY SUPRATRANSUS FORGED TO 0.5-INCH FLAT PLATE AND VARIOUSLY HEAT TREATED (20)

Alloy	Ti-10V-2Fe-3Al					
Form	0.5-inch Thick Flat Plate Conventionally or Isothermally Subtransus Forged From 3-inch diam Subtransus Processed Round Bar					
Forging Condition(a)	Heat Treatment	Test Direction	Room Temperature Tensile Properties			
			F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent
CC	1350 F, 1 hr, AC + 1100 F, 8 hr, AC	L	132.4	137.6	21.0	59.8
		L	134.9	139.1	21.5	63.1
		T	128.6	134.6	22.5	58.3
		T	128.1	133.9	23.5	54.5
CC	1350 F, 1 hr, AC + 1150 F, 8 hr, AC	L	132.9	137.5	21.0	57.5
		L	130.9	134.9	21.0	58.5
		T	123.5	130.3	23.5	53.4
		T	124.3	129.9	23.5	58.2
CC	1100 F, 8 hr, AC	L	136.8	140.8	21.5	59.8
		L	138.1	141.3	21.0	58.2
		T	126.6	133.0	20.5	54.7
		T	128.1	132.3	23.0	57.7
CC	1530 F, 1 hr, AC + 1050 F, 8 hr, AC	L	160.8	169.8	6.0	12.6
		L	161.2	169.8	6.0	15.6
		T	151.2	161.4	11.5	20.6
		T	153.0	162.2	10.0	18.9
CC	1530 F, 1 hr, AC + 1400 F, 1 hr, AC + 1050 F, 8 hr, AC	L	145.8	154.8	10.0	28.8
		L	147.6	157.8	15.0	25.9
		T	134.9	146.8	16.5	24.5
		T	136.0	147.9	16.0	36.9
CI	1350 F, 1 hr, AC + 1100 F, 8 hr, AC	L	136.7	144.5	20.5	54.9
		L	135.3	142.7	21.5	54.3
		T	126.5	133.7	23.0	53.9
		T	129.8	134.4	21.5	59.8
CI	1300 F, 1 hr, AC + 1100 F, 8 hr, AC	L	132.8	136.4	21.5	59.4
		L	133.3	137.3	20.0	56.4
		T	126.7	132.7	23.0	52.9
		T	125.7	131.9	22.0	54.5
CI	1100 F, 8 hr, AC	L	137.8	142.1	20.0	58.3
		L	137.3	142.7	21.0	58.7
		T	132.0	137.8	20.5	56.8
		T	136.2	129.0	21.5	57.8
CI	1425 F, 1 hr, AC + 1050 F, 8 hr, AC	L	150.2	156.6	17.0	59.7
		L	152.6	158.0	13.5	54.7
		T	145.8	154.0	20.0	58.2
		T	147.4	154.6	17.0	58.2
CI	1530 F, 1 hr, AC + 1350 F, 1 hr, AC + 1000 F, 8 hr, AC	L	145.2	151.6	15.0	31.8
		L	143.0	150.4	15.5	35.0
		T	139.5	145.5	16.0	30.3
		T	139.7	147.1	17.5	35.9

(a) See Figure 4.0138 for conversion schedule.

TABLE 4.01311. ROOM TEMPERATURE TENSILE PROPERTIES OF SUBTRANSUS PROCESSED 3-INCH ROUND BAR CONVENTIONALLY AND ISOTHERMALLY SUBTRANSUS FORGED TO 0.5-INCH THICK FLAT PLATE AND VARIOUSLY HEAT TREATED (20)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Alloy	Ti-10V-2Fe-3Al				
Form	11/32-inch diam Bar, Hot-Rolled From 1750 F				
	RT Tensile Properties				
Condition	F_{ty}, ksi	F_{tu}, ksi	e (4D), percent	RA, percent	D_f/D_o(a)
As-Hot Rolled	198.5	212.8	8.0	28.5	–
1400 F, 1/4 hr, AC	152.8	171.0	12.0	35.8	1.10
1500 F, 1/4 hr, AC	118.0	130.1	18.0	34.5	–
1400 F, 1/4 hr, WQ	112.5	136.1	20.0	44.6	1.10
1500 F, 1/4 hr, WQ	84.3	126.7	30.0	40.4	1.15
1400 F, 1/4 hr, AC + 900 F, 8 hr, AC	181.8	195.6	16.0	54.5	–
1400 F, 1/4 hr, WQ + 900 F, 8 hr, AC	186.6	198.7	14.0	51.6	–

(a) D_f/D_o represents the cold heading capabilities with D_f = final diameter after upset (puck test) and D_o = initial diameter. Initial height is 2.5 x diameter.

TABLE 4.01312. ROOM TEMPERATURE TENSILE AND COLD DEFORMABILITY PROPERTIES OF HOT-ROLLED BAR VARIOUSLY HEAT TREATED (5)

Alloy	Ti-10V-2Fe-3Al								
Form	3/4-inch Thick Plate Extracted From Rough Upset Forged Billet								
Condition	Solution Treated + Electron Beam Welded + Aged								
				Average Room Temperature Properties					
Heat Treatment	Type of Specimen	Test Direction(a)	Number of Specimens	F_{ty}, ksi	F_{tu}, ksi	e, percent	RA, percent	E, 10^3 ksi	K_{Ic}, ksi $\sqrt{in.}$
(b)	Base Metal	LT	1	138.6	143.9	16.0	51.3	15.15	–
(b)	Weld	TT	3	134.2	138.1	10.0	40.8	15.54	–
(c)	Base Metal	LT	2	175.5	185.8	5.0	7.9	15.41	–
(c)	Weld	TT	3	171.5	182.2	5.5(d)	9.9	15.62	–
(c)	Base Metal	FT	2	–	–	–	–	–	52.5
(c)	Weld	FT	1	–	–	–	–	–	55.7

(a) For base metal specimens, "LT" and "T" designate loading in the grain and perpendicular directions, respectively, while "FT" designates compact tension specimens. For welded specimens, "LT" and "TT" designate longitudinal and transverse welds, respectively, while "FT" designates compact tension specimens.
(b) Solution treat: 1350 F, 1 hr, fan cool; age: 1075 F, 8 hr, air cool.
(c) Solution treat: 1400 F, 1 hr, fan cool; age: 950 F, 8 hr, air cool.
(d) Specimen broke at gage mark.

Welding Parameters: Beam current, 300 MA; beam voltage, 45 KV; travel speed, 40 in./min; gun-to-work distance, 8 inch; focus adjustment, 4.98; focus meter reading, 4.35; focus delta, −5; sharp focus, 4.40.

TABLE 4.031. ROOM TEMPERATURE STRENGTH, ELASTIC MODULUS, AND PLANE STRAIN FRACTURE TOUGHNESS OF ELECTRON BEAM WELDED PLATE (7)

Ti	
10	V
2	Fe
3	Al

Ti-10-2-3

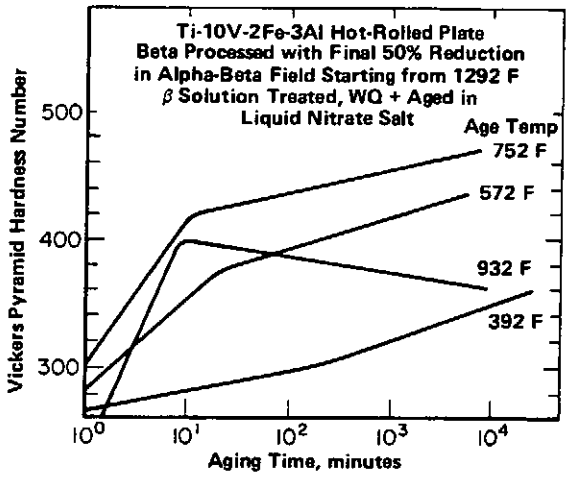


FIGURE 1.062. EFFECT OF AGING TIME ON HARDNESS OF HOT-ROLLED PLATE, BETA SOLUTION TREATED AND AGED AT SEVERAL TEMPERATURES (18)

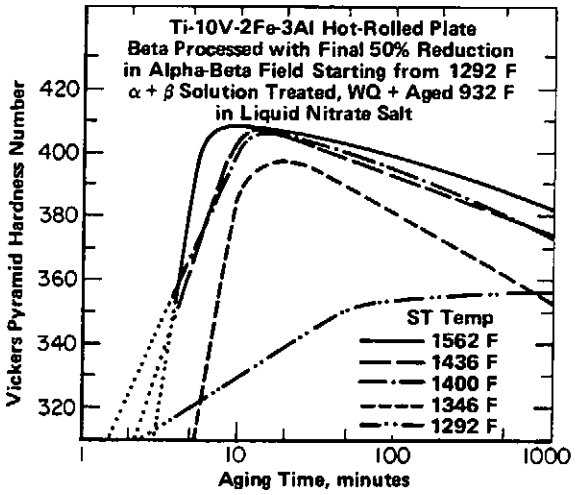


FIGURE 1.063. EFFECT OF 500 F AGING TIME ON HARDNESS OF HOT-ROLLED PLATE, ALPHA + BETA SOLUTION TREATED AND AGED AT 932 F (18)

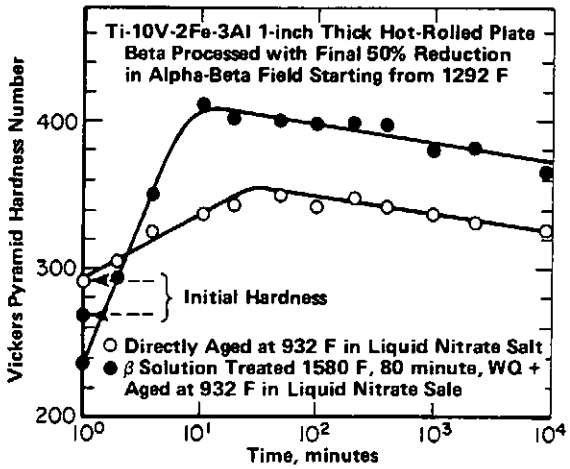


FIGURE 1.064. EFFECT OF 932 F AGING TIME ON HARDNESS OF HOT-ROLLED PLATE EITHER DIRECTLY AGED OR BETA SOLUTION TREATED AND THEN AGED (18)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Forging 1
Forging 2
Forging 3

Forging	Prefinish Upset		Finish Upset	
	Temp, F	Reduction, percent	Temp, F	Reduction, percent
1	1550	50	1425	15
2	1250	50	1300	15
3	1400	50	1425	15

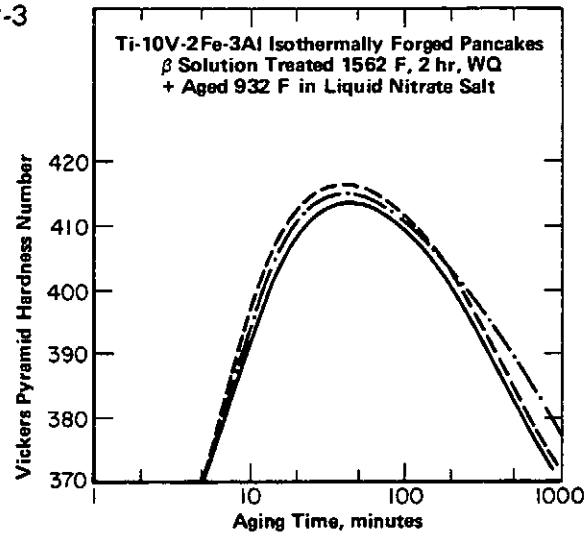


FIGURE 1.065. EFFECT OF 932 F AGING TIME ON HARDNESS OF BETA SOLUTION TREATED ISOTHERMALLY FORGED PANCAKES (18)

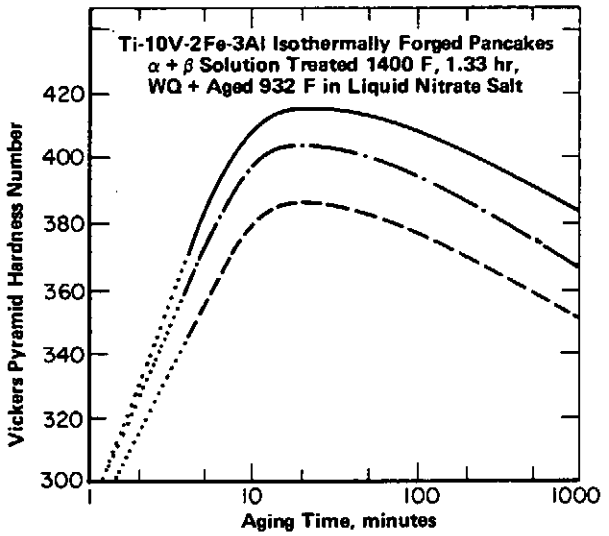


FIGURE 1.066. EFFECT OF 932 F AGING TIME ON HARDNESS OF ALPHA + BETA SOLUTION TREATED ISOTHERMALLY FORGED PANCAKES (18)

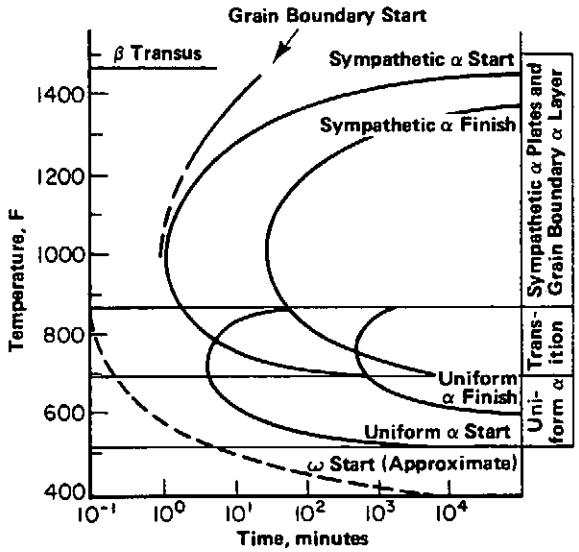


FIGURE 2.01211. SCHEMATIC TIME-TEMPERATURE-TRANSFORMATION (TTT) DIAGRAM FOR Ti-10V-2Fe-3Al BETA SOLUTION TREATED, QUENCHED, AND RAPIDLY HEATED TO THE AGING TEMPERATURE (18)

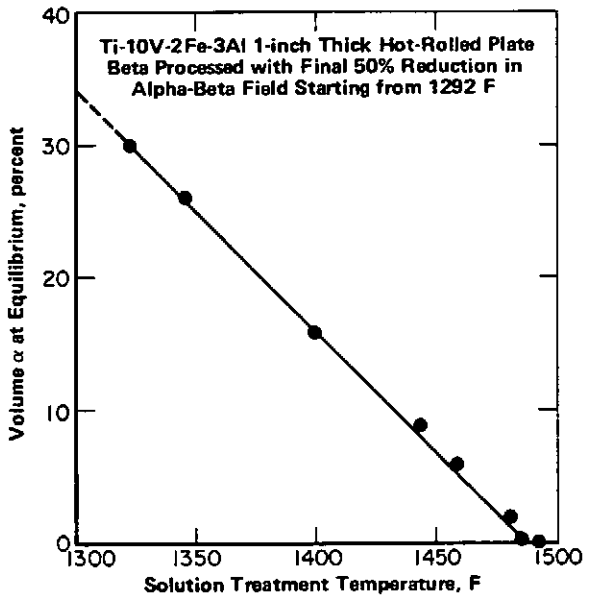


FIGURE 2.01212. DEPENDENCE OF PRIMARY ALPHA VOLUME FRACTION ON SOLUTION TREATMENT TEMPERATURE (18)

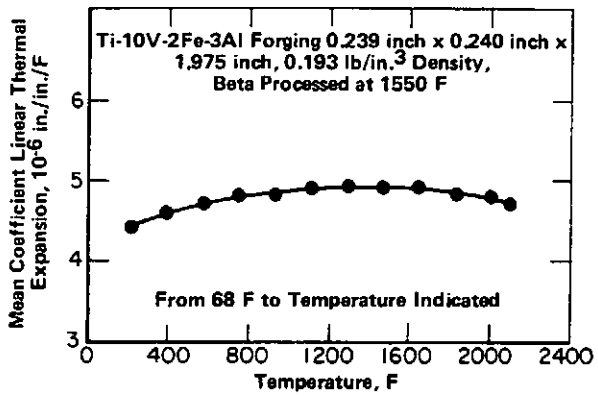


FIGURE 2.0141. THERMAL EXPANSION OF BETA PROCESSED FORGING (6)

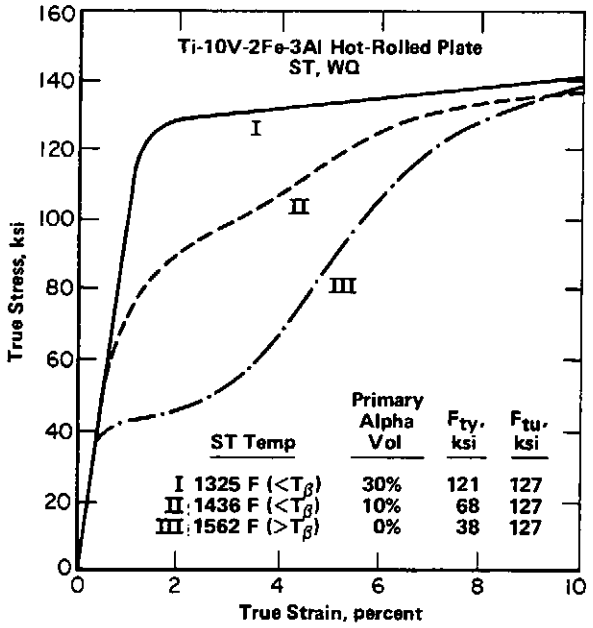


FIGURE 3.0211. ROOM TEMPERATURE TRUE STRESS-TRUE STRAIN CURVES FOR HOT-ROLLED PLATE WATER QUENCHED FROM SEVERAL SOLUTION TEMPERATURES (15)

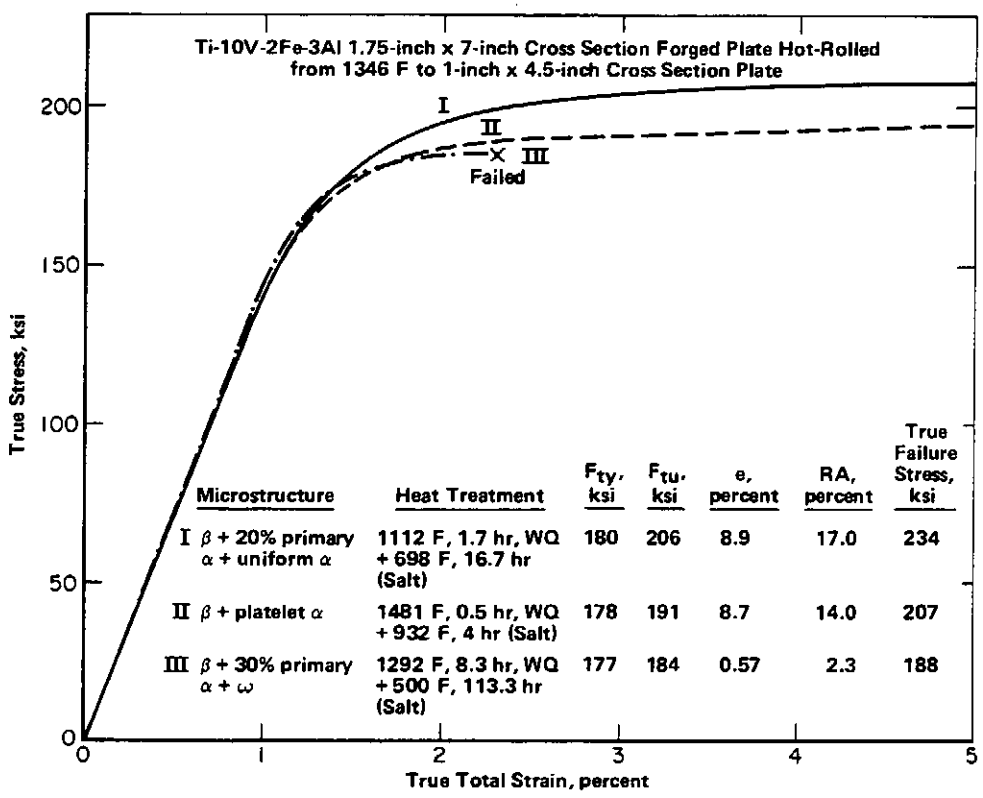


FIGURE 3.0212. ROOM TEMPERATURE TRUE STRESS-TRUE STRAIN BEHAVIOR OF HOT-ROLLED PLATE SOLUTION TREATED PLUS AGED TO THREE MICROSTRUCTURAL CONDITIONS (17)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

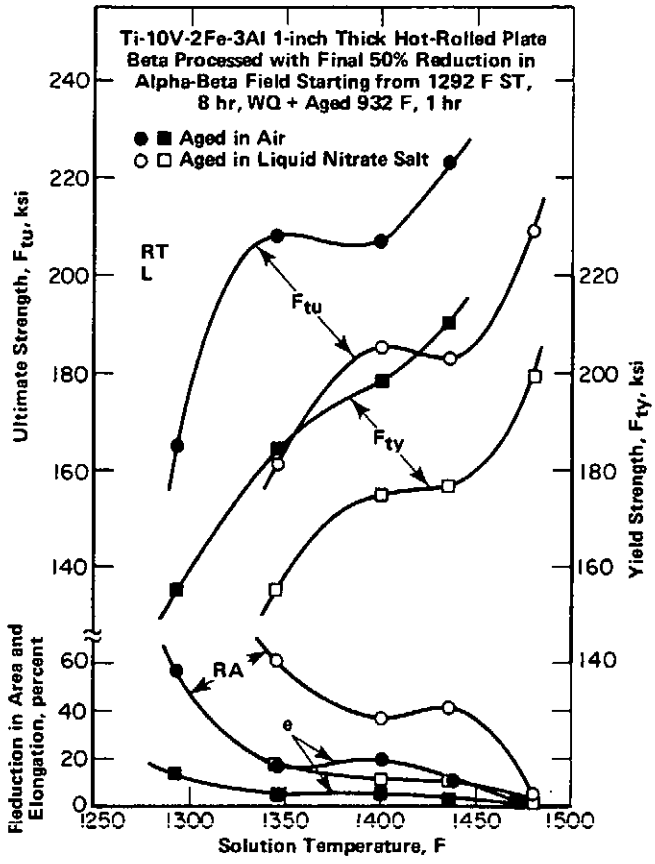


FIGURE 3.0219. EFFECT OF SOLUTION TREATMENT TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF 1-INCH THICK HOT-ROLLED PLATE SOLUTION TREATED AND AGED AT 932 F IN AIR OR LIQUID SALT (18)

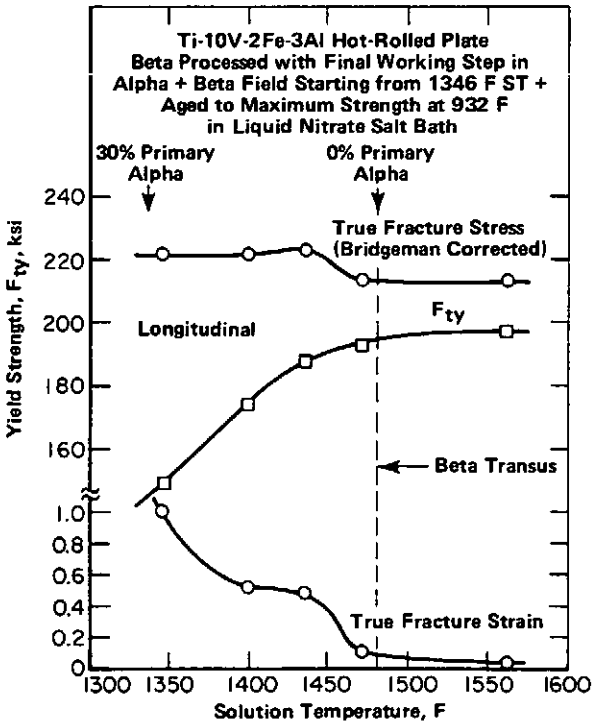


FIGURE 3.02110. EFFECT OF SOLUTION TREATMENT TEMPERATURE ON ROOM TEMPERATURE TENSILE YIELD STRENGTH, TRUE FRACTURE STRESS AND TRUE FRACTURE STRAIN OF HOT-ROLLED PLATE SOLUTION TREATED (PRIMARY ALPHA CONTENTS FROM 30 PERCENT TO 0 PERCENT) AND AGED TO MAXIMUM STRENGTH ATTAINABLE AT 932 F (16)

Ti
10 V
2 Fe
3 Al

Ti-10-2-3

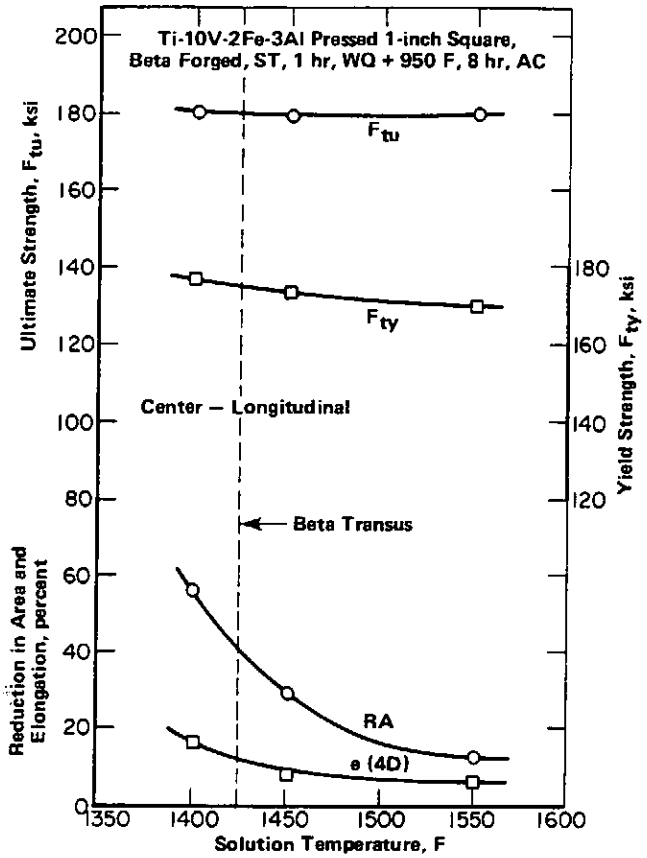


FIGURE 3.02111. EFFECT OF SUPER TRANSUS SOLUTION ANNEAL TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF PRESSED 1-INCH SQUARE, BETA FORGED PLUS SOLUTION TREATED AND AGED (5)

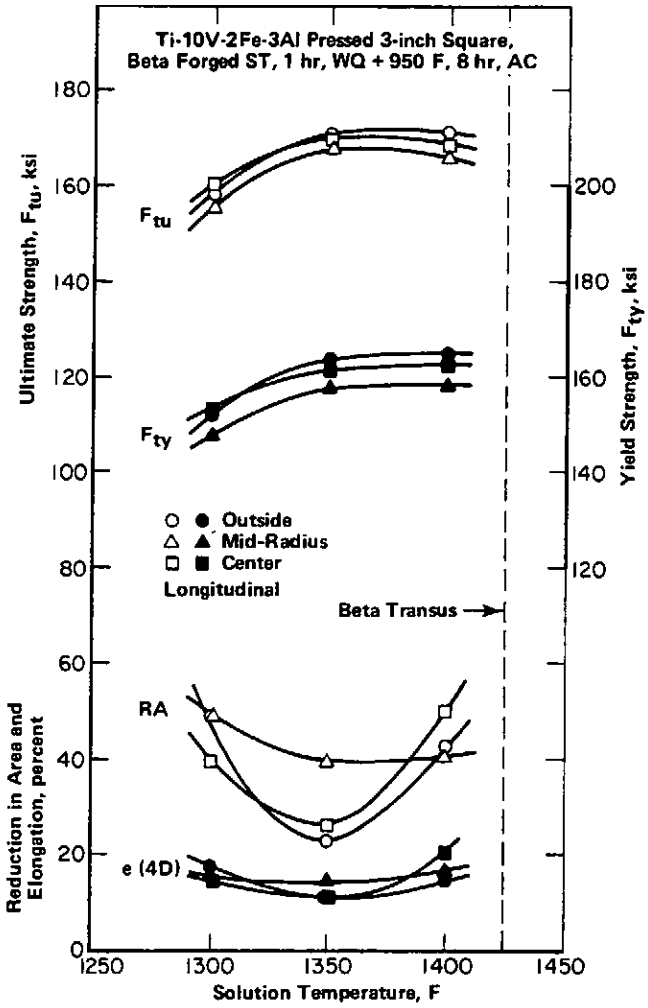


FIGURE 3.02112. EFFECT OF SUBTRANSUS SOLUTION ANNEAL TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF PRESSED 3-INCH SQUARE, BETA FORGED PLUS SOLUTION TREATED AND AGED (5)

Ti
10 V
2 Fe
3 Al

Ti-10-2-3

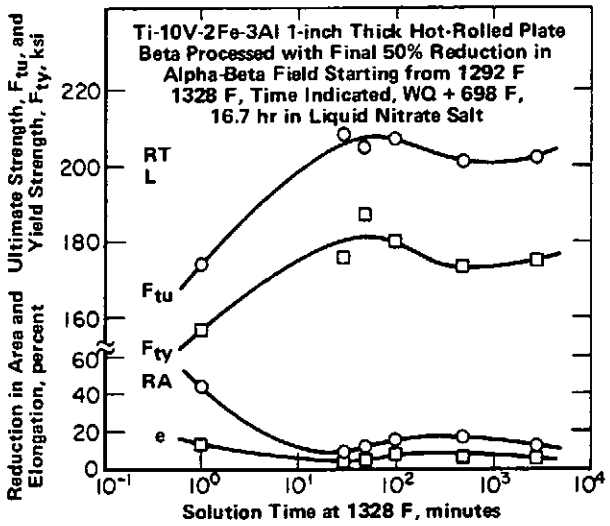


FIGURE 3.02113. EFFECT OF SOLUTION TREATMENT TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF 1-INCH THICK HOT-ROLLED PLATE SOLUTION TREATED AND AGED (18)

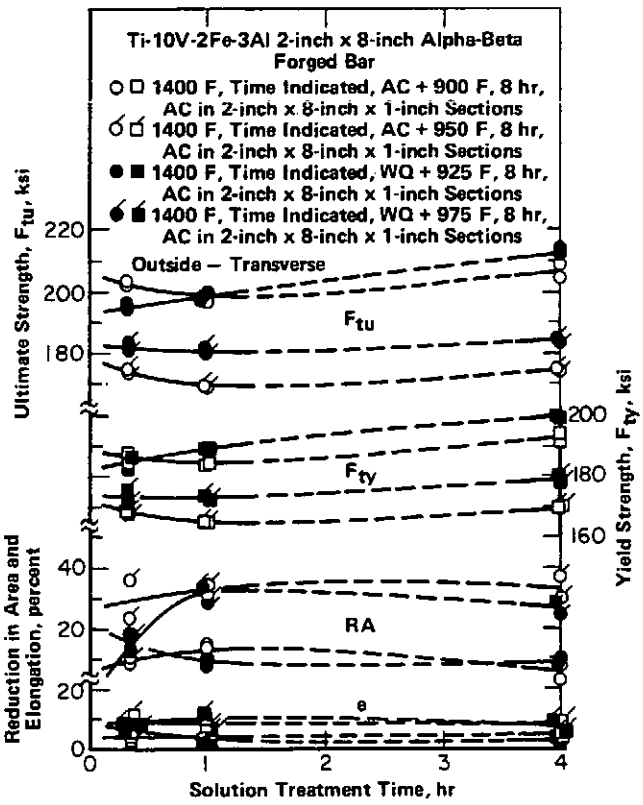


FIGURE 3.02115. EFFECT OF SOLUTION TREATMENT TIME AND QUENCH RATE AND OF AGING TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF ALPHA-BETA FORGED BAR SOLUTION TREATED AT 1400 F AND AGED (14)

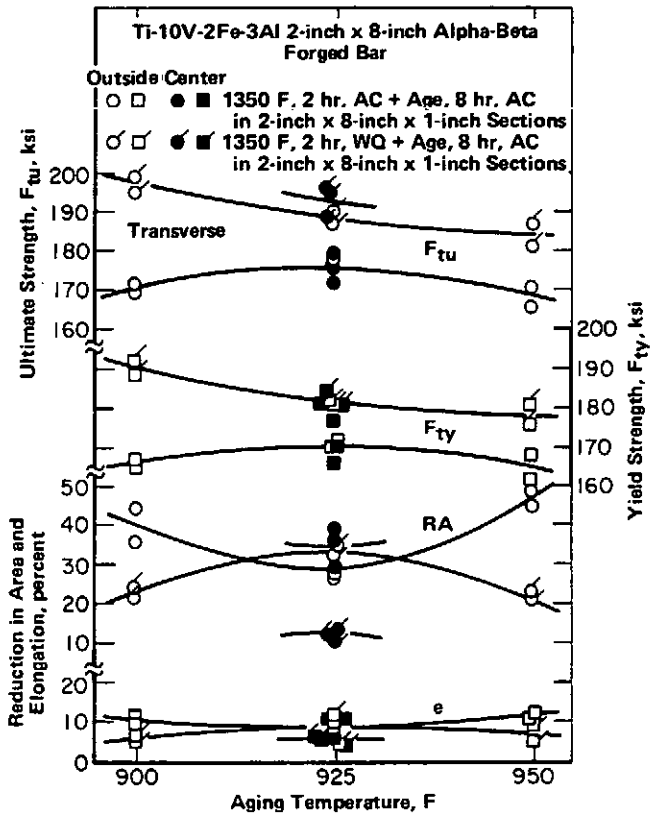


FIGURE 3.02116. EFFECT OF SOLUTION TREATMENT QUENCH RATE AND OF AGING TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF ALPHA-BETA FORGED BAR SOLUTION TREATED AT 1350 F AND AGED. (LOW CENTER DUCTILITY OF WATER QUENCHED PRODUCT DUE TO HIGH LEVEL OF SEGREGATED IRON AT BAR CENTER) (14)

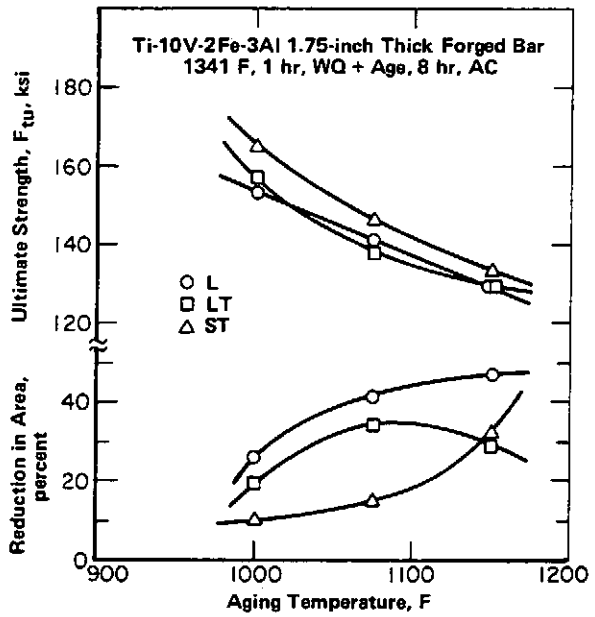


FIGURE 3.02117. EFFECT OF AGING TEMPERATURE AND TEST DIRECTION ON ROOM TEMPERATURE TENSILE PROPERTIES OF FORGED BAR (9)

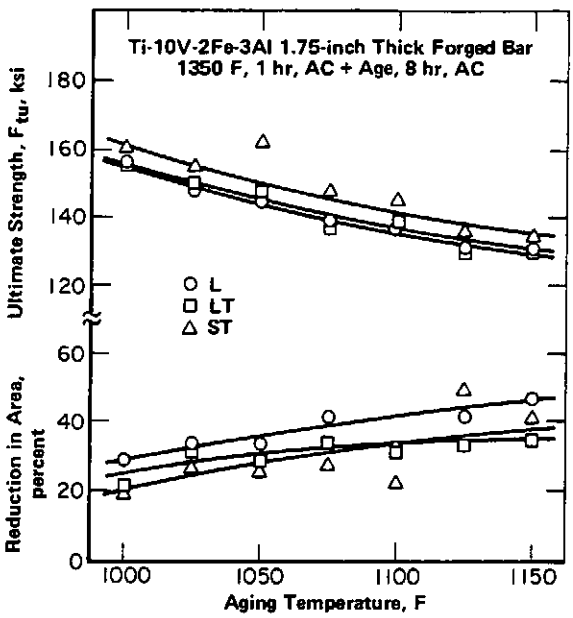


FIGURE 3.02118. EFFECT OF AGING TEMPERATURE AND TEST DIRECTION ON ROOM TEMPERATURE TENSILE PROPERTIES OF FORGED BAR (9)

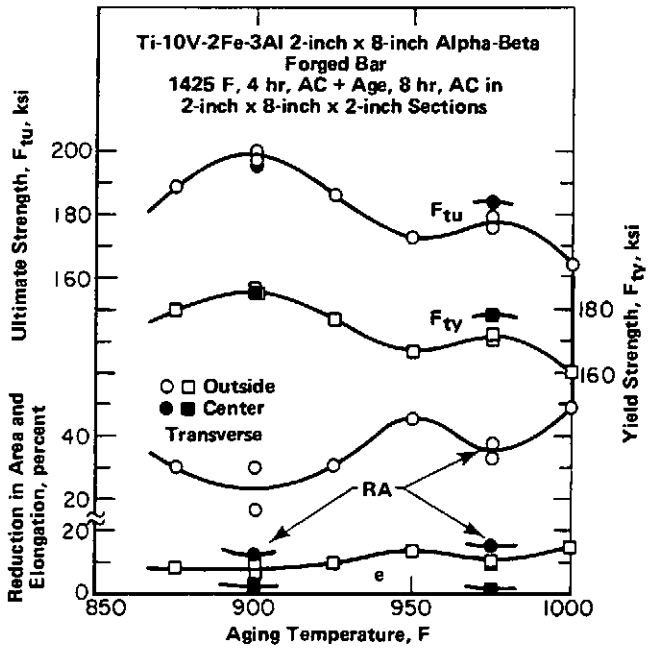


FIGURE 3.02119. EFFECT OF AGING TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF ALPHA-BETA FORGED BAR SOLUTION TREATED AND AGED. (LOW CENTER DUCTILITY DUE TO HIGH LEVEL OF SEGREGATED IRON AT BAR CENTER) (14)

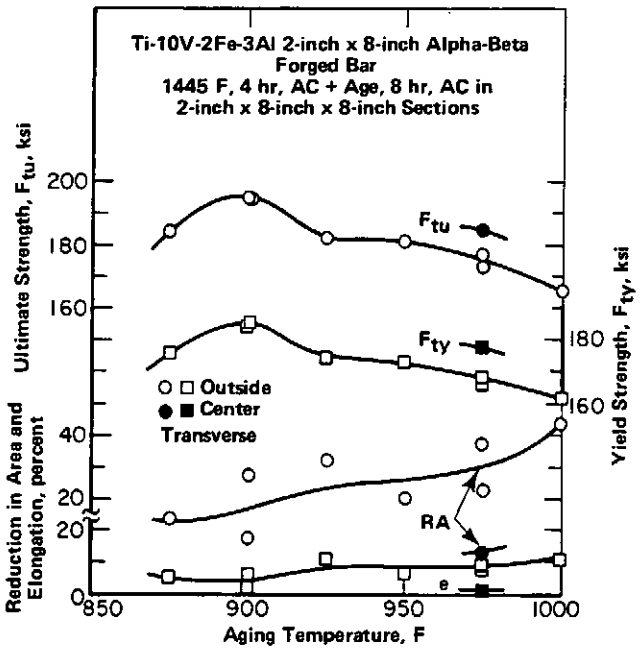


FIGURE 3.02120. EFFECT OF AGING TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF ALPHA-BETA FORGED BAR SOLUTION TREATED AND AGED. (LOW CENTER DUCTILITY DUE TO HIGH LEVEL OF SEGREGATED IRON AT BAR CENTER) (14)

Ti
10 V
2 Fe
3 Al

Ti-10-2-3

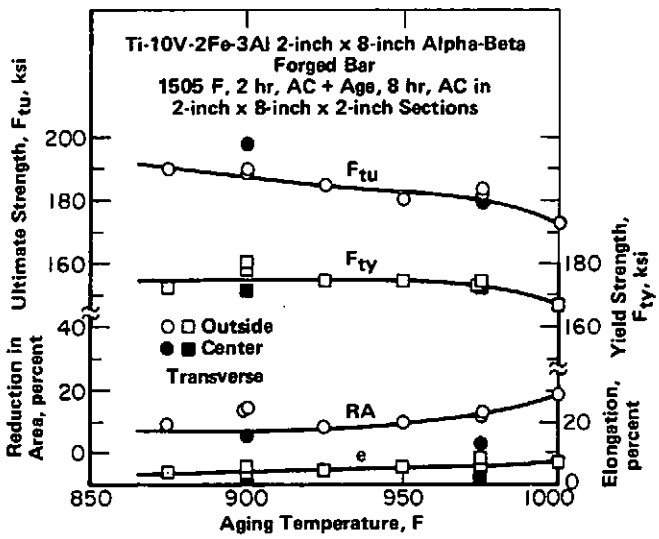


FIGURE 3.02121. EFFECT OF AGING TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF ALPHA-BETA FORGED BAR SOLUTION TREATED AND AGED (14)

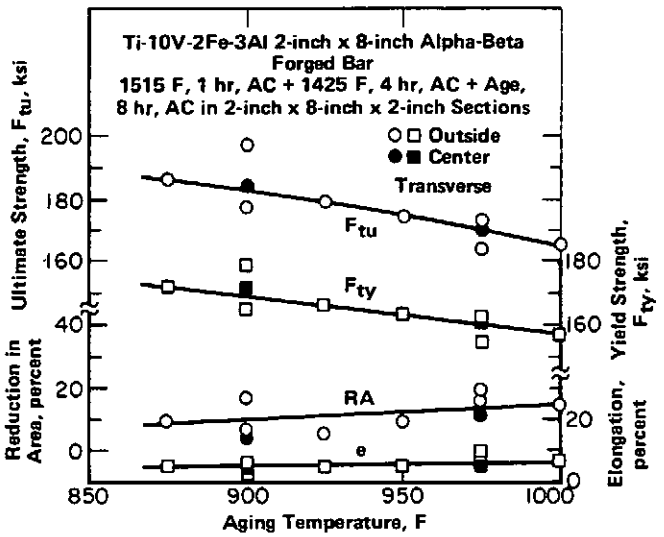


FIGURE 3.02122. EFFECT OF AGING TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF ALPHA-BETA FORGED BAR DOUBLE SOLUTION TREATED AND AGED (14)

Ti
10 V
2 Fe
3 Al

Ti-10-2-3

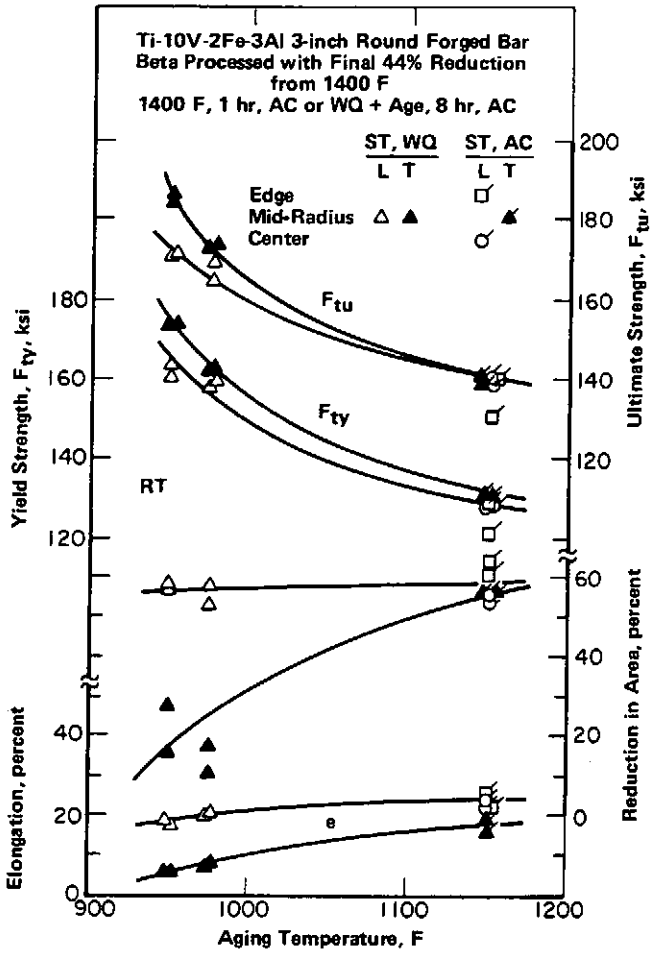


FIGURE 3.02123. EFFECT OF AGING TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF SOLUTION TREATED AND AGED 3-INCH ROUND FORGED BAR BETA PROCESSED WITH FINAL REDUCTION BELOW THE BETA TRANSUS TEMPERATURE (19)

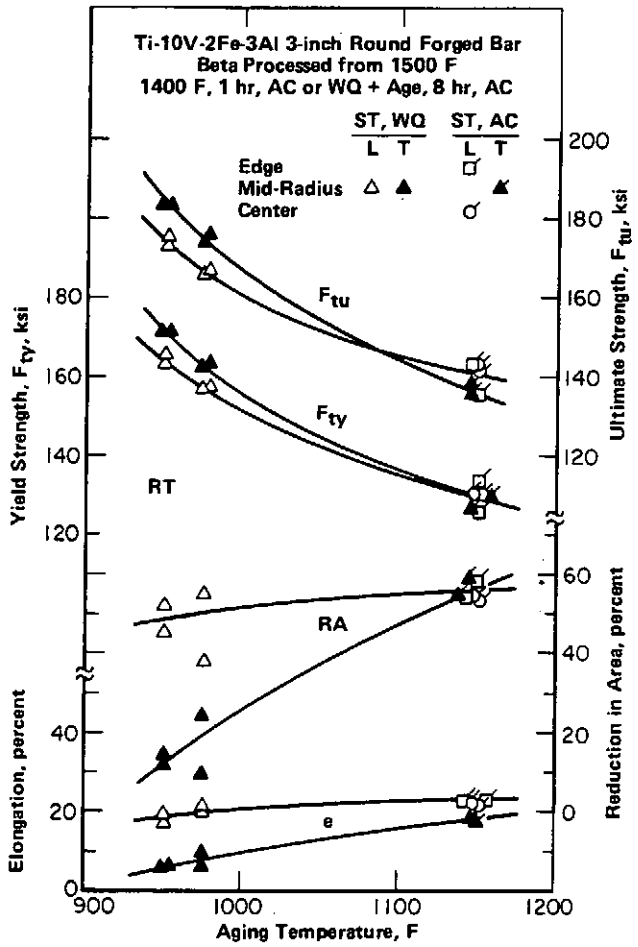


FIGURE 3.02124. EFFECT OF AGING TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF SOLUTION TREATED AND AGED 3-INCH ROUND FORGED BAR BETA PROCESSED (19)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

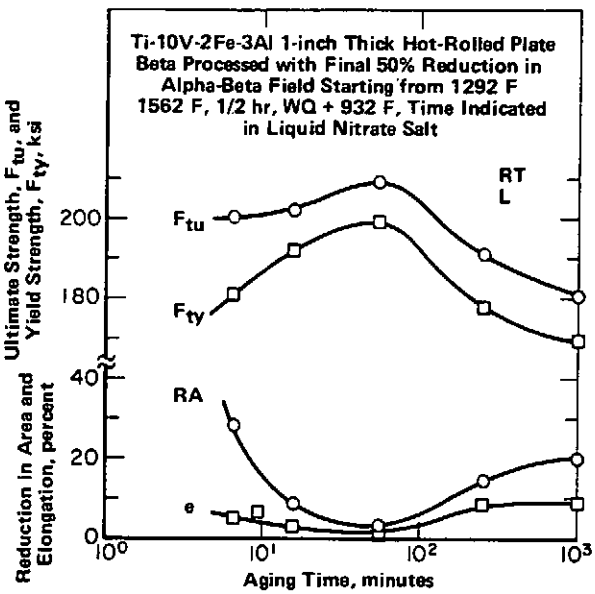


FIGURE 3.02125. EFFECT OF AGING TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF 1-INCH THICK HOT-ROLLED PLATE BETA SOLUTION TREATED AT 1562 F AND AGED IN SALT AT 932 F (18)

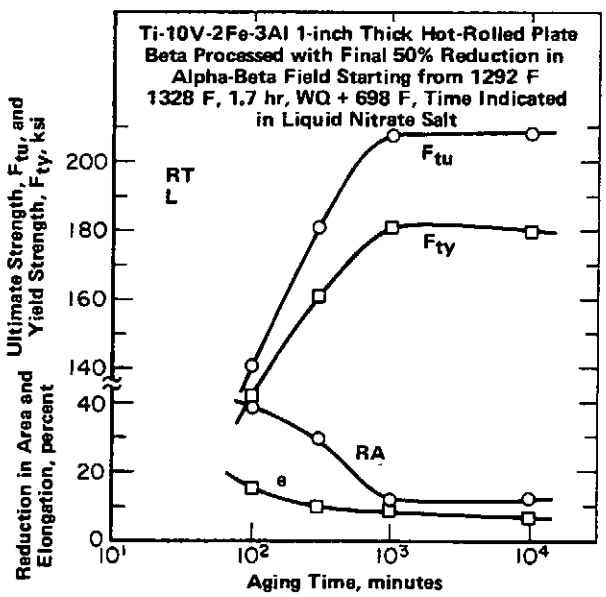


FIGURE 3.02126. EFFECT OF AGING TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF 1-INCH THICK HOT-ROLLED PLATE ALPHA + BETA SOLUTION TREATED AT 1328 F AND AGED IN SALT AT 698 F (18)

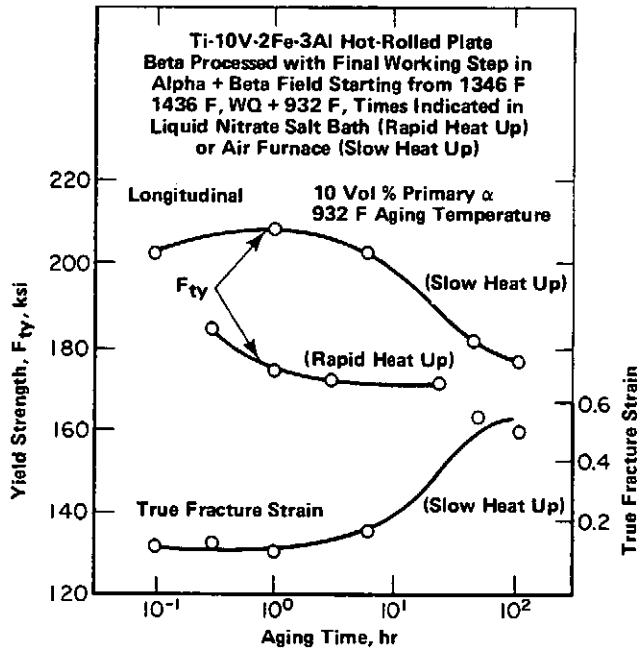


FIGURE 3.02127. EFFECT OF 932 F AGE TIME ON ROOM TEMPERATURE YIELD STRENGTH AND TRUE FRACTURE STRAIN OF HOT-ROLLED PLATE CONTAINING 10 PERCENT CONSTANT PRIMARY ALPHA CONTENT, HEATED AT TWO RATES TO THE AGING TEMPERATURE (16)

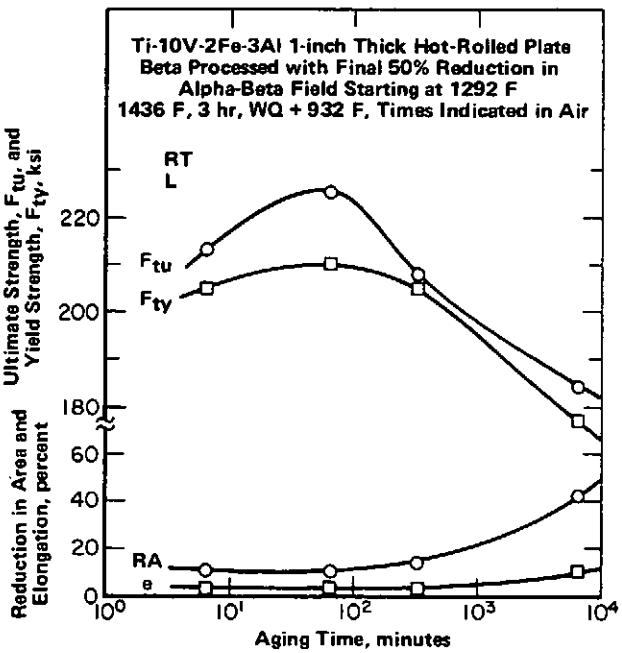


FIGURE 3.02128. EFFECT OF AGING TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF 1-INCH THICK HOT-ROLLED PLATE ALPHA + BETA SOLUTION TREATED AT 1436 F AND AGED IN AIR AT 932 F (18)

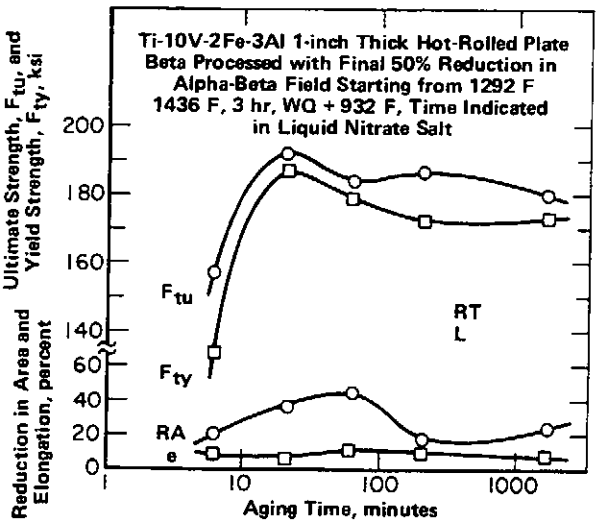


FIGURE 3.02129. EFFECT OF AGING TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF 1-INCH THICK HOT-ROLLED PLATE ALPHA + BETA SOLUTION TREATED AT 1436 F AND AGED IN SALT AT 932 F (18)

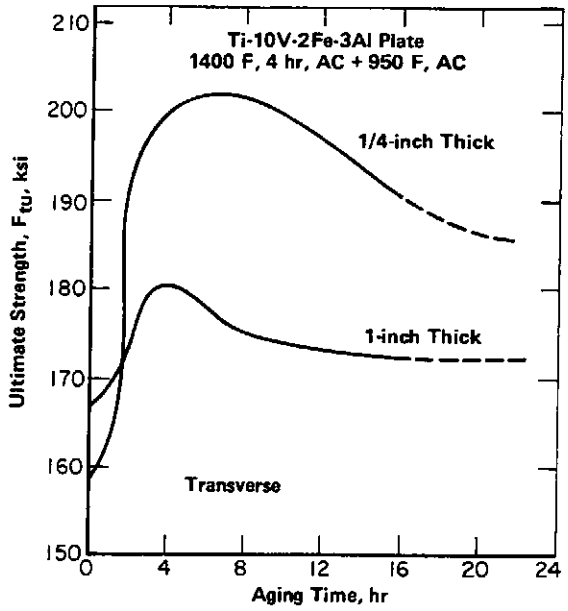


FIGURE 3.02130. EFFECT OF AGING TIME ON ROOM TEMPERATURE ULTIMATE TENSILE STRENGTH OF PLATE OF TWO THICKNESSES (9)

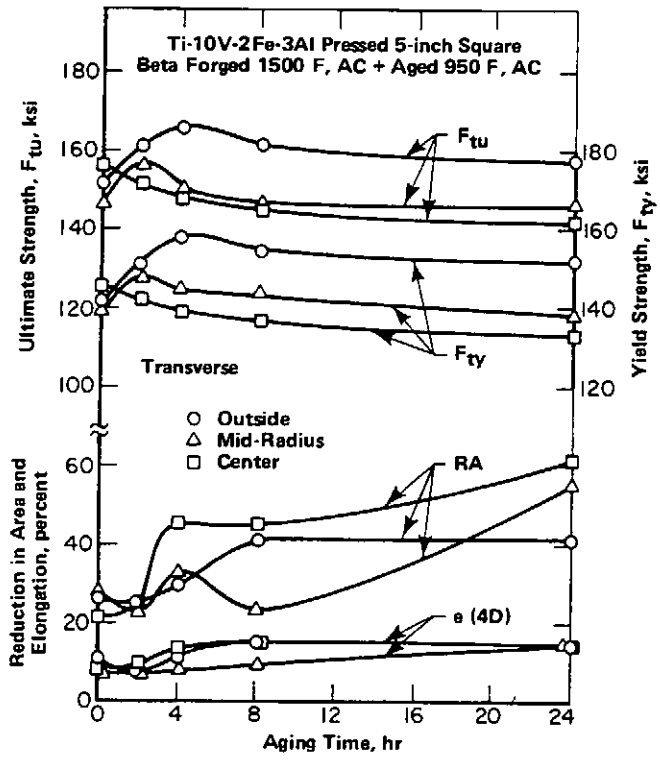


FIGURE 3.02131. EFFECT OF AGING TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF PRESSED 5-INCH SQUARE, BETA FORGED PLUS DIRECTLY AGED AT 950 F (5)

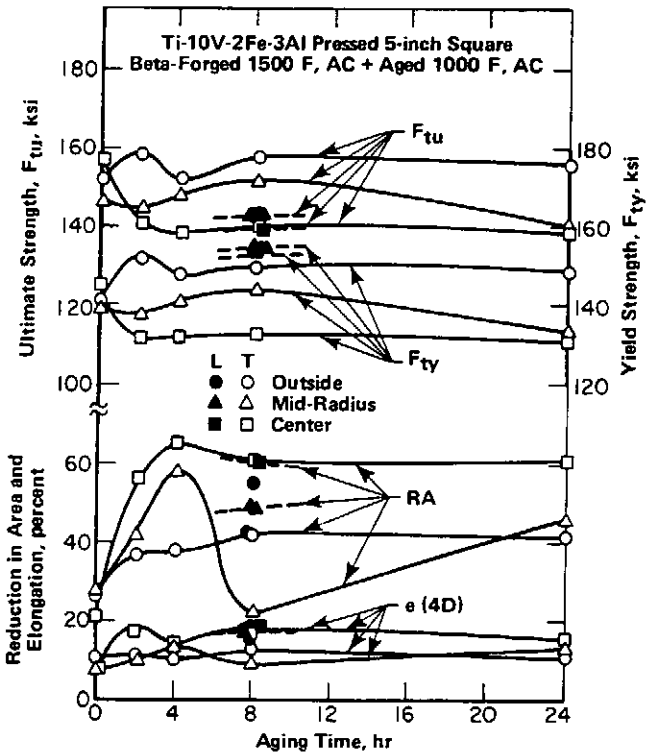


FIGURE 3.02132. EFFECT OF AGING TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF PRESSED 5-INCH SQUARE, BETA FORGED PLUS DIRECTLY AGED AT 1000 F (5)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

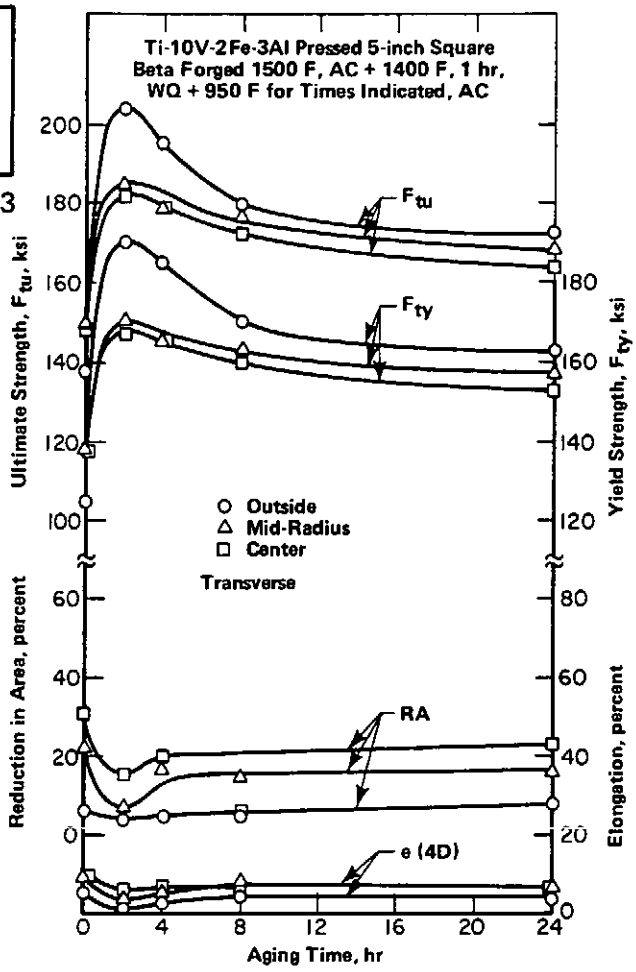


FIGURE 3.02133. EFFECT OF AGING TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF PRESSED 5-INCH SQUARE, BETA FORGED PLUS SOLUTION TREATED AND AGED AT 950 F (5)

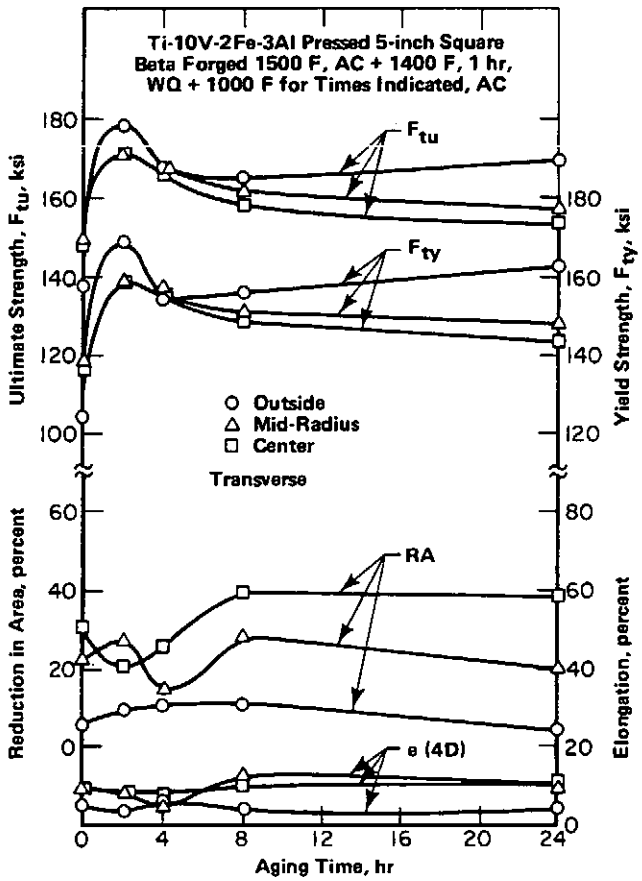


FIGURE 3.02134. EFFECT OF AGING TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF PRESSED 5-INCH SQUARE, BETA FORGED PLUS SOLUTION TREATED AND AGED AT 1000 F (5)

Ti
10 V
2 Fe
3 Al

Ti-10-2-3

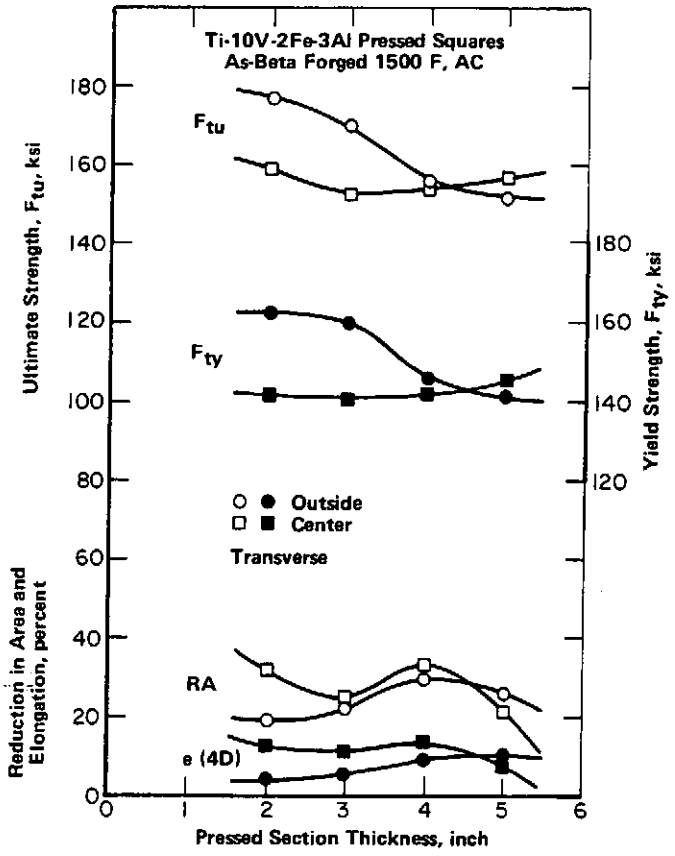


FIGURE 3.02135. EFFECT OF SECTION THICKNESS ON ROOM TEMPERATURE TENSILE PROPERTIES OF PRESSED SQUARES, AS-BETA FORGED (5)

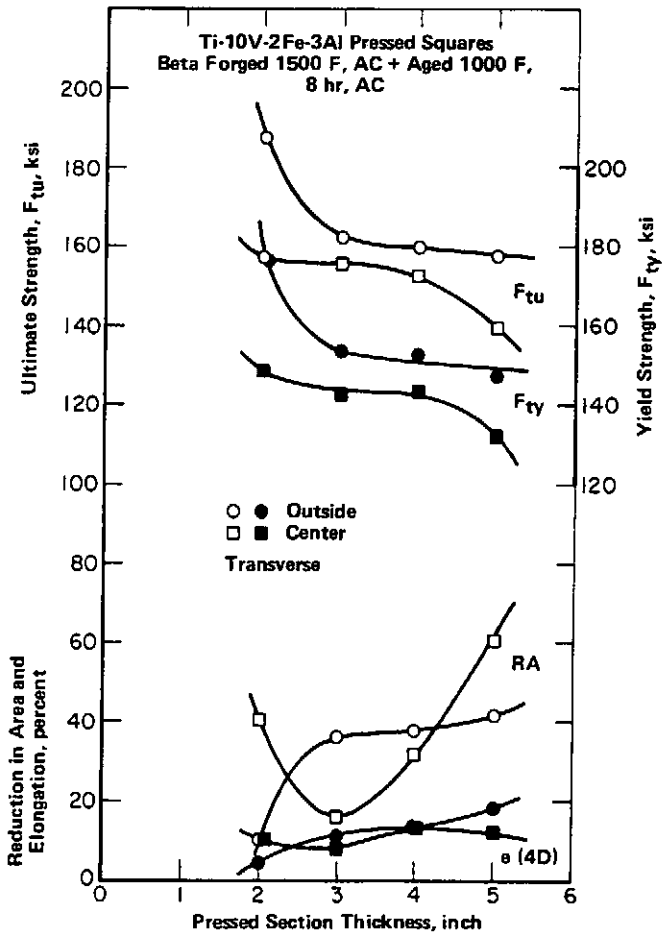


FIGURE 3.02136. EFFECT OF SECTION THICKNESS ON ROOM TEMPERATURE TRANSVERSE TENSILE PROPERTIES OF PRESSED SQUARES, BETA FORGED PLUS DIRECTLY AGED AT 1000 F (5)

Ti
10 V
2 Fe
3 Al

Ti-10-2-3

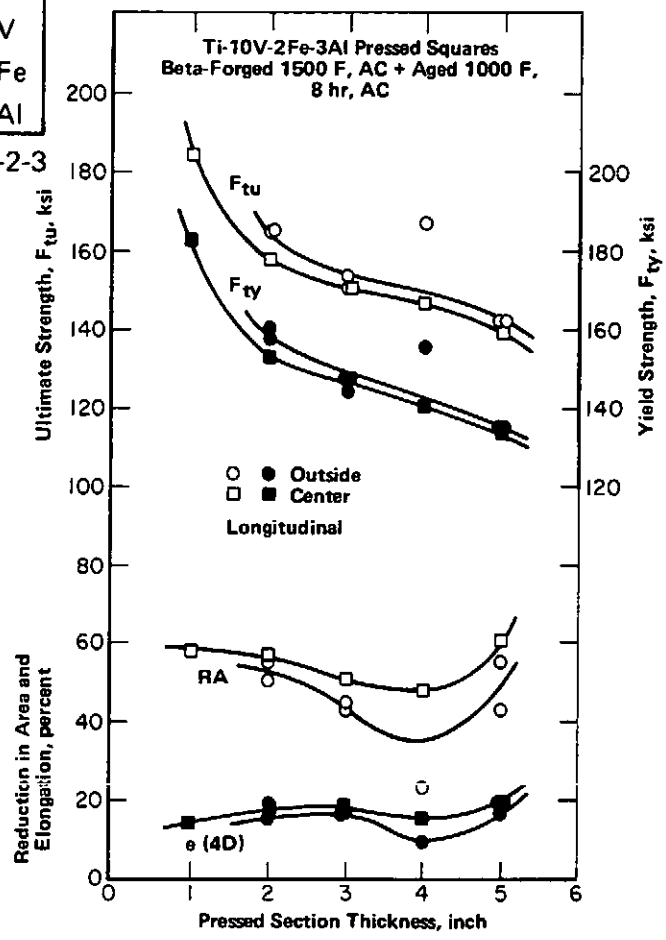


FIGURE 3.02137. EFFECT OF SECTION THICKNESS ON ROOM TEMPERATURE LONGITUDINAL TENSILE PROPERTIES OF PRESSED SQUARES, BETA FORGED PLUS DIRECTLY AGED AT 1000 F (5)

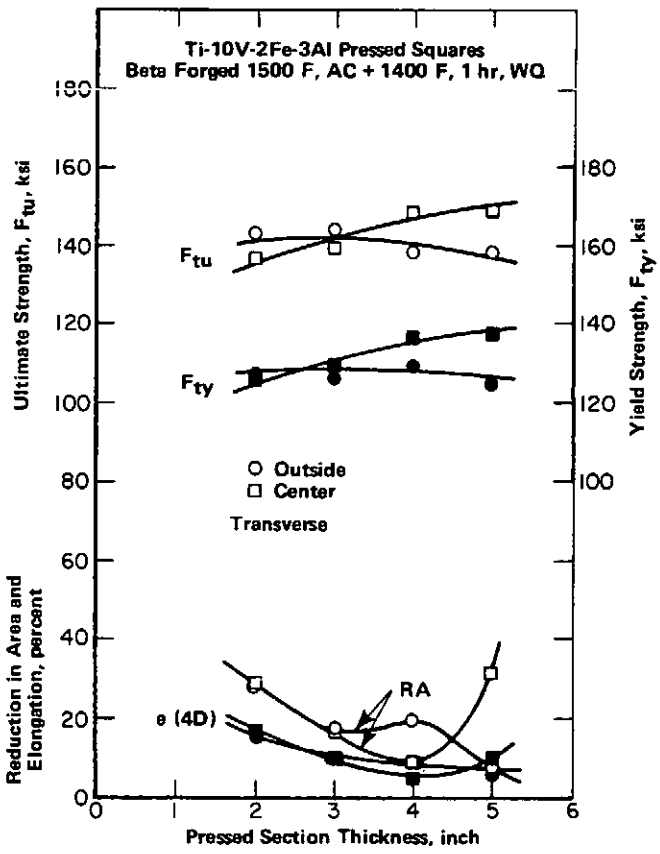


FIGURE 3.02138. EFFECT OF SECTION THICKNESS ON ROOM TEMPERATURE TENSILE PROPERTIES OF PRESSED SQUARES, BETA FORGED PLUS SOLUTION TREATED (5)

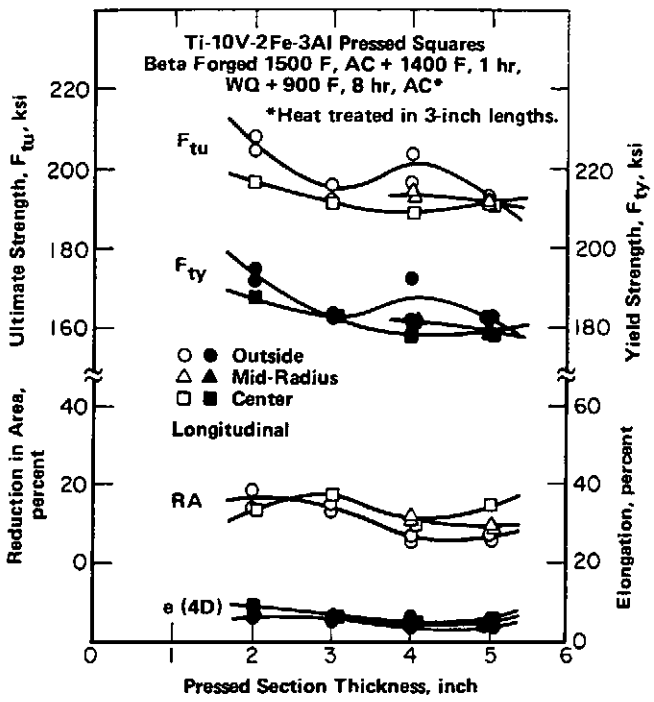


FIGURE 3.02139. EFFECT OF SECTION THICKNESS ON ROOM TEMPERATURE TENSILE PROPERTIES OF PRESSED SQUARES, BETA FORGED PLUS SOLUTION TREATED AND AGED AT 900 F (5)

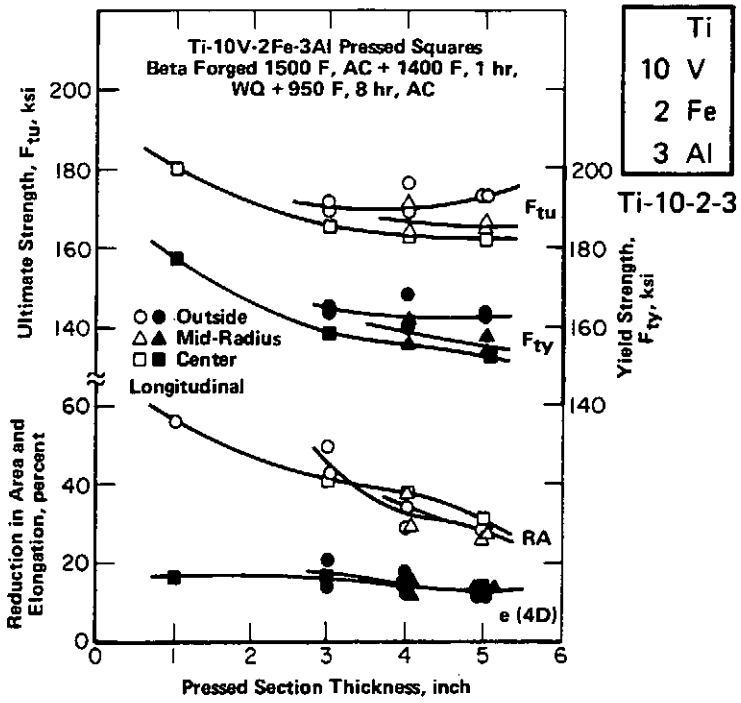


FIGURE 3.02140. EFFECT OF SECTION THICKNESS ON ROOM TEMPERATURE LONGITUDINAL TENSILE PROPERTIES OF PRESSED SQUARES, BETA FORGED PLUS SOLUTION TREATED AND AGED AT 950 F (5)

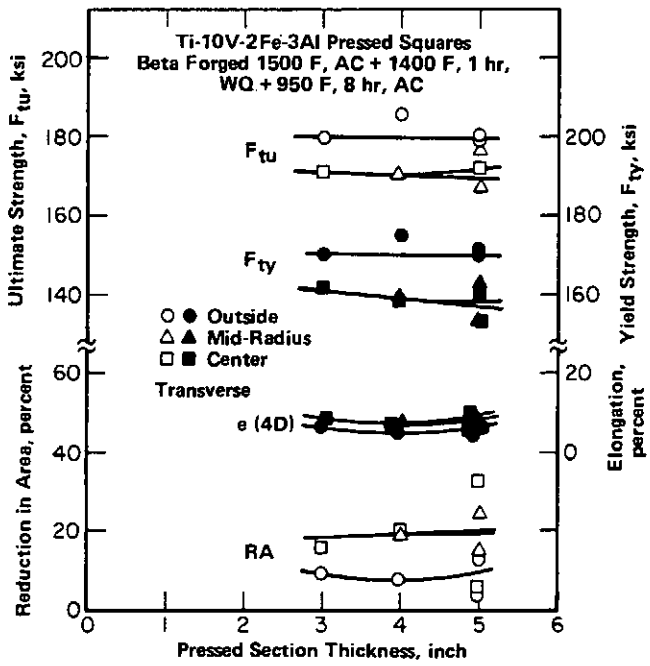


FIGURE 3.02141. EFFECT OF SECTION THICKNESS ON ROOM TEMPERATURE TRANSVERSE TENSILE PROPERTIES OF PRESSED SQUARES, BETA FORGED PLUS SOLUTION TREATED AND AGED AT 950 F (5)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

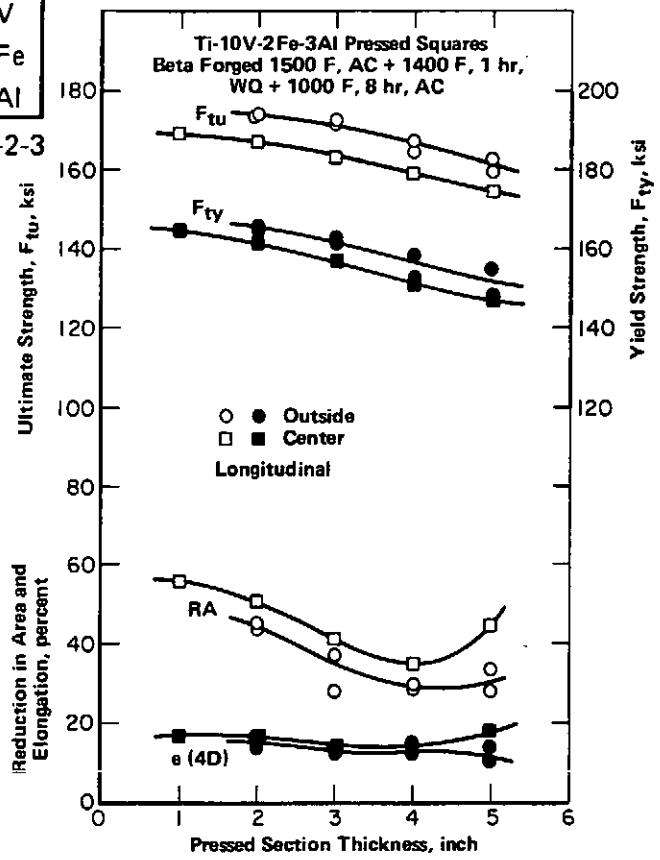


FIGURE 3.02142. EFFECT OF SECTION THICKNESS ON ROOM TEMPERATURE TENSILE PROPERTIES OF PRESSED SQUARES, BETA FORGED PLUS SOLUTION TREATED AND AGED AT 1000 F (5)

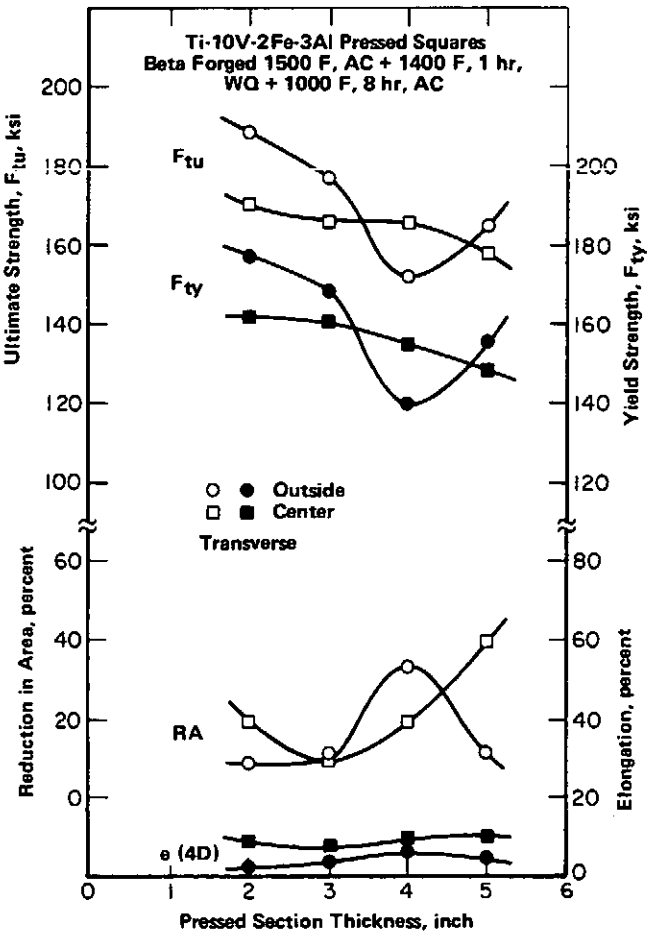


FIGURE 3.02143. EFFECT OF SECTION THICKNESS ON ROOM TEMPERATURE TRANSVERSE TENSILE PROPERTIES OF PRESSED SQUARES, BETA FORGED PLUS SOLUTION TREATED AND AGED AT 1000 F (5)

Ti
10 V
2 Fe
3 Al

Ti-10-2-3

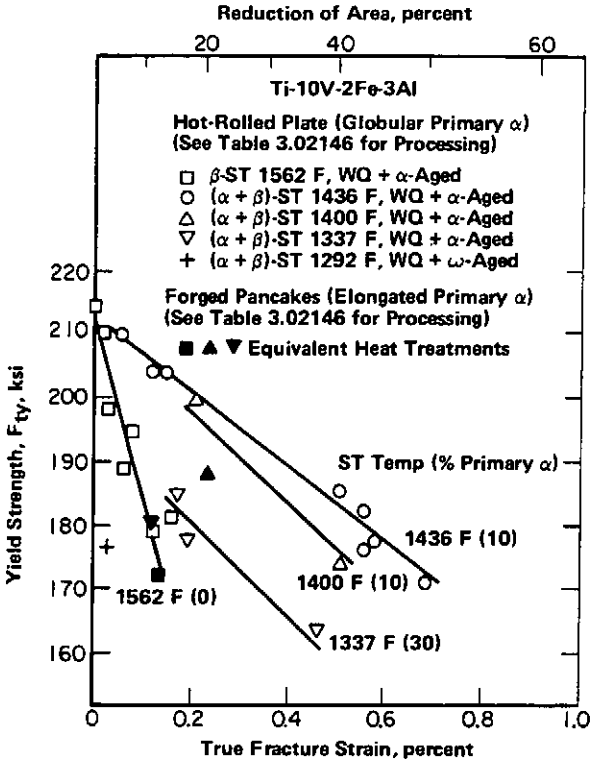


FIGURE 3.02144. RELATION BETWEEN TENSILE YIELD STRENGTH AND TRUE FRACTURE STRAIN OR REDUCTION IN AREA FOR VARIOUS MICROSTRUCTURES (16)

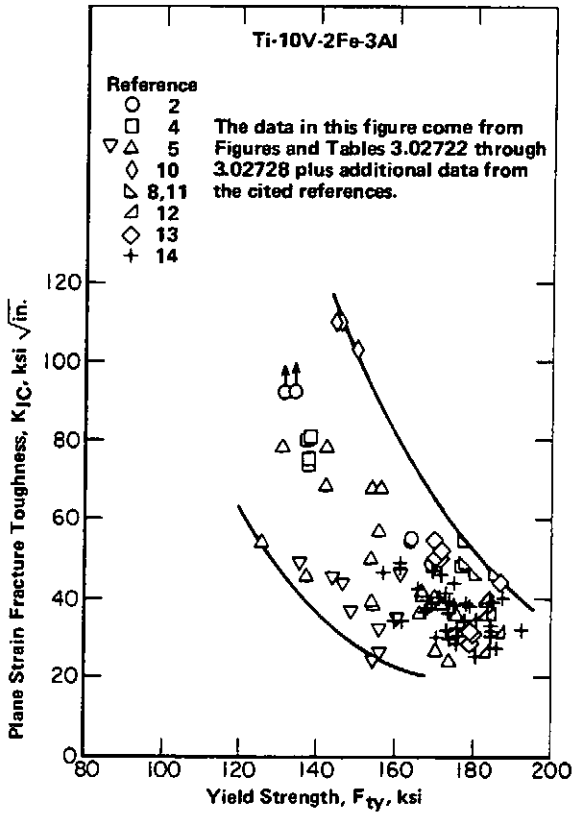


FIGURE 3.02721. SUMMARY REPRESENTATION OF ROOM TEMPERATURE PLANE STRAIN FRACTURE TOUGHNESS AS A FUNCTION OF TENSILE YIELD STRENGTH FOR ALL PRODUCTS AND CONDITIONS REPORTED IN THE REFERENCED LITERATURE

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

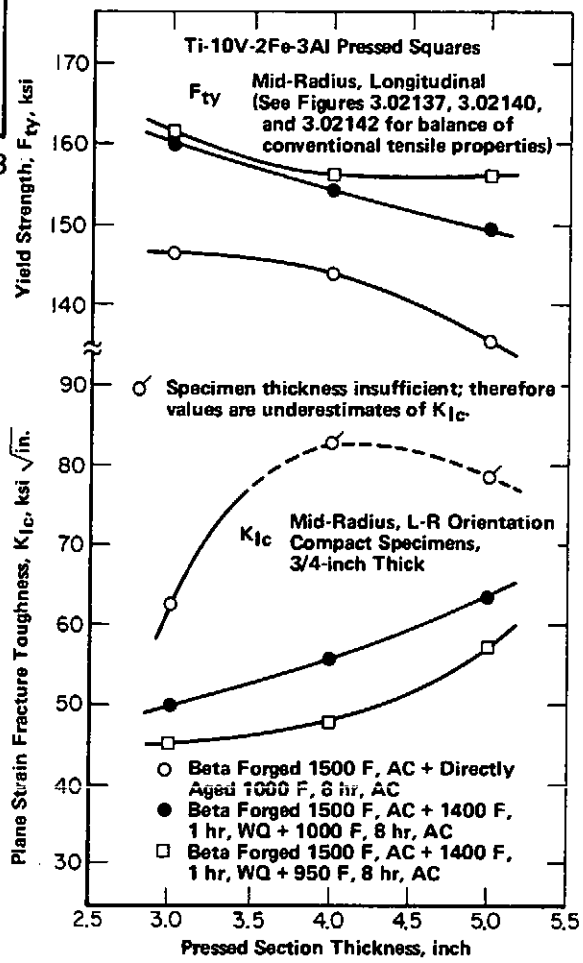


FIGURE 3.02724. EFFECT OF SECTION THICKNESS AND HEAT TREATMENT ON ROOM TEMPERATURE TENSILE YIELD STRENGTH AND PLANE STRAIN FRACTURE TOUGHNESS OF BETA FORGED PRESSED SQUARES (5)

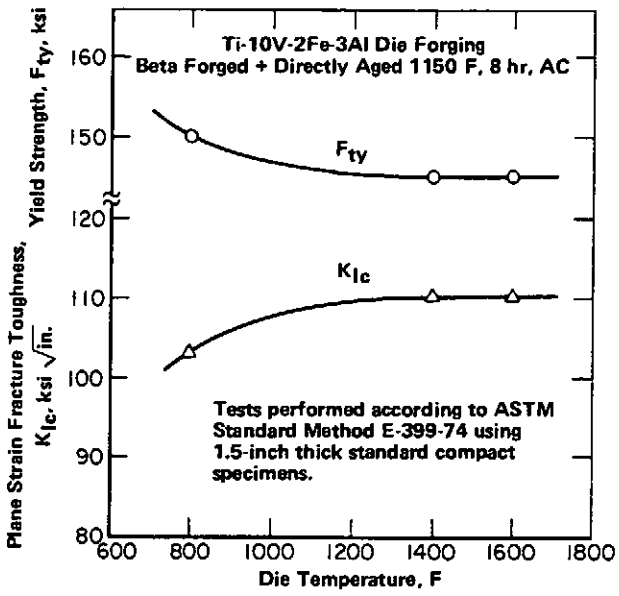


FIGURE 3.02725. EFFECT OF DIE TEMPERATURE ON ROOM TEMPERATURE STRENGTH AND TOUGHNESS OF FORGING, BETA FORGED PLUS DIRECTLY AGED (10)

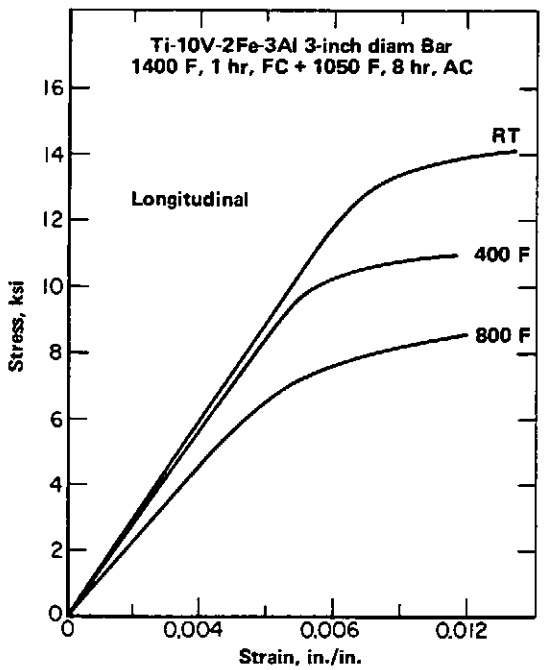


FIGURE 3.0311. TYPICAL TENSILE STRESS-STRAIN CURVES AT ROOM TEMPERATURE, 400 F, AND 800 F FOR HEAT TREATED BAR (4)

Ti
10 V
2 Fe
3 Al

Ti-10-2-3

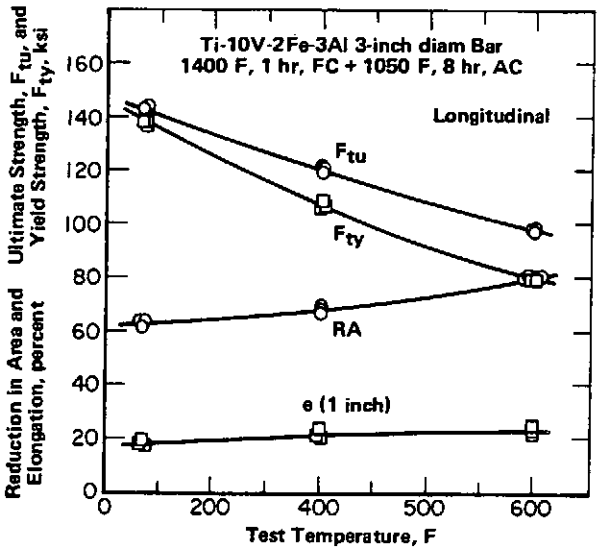


FIGURE 3.0312. EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF HEAT TREATED BAR (4)

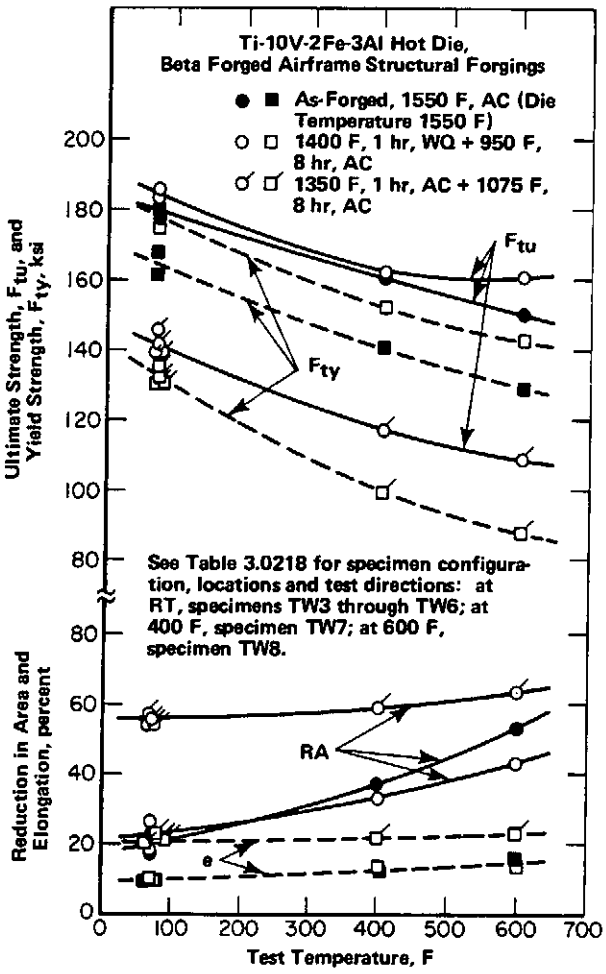


FIGURE 3.0314. EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF AS-FORGED AND HEAT TREATED HOT DIE, BETA FORGED AIRFRAME STRUCTURAL FORGINGS (2)

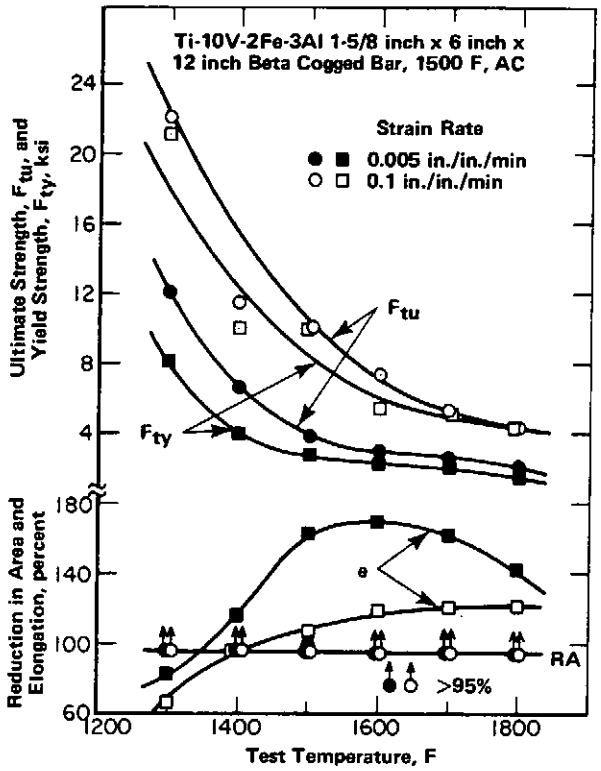


FIGURE 3.0315. EFFECT OF VERY HIGH TEST TEMPERATURES ON TENSILE PROPERTIES AT TWO STRAIN RATES FOR BETA COGGED BAR (3)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

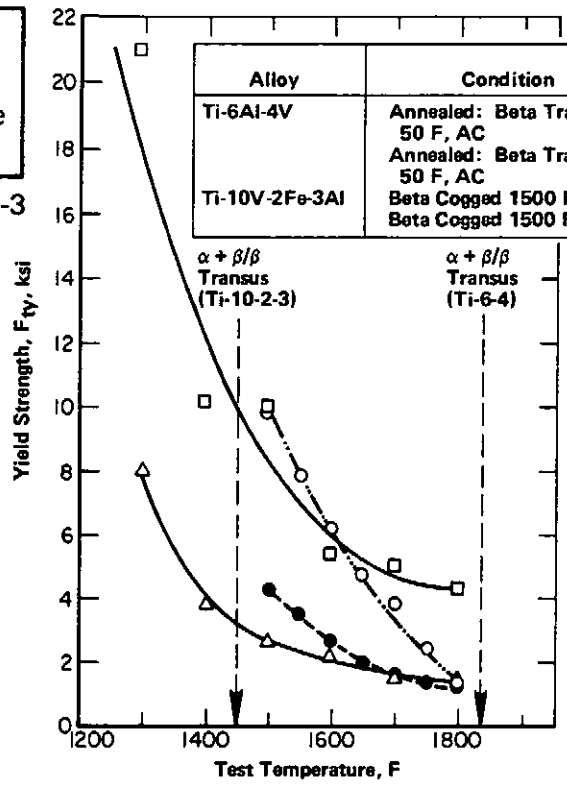


FIGURE 3.0316. COMPARISON OF STRAIN RATE AND TEST TEMPERATURE EFFECTS ON TENSILE YIELD STRENGTH OF Ti-10V-2Fe-3Al AND Ti-6Al-4V ALLOYS (3)

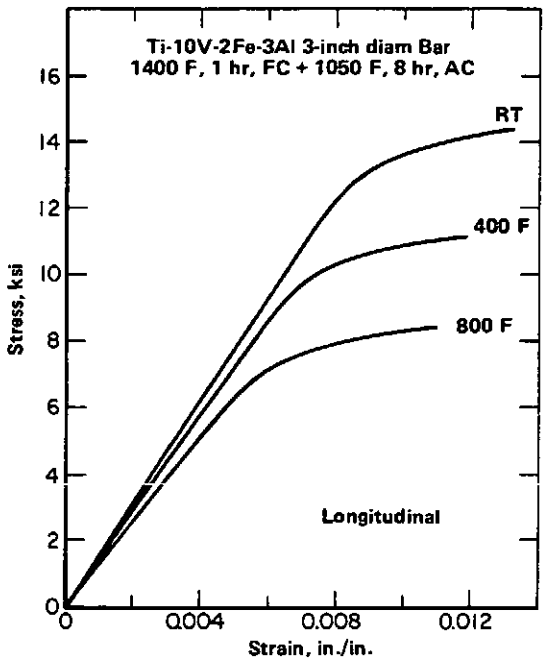


FIGURE 3.0321. TYPICAL COMPRESSIVE STRESS-STRAIN CURVES AT ROOM TEMPERATURE, 400 F, AND 800 F FOR HEAT TREATED BAR (4)

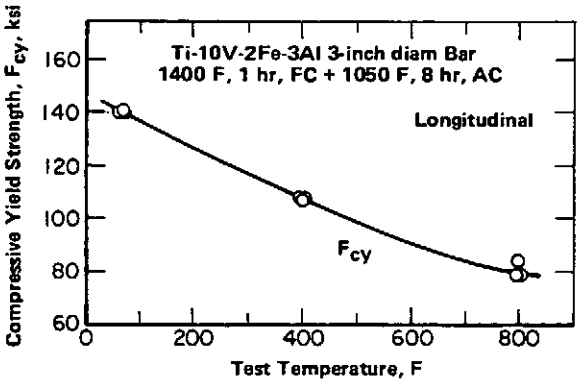


FIGURE 3.0322. EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF HEAT TREATED BAR (4)

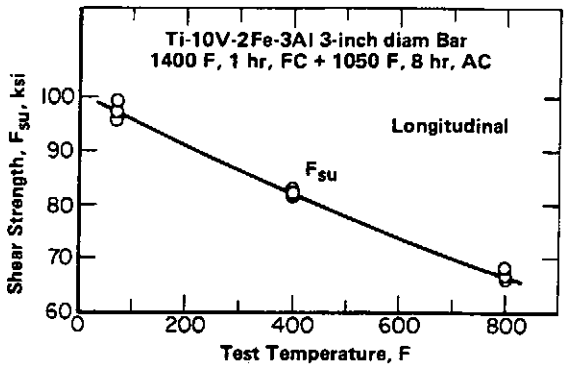
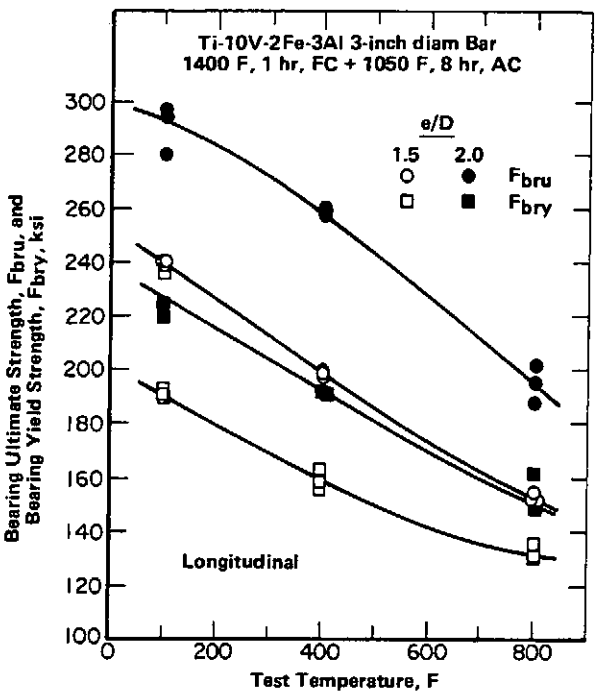


FIGURE 3.0351. EFFECT OF TEST TEMPERATURE ON SHEAR ULTIMATE STRENGTH OF HEAT TREATED BAR (4)



Ti
10 V
2 Fe
3 Al
Ti-10-2-3

FIGURE 3.0361. EFFECT OF TEST TEMPERATURE ON BEARING STRENGTH OF HEAT TREATED BAR (4)

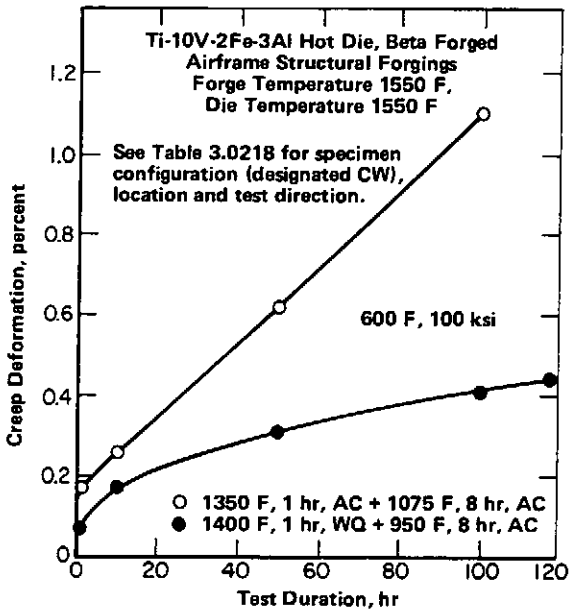


FIGURE 3.041. CREEP CURVES AT 600 F, 100 KSI, FOR HEAT TREATED HOT DIE, BETA FORGED AIRFRAME STRUCTURAL FORGINGS (2)

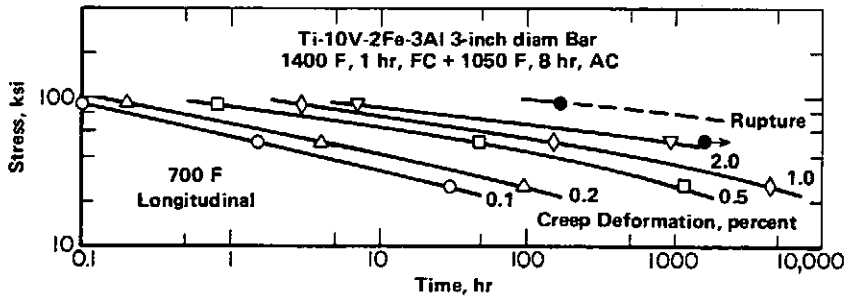


FIGURE 3.042. CREEP DEFORMATION AND RUPTURE CURVES AT 700 F FOR HEAT TREATED BAR (4)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

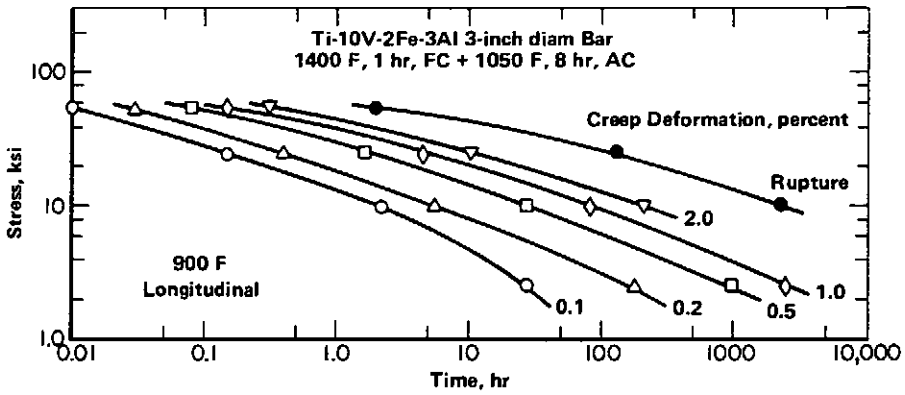


FIGURE 3.043. CREEP DEFORMATION AND RUPTURE CURVES AT 900 F FOR HEAT TREATED BAR (4)

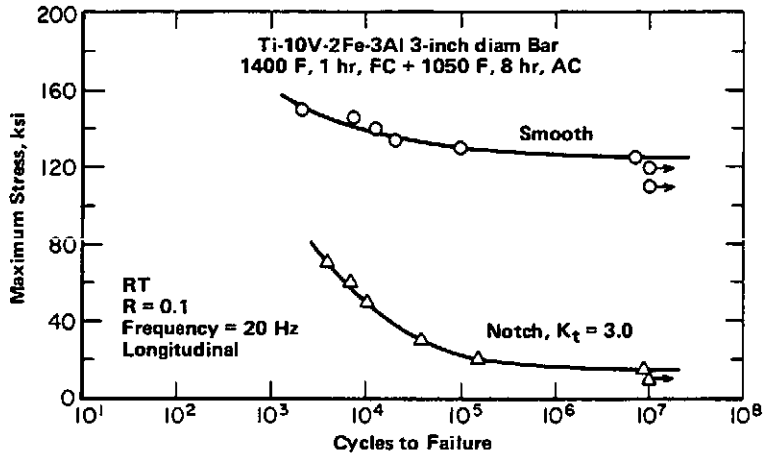


FIGURE 3.051. ROOM TEMPERATURE SMOOTH AND NOTCH AXIAL LOAD FATIGUE PROPERTIES OF HEAT TREATED BAR (4)

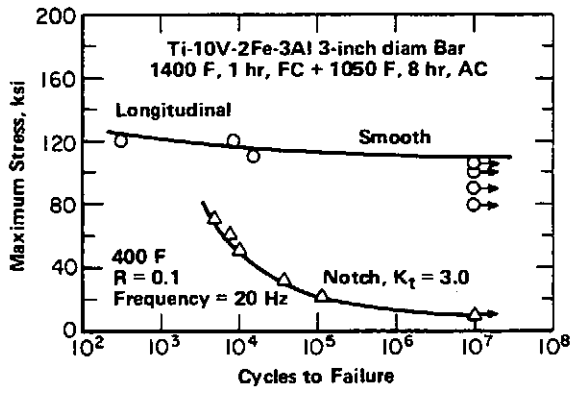


FIGURE 3.052. SMOOTH AND NOTCH AXIAL LOAD FATIGUE PROPERTIES AT 400 F OF HEAT TREATED BAR (4)

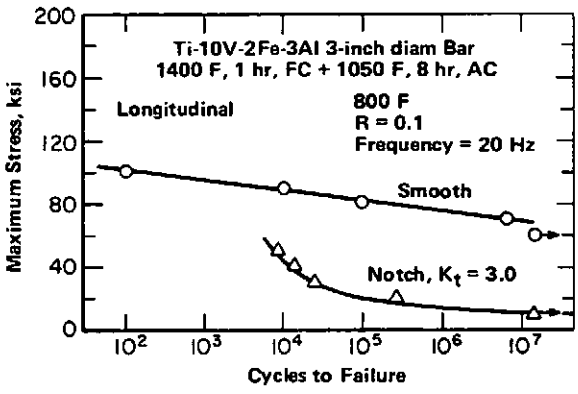


FIGURE 3.053. SMOOTH AND NOTCH AXIAL LOAD FATIGUE PROPERTIES AT 800 F OF HEAT TREATED BAR (4)

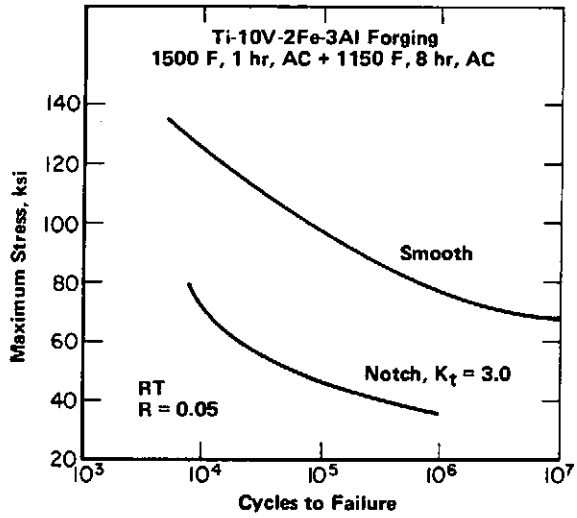


FIGURE 3.054. ROOM TEMPERATURE SMOOTH AND NOTCH AXIAL LOAD FATIGUE PROPERTIES OF HEAT TREATED FORGING (1)

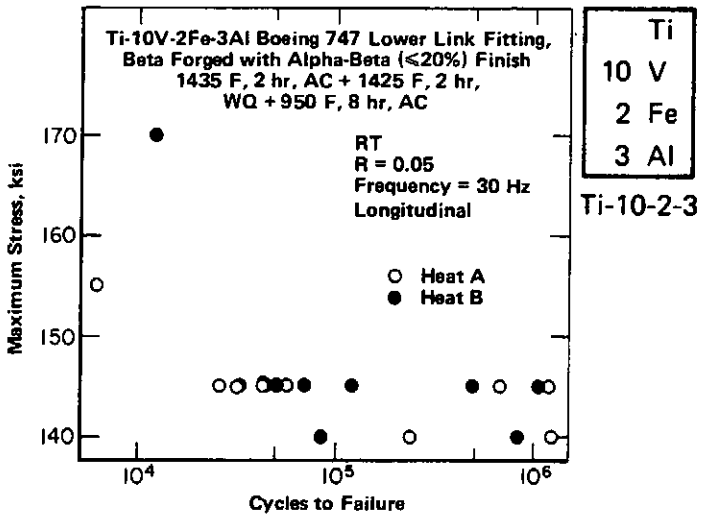


FIGURE 3.055. ROOM TEMPERATURE SMOOTH FATIGUE PROPERTIES OF HEAT TREATED BETA FORGED AIRFRAME STRUCTURAL FORGING (8)

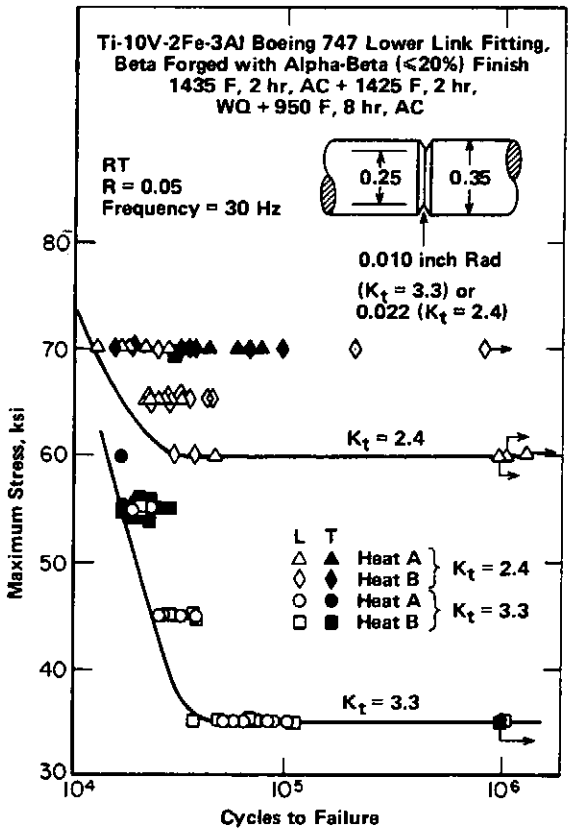


FIGURE 3.056. ROOM TEMPERATURE MILD-NOTCH FATIGUE PROPERTIES OF HEAT TREATED BETA FORGED AIRFRAME STRUCTURAL FORGING (8)

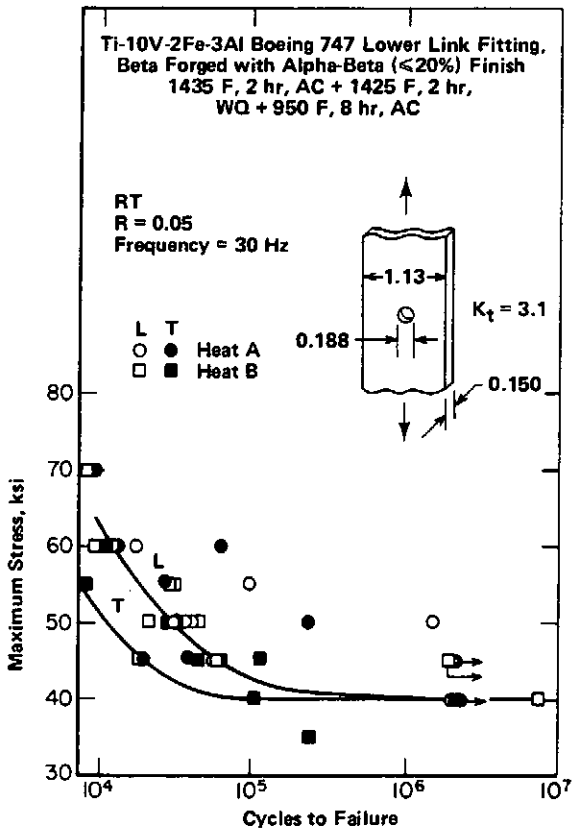


FIGURE 3.057. ROOM TEMPERATURE SINGLE-HOLE SPECIMEN FATIGUE PROPERTIES OF HEAT TREATED BETA FORGED AIRFRAME STRUCTURAL FORGING (8)

Ti
10 V
2 Fe
3 Al

Ti-10-2-3

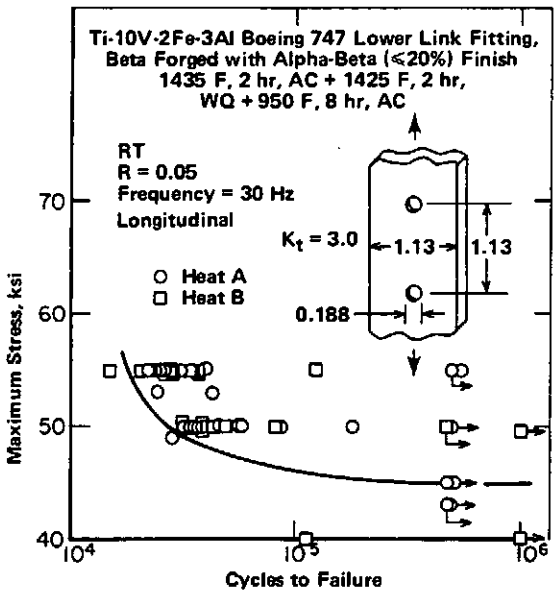


FIGURE 3.058. ROOM TEMPERATURE DOUBLE-HOLE SPECIMEN FATIGUE PROPERTIES OF HEAT TREATED BETA FORGED AIRFRAME STRUCTURAL FORGING (8)

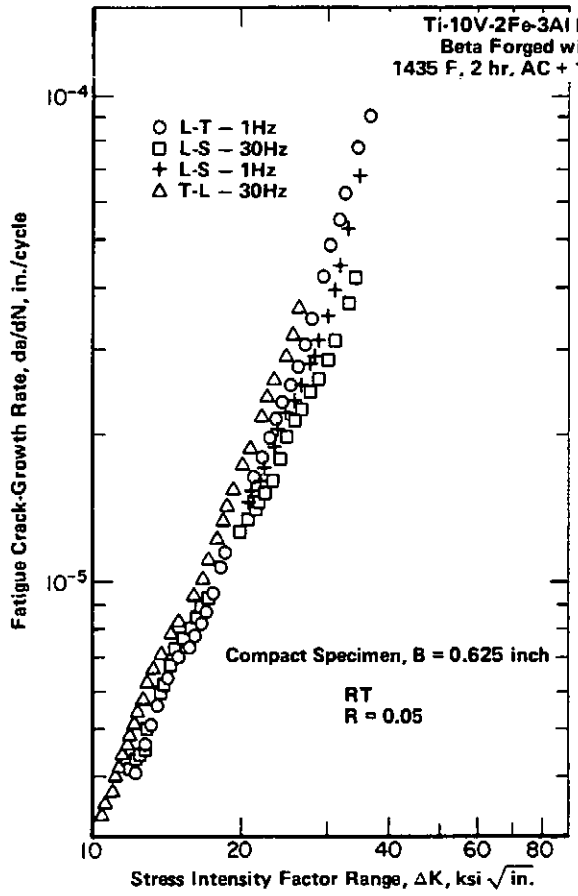


FIGURE 3.059. ROOM TEMPERATURE FATIGUE CRACK-GROWTH IN AIR FOR AIRFRAME STRUCTURAL FORGING (8)

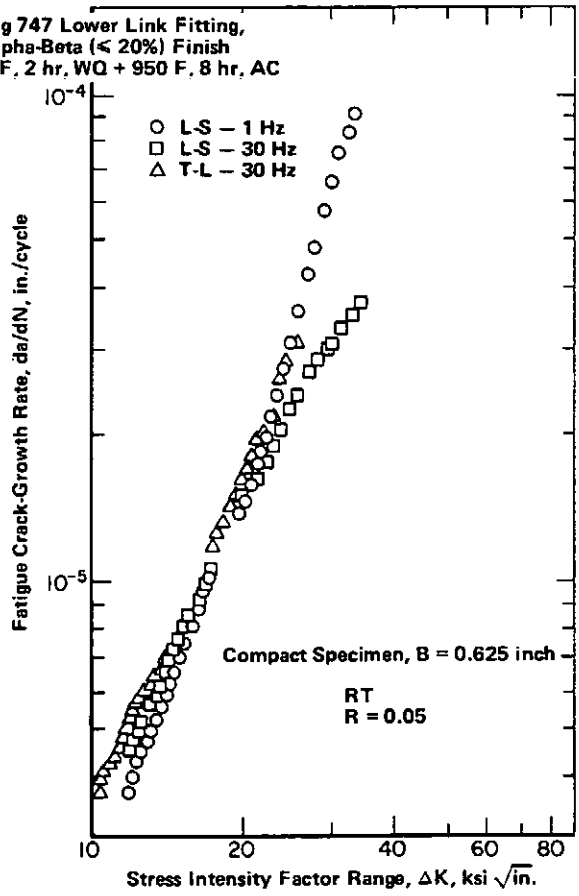


FIGURE 3.0510. ROOM TEMPERATURE FATIGUE CRACK-GROWTH IN 3.5 PERCENT NaCl SOLUTION FOR AIRFRAME STRUCTURAL FORGING (8)

Ti
10 V
2 Fe
3 Al

Ti-10-2-3

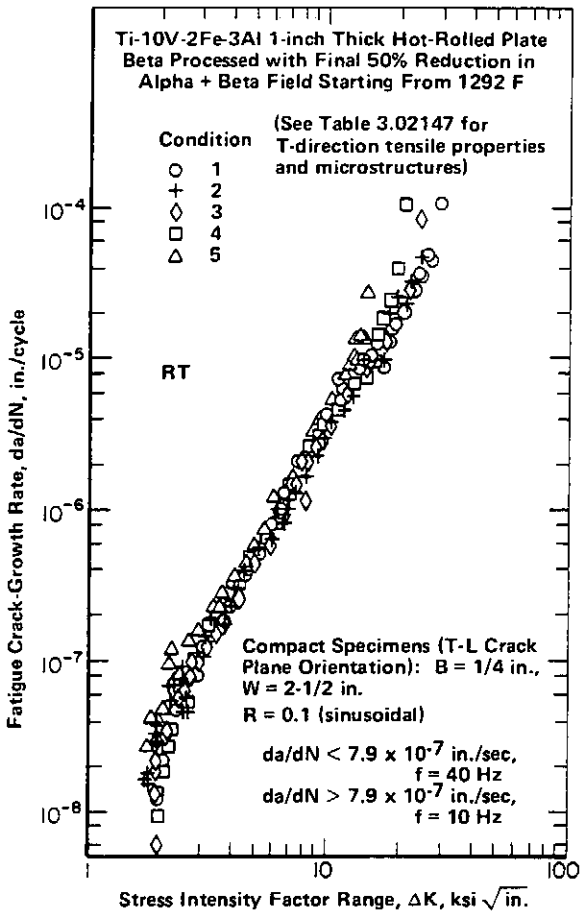


FIGURE 3.0511. ROOM TEMPERATURE FATIGUE CRACK-GROWTH RATES FOR HOT-ROLLED PLATE SOLUTION TREATED AND ALPHA-AGED TO FIVE DIFFERENT MICROSTRUC-CONDITIONS, ALL AT APPROX-IMATELY THE SAME YIELD STRENGTH LEVEL (18)

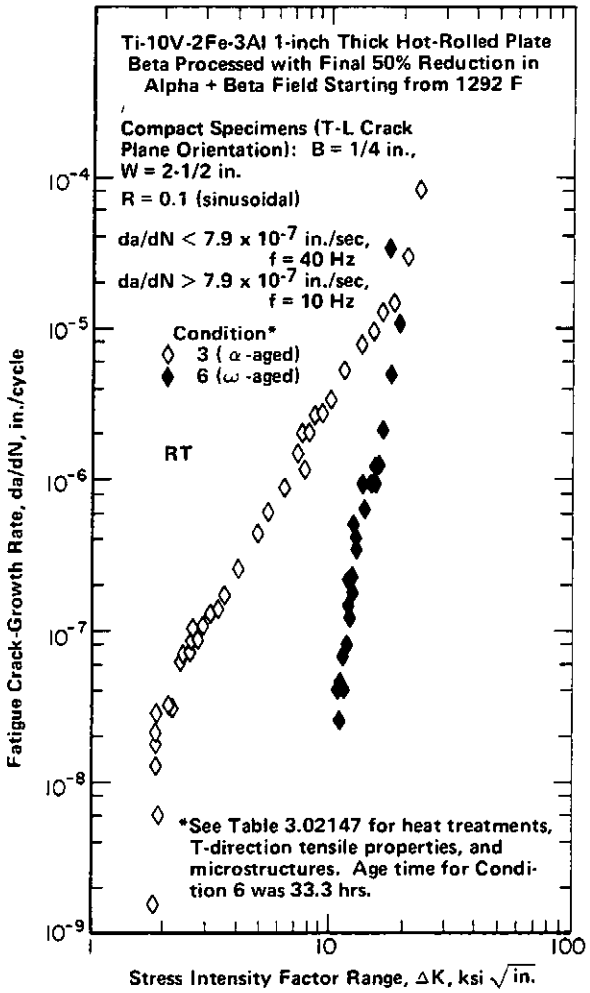


FIGURE 3.0512. ROOM TEMPERATURE FATIGUE CRACK-GROWTH RATES FOR HOT-ROLLED PLATE SOLUTION TREATED AND EITHER ALPHA-AGED OR OMEGA-AGED TO A COMMON YIELD STRENGTH LEVEL (18)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

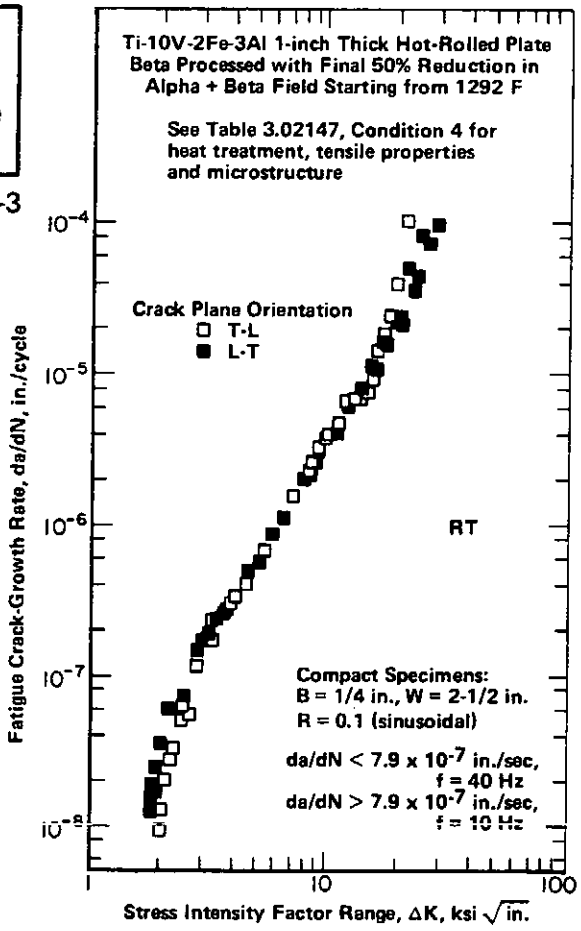


FIGURE 3.0513. EFFECT OF TEST DIRECTION ON ROOM TEMPERATURE FATIGUE CRACK-GROWTH RATE FOR HOT-ROLLED PLATE SOLUTION TREATED AND ALPHA-AGED (18)

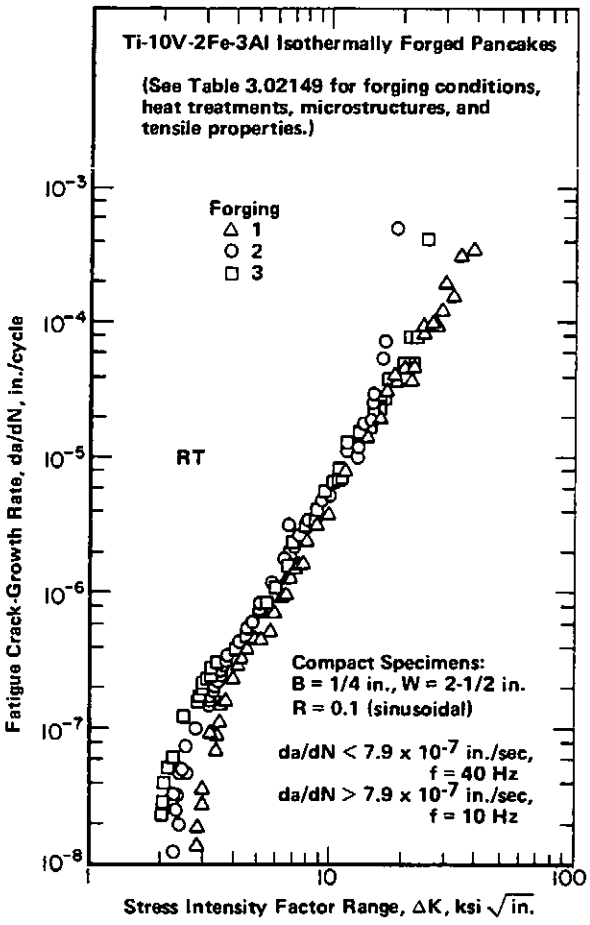


FIGURE 3.0514. ROOM TEMPERATURE FATIGUE CRACK-GROWTH RATES FOR SOLUTION TREATED AND AGED ISOTHERMALLY FORGED PANCAKES (18)

Ti
10 V
2 Fe
3 Al

Ti-10-2-3

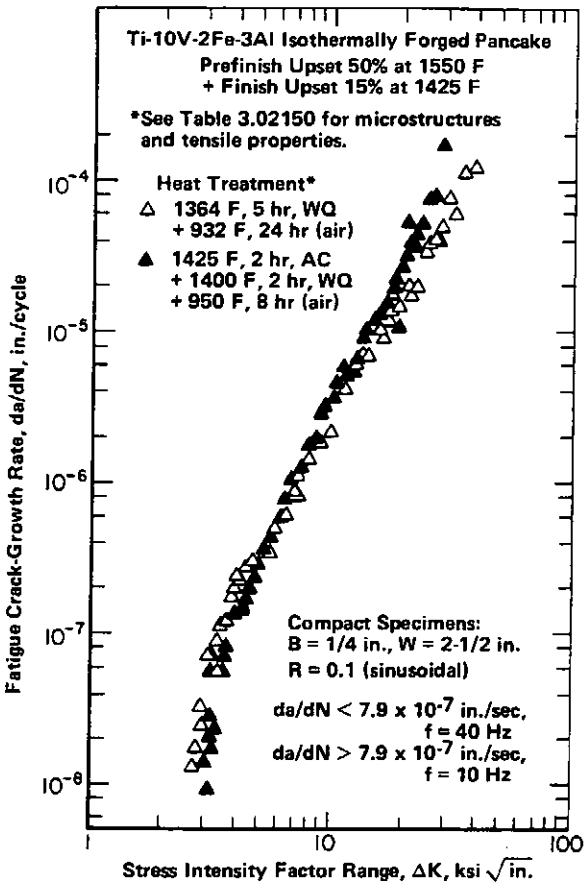


FIGURE 3.0515. ROOM TEMPERATURE FATIGUE CRACK-GROWTH RATES FOR ISOTHERMALLY FORGED PANCAKE SOLUTION TREATED OR DUPLEX SOLUTION TREATED PRIOR TO AGING TO NEARLY EQUAL YIELD STRENTH LEVELS (18)

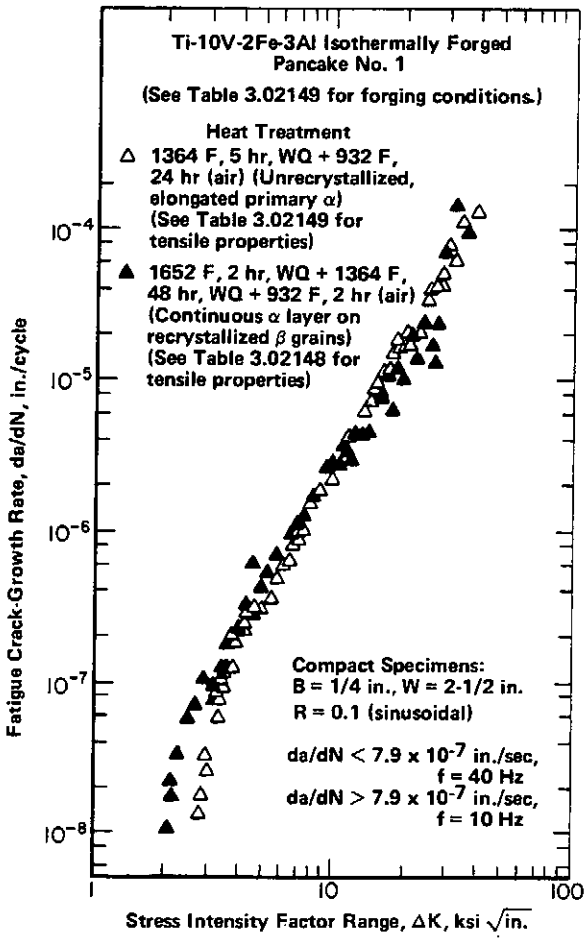


FIGURE 3.0516. ROOM TEMPERATURE FATIGUE CRACK-GROWTH RATES FOR ISOTHERMALLY FORGED PANCAKE SOLUTION TREATED AND AGED (ELONGATED PRIMARY ALPHA) OR DUPLEX SOLUTION TREATED AND AGED (CONTINUOUS GRAIN BOUNDARY ALPHA-LAYER) (18)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

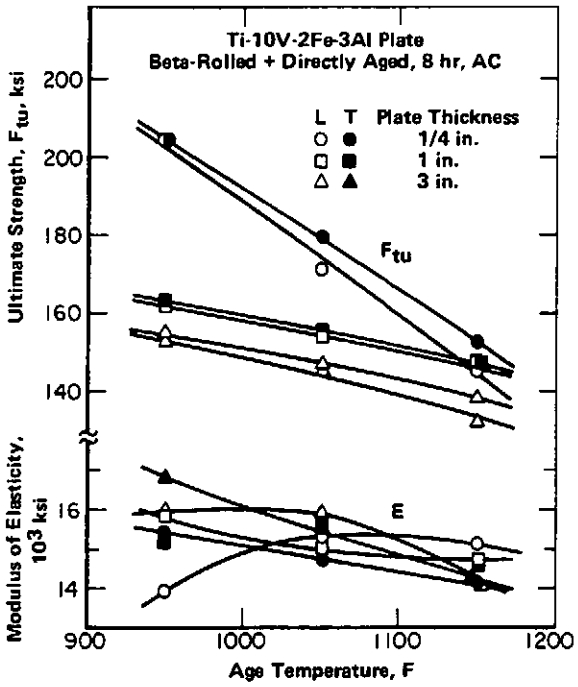


FIGURE 3.0621. ROOM TEMPERATURE ULTIMATE STRENGTH AND ELASTIC MODULUS FOR PLATE OF VARIOUS THICKNESSES, BETA-ROLLED AND DIRECTLY AGED (9)

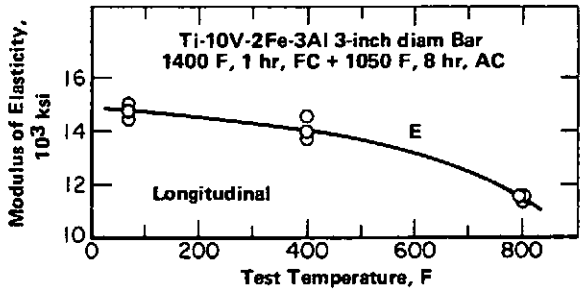


FIGURE 3.0622. EFFECT OF TEST TEMPERATURE ON TENSILE ELASTIC MODULUS OF HEAT TREATED BAR (4)

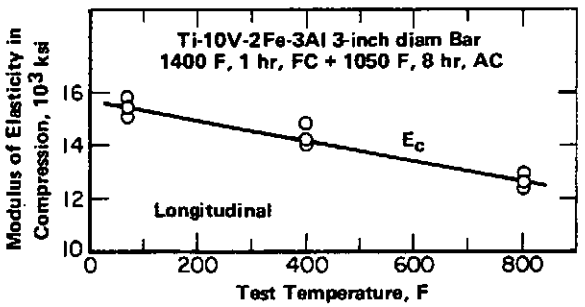


FIGURE 3.0624. EFFECT OF TEST TEMPERATURE ON COMPRESSIVE ELASTIC MODULUS OF HEAT TREATED BAR (4)

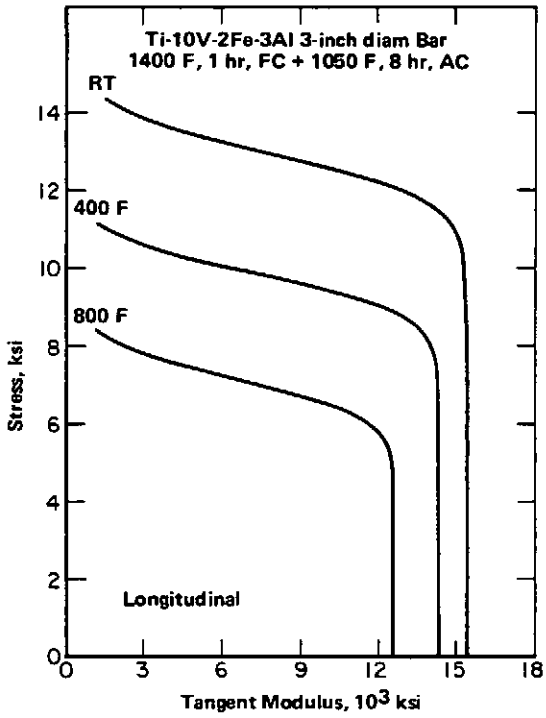


FIGURE 3.0641. TYPICAL COMPRESSIVE TANGENT MODULUS CURVES AT ROOM TEMPERATURE, 400 F, AND 800 F FOR HEAT TREATED BAR (4)

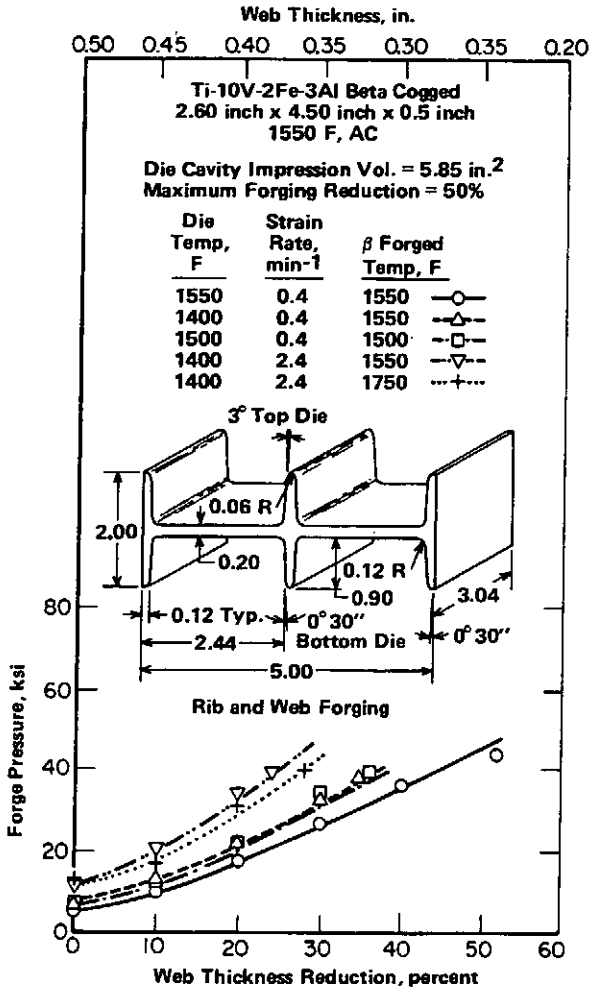


FIGURE 4.0111. VARIATION OF FORGE PRESSURE WITH WEB THICKNESS FOR Ti-10V-2Fe-3Al EXPERIMENTAL RIB-AND-WEB FORGINGS (3)

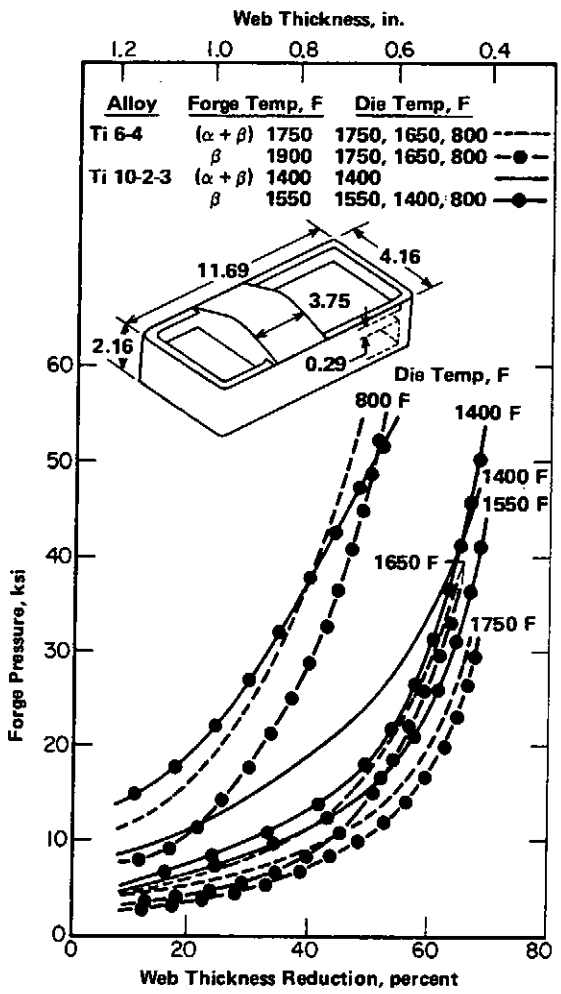


FIGURE 4.0112. VARIATION OF FORGE PRESSURE WITH WEB THICKNESS FOR Ti-6Al-4V AND Ti-10V-2Fe-3Al EXPERIMENTAL STRUCTURAL SHAPE FORGINGS (10)

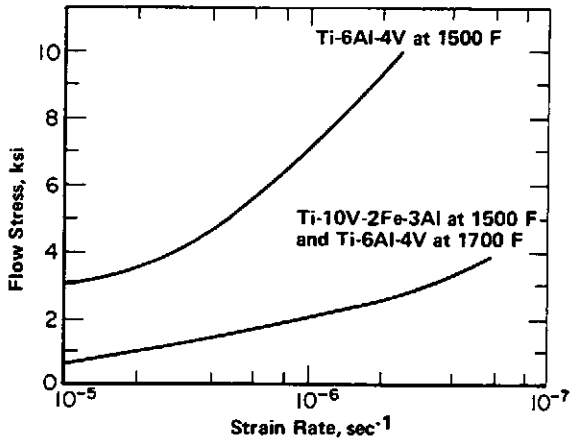


FIGURE 4.0113. HOT FLOW STRESS OF Ti-10V-2Fe-3Al COMPARED TO THAT OF Ti-6Al-4V (9)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

Ti
10 V
2 Fe
3 Al

Ti-10-2-3

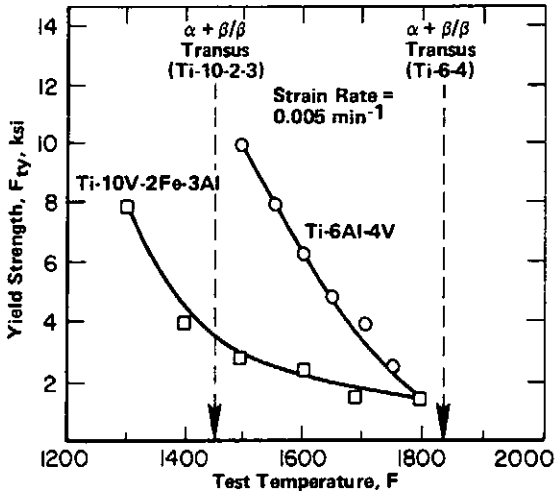


FIGURE 4.0115. TEMPERATURE DEPENDENCE OF TENSILE YIELD STRENGTH FOR Ti-10V-2Fe-3Al AND Ti-6Al-4V ALLOYS (1)

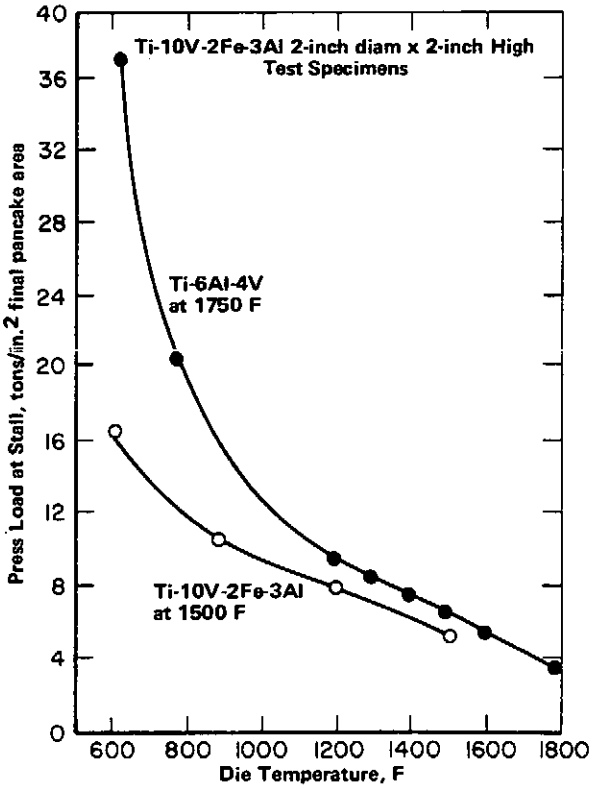


FIGURE 4.0116. HOT COMPRESSION TEST RESULTS (1)

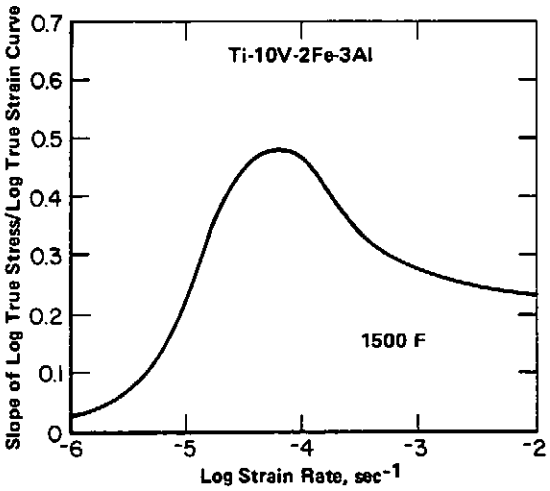


FIGURE 4.0117. STRAIN RATE SENSITIVITY OF Ti-10V-2Fe-3Al AT 1500 F (1)

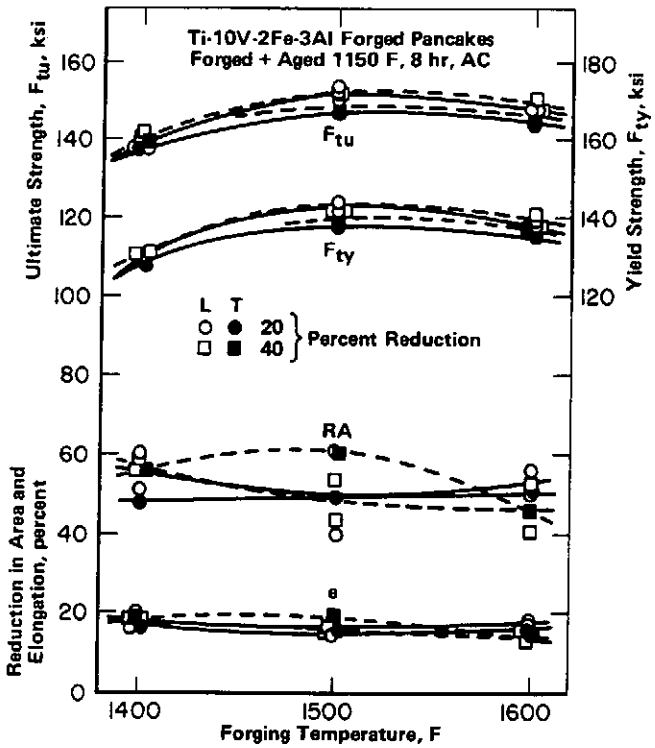
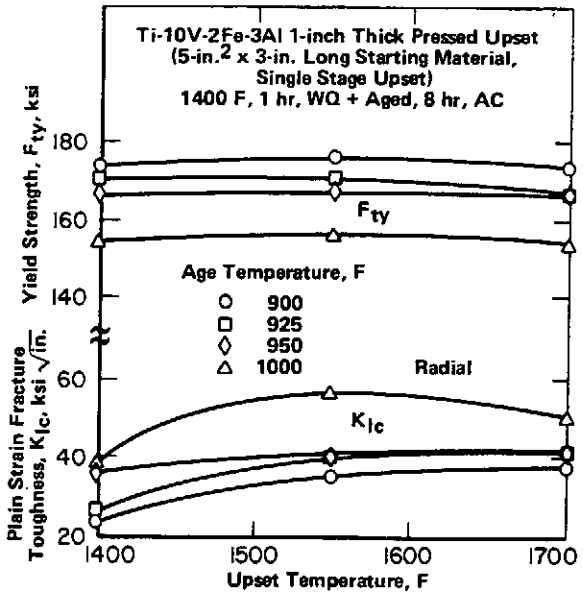


FIGURE 4.0131. EFFECT OF FORGING TEMPERATURE AND PERCENT REDUCTION ON ROOM TEMPERATURE TENSILE PROPERTIES OF FORGED PANCAKES (9)



Ti
10 V
2 Fe
3 Al
Ti-10-2-3

FIGURE 4.0132. EFFECT OF FORGING TEMPERATURE ON ROOM TEMPERATURE TENSILE YIELD STRENGTH AND PLANE STRAIN FRACTURE TOUGHNESS OF HEAT TREATED 1-INCH THICK UPSET FORGINGS (5)

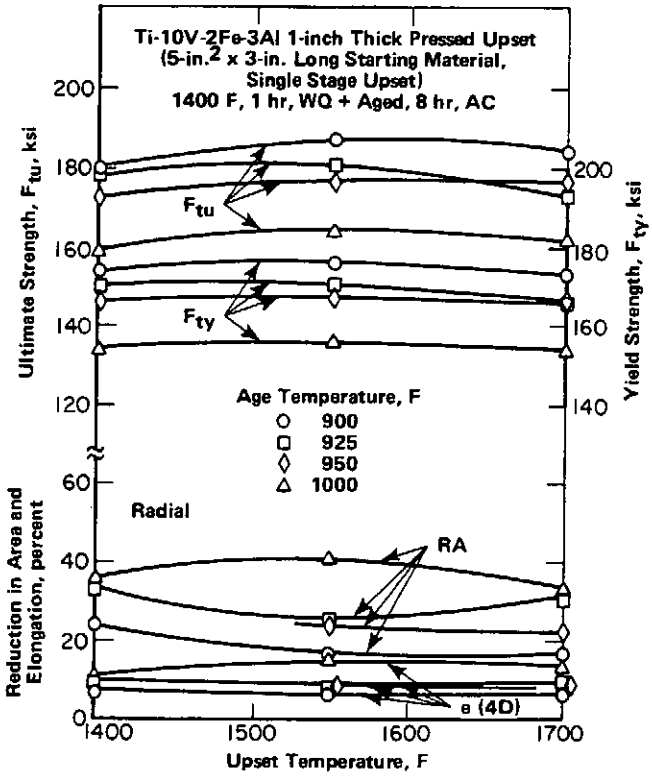


FIGURE 4.0133. EFFECT OF UPSET FORGING TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF HEAT TREATED 1-INCH THICK UPSET FORGINGS (5)

Ti
10 V
2 Fe
3 Al
Ti-10-2-3

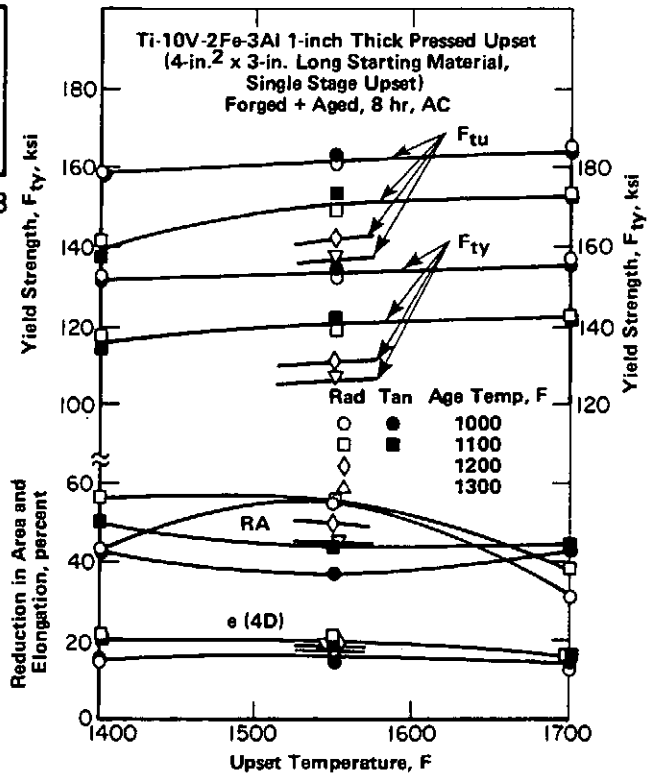


FIGURE 4.0134. EFFECT OF UPSET FORGING TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF FORGED PLUS DIRECTLY AGED 1-INCH THICK UPSET FORGINGS (5)

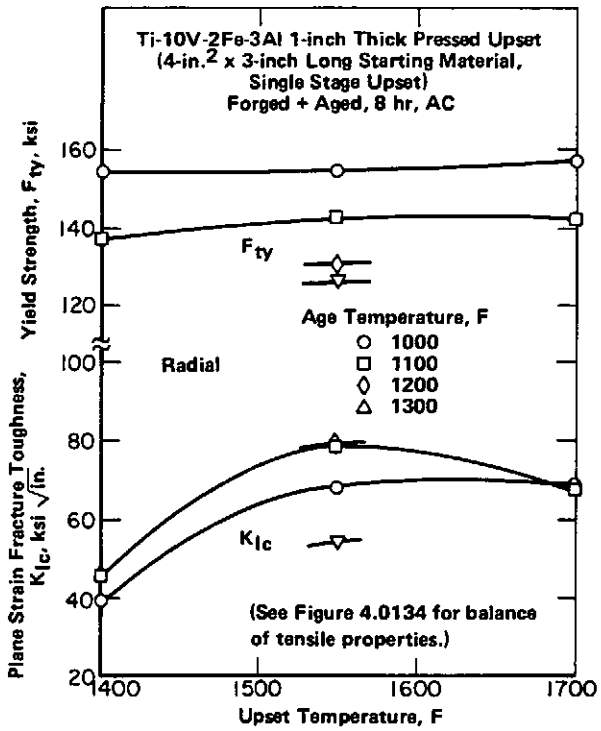


FIGURE 4.0135. EFFECT OF FORGING TEMPERATURE ON ROOM TEMPERATURE TENSILE YIELD STRENGTH AND PLANE STRAIN FRACTURE TOUGHNESS OF FORGED PLUS DIRECTLY AGED 1-INCH THICK UPSET FORGINGS (5)

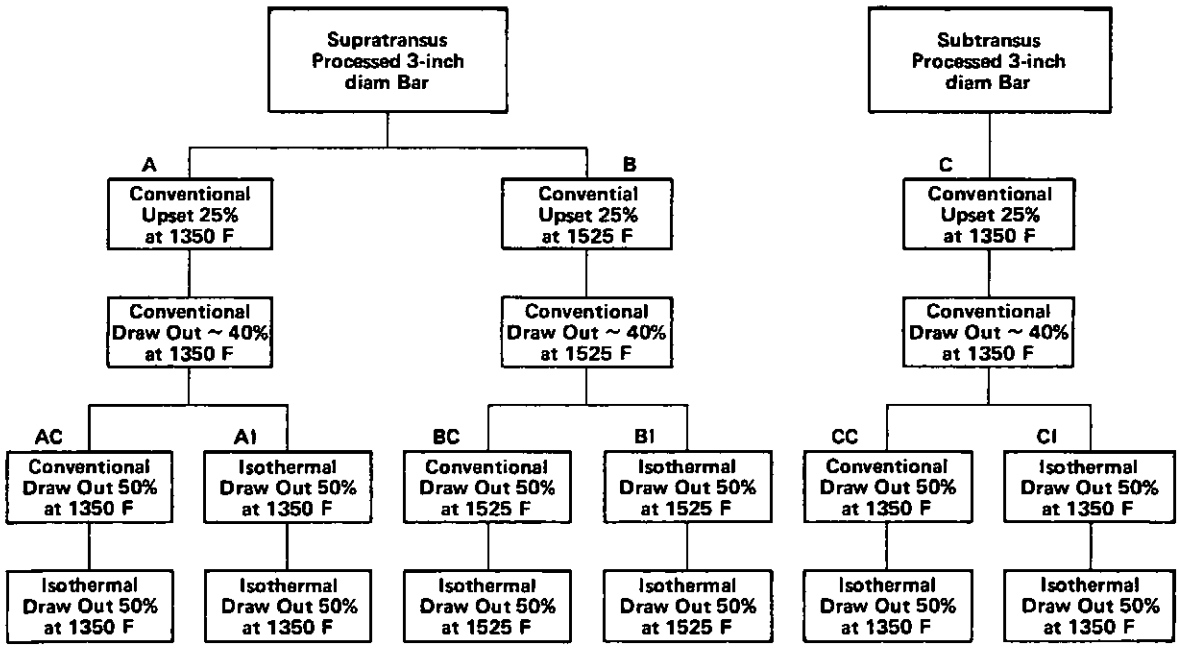


FIGURE 4.0138. CONVERSION SCHEDULE FOR 3-INCH DIAMETER BAR ISOTHERMALLY FORGED TO 0.5-INCH THICK FLAT PLATE FOR USE IN PROCESSING AND HEAT TREATMENT STUDY REPORTED UPON IN TABLES 4.0139 THROUGH 4.01311 (20)

Author **William D. Klopp**

1. GENERAL

The Ti-15V-3Cr-3Sn-3Al alloy, generally referred to as Ti-15-3 or simply 15-3, is a metastable beta alloy which was originally developed for sheet metal applications. Its background is traced to Air Force programs of the late 1960's aimed at reducing the cost of titanium sheet metal structures. Ti-15-3 is the most forgiving of several compositions evaluated during these programs, leading to high product uniformity. By virtue of composition, it retains the high temperature body-centered-cubic beta phase when quenched from the beta field but this metastable structure precipitates fine alpha phase during subsequent low temperature aging. Thus, the alloy is capable of being heat treated to high strength levels after forming. Ti-15-3 is also more versatile than the popular Ti-6Al-4V alloy, which exhibits only limited cold formability and is not generally considered to be strip producible. Compared with Ti-6Al-4V, the beta Ti-15-3 alloy offers lower costs, better cold formability, improved property uniformity, and better dimensional tolerance and finish. Cost savings of 35 to 50 percent have been estimated for a generic airframe parts when using cold formed Ti-15-3 instead of hot formed Ti-6Al-4V.

Although originally developed as a sheet alloy, Ti-15-3 is also produced in other forms such as foil, tubing, castings, and forgings. It is normally used in the fully heat treated condition to utilize its high strength; however, as a substitute for aluminum, it is sometimes employed in the softer, solution annealed condition. It is used in a variety of airframe applications and has also been evaluated for aerospace tankage applications, high-strength hydraulic tubing, and fasteners. (Refs. 3-6)

1.1 Commercial Designation - Ti-15-3

1.2 Alternate Designations - Ti-15-3-3-3, 15-3 R58153 (Sheet and Strip)

1.3 Specifications

1.3.1 *[Table]* AMS specifications.

1.4 Composition

1.4.1 *[Table]* AMS specified composition.

The rationale for the compositional make-up of Ti-15-3 is as follows:

(a) Vanadium is the preferred beta isomorphous stabilizer since it has a lower density than molybdenum, the other common isomorphous stabilizer.

(b) Vanadium-aluminum master alloys are commercially available, circumventing the melting problems associated with additions of elemental molybdenum.

Ti
15 V
3 Cr
3 Sn
3 Al

(c) Chromium helps to suppress omega formation and thus acts as a eutectoid beta stabilizer; it is also believed to beneficial for cold formability.

(d) Tin also helps to suppress omega formation and enhances aging response.

(e) Aluminum also helps to suppress omega formation, lowers the overall density, and promotes the desired aging response. (Refs. 6, 7)

1.5 Heat Treatment

1.5.1 Standard Heat Treatments. Heat treatment schedules recommended for Ti-15-3 are as follows:

Stress Relieve	1200F, 15 min, air cool
Solution Anneal	1450-1550F, 3-30 min, rapid cool
Age	900F, 16-48 hr, air cool
	950F, 8-32 hr, air cool
	1000F, 8-24 hr, air cool
	1050F, 8-16 hr, air cool

The heat treatment conditions referred to in AMS specifications (see Table 3.1.1) fall within the above recommendations. (Refs. 1, 2, 8)

Solution treatment conducted in air requires the removal of 0.0015 to 0.002 inch of alpha case. Alternatively, the solution and aging heat treatments can be conducted in vacuum, eliminating oxidation from heat treatment in air and possible hydrogen pickup from subsequent chemical descaling operations. (Ref. 6)

The longer aging times above are recommended when it is desireable to minimize property scatter, although in many cases the shorter times can be satisfactorily used. Close temperature control is also required during aging in order to minimize property scatter. (Refs. 6, 8)

1.5.2 Microstructural Effects. The Ti-15-3 alloy is a metastable beta alloy. Thus, the alloy can retain an all-beta body-centered-cubic structure after sufficiently rapid cooling from temperatures above the beta transus (about 1400F). This microstructure, however, is unstable and precipitates a fine hexagonal-close-packed alpha phase during subsequent aging at lower temperatures. The heat treatability of Ti-15-3 derives from the solutioning of alpha phase above the beta transus and its precipitation below the beta transus temperature. (Ref. 7)

The precipitation reaction is sluggish so that air cooling is sufficient to retain the beta structure for thicknesses less than about 0.1875 inch; thicker material may require fan cooling or water quenching. (see Figure 2.1.2.1.1 for the T-T-T diagram)

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Progress of the aging reaction can be followed by hardness measurements, which correlate well with the volume fraction of alpha precipitate (determined by X-ray diffraction techniques). The effects of solutioning temperature and aging conditions on hardness and microstructure are shown in Figures 1.5.2.1 and 1.5.2.2, respectively. Little hardening or alpha phase precipitation occurs during aging at 572F for times up to 120 hours, but substantial reaction occurs during this time at 752 and 932F. The reactions are essentially complete after about 100 hours at 752F and after less than 20 hours at 932F. Increasing the solutioning temperature from 1472 to 1832F has only a minor effect on the age hardening reaction but further increase to 2372F significantly increases hardness and amount of alpha phase precipitation during subsequent aging. This effect is attributed to a larger number of lattice vacancies at the higher solutioning temperature, resulting in an increased nucleation rate for alpha phase precipitation during aging. (Ref. 9)

1.5.2.1 *[Figure]* Effects of aging time and temperature on hardness of solution annealed alloy.

1.5.2.2 *[Figure]* Effects of aging time and temperature on alpha phase precipitation in solution annealed sheet.

Recrystallization occurs rapidly at temperatures of 1472F and higher, as shown in Figure 1.5.2.3, accompanied by increasing grain size, Figure 1.5.2.4. The grain growth kinetics are shown in Figure 1.5.2.5. (Refs. 10, 11)

1.5.2.3 *[Figure]* Effects of annealing time and temperature on recrystallization behavior of hot worked alloy.

1.5.2.4 *[Figure]* Effects of annealing temperature on grain size of hot rolled alloy.

1.5.2.5 *[Figure]* Effects of annealing time and temperature on grain growth behavior.

1.5.3 Effects of solution annealing. (See also Figures 1.5.2.1, 1.5.2.2, and 3.2.7.1.1) Solution annealing conditions have a generally modest effect on resultant tensile properties. Tensile strength of cold rolled solution annealed and aged alloy decreases and ductility increases as the solution annealing temperature is increased from below to above the beta transus at about 1400F, Figure 1.5.3.1. (Ref. 12) This behavior is likely due to recrystallization during solution annealing. However, as the solution annealing temperature is further increased up to 1652F, strength is little affected but ductility decreases, as shown in Figure 1.5.3.2 (Ref. 13) and Table 1.5.3.3. The decrease in ductility with increasing solution annealing temperature is attributed to increasing grain size. (Refs. 14, 15)

1.5.3.1 *[Figure]* Effects of solution annealing temperature on tensile properties after aging at 842F.

1.5.3.2 *[Figure]* Effects of solution annealing temperature on tensile properties after aging at 932F.

1.5.3.3 *[Table]* Effects of grain size and aging conditions on tensile properties of solution annealed alloy.

1.5.4 Effects of aging. Aging conditions significantly affect subsequent mechanical properties such as hardness, strength, and toughness through their effects on the amount and morphology of the alpha phase precipitate. Aging temperature in particular has a strong effect. As shown in Figure 1.5.4.1, the amount of hardening after 50 hours aging is greatest at about 600F, due to the fine, coherent precipitate. (Ref. 13) The hardness change is time and temperature dependent with the hardness peak fading and shifting to higher aging temperatures as the aging time decreases. Additional hardness studies, presented in Figures 1.5.4.2 through 1.5.4.7, illustrate the time dependency of the aging reaction. An incubation period is noted at lower aging temperatures, during which no hardness increase is observed. The rate of age hardening increases with increasing aging temperature.

These data also further illustrate the increase in rate of age hardening with increasing temperature of the prior solution anneal, shown earlier in Figure 1.5.2.1. In Figure 1.5.4.2, age hardening at 932F is faster for alloy solution annealed at 1562 than at 1382F. Similarly, alloy solution annealed at 1652 or 2372F, Figures 1.5.4.6 and 1.5.4.7, age-hardens more rapidly than alloy solution annealed at 1472 or 1562F, Figures 1.5.4.3 to 1.5.4.5. (Refs. 10, 17, 18)

1.5.4.1 *[Figure]* Effects of aging temperature and time on hardness of alloy solution annealed at 1472F.

1.5.4.2 *[Figure]* Effects of aging time and temperature on hardness of plate solution annealed at 1382 or 1562F.

1.5.4.3 *[Figure]* Effects of aging time and temperature on hardness of plate solution annealed at 1472F.

1.5.4.4 *[Figure]* Effects of aging time and temperature on hardness of rod solution annealed at 1472F.

1.5.4.5 *[Figure]* Effects of aging time and temperature on hardness of plate solution annealed at 1562F.

1.5.4.6 *[Figure]* Effects of aging time and temperature on hardness of sheet solution annealed at 1652F.

1.5.4.7 *[Figure]* Effects of aging time and temperature on hardness of plate solution annealed at 2372F.

The effects of aging conditions on tensile properties are similar to those described above for hardness. Higher strengths are obtained after aging at lower temperatures and the time to reach the strength peak decreases with increasing aging temperature. How-

ever, ductility is reduced with increasing strength. These trends are shown in Figures 1.5.4.8 through 1.5.4.14. (Ref. 11)

Ti-15-3 can be direct aged (no solution anneal) to a tensile strength of at about 190 to 200 ksi while retaining adequate ductility. Between 950 and 1000F, the fully aged strength is a function of aging temperature, as shown in Table 1.5.4.15. Aging at 1050F produces an overaged condition with tensile strength of about 140 to 150 ksi. Aging at 850 to 900F is suitable primarily for those applications requiring higher strength where ductility is of lesser importance. (Refs. 8, 21-23)

Note that the solution annealing and aging conditions in Figure 1.5.4.13 are similar to those referred to in AMS specifications, described later in Table 3.1.1.

1.5.4.8 *[Figure]* Effects of aging at 842 to 1058F on tensile properties of sheet solution annealed at 1436F.

1.5.4.9 *[Figure]* Effects of aging time at 572F on the tensile properties of sheet solution annealed at 1472F.

1.5.4.10 *[Figure]* Effects of aging time at 842F on tensile properties of sheet solution annealed at 1472F.

1.5.4.11 *[Figure]* Effects of aging time at 1112F on tensile properties of sheet solution annealed at 1472F.

1.5.4.12 *[Figure]* Effects of aging time at 896 to 1004F on tensile properties of sheet solution annealed at 1472F.

1.5.4.13 *[Figure]* Effects of aging time at 900 and 950F on tensile properties of plate solution annealed at 1472F.

1.5.4.14 *[Figure]* Effects of aging time at 756 to 1116F on tensile properties of rod solution annealed at 1656F.

1.5.4.15 *[Table]* Effects of aging temperature and orientation on strength properties at room temperature.

Duplex aging treatments can be employed to further increase tensile strength. As shown in Figure 1.5.4.16, aging at 572F followed by a secondary age at 896F results in higher strength (but much lower ductility) than direct aging at 896F. These tensile property changes are attributed to the finer alpha phase precipitate resulting from the primary age at 572F.

1.5.4.16 *[Figure]* Effects of aging time at 896F on tensile properties of solution annealed alloy with and without aging at 572F.

Duplex aging at higher temperatures, however, can be employed to produce higher toughness at given strength levels than single aging treatments. Data illustrating this behavior are presented in Table 1.5.4.17 and compared graphically in Figure 1.5.4.18. Aging at a higher temperature followed by aging at a lower temperature after solution annealing produces a bimodal microstructure containing both large and small alpha precipitate particles. Although there is little change in strength properties as compared to single aging, a substantial improvement in fracture toughness is obtained. (Refs. 20, 25-27)

1.5.4.17 *[Table]* Effects of aging treatments on fracture toughness and tensile properties.

1.5.4.18 *[Figure]* Variation of fracture toughness and yield strength with aging treatment.

1.5.5 Thermomechanical processing. In addition to solution annealing and aging conditions, the mechanical properties of Ti-15-3 can be significantly and beneficially affected by inclusion of appropriate deformation steps during final processing. Such thermomechanical processing affects mechanical properties by changing not only the alpha phase precipitation behavior but also the dislocation substructure of the final product.

Cold-working prior to aging increases the dislocation density and refines the precipitate size, generating strengths moderately higher than can be achieved by aging directly after solution annealing. The aging rate is also increased. The strengths obtainable in this manner are shown in Figure 1.5.5.1. (Refs. 7, 8)

1.5.5.1 *[Figure]* Effects of cold rolling and aging temperature on yield strength and elongation.

The intermediate cold working step can be combined with duplex aging to provide a further strength increase. Exceptional strength, up to 280 ksi, coupled with reasonable ductility is achieved by cold working plus short time aging at 1112F followed by longer time aging at 752F, as shown in Figure 1.5.5.2. (Ref. 28)

1.5.5.2 *[Figure]* Effects of aging time at 752F on tensile properties of cold worked plus duplex aged alloy.

The introduction of cold work before solution annealing and aging can also effect a substantial improvement in tensile properties. An experimental schedule including two cycles of cold work plus solution annealing before aging has been studied. The first cold reduction should be greater than 50 percent and the second cold reduction approximately 10-20 percent. Strengths of about 280 ksi accompanied by elongations approaching 10 percent can be achieved by this approach, as shown in Figure 1.5.5.3. (Ref. 29)

1.5.5.3 *[Figure]* Effects of second rolling reduction on tensile properties of thermomechanically processed sheet.

1.5.6 Casting heat treatments. Feasibility studies have shown that shrinkage voids in cast Ti-15-3 can be healed by a hot isostatic pressure (HIP) cycle of 2 hours at 1750F at 15 ksi, followed by cooling at 1100F/hr. This HIP treatment can also function as a solution anneal. The strengths and ductilities of cast, HIPped and aged

alloy, shown in Figure 1.5.6.1, are comparable to those of wrought solution annealed and aged alloy, as shown earlier in Figure 1.5.4.12. (Ref. 30)

1.5.6.1 *[Figure]* Effects of aging at 900 to 1000F on tensile properties of hot isostatically pressed cast alloy.

1.6 Hardness

(See Figures 1.5.2.1 and 1.5.4.1 through 1.5.4.7.)

1.7 Forms and Conditions Available

Ti-15-3 is available as bar, rod, plate, sheet, strip and as foil in thickness as low as 0.0003 inch. (Ref. 31) It is normally supplied in the solution annealed (recrystallized) condition.

1.8 Melting and Casting Practice

1.8.1 The Ti-15-3 alloy is normally consolidated by double or triple vacuum arc remelting. Since the alloy does not exhibit strong segregation tendencies, no extraordinary precautions are necessary to minimize segregation. (Ref. 6)

Ti-15-3 is suitable as a casting alloy. It is not prone to segregation during solidification, does not require a water quench during heat treatment, and is readily weld repaired. (Ref. 6)

Rapidly solidified powder can be produced by electron-beam-melting/splat quenching, laser melt/spin atomization, and ultrasonic gas atomization. (Refs. 32-34)

1.9 Special Considerations

1.9.1 Ti-15-3 can be heat treated to precipitate fine alpha phase in the beta phase matrix. Standard solution annealing and aging treatments can be employed to produce material with tensile strengths up to about 180 ksi accompanied by elongations of about 10 percent. (see Sections 1.5.3 and 1.5.4) Thermomechanical processing can be tailored to emphasize certain properties, for example, higher fracture toughness or higher tensile strength (see Sections 1.5.4 and 1.5.5).

1.9.2 Ti-15-3 is characterized by excellent uniformity of properties with regard to orientation, thickness, and lot-to-lot (see Figures 3.2.1.5 to 3.2.1.8, 3.3.1.4, and 3.3.2.1, Tables 1.5.4.15, 3.2.6.1, 3.3.5.1, 3.3.6.1, and 4.3.1.1, and Paragraph 3.2.5).

1.9.3 Beta titanium alloys such at Ti-15-3 have excellent resistance to hydrogen embrittlement. Hydrogen levels of several thousand ppm do not adversely affect room temperature mechanical properties or formability (see Section 2.3.3).

1.9.4 Wrought Ti-15-3 is not notch sensitive to mild notches except for solution annealed and 900F-aged alloy at -320F. Fusion weldments, however, are notch sensitive (see Paragraphs 3.2.7.1 and 3.3.7.1 and Table 4.3.1.2).

1.9.5 Ti-15-3 has very good room temperature formability in the solution annealed condition, approximately equivalent to that of 2024-0 aluminum. Cold formed parts can be subsequently aged to develop higher strengths (see Section 4.1).

1.9.6 Ti-15-3 can be readily joined by fusion welding. Weldments can be aged to produce mechanical properties nearly equivalent to those of parent material (see Section 4.3.1).

1.9.7 A maximum use temperature of 400F has been suggested for solution annealed alloy and 500 to 550F for aged alloy (see paragraph following 3.2.1.10).

2. Physical Properties and Environmental Effects

2.1 Thermal Properties

2.1.1 Melting Range.

2.1.2 Phase Changes. Solution annealed Ti-15-3 usually decomposes during aging directly to an alpha plus beta mixture without forming an intermediate omega phase. (Ref. 6) However, omega phase has been observed to form initially on aging at 572F or lower, but omega changes to alpha phase after 16 hours at 572F or higher. (Ref. 18) The beta transus temperature is reported as 1391 to 1400F (Ref. 17); 1380 to 1410F (Ref. 6); 1385 to 1415F (Refs. 7, 8); and 1450F. (Ref. 4)

2.1.2.1 Time-temperature-transformation diagrams.

2.1.2.1.1 *[Figure]* Time-temperature-transformation diagram.

2.1.3 Thermal Conductivity.

2.1.3.1 *[Figure]* Thermal conductivity from RT to 1400F.

2.1.4 Thermal Expansion.

2.1.4.1 *[Figure]* Thermal expansion from RT to 1472F.

2.1.5 Specific Heat.

2.1.5.1 *[Figure]* Specific heat from RT to 1400F.

2.1.6 Thermal Diffusivity.

2.2 Other Physical Properties

2.2.1 Density: 0.170 lb/cu.in. (Ref. 8)
0.171 lb/cu.in. (Ref. 4)
0.1722 lb/cu.in. (Ref. 6)

2.2.2 Electrical Properties.

2.2.2.1 *[Figure]* Electrical resistivity from RT to 1000F.

2.2.3 Magnetic Properties.

2.2.4 Emittance.

2.2.5 Damping Capacity.

2.3 Chemical Environments

2.3.1 General Corrosion. Ti-15-3, along with other beta titanium alloys, derives its passivity and corrosion resistance from the formation of a thin (typically 50-200 angstroms thick) adherent protective titanium oxide (primarily TiO_2) film. It is considered fully resistant to corrosion in distilled water, fresh water, seawater, and natural brines. It is also resistant to practically all common salt solutions, including chlorides, sulfates, carbonates, and phosphates over the pH range of 3-12 and at temperatures up to 392F. However, it is less resistant to boiling HCl solutions than unalloyed titanium and other beta alloys. (Ref. 35)

Ti-15-3 has excellent compatibility with common rocket propellant fuels. Material in the solution treated (1450F, AC), solution treated plus aged (950F, 8 hr), and solution treated plus EB-welded plus aged conditions were exposed for 6- and 12-month periods to N_2O_4 (MON-1) at 160F, to hydrazine at 140F, and to monomethyl hydrazine at 140F. The tensile properties after exposure were typical for the heat treatments given and indicated no deterioration due to propellant exposures. (Ref. 36)

2.3.2 Stress Corrosion. (See also paragraph after 3.2.1.10) Ti-15-3 has intermediate resistance to hot salt stress corrosion cracking as compared to Ti-6Al-4V and other titanium alloys. (Ref. 35)

2.3.3 Hydrogen Effects. Although alpha and alpha-beta titanium alloys have limited tolerance for hydrogen due to the formation of brittle titanium hydride phase, beta alloys such as Ti-15-3 do not form hydrides and possess very high hydrogen solubilities. The beta phase is also characterized by its relatively high hydrogen diffusion coefficient, which is on the order of 1000 times greater than that of alpha phase at room temperature (i.e., about $5x10^{-7}$ versus about 10^{-10} cm^2/sec). At temperatures below about 1100F, the surface oxide film on Ti-15-3 acts as a barrier to hydrogen absorption. However, at higher temperatures, the oxide film is dissolved and significant hydrogen absorption occurs. The extent of reversible hydrogen absorption into oxide-free Ti-15-3 increases with increasing temperature and hydrogen gas pressure, as shown in Figure 2.3.3.1. (Ref. 35)

2.3.3.1 *[Figure]* Effects of temperature and hydrogen pressure on solubility of hydrogen in Ti-15-3.

Ti-15-3 has excellent tolerance for hydrogen. Hydrogen levels of up to 2000 ppm have no significant effect on the room temperature strength or ductility of solution annealed material. Bend tests and cup tests on solution annealed material also indicate no effect on formability for hydrogen levels up to 4000 ppm, shown in Table 2.3.3.2. (Ref. 7)

2.3.3.2 *[Table]* Effects of hydrogen on room-temperature formability.

Similarly, hydrogen does not affect the tensile properties of fully aged material at levels up to 2000 ppm. However, when hydrogen is introduced before aging, strength of the aged material is reduced by about 40 ksi at 1000 ppm, as shown in Figure 2.3.3.3; ductilities are not reduced. The strength reduction results because hydrogen is a potent beta stabilizer and acts to suppress the aging response.

2.3.3.3 *[Figure]* Effects of hydrogen on tensile properties of sheet.

Although Ti-15-3 is very tolerant of hydrogen at room and elevated temperatures, it is embrittled by hydrogen at low temperatures. The tensile ductile-brittle transition temperature of alloy containing 3900 ppm hydrogen, for example, is just below room temperature, as shown in Figure 2.3.3.4. At -100F, less than 1000 ppm hydrogen is embrittling, while at 200F, alloy is ductile up to hydrogen levels of 7000 ppm, as shown in Figure 2.3.3.5.

2.3.3.4 *[Figure]* Ductile-brittle transition behavior of alloy containing 3900 ppm hydrogen.

2.3.3.5 *[Figure]* Effects of hydrogen on ductile-to-brittle transition temperature.

It is clear from these data that Ti-15-3 is very hydrogen tolerant and is well within the safe range at the AMS specification upper limit of 150 ppm, shown earlier in Table 1.4.1. (Refs. 6, 7)

2.3.4 Oxidation. The presence of vanadium and tin in Ti-15-3 interferes with the production of a protective oxidation film and results in reduced oxidation resistance relative to unalloyed titanium, as shown in Figure 2.3.4.1.

2.3.4.1 *[Figure]* Oxidation weight gain behavior of Ti-15-3 alloy and unalloyed titanium in air at 1202F.

2.4 Nuclear Environments

3. Mechanical Properties

3.1 Specified Mechanical Properties

3.1.1 *[Table]* AMS specified room-temperature mechanical properties.

3.2 Mechanical Properties at Room Temperature

3.2.1 Tension Stress-strain Diagrams and Tensile Properties. (See also Tables 1.5.1.1, 1.5.3.3, 1.5.4.16, and 1.5.4.17 and Figures 1.5.3.1, 1.5.3.2, 1.5.4.8 to 1.5.4.15, 1.5.5.1, 1.5.5.2, 1.5.6.1, and 2.3.3.2)

3.2.1.1 *[Figure]* Stress-strain diagram for solution annealed and aged alloy at strain rate of 6×10^{-2} min^{-1}.

3.2.1.2 *[Figure]* Stress-strain diagram for solution annealed and aged alloy at strain rate of 6×10^4 min^{-1}.

The tensile properties of solution annealed Ti-15-3 are insensitive to a 20-fold change in strain rate, as shown by the data in Table 3.2.1.3. (Ref. 8) However, a 10^6-fold increase in strain rate effects a significant increase in the strength of solution annealed and aged alloy, as shown in Figure 3.2.1.4.

3.2.1.3 *[Table]* Effects of strain rate on tensile properties of solution annealed alloy.

3.2.1.4 *[Figure]* Effects of strain rate on tensile properties of solution annealed and aged alloy.

An important feature of Ti-15-3 is good uniformity of properties at different thicknesses and orientations. As shown in Figure 3.2.1.5, the changes in strength are slight with changes in thickness or lot-to-lot for both the aged and solution annealed conditions. The transverse orientation is slightly stronger than the longitudinal. (Ref. 7)

3.2.1.5 *[Figure]* Effects of orientation and thickness on yield strength of heat treated alloy.

The effects of cold rolling on tensile properties before and after heat treatment are shown in Figures 3.2.1.6 through 3.2.1.8 for three different orientations. The effects of cold rolling are essentially eliminated by subsequent heat treatment and, as indicated above, orientation effects are minor. (Ref. 38)

3.2.1.6 *[Figure]* Effects of cold rolling and heat treatment on tensile properties in rolling direction.

3.2.1.7 *[Figure]* Effects of cold rolling and heat treatment on tensile properties at 45 degrees to rolling direction.

3.2.1.8 *[Figure]* Effects of cold rolling and heat treatment on tensile properties transverse to rolling direction.

The stability of tensile properties during exposure of 1000 hours at 650F and up to 1500 hours at 500F depends on the extent of prior aging. Material which has been aged for only two hours at 950 to 1150F is initially underaged and is further strengthened during 650F exposure. In contrast, material aged for 8 to 24 hours at the same temperatures is more fully aged and exhibits less strengthening and insignificant embrittlement on exposure, as shown in Table 3.2.1.9. Dimensional changes are small. (Ref. 8) Similarly, material which has been single or duplex aged for 8 hours at 1000F is stable and undergoes little further change on exposure at 500F for times up to 1500 hours. (see Table 3.2.1.10)

3.2.1.9 *[Table]* Tensile properties and dimensional stabilities of solution annealed and aged alloy after 1000 hours exposure at 650F.

3.2.1.10 *[Table]* Effects of long time exposure at 500F on room temperature tensile properties of aged alloy.

The Ti-15-3 alloy should not be used above about 400F in the solution annealed condition since exposure at such low temperatures can result in aging and accompanying low ductility (embrittlement). However, fully aged material is quite stable, as shown above. Based on these data and considering that hot-salt stress corrosion cracking susceptibility has been noted for the alloy under conditions of 600F/30ksi/300hrs exposure but not at 500F/120ksi/300hrs, a maximum use temperature of 500 to 550F for aged alloy has been suggested for long service applications. (Ref. 6)

3.2.2 Compression Stress-strain Diagrams and Compression Properties.

3.2.3 Impact.

3.2.4 Bending.

3.2.5 Torsion and Shear. The average shear strength in the solution annealed condition for 8 lots (representing 5 different heats, tested in triplicate) ranging in thickness from 0.040 to 0.116 inch was 90.2 ± 2.0 ksi longitudinal and 89.2 ± 1.8 ksi long transverse. (Ref. 39)

3.2.6 Bearing.

3.2.6.1 *[Table]* Bearing strength of solution annealed alloy.

3.2.7 Stress Concentration.

3.2.7.1 Notch properties. (See also Figure 4.3.1.2) The notch strength of solution annealed and aged alloy is essentially independent of solution annealing temperature, as shown in Figure 3.2.7.1.1. Comparison of these data with those for smooth ultimate tensile strength for the same material, presented earlier in Figure 1.5.3.2, indicates a notched strength ratio in excess of unity and absence of notch sensitivity for mild notches.

3.2.7.1.1 *[Figure]* Effects of solution annealing temperature on notched tensile strength after aging at 932F.

3.2.7.2 Fracture toughness. (See also Figure 1.5.4.18 and Tables 1.5.4.17 and 4.3.1.3) Ti-15-3 has good fracture toughness in the solution annealed and aged condition. The fracture toughness increases moderately with increasing solution annealing temperature, as shown in Figure 3.2.7.2.1, possibly attributable to increasing grain size. (Ref. 16) Lower temperature aging at 752F, particularly for longer times, reduces fracture toughness as compared to aging at 932 or 1112F, Table 3.2.7.2.2. Fracture toughness for the LT orientation also is consistently higher than for the TL orientation. (Ref. 10)

3.2.7.2.1 *[Figure]* Effects of solution annealing temperature on fracture toughness after aging at 932F.

3.2.7.2.2 *[Table]* Effects of heat treatment and orientation on fracture toughness.

3.2.8 Combined Loading.

3.3 Mechanical Properties at Various Temperatures

3.3.1 Tension Stress-strain Diagrams and Tensile Properties.

3.3.1.1 *[Figure]* Effects of strain rate on flow curves at 1500F.

Deformation-induced twinning of the beta phase occurs and an abnormally increased elongation is observed in solution annealed alloy deformed at -238F, as shown in Figure 3.3.1.2.

3.3.1.2 *[Figure]* Tensile properties of solution annealed alloy at low temperatures.

The effects of test temperature on strength and ductility of alloy in three heat treated conditions are shown in Figure 3.3.1.3. Reduced ductility is observed for all three of these heat treated conditions at temperatures below room temperature. (Ref. 7)

3.3.1.3 *[Figure]* Effects of temperature on tensile properties in three heat treated conditions.

Tensile properties of solution treated and aged alloy at room and elevated temperatures are given in Figures 3.3.1.4 and 3.3.1.5. Substantial loss in short-time strength occurs above about 900F. (Refs. 8, 11)

3.3.1.4 *[Figure]* Tensile properties of solution annealed and aged alloy at room temperature to 800F.

3.3.1.5 *[Figure]* Tensile properties of solution annealed and aged alloy at room temperature to 1112F.

Prestraining by 10 percent prior to aging increases tensile strength at room temperature and 600F but has little effect on elongation, as shown in Figure 3.3.1.6. Higher strength and lower ductility result from aging at 925F than at 950F for both prestrained and non-prestrained alloy, consistent with results presented earlier for non-prestrained alloy in Figure 1.5.4.13 and Table 1.5.4.15. (Ref. 42)

3.3.1.6 *[Figure]* Effects of prestraining and aging on tensile properties of sheet at room temperature and 600F.

3.3.2 Compression Stress-strain Diagrams and Compression Properties. Typical compressive strength data are given in Figure 3.3.2.1. (Ref. 8)

3.3.2.1 *[Figure]* Effects of temperature and orientation on compressive yield strength.

Compressive strengths at room temperature and 600F are increased by tensile prestraining to 10 percent, as shown in Figure 3.3.2.2. Highest compressive strength is obtained after aging at 925F, while lower strength results from aging at 950F. (Ref. 42)

3.3.2.2 *[Figure]* Effects of prestraining and aging on compressive yield strength of sheet at room temperature and 600F.

3.3.3 Impact.

3.3.3.1 *[Figure]* Effects of low temperatures on Charpy impact energy of solution annealed alloy.

3.3.4 Bending.

3.3.5 Torsion and Shear.

3.3.5.1 *[Table]* Shear strength of solution annealed and aged alloy at room and elevated temperature.

3.3.6 Bearing.

3.3.6.1 *[Table]* Bearing properties of aged alloy at room and elevated temperaturs.

3.3.7 Stress Concentration.

3.3.7.1 Notch properties. Ti-15-3 is not notch sensitive to mild notches from cryogenic temperatures up to 600F, with exception of the solution annealed and 900F-aged alloy at -320F, as shown in Figure 3.3.7.1.2. (Ref. 7)

3.3.7.1.2 *[Figure]* Effects of temperature on mild notch strength ratio for three heat treated conditions.

3.3.7.2 Fracture toughness.

3.3.8 Combined Loading.

3.4 Creep and Creep Rupture Properties

3.4.1 *[Figure]* Times to various creep strains for aged alloy at 800F.

3.5 Fatigue Properties

3.5.1 Conventional High-Cycle Fatigue.

3.5.1.1 *[Figure]* High-cycle fatigue behavior of sheet material.

3.5.1.2 *[Figure]* High-cycle fatigue behavior of notched sheet material.

3.5.1.3 *[Figure]* High-cycle fatigue behavior of cast alloy.

3.5.2 Low-Cycle Fatigue.

3.5.3 Fatigue Crack Propagation.

3.5.3.1 *[Figure]* Fatigue crack growth behavior of heat treated alloy at room temperature.

The fatigue crack growth rates are unaffected by salt water. (Ref. 8)

3.6 Elastic Properties

3.6.1 Poisson's Ratio.

3.6.2 Modulus of Elasticity. Solution annealed alloy, 12×10^6 psi; aged alloy, 15.5×10^6 psi. (Ref. 6)

3.6.3 Modulus of Rigidity.

3.6.4 Tangent Modulus.

3.6.4.1 *[Figure]* Effects of temperature on longitudinal compressive tangent-modulus curves.

3.6.4.2 *[Figure]* Effects of temperature on transverse compressive tangent-modulus curves.

3.6.5 Secant Modulus.

4. Fabrication

4.1 Forming

Conversion of the alloy is accomplished by conventional practice. Since this is a beta alloy with a characteristically low beta transus, typically 1380 to 1410F, care must be exercised to employ a conversion routine which will produce a uniformly fine grain size. The fact that the alloy is cold strip producible results in significant cost savings compared to conventional hot hand-mill rolling. Also, the cold-rolled product is a close tolerance product which does not require grinding. Mill product is normally supplied in the completely recrystallized condition. (Ref. 6)

Typical processing steps to convert Ti-15-3 from double- or triple-melted ingot to strip are as follows:

(1) Hot-forge to nominally 4 to 6-inch thick slab and condition as required.

(2) Hot roll slab to nominally 0.12 to 0.18-inch thick bar.

(3) Cold-roll flatten, air anneal and blast, pickle, grind and trim as required.

(4) Cold-roll to desired gage. This step may include an intermediate anneal, depending on the final gage. Although the alloy is capable of cold reductions in excess of 90 percent, reductions in the 30 to 70 percent range are more commonly used.

(5) Continuous vacuum anneal for gages less than 0.070 inch. For heavier gages, a batch vacuum anneal to reduce hydrogen content followed by air solution annealing, grinding and pickling is required.

(6) Cut to size, inspect, and ship. (Ref. 7)

One of the most outstanding features of the Ti-15-3 alloy is its cold (room temperature) formability. Table 4.1.1 provides a summary of the cold forming limits which have been reported for the alloy. In many cases, these limits are comparable to or better than those established for hot forming of Ti-6Al-4V. The formability of annealed Ti-15-3 is roughly equivalent to that of 2024-0 aluminum. The alloy is best worked and welded in its solution treated condition. An aging treatment of 8 hours at 986F will develop mechanical properties about 50 percent greater than those obtainable in Ti-6Al-4V. (Refs. 6, 8, 44)

4.1.1 *[Table]* Practical cold forming limits.

The shear spinnability of Ti-15-3, determined by spinning a sheet metal blank over a spherical mandrel until the material ruptures, is excellent compared to other aerospace alloys, as shown in Table 4.1.2. (Ref. 36)

4.1.2 *[Table]* Shear spinnabilities of Ti-15-3 and other aerospace alloys at room temperature.

Seamless tubing can be produced by hot extrusion over a mandrel followed by solution annealing and cold reduction to the desired dimensions. (Ref. 45)

The excellent cold formability of Ti-15-3 lends itself well to foil production. Material has been produced as thin as 0.0003 inch. Representative foil properties are given in Table 4.1.3.

4.1.3 *[Table]* Room temperature tensile properties of foil.

In cases where a part requires severe forming beyond the room temperature capability of the alloy, the alloy may be hot formed in the 1000F range. Care should be exercised to keep the heating time to less than about one hour in order to prevent aging prior to the forming operation. The subsequent aging time should be reduced to account for heating during hot forming. Flow stresses for Ti-15-3 and Ti-6Al-4V in the typical hot forming range are compared in Figure 4.1.4. The flow stresses are significantly affected by strain rate. (Ref. 6)

4.1.4 *[Figure]* Effects of temperature and strain rate on flow stresses for Ti-15-3 and Ti-6Al-4V.

Beta alloys such as Ti-15-3 exhibit low flow stresses and high tensile elongations at elevated temperatures, but grain sizes are large because the alloys are single phase at temperatures above the beta transus. Tensile elongations of over 300 percent can be obtained at 1490F at strain rates on the order of 2.5×10^{-2} min^{-1}. Deformation is accompanied by continuous grain refining controlled by dynamic recrystallization. (Ref. 46) These alloys do not show a promising degree of strain-rate sensitivity at temperatures and strain rates of practical interest for superplastic forming. (Ref. 40)

4.2 Machining and Grinding

4.3 Joining

4.3.1 Fusion welding. Ti-15-3 is readily weldable by gas-tungsten-arc (GTA) and electron-beam (EB) processes. No tendency for restraint cracking is observed. The tendency to develop weld porosity is comparable to that of other weldable titanium alloys such as Ti-6Al-4V and commercially pure titanium; control and elimination depends on adequate preweld cleaning and control of welding parameters. The sluggish transformation reactions in Ti-15-3 result in soft,

ductile weld beads and virtually undetectable heat affected zone in the as-welded condition. The recommended sequence for welding is (1) solution treat, (2) weld, and (3) age harden. This procedure produces weld strengths essentially equivalent to that of the base metal and weld ductilities only slightly less than base metal. The notch strength ratio is less for weld metal than for wrought alloy. (see paragraphs 3.2.7.1 and 3.3.7.1) Smooth and notched tensile and fracture toughnesses of fusion welds with various combinations of pre- and post-weld heat treatments are given in Tables 4.3.1.1, 4.3.1.2, and 4.3.1.3. (Refs. 6, 36, 47)

4.3.1.1 *[Table]* Effects of fusion welding and heat treatment on tensile properties.

4.3.1.2 *[Table]* Effects of fusion welding and heat treatment on sharp notched tensile properties.

4.3.1.3 *[Table]* Effects of heat treatment on fracture toughness of 0.30-inch thick electron beam weldments.

4.3.1.4 *[Figure]* Effects of aging time and temperature on tensile properties of autogenous GTA weldments.

4.4 Surface Treating

4.4.1 Cleaning. Solutions of 35 percent HNO_3-2.5 percent HF and 30 percent HNO_3-4 percent NH_4F are effective cleaning and descaling agents, especially when used with an aqueous sodium nitrate-carbonate pretreatment. (Ref. 49)

4.4.2 Hardening. Ti-15-3 can be surface-hardened by ion implantation of nitrogen and oxygen for improved resistance to wear and galling. (Ref. 50)

The surface of solution annealed and aged alloy can also be further hardened by localized laser heating to resolution anneal a thin surface layer at a higher temperature than the original solution anneal followed by aging of the entire piece at a lower temperature than the original aging treatment. The combination of higher solution anneal temperature and lower aging temperature produces substantially higher hardness than the original conditions. (Ref. 19)

Table 1.3.1 AMS specifications (Refs. 1, 2)

Alloy	Ti-15-3
AMS Specifications	Product Form
4914A	Sheet strip
4922	Seamless tubing

Table 1.4.1 AMS specified composition (Refs. 1, 2)

Alloy	Ti-15-3	
Element	Percent	
	Minimum	Maximum
Vanadium	14.0	16.0
Chromium	2.5	3.5
Tin	2.5	3.5
Aluminum	2.5	3.5
Iron	—	0.25
Oxygen	—	0.13
Carbon	—	0.05
Nitrogen	—	0.05
Hydrogen	—	0.015
Residual Elements, each	—	0.10
Residual Elements, total	—	0.40
Titanium	remainder	

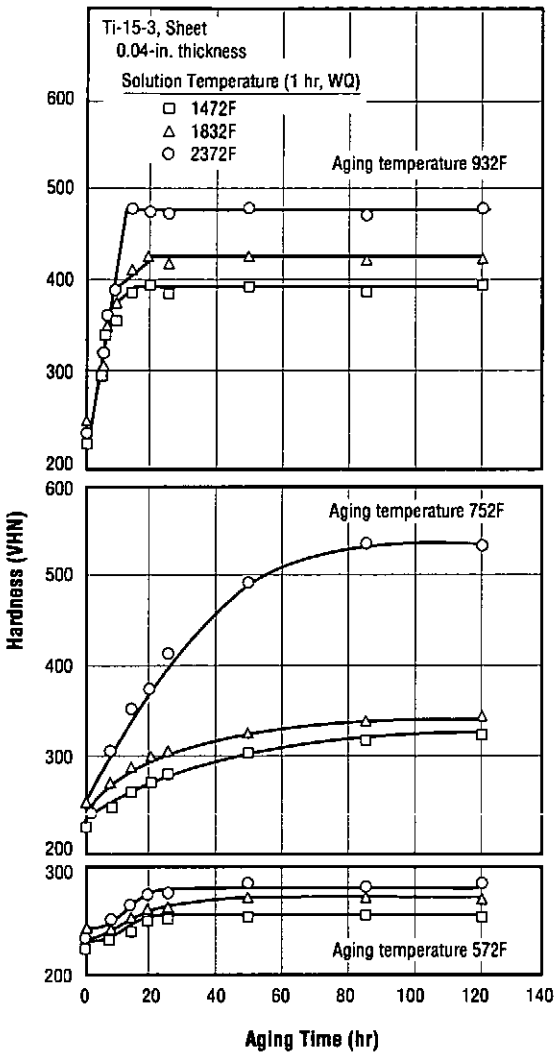


Figure 1.5.2.1 Effects of aging time and temperature on hardness of solution annealed alloy (Ref. 9)

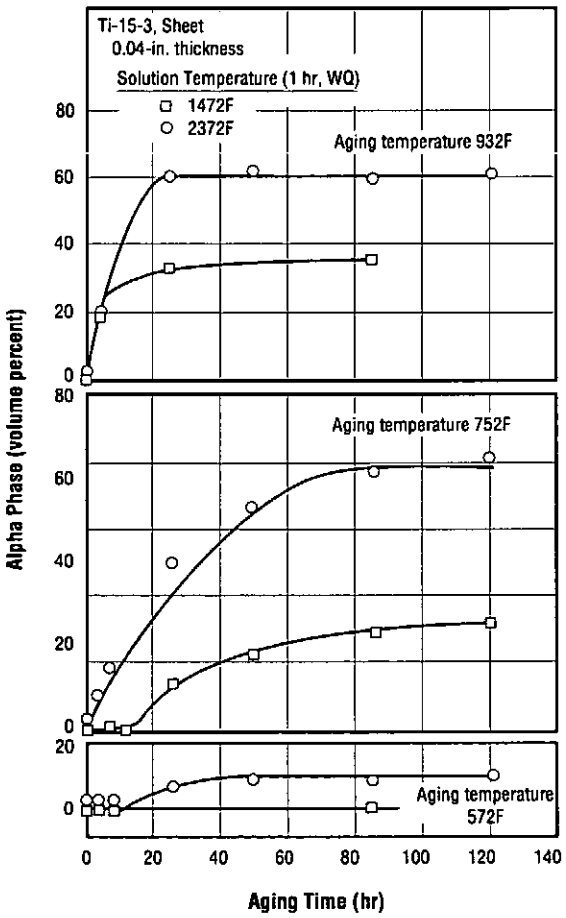


Figure 1.5.2.2 Effects of aging time and temperature on alpha phase precipitation in solution annealed sheet (Ref. 9)

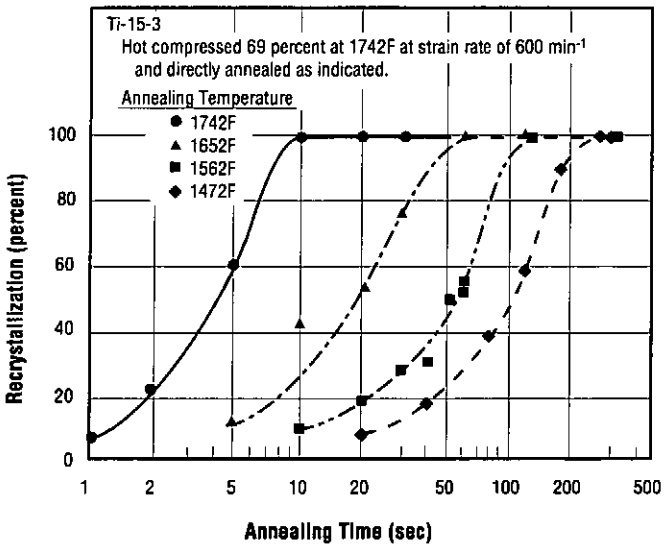


Figure 1.5.2.3 Effects of annealing time and temperature on recrystallization behavior of hot worked alloy (Ref. 11)

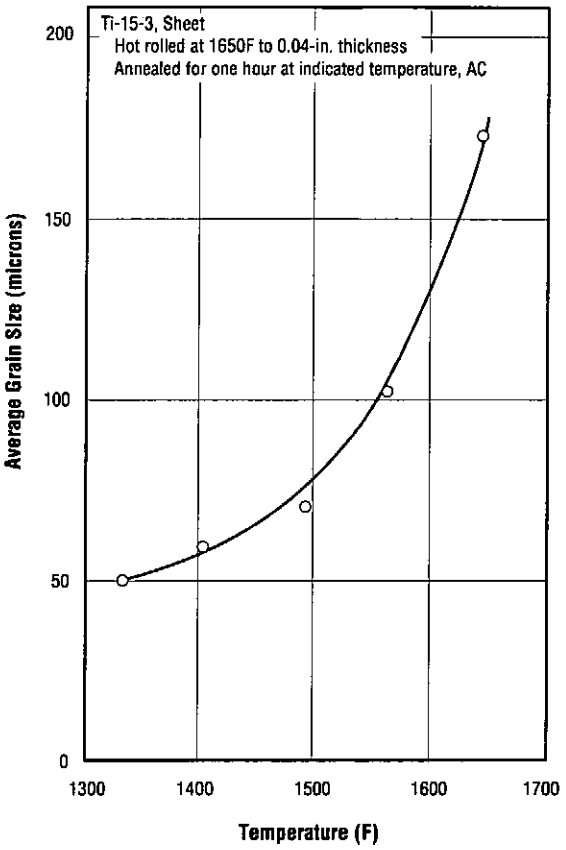


Figure 1.5.2.4 Effects of annealing temperature on grain size of hot rolled alloy (Ref. 10)

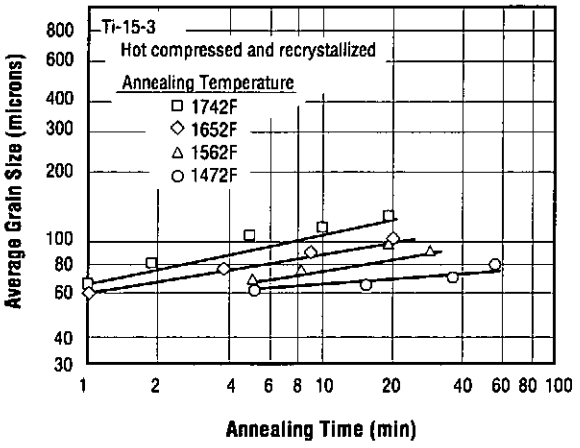


Figure 1.5.2.5 Effects of annealing time and temperature on grain growth behavior (Ref. 11)

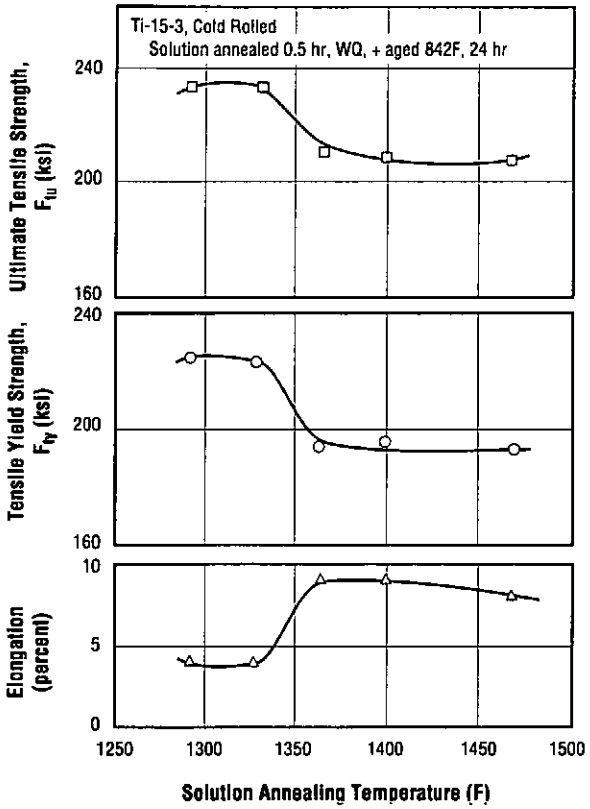


Figure 1.5.3.1 Effects of solution annealing temperature on tensile properties after aging at 842F (Ref. 12)

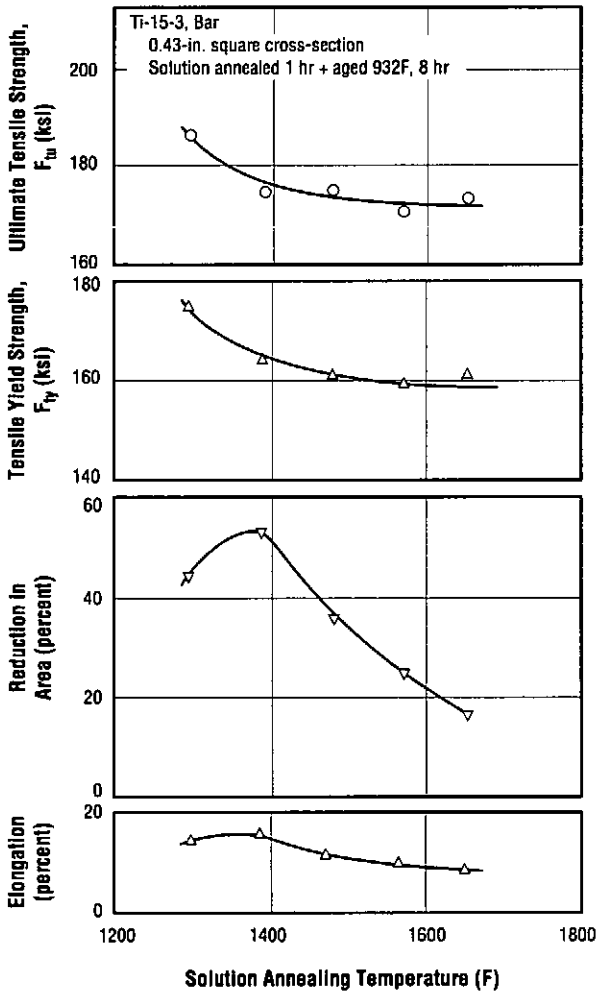


Figure 1.5.3.2 Effects of solution annealing temperature on tensile properties after aging at 932F (Ref. 13)

Table 1.5.3.3 Effects of grain size and aging conditions on tensile properties of solution annealed alloy (Ref. 16)

Alloy	Ti-15-3[a]				
Grain Size (microns)	Aging Conditions[d]		Tensile Properties		
	Temperature (F)	Time (hr)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (percent)
35[b]	(No age)	—	107	108	19.7
	900	8	182	199	8.3
		16	181	199	8.0
	950	8	148	162	11.3
		12	169	183	10.3
		16	166	179	9.8
	1000	8	160	173	14.2
		12	158	172	11.7
		16	151	163	13.4
120[c]	(No age)	—	99	108	19.9
	900	8	178	191	6.3
		16	193	199	4.4
	950	8	160	173	5.9
		12	173	186	5.6
		16	178	186	5.0
	1000	8	163	178	10.2
		12	166	178	7.2
		16	169	181	7.9

[a] Cold rolled 50 percent before heat treating.

[b] Solution annealed 1450F, 0.17 hour, vacuum.

[c] Solution annealed 1525F, 24 hour, vacuum.

[d] Aged in argon.

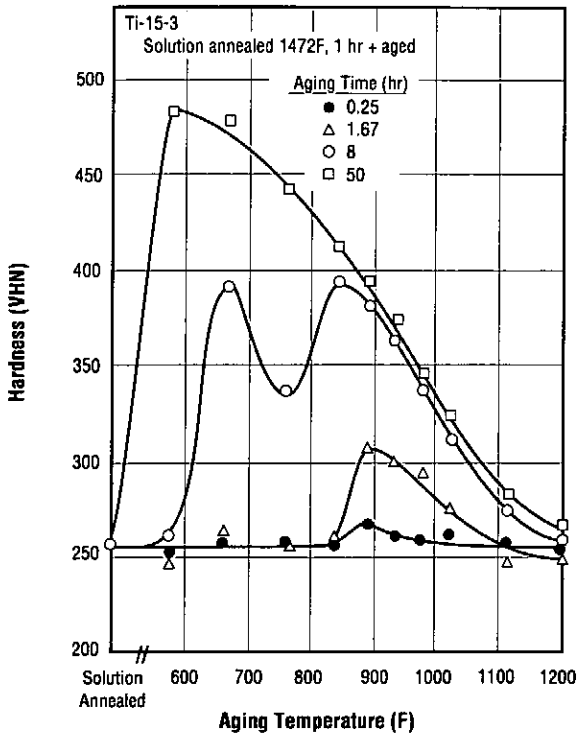


Figure 1.5.4.1 Effects of aging temperature and time on hardness of alloy solution annealed at 1472F (Ref. 13)

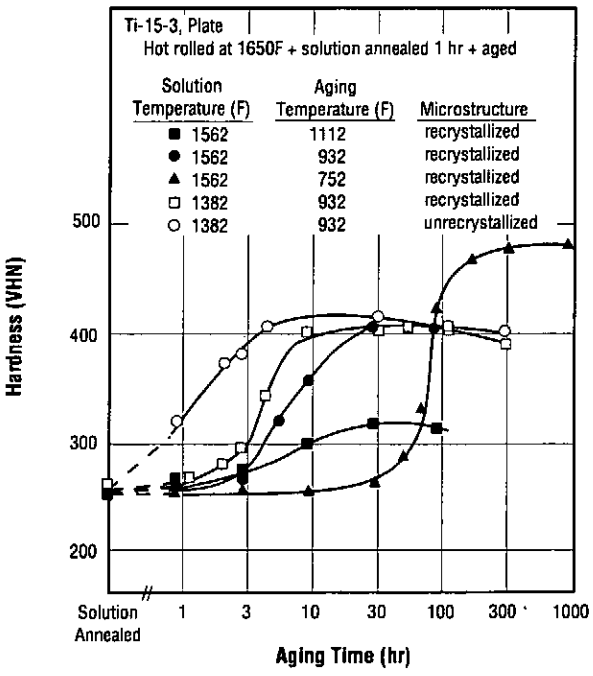


Figure 1.5.4.2 Effects of aging time and temperature on hardness of plate solution annealed at 1382 or 1562F (Ref. 10)

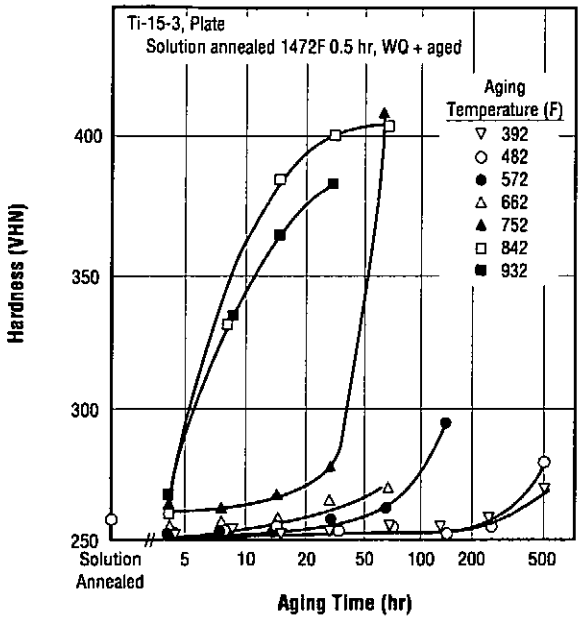


Figure 1.5.4.3 Effects of aging time and temperature on hardness of plate solution annealed at 1472F (Ref. 19)

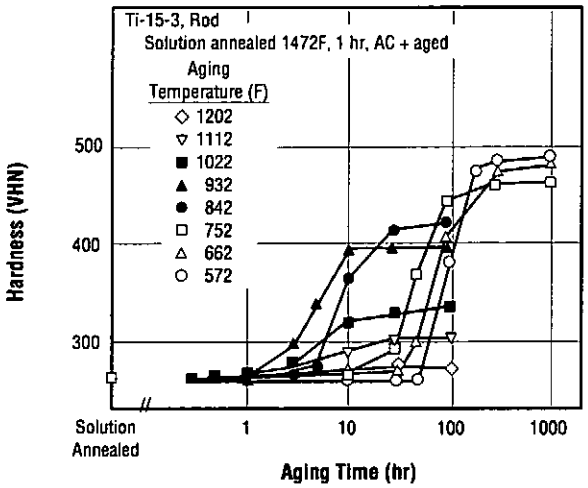


Figure 1.5.4.4 Effects of aging time and temperature on hardness of rod solution annealed at 1472F (Ref. 17)

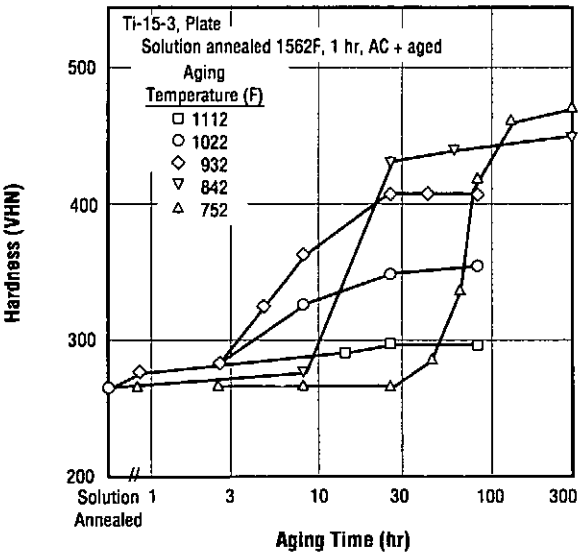


Figure 1.5.4.5 Effects of aging time and temperature on hardness of plate solution annealed at 1562F (Ref. 20)

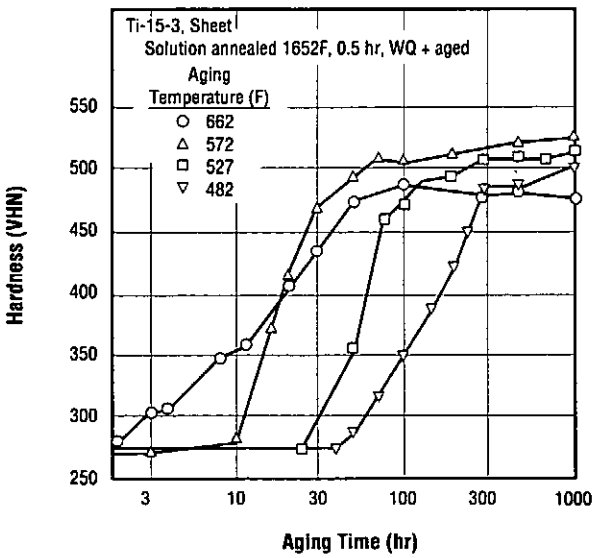


Figure 1.5.4.6 Effects of aging time and temperature on hardness of sheet solution annealed at 1652F (Ref. 18)

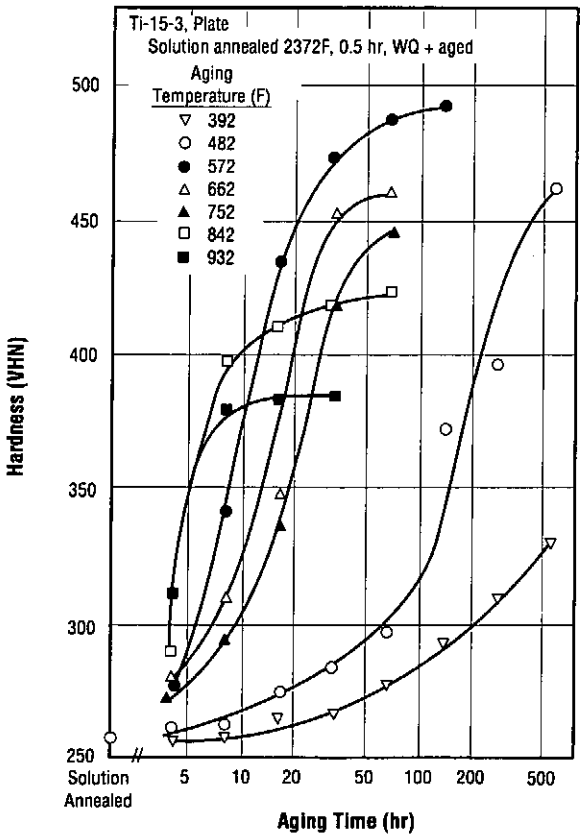


Figure 1.5.4.7 Effects of aging time and temperature on hardness of plate solution annealed at 2372F (Ref. 19)

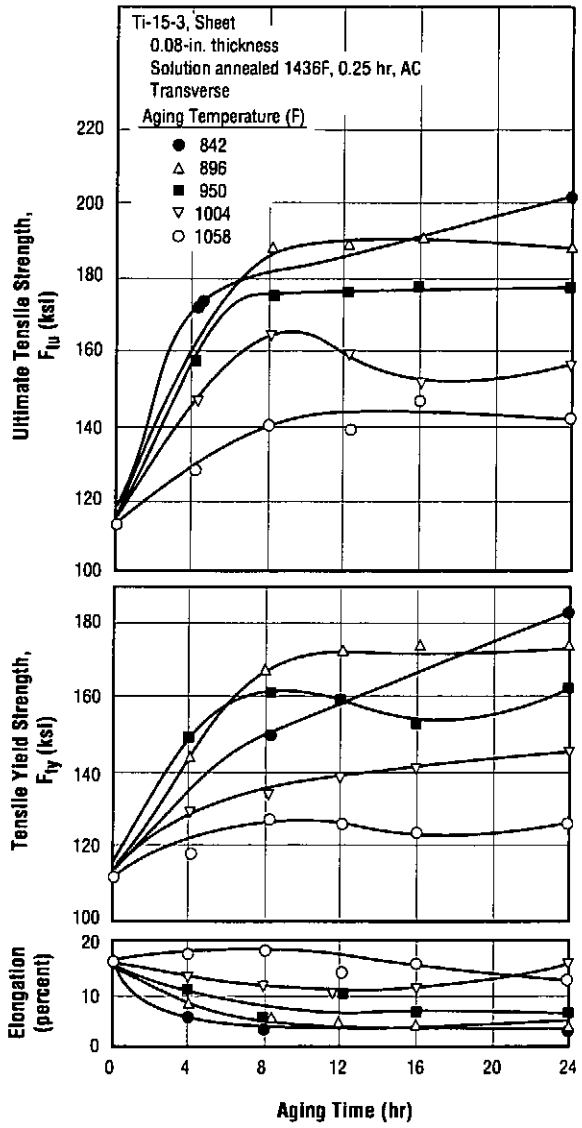


Figure 1.5.4.8 Effects of aging time at 842 to 1058F on tensile properties of sheet solution annealed at 1436F (Ref. 23)

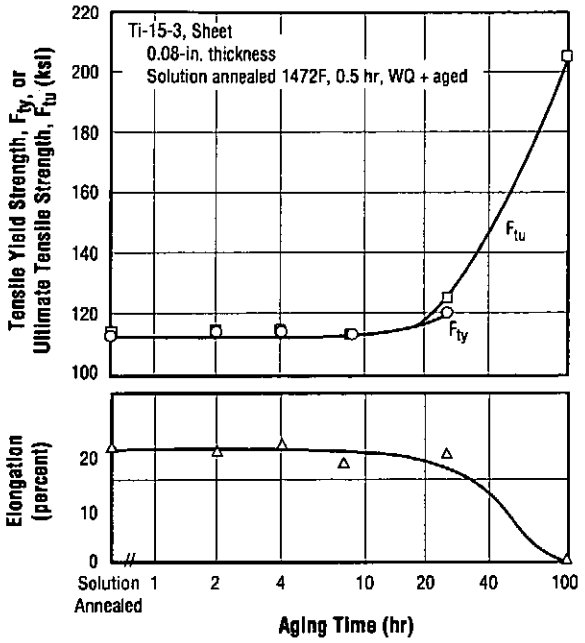


Figure 1.5.4.9 Effects of aging time at 572F on tensile properties of sheet solution annealed at 1472F (Ref. 21)

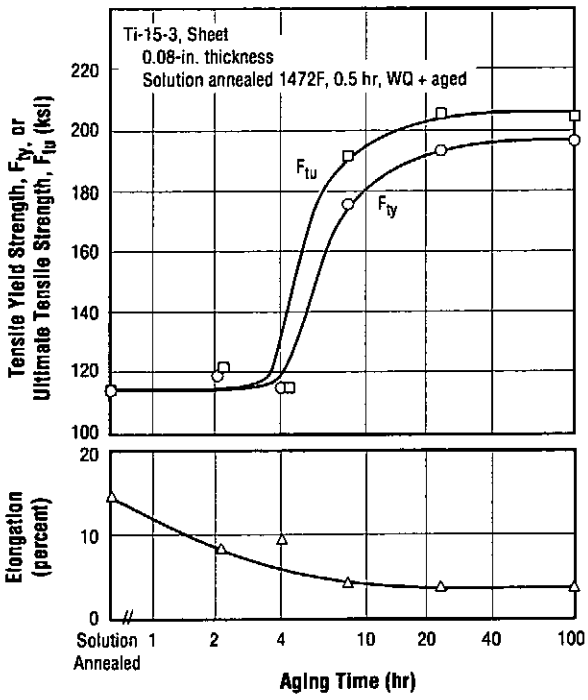


Figure 1.5.4.10 Effects of aging time at 842F on tensile properties of sheet solution annealed at 1472F (Ref. 21)

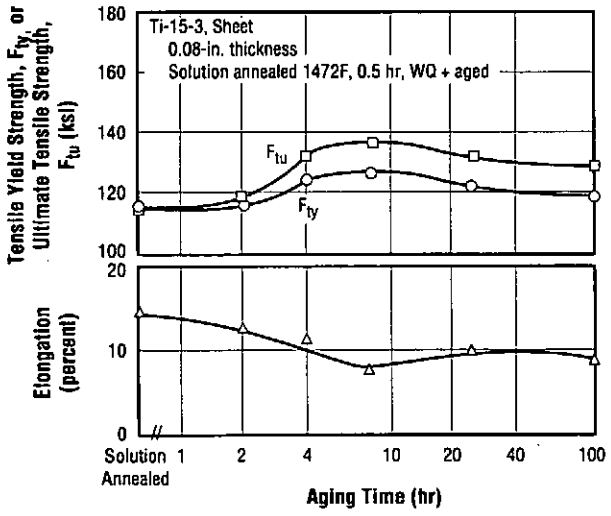


Figure 1.5.4.11 Effects of aging time at 1112F on tensile properties of sheet solution annealed at 1472F (Ref. 21)

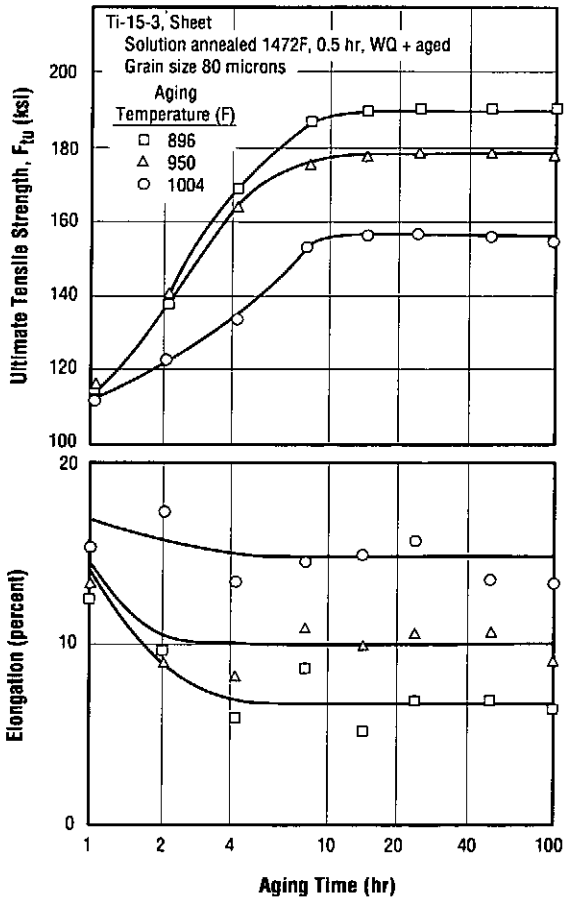


Figure 1.5.4.12 Effects of aging time at 896 to 1004F on tensile properties of sheet solution annealed at 1472F (Ref. 15)

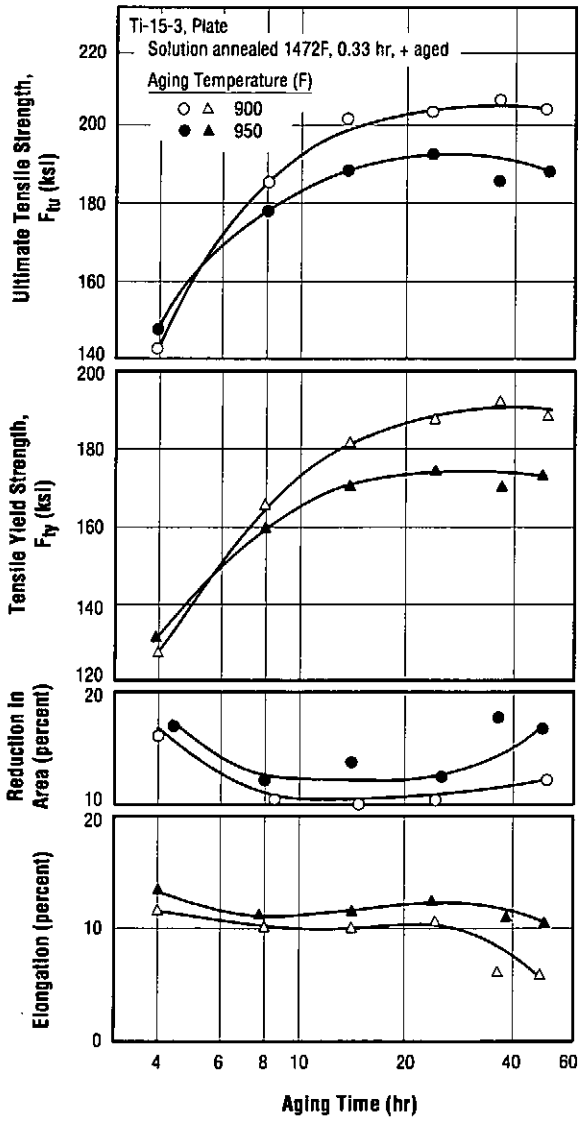


Figure 1.5.4.13 Effects of aging time at 900 and 950F on tensile properties of plate solution annealed at 1472F (Ref. 11)

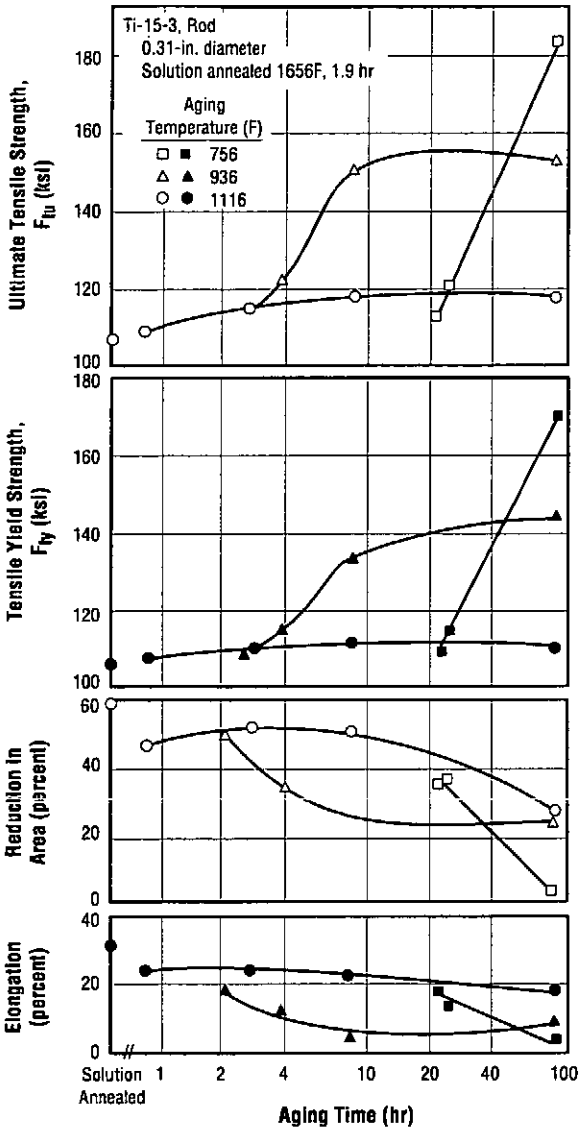


Figure 1.5.4.14 Effects of aging time at 756 to 1116F on tensile properties of rod solution annealed at 1656F (Ref. 22)

Table 1.5.4.15 Effects of aging temperature and orientation on strength properties at room temperature (Ref. 8)

Alloy	Ti-15-3			
Aging Temperature[a] (F)	Orientation	Tensile Properties[b]		
		F_{tu} (ksi)	F_{ty} (ksi)	Elongation (percent)
950	L	190.5	177.2	7.8
	T	193.6	180.5	
975	L	174.7	160.2	10.2
	T	177.6	163.3	
1000	L	159.0	143.2	12.6
	T	161.6	146.3	

[a] Aged 14 hours at indicated temperature.

[b] Average data from 4 lots ranging in thickness from 0.035 to 0.070 inch.

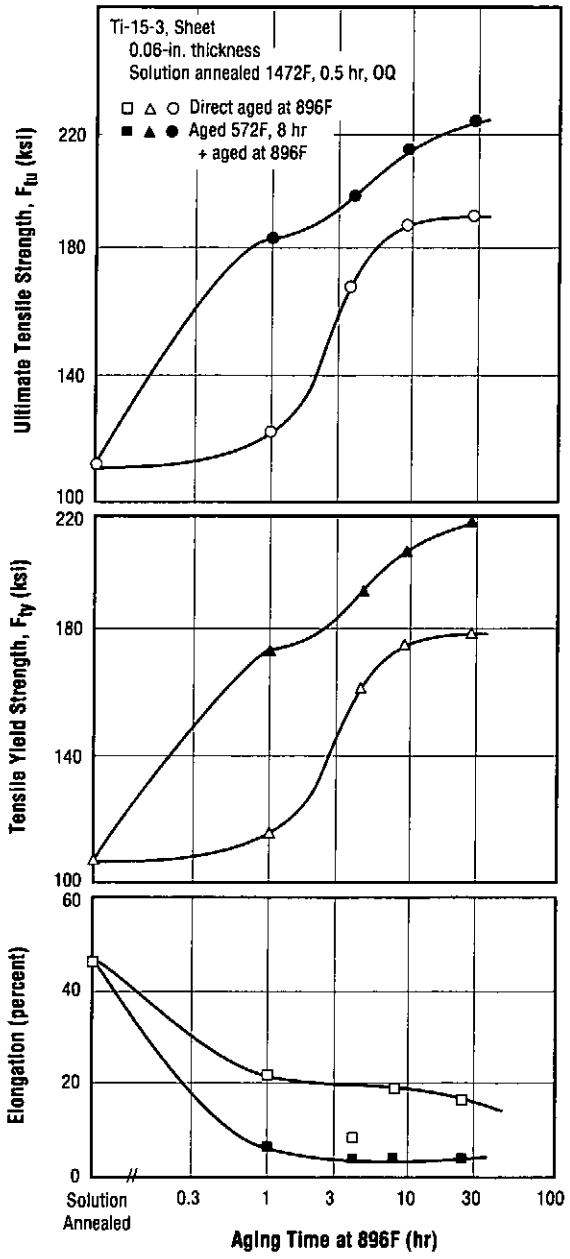


Figure 1.5.4.16 Effects of aging time at 896F on tensile properties of solution annealed alloy with and without aging at 572F (Ref. 24)

Table 1.5.4.17 Effects of aging treatments on fracture toughness and tensile properties (Ref. 25)

Alloy	Ti-15-3[a]			
Aging Conditions[b]	Tensile Properties			Fracture Toughness[c] (ksi $\sqrt{in}$)
	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (percent)	
900F/24 hr.	184.6	194.4	4.4	43.2
1000F/48 hr.	151.3	163.6	10.0	44.5
1050F/24 hr.	140.1	153.9	12.7	55.7
850F/24 hr. + 1050F/6 hr.	173.0	181.2	4.6	55.6
800F/24 hr. + 1100F/4 hr.	156.0	165.6	6.4	63.6
1000F/24 hr. + 800F/24 hr.	162.4	176.6	7.0	—
800F/6 hr. + 1075F/8 hr. + 1125F/18 hr.	153.0	165.2	7.1	69.8

[a] Hot rolled at 1700F to 1.5-inch plate.

[b] Aged from hot rolled condition.

[c] ASTM E 399.

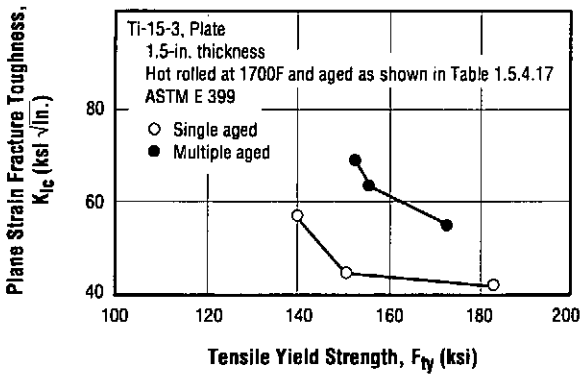


Figure 1.5.4.18 Variation of fracture toughness and yield strength with aging treatment (Ref. 25)

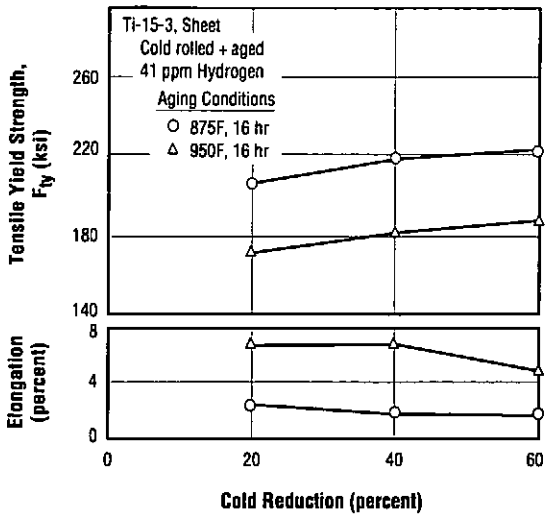


Figure 1.5.5.1 Effects of cold rolling and aging temperature on yield strength and elongation (Ref. 7)

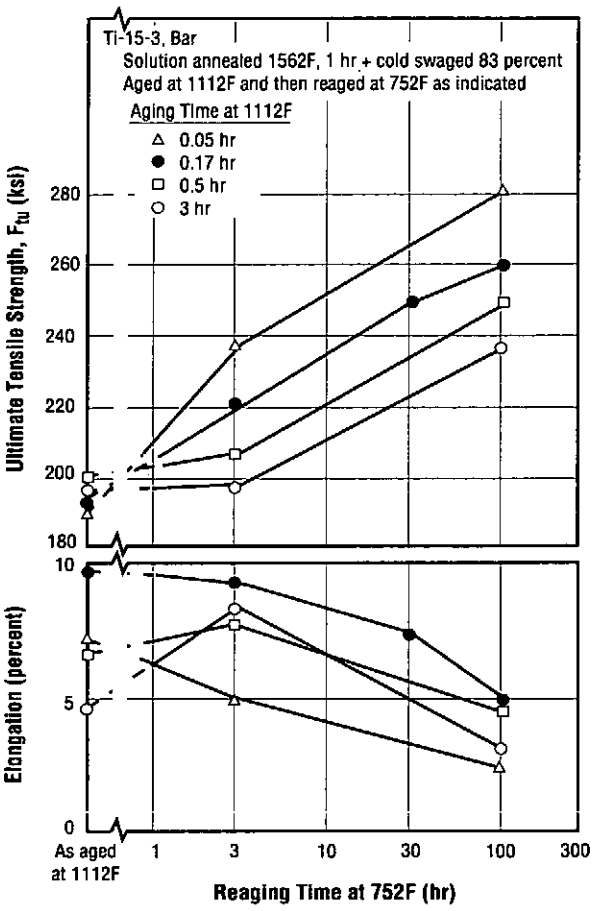


Figure 1.5.5.2 Effects of aging time at 752F on tensile properties of cold worked plus duplex aged alloy (Ref. 28)

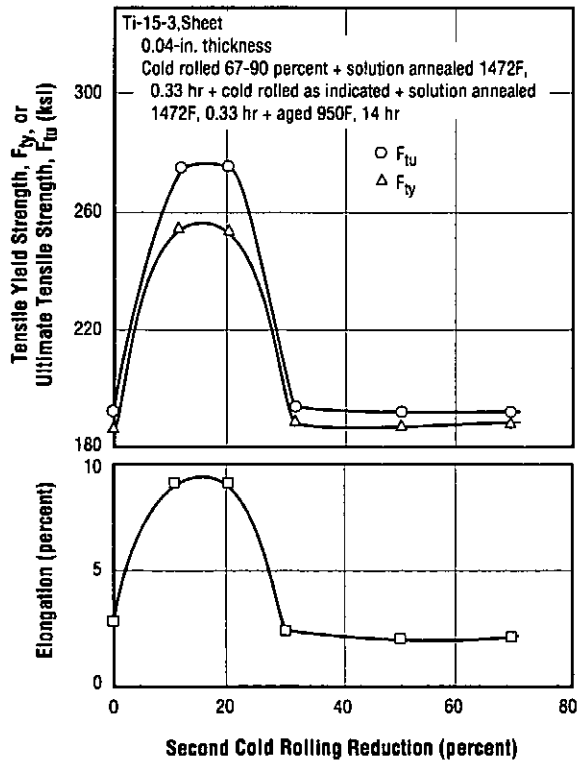


Figure 1.5.5.3 Effects of second rolling reduction on tensile properties of thermomechanically processed sheet (Ref. 29)

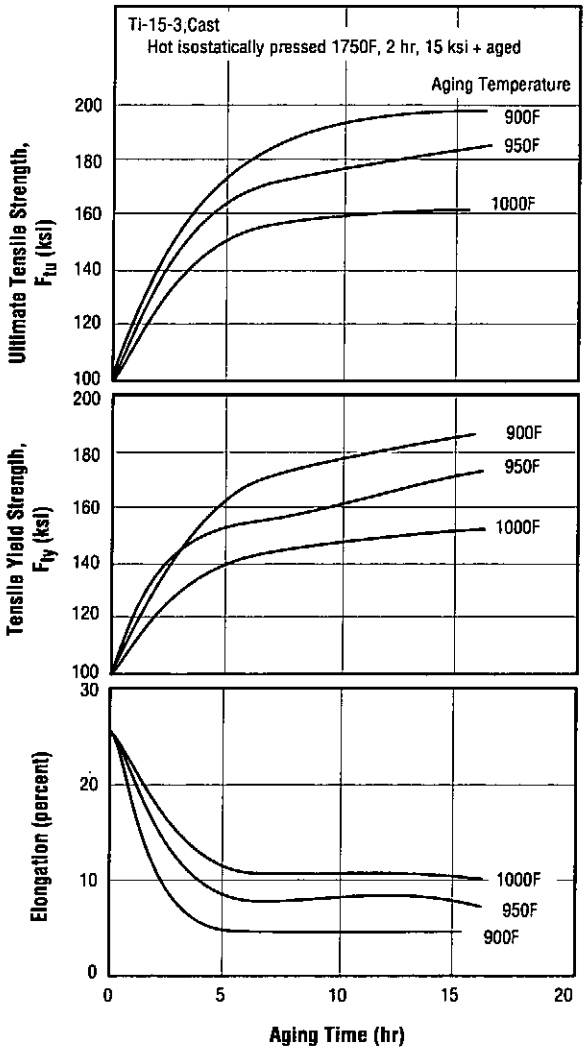


Figure 1.5.6.1 Effects of aging at 900 to 1000F on tensile properties of hot isostatically pressed cast alloy (Ref. 30)

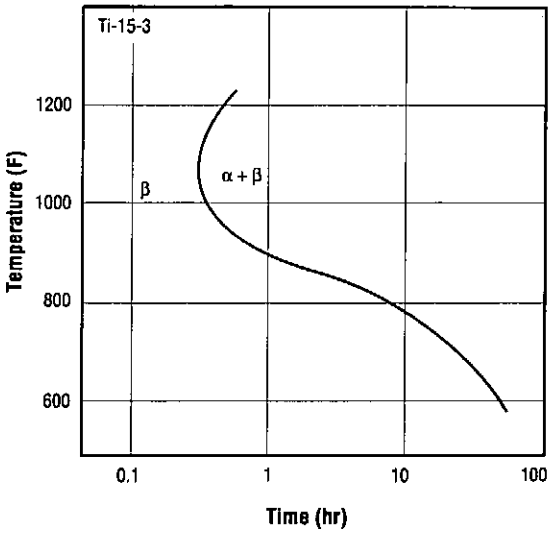


Figure 2.1.2.1.1 Time-temperature-transformation diagram (Ref. 17)

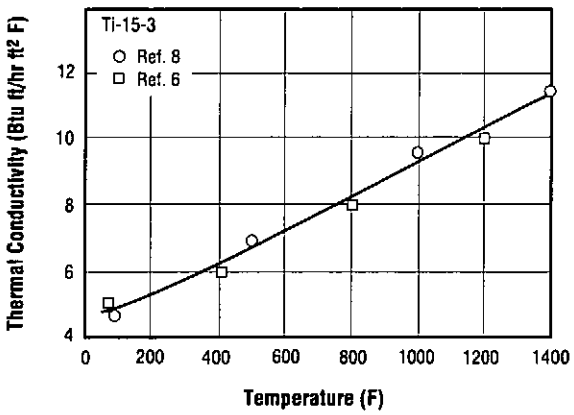


Figure 2.1.3.1 Thermal conductivity from RT to 1400F (Refs. 6, 8)

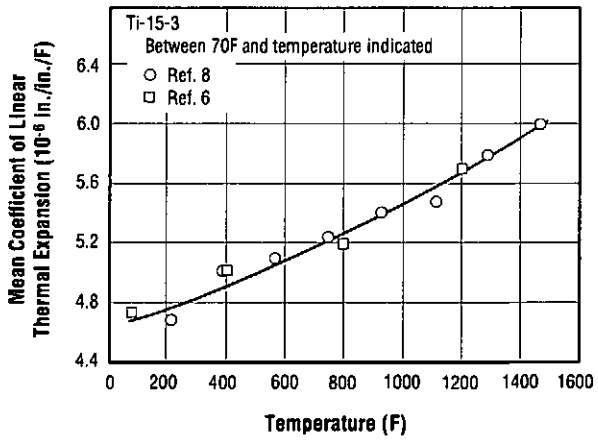


Figure 2.1.4.1 Thermal expansion from RT to 1472F (Refs. 6, 8)

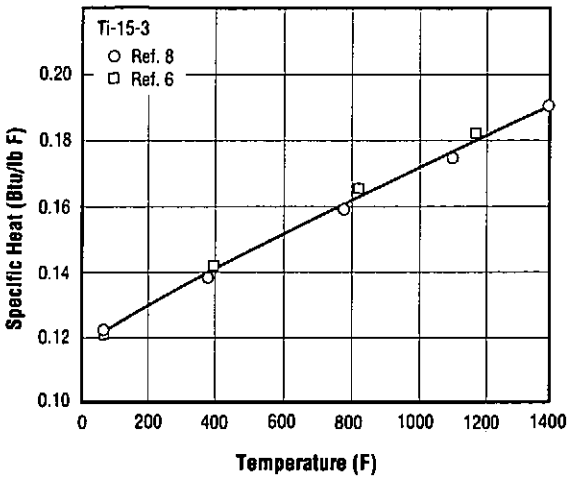


Figure 2.1.5.1 Specific heat from RT to 1400F (Refs. 6, 8)

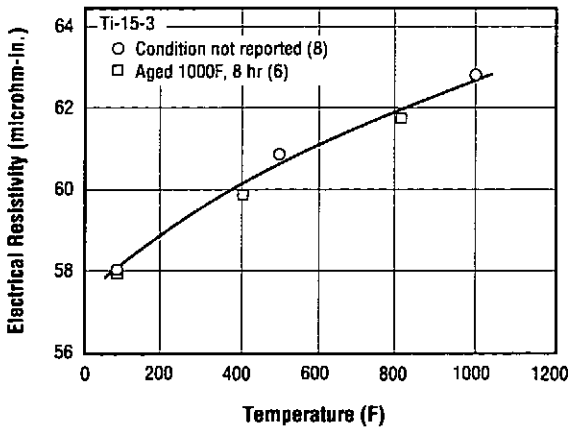


Figure 2.2.2.1 Electrical resistivity from RT to 1000F (Refs. 6, 8)

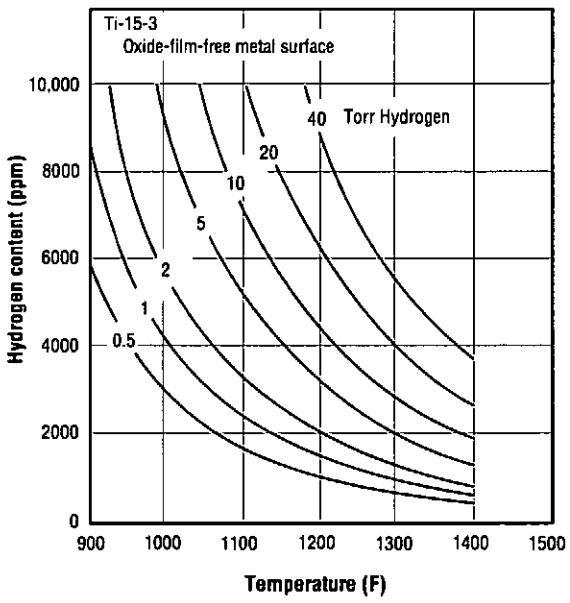


Figure 2.3.3.1 Effects of temperature and hydrogen pressure on solubility of hydrogen in Ti-15-3 (Ref. 35)

Table 2.3.3.2 Effects of hydrogen on room-temperature formability (Ref. 7)

Alloy	Ti-15-3[a]		
Hydrogen Content (ppm)	0.035-in. thick		0.070-in. thick
	Minimum Bend Radius[b] (t)		Cup Height[c] (in.)
	Longitudinal	Transverse	
90	—		0.37
129	0.44	0.74	—
970	—		0.36
1575	0.65	0.94	—
2000	—		0.37
3300	—		0.35
4000	>13		—

[a] Annealed.

[b] Minimum bend radius for 105° bend, expressed as multiple of specimen thickness.

[c] Olsen-type cup test.

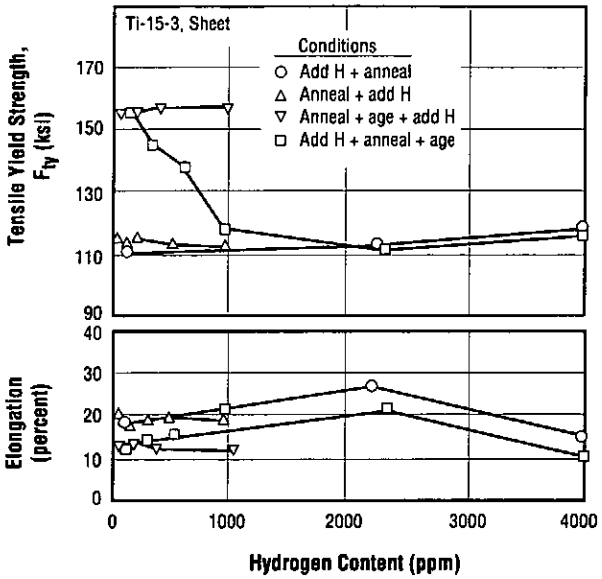


Figure 2.3.3.3 Effects of hydrogen on tensile properties of sheet (Ref. 7)

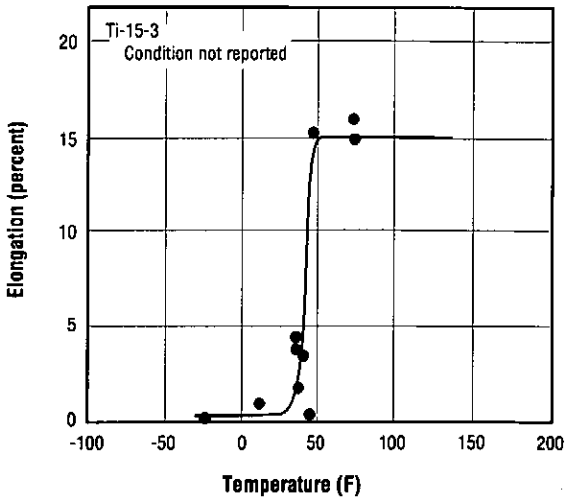


Figure 2.3.3.4 Ductile-brittle transition behavior of alloy containing 3900 ppm hydrogen (Ref. 35)

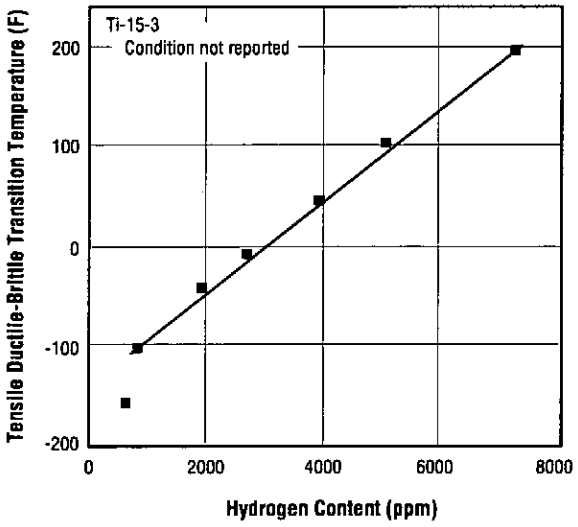


Figure 2.3.3.5 Effects of hydrogen on ductile-brittle transition temperature (Ref. 35)

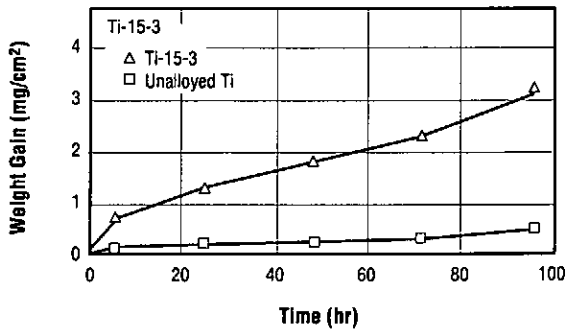


Figure 2.3.4.1 Oxidation weight gain behavior of Ti-15-3 alloy and unalloyed titanium in air at 1202F (Ref. 35)

Table 3.1.1 AMS specified room-temperature mechanical properties (Refs. 1, 2)

Alloy	Ti-15-3								
AMS Specification	Form	Condition	Thickness (in)	Tensile Properties					
				F_{ty} (ksi)		F_{tu} (ksi)		Elongation,[a] min (percent)	Bend Factor
				Minimum	Maximum	Minimum	Maximum		
4914A	Sheet and Strip	Annealed[b]	≤ 0.125	100	126	102	137	12	4/5[c]
		Annealed[b] + Age[d]		140	—	145	—	7	—
		Annealed[b] + Age[e]		170		180		5	
4922	Seamless Tubing	CW + Age[f]	—	125[g]	—	135	—	10/12[h]	3[i]

Note: The original AMS documents should be consulted for complete specification details.

[a] 2 inches or 4D.

[b] Annealed 1450 to 1500F, 3 to 30 minutes, rapid cool.

[c] Product must bend without cracking through an angle of 105 degrees around a diameter equal to the nominal product thickness times the bend factor. Bend factor is equal to 4 for the product up to thickness of 0.070 inch and 5 for product with thickness greater than 0.070 inch up to 0.125 inch.

[d] Aged 1000F, 8 hour, AC.

[e] Aged 900F, 16 hour, AC.

[f] Cold worked plus aged 900 to 1250F, minimum of 2 hours.

[g] Tubing shall also withstand internal hydrostatic pressure equivalent to 125 ksi tensile stress in tubing wall.

[h] Minimum elongation 10 percent for nominal wall thickness ≤ 0.020 inch and 12 percent for nominal wall thickness > 0.020 inch.

[i] Tubing must bend through angle of 180 degrees around a radius equal to three times nominal tubing OD with appropriate tube filler to restrict tube flattening.

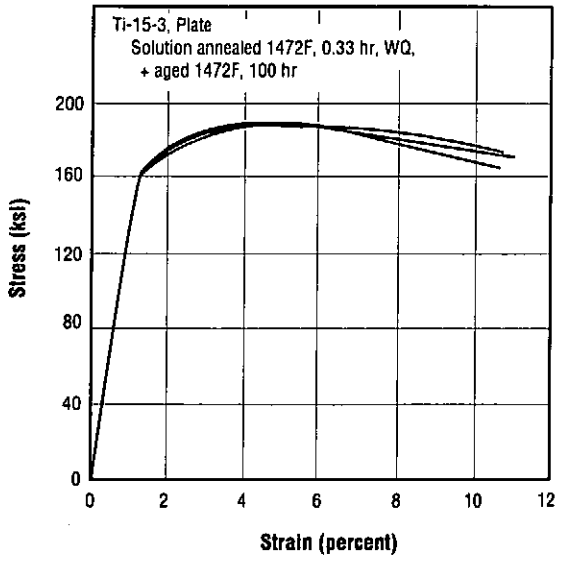


Figure 3.2.1.1 Stress-strain diagram for solution annealed and aged alloy at strain rate of 6 x 10^{-2} min^{-1} (Ref. 37)

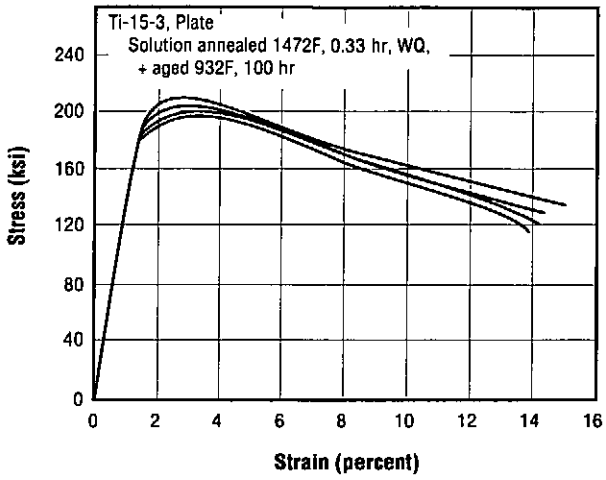


Figure 3.2.1.2 Stress-strain diagram for solution annealed and aged alloy at strain rate of 6 x 10^{4} min^{-1} (Ref. 37)

Table 3.2.1.3 Effects of strain rate on tensile properties of solution annealed alloy (Ref. 8)

Alloy	Ti-15-3[a]		
Strain Rate (min^{-1})	Tensile Properties		
	F_{tu} (ksi)	F_{ty} (ksi)	Elongation (percent)
0.005	109	108	30
0.050	109	106	25
0.100	111	107	24

[a] Solution annealed at 1400F.

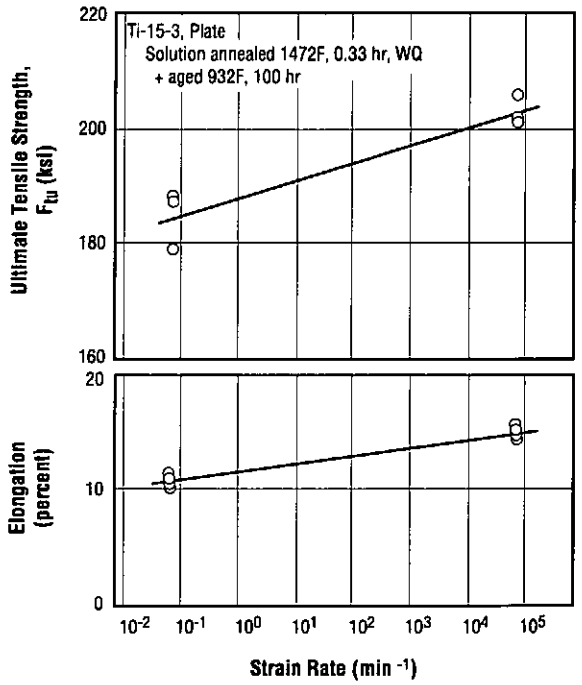


Figure 3.2.1.4 Effects of strain rate on tensile properties of solution annealed and aged alloy (Ref. 37)

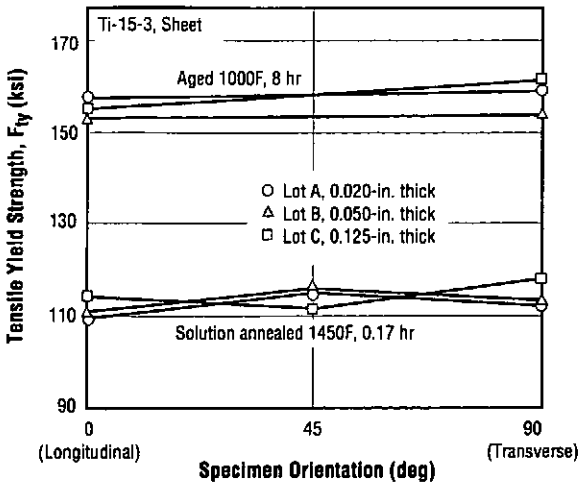


Figure 3.2.1.5 Effects of orientation and thickness on yield strength of heat treated alloy (Ref. 7)

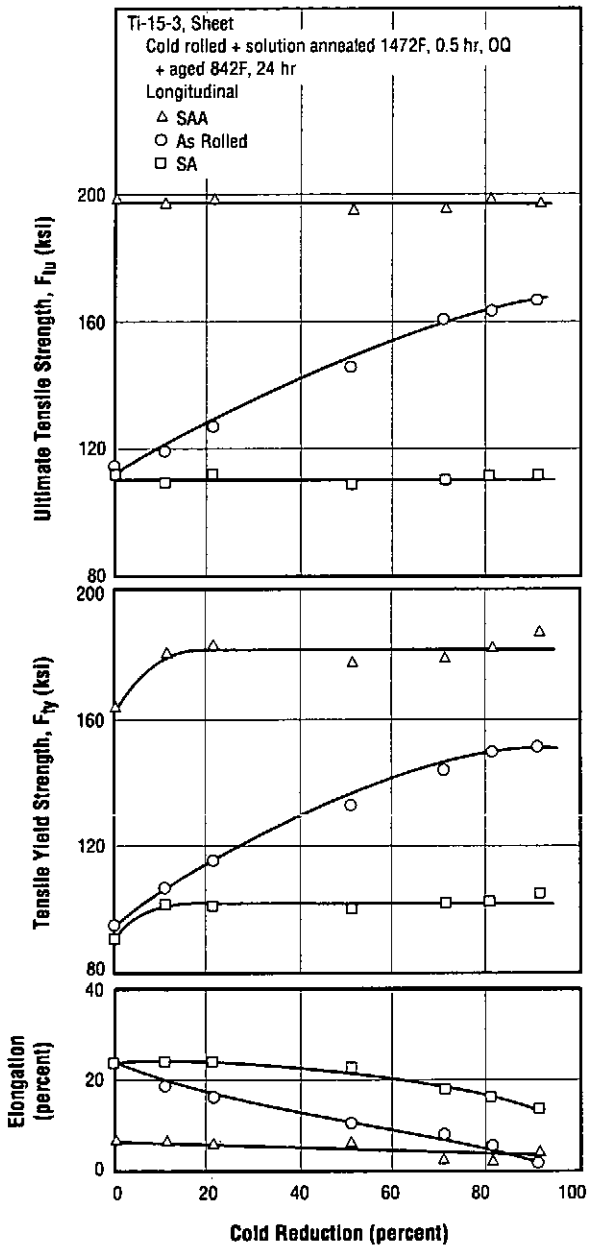


Figure 3.2.1.6 Effects of cold rolling and heat treatment on tensile properties in rolling direction (Ref. 38)

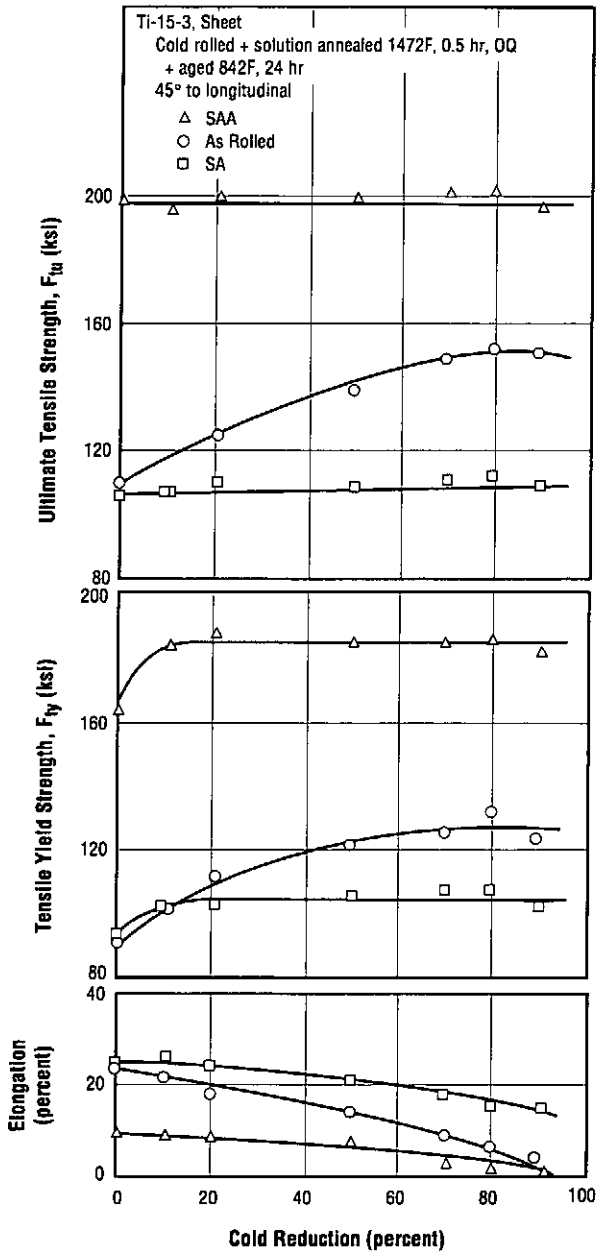


Figure 3.2.1.7 Effects of cold rolling and heat treatment on tensile properties 45 degrees to rolling direction (Ref. 38)

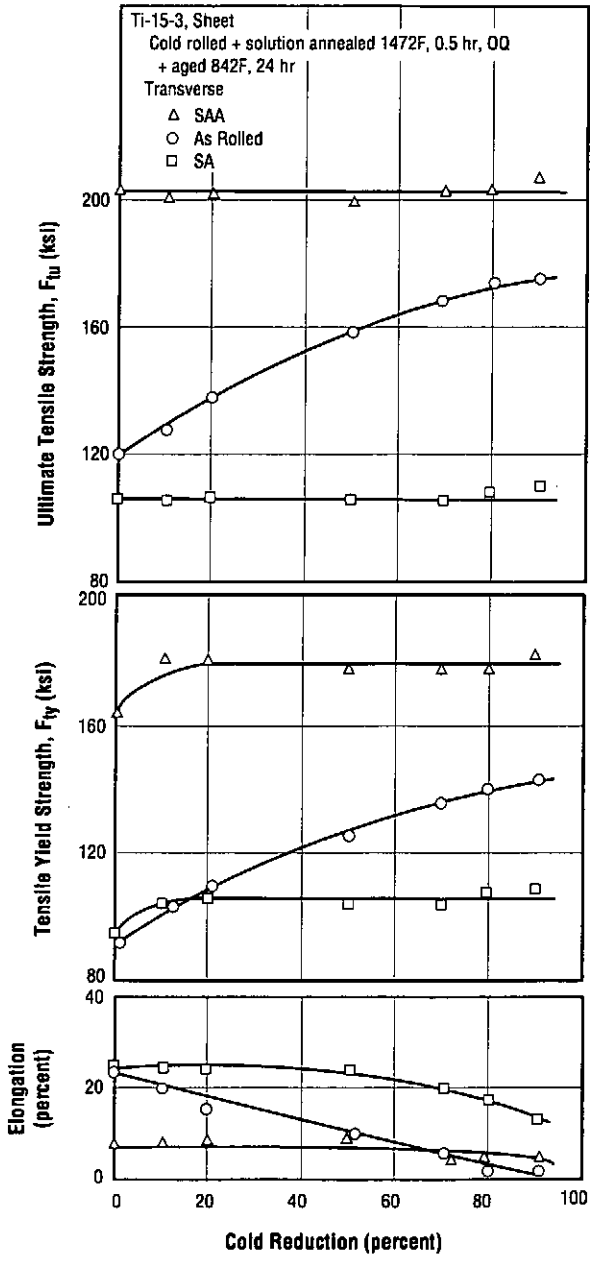


Figure 3.2.1.8 Effects of cold rolling and heat treatment on tensile properties transverse to rolling direction (Ref. 38)

Table 3.2.1.9 Tensile properties and dimensional stabilities of solution annealed and aged alloy after 1000 hours exposure at 650F (Ref. 8)

Alloy		Ti-15-3[a]						
		Tensile Properties[b]						
		As Aged			As Exposed			
Aging Temperature (F)	Aging Time (hr)	F_{tu} (ksi)	F_{ty} (ksi)	Elongation (percent)	F_{tu} (ksi)	F_{ty} (ksi)	Elongation (percent)	Dimensional Change (percent)
950	2	129	119	12	185	166	2	−.02
	8	171	158	10	186	169	9	−.02
	16	180	168	10	188	175	8	+.03
	24	178	168	8	186	172	10	+.03
1050	2	128	117	17	174	160	6	−.03
	8	145	132	12	158	144	13	+.05
	16	146	132	14	155	141	17	+.02
	24	141	128	13	153	139	16	0
1150	2	117	110	17	161	146	6	0
	8	129	117	15	145	133	15	+.09
	16	125	113	19	140	127	18	0
	24	125	114	21	138	125	18	+.01

[a] Solution annealed 1400F, 4 minutes.

[b] Properties averaged from duplicate longitudinal tests.

Table 3.2.1.10 Effects of long time exposure at 500F on room temperature tensile properties of aged alloy (Ref. 6)

Alloy	Ti-15-3		
Pre-exposure conditions[a]	Exposure Time at 500F (hr)	Tensile Properties	
		F_{tu} (ksi)	Elongation (percent)
None	0	167.9	10.1
	500	168.7	11.1
	1000	161.5	11.8
	1500	166.3	11.7
850F, 24 hr.	0	172.7	12.7
	500	175.6	12.2
	1000	174.6	12.3
	1500	174.3	11.4
900F, 24 hr.	0	174.3	11.5
	500	174.1	11.6
	1000	174.4	12.5
	1500	174.6	13.9

[a] All material was first aged 100F, 8 hours.

Table 3.2.6.1 Bearing strength of solution annealed alloy (Ref. 39)

Alloy	Ti-15-3[a]		
e/D[b]	Orientation	Bearing Properties[c]	
		Yield Strength, F_{bry} (ksi)	Ultimate Strength, F_{bru} (ksi)
1.5	L	160.8	198.1
	T	161.2	198.8
2.0	L	179.7	258.9
	T	182.1	257.0

[a] Solution annealed by manufacturer; conditions not reported.

[b] Ratio of edge distance to hole diameter.

[c] Average data for eight lots representing five different heats, tested in triplicate. Sheet thicknesses ranged from 0.040 to 0.116 inches.

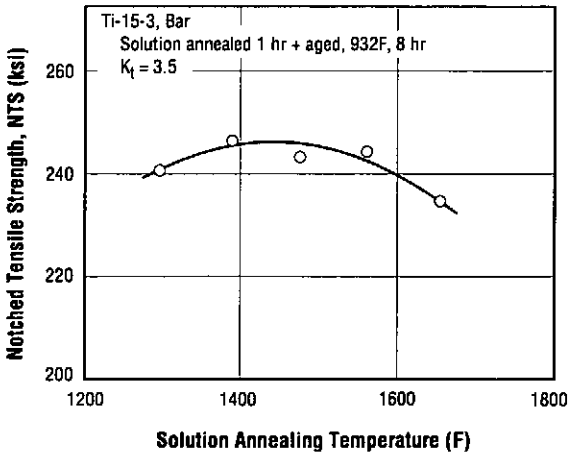


Figure 3.2.7.1.1 Effects of solution annealing temperature on notched tensile strength after aging at 932F (Ref. 13)

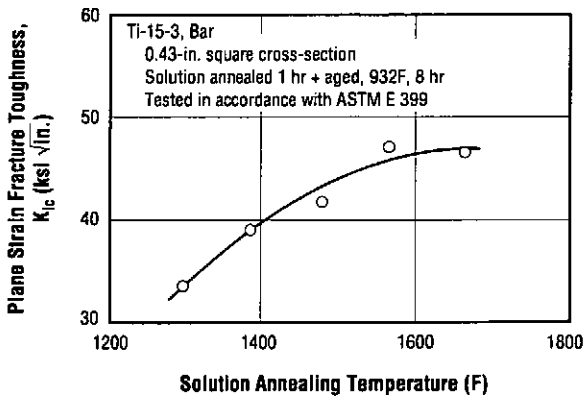


Figure 3.2.7.2.1 Effects of solution annealing temperature on fracture toughness after aging at 932F (Ref. 13)

Table 3.2.7.2.2 Effects of heat treatment and orientation on fracture toughness (Ref. 10)

Alloy		Ti-15-3[a]			
Solution Annealing Conditions		Aging Conditions		Fracture Toughness,[b] K_{Ic} (ksi $\sqrt{in}$) for indicated crack plane orientation	
Temperature (F)	Time (hr)	Temperature (F)	Time (hr)	LT	TL
1382	1	932	4.2	53.3	46.0
			27.8	42.5	35.8
1562	1	752	75	38.6	35.3
			278	23.8	—
		932	8.3	56.1	45.8
			27.8	42.5	36.7
		1112	27.8	(73.9)[c]	(65.4)[c]

[a] Plate, 0.39-inch thickness.

[b] Tested in accordance with ASTM E 399.

[c] Invalid because of specimen thickness requirement.

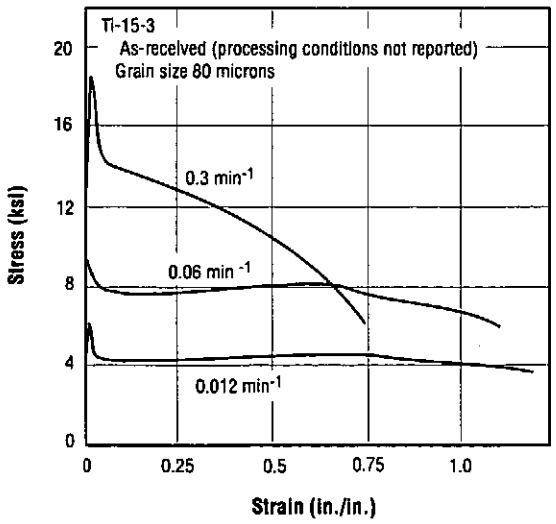


Figure 3.3.1.1 Effects of strain rate on flow curves at 1500F (Ref. 40)

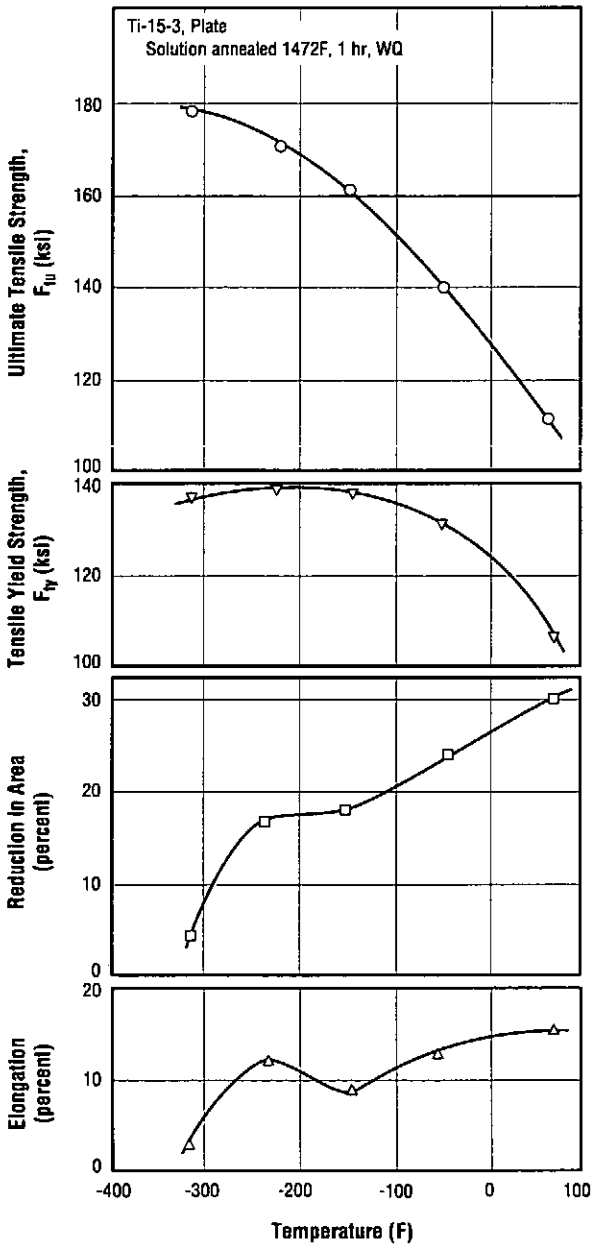


Figure 3.3.1.2 Tensile properties of solution annealed alloy at low temperatures (Ref. 41)

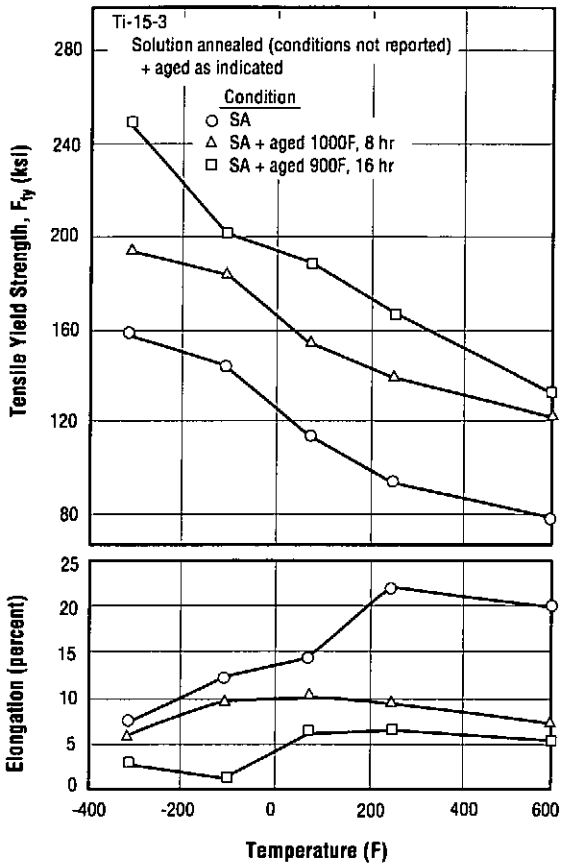


Figure 3.3.1.3 Effects of temperature on tensile properties in three heat treated conditions (Ref. 7)

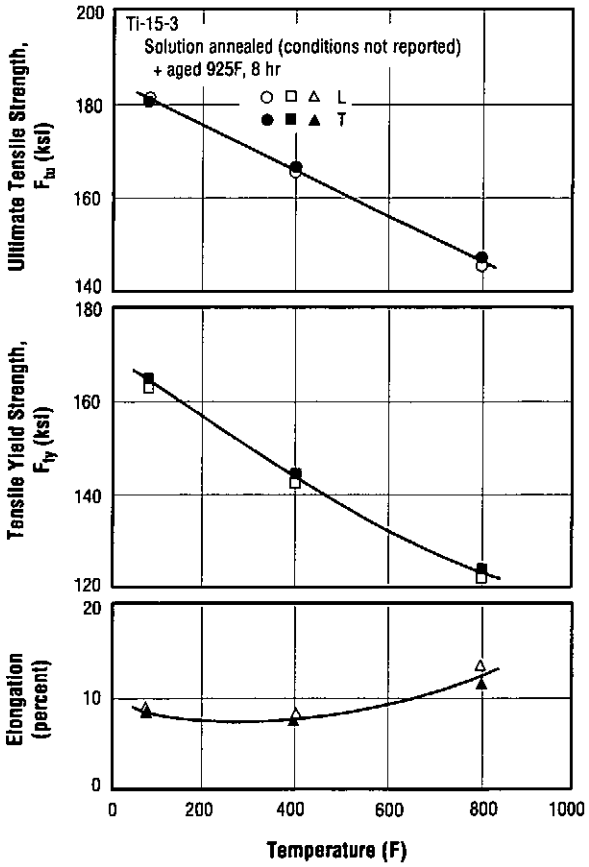


Figure 3.3.1.4 Tensile properties of solution annealed and aged alloy at room temperature to 800F (Ref. 8)

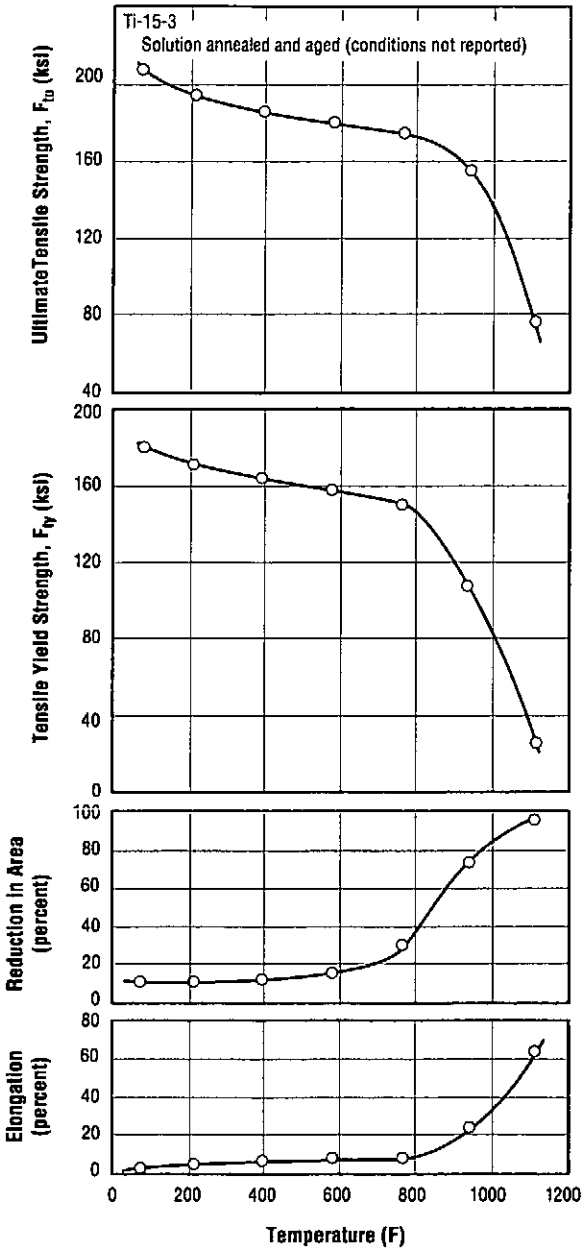


Figure 3.3.1.5 Tensile properties of solution annealed and aged alloy at room temperature to 1112F (Ref. 11)

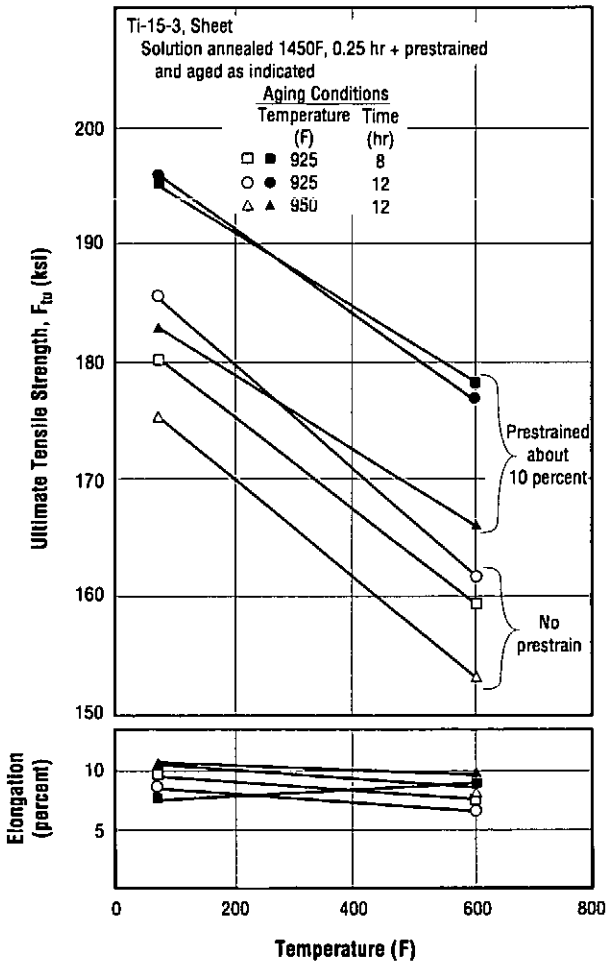


Figure 3.3.1.6 Effects of prestraining and aging on tensile properties of sheet at room temperature and 600F (Ref. 42)

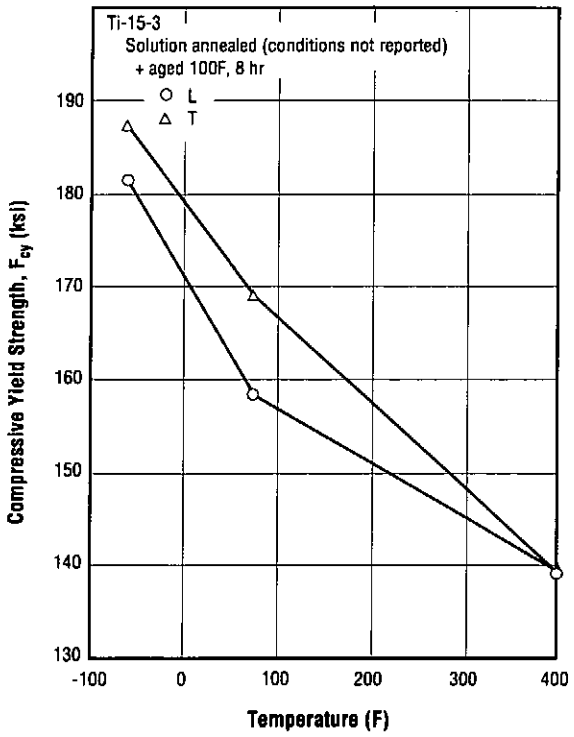


Figure 3.3.2.1 Effects of temperature and orientation on compressive yield strength (Ref. 8)

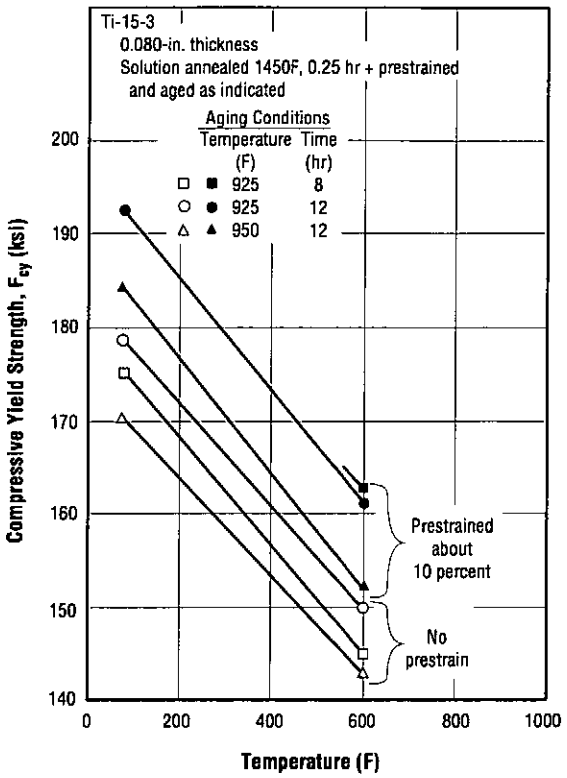


Figure 3.3.2.2 Effects of prestraining and aging on compressive yield strength of sheet at room temperature and 600F (Ref. 42)

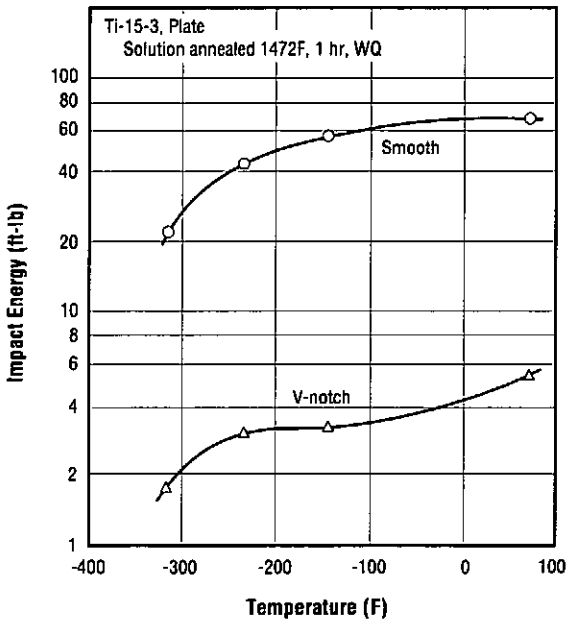


Figure 3.3.3.1 Effects of low temperatures on Charpy impact energy of solution annealed alloy (Ref. 41)

Table 3.3.5.1 Shear strength of solution annealed and aged alloy at room and elevated temperatures (Ref. 8)

Alloy	Ti-15-3[a]	
Temperature (F)	Ultimate Shear Strength, F_{su} (ksi)	
	L	T
70	113.7	115.9
400	103.1	102.3
800	92.3	92.4

[a] Solution annealed (conditions not reported) plus aged 925F, 8 hours.

Table 3.3.6.1 Bearing properties of aged alloy at room and elevated temperatures (Ref. 8)

Alloy	Ti-15-3[a]			
			Bearing Properties	
e/D	Temperature (F)	Orientation	Yield Strength, F_{bry} (ksi)	Ultimate Strength, F_{bru} (ksi)
1.5	70	L	244.9	288.2
		T	252.8	272.3
	400	L	224.1	247.3
		T	225.9	253.2
	800	L	211.8	241.7
		T	207.5	239.5
2.0	70	L	265.4	323.6
		T	288.5	336.9
	400	L	255.6	298.4
		T	260.3	299.1
	800	L	234.2	290.9
		T	238.5	297.1

[a] Aged 925F, 8 hours.

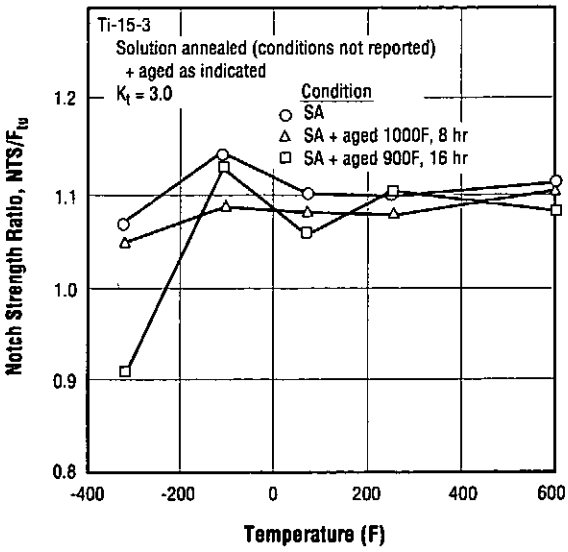


Figure 3.3.7.1.2 Effects of temperature on mild notch strength ratio for three heat treated conditions (Ref. 7)

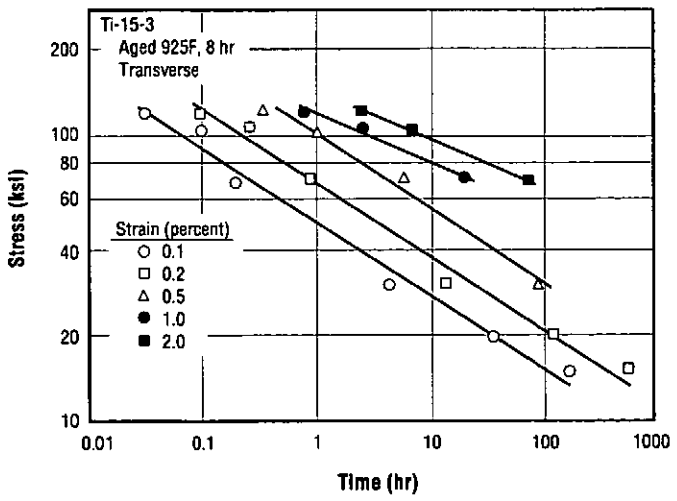


Figure 3.4.1 Times to various creep strains for aged alloy at 800F (Ref. 8)

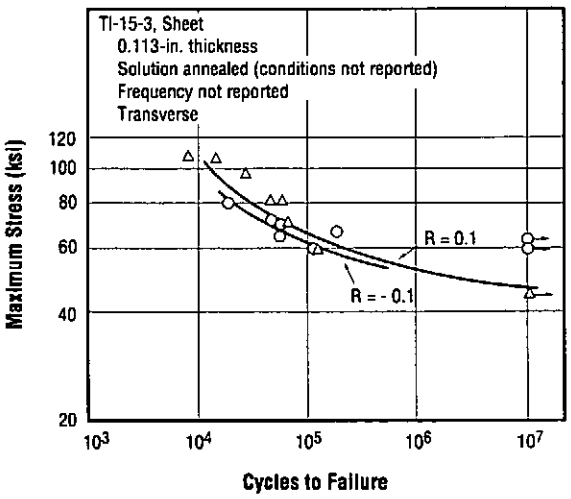


Figure 3.5.1.1 High-cycle fatigue behavior of sheet material (Ref. 39)

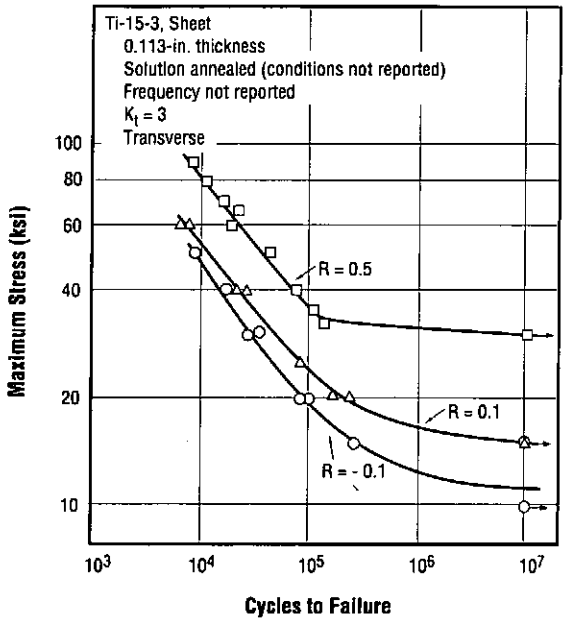


Figure 3.5.1.2 High-cycle fatigue behavior of notched sheet material (Ref. 39)

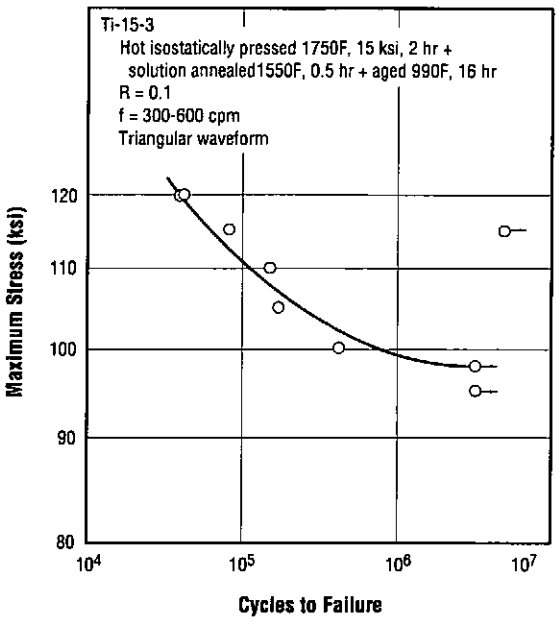


Figure 3.5.1.3 High-cycle fatigue behavior of cast alloy (Ref. 43)

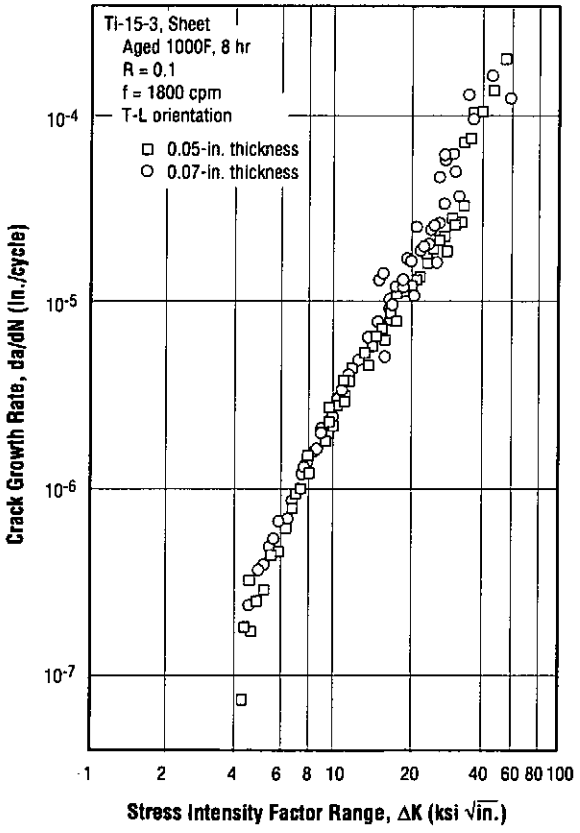


Figure 3.5.3.1 Fatigue crack growth behavior of heat treated alloy at room temperature (Ref. 7)

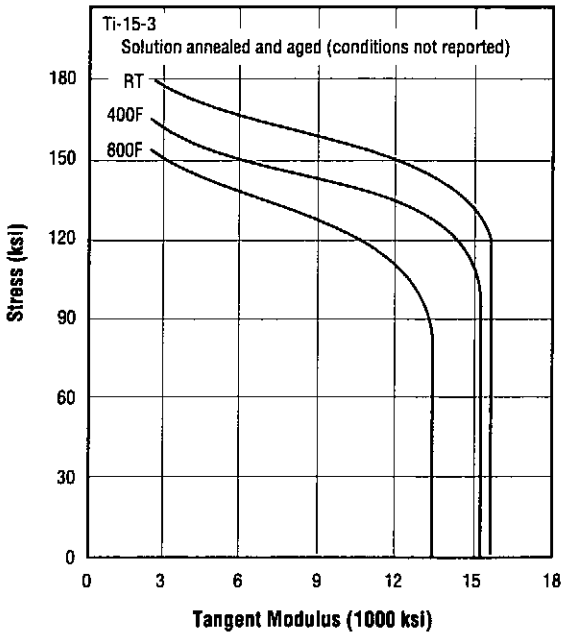


Figure 3.6.4.1 Effects of temperature on longitudinal compressive tangent-modulus curves (Ref. 8)

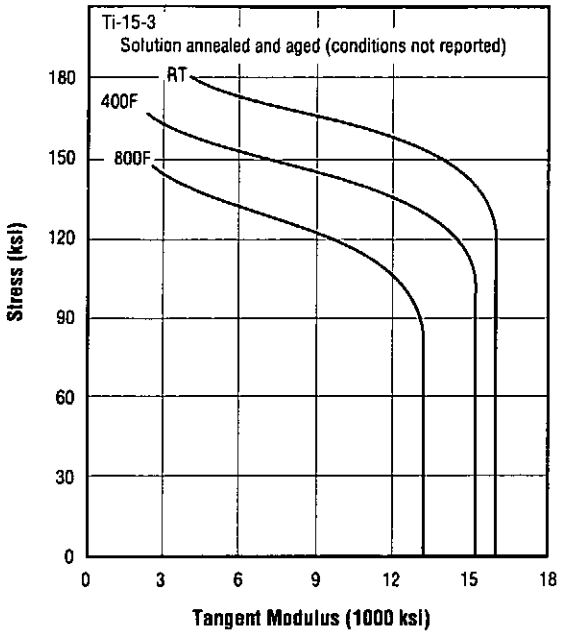


Figure 3.6.4.2 Effects of temperature on transverse compressive tangent-modulus curves (Ref. 8)

Table 4.1.1 Practical cold forming limits (Ref. 6)

Alloy	Ti-15-3[a]
Parameter	Limit
Bend Radius	2.5 t
Shrink Flange	12 percent
Stretch Flange	23 percent
Joggle, L/d	2
Springback	12 - 15 degrees
Draw	> 46 percent
Shear Spin	about 75 percent
Cold Rolling	about 70 percent

[a] Condition not reported but probably solution annealed.

Table 4.1.2 Shear spinnabilities of Ti-15-3 and other aerospace alloys at room temperature (Ref. 36)

Alloy	Ti-15-3
Material[a]	Maximum Reduction[b] (percent)
17-7PH	38
L-605	40
Ti-6Al-4V	50
6061 Al Alloy	63
C-103 Cb Alloy	66
Ti-8V-7Cr-3Al-4Sn-1Zr	69
1100 Al Alloy	83
Ti-8V-4Cr-2Mo-2Fe-3Al	83
Type 301 Stainless Steel	83
Ti-15-3	84

[a] Heat treat conditions not reported.

[b] Reduction in thickness at rupture when sheet metal blank is spun over a spherical mandrel.

Table 4.1.3 Room temperature tensile properties of foil (Ref. 6)

Alloy	Ti-15-3			
Condition	Foil Thickness (in.)	Tensile Properties		
		F_{ty} (ksi)	F_{tu} (ksi)	Elongation (percent)
Solution Annealed[a]	0.004	120	122	19.3
	0.006	119	120	19.8
	0.011	116	118	19.0
Aged[b]	0.004	157	165	4.0
	0.006	153	162	5.8
	0.011	149	156	6.0

[a] Conditions not reported.

[b] 1000F, 8 hours.

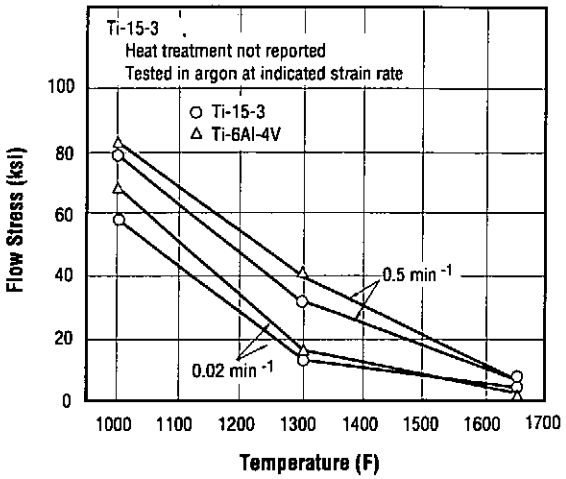


Figure 4.1.4 Effects of temperature and strain rate on flow stresses for Ti-15-3 and Ti-6Al-4V (Ref. 6)

Table 4.3.1.1 Effects of fusion welding and heat treatment on tensile properties (Ref. 47)

Alloy		Ti-15-3[a]								
				Tensile Properties						
				Longitudinal			Transverse			
Thickness (in.)	Pre-Age Weld Type	Age Conditions	Post-Age Weld Type	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (percent)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (percent)
0.050	—	—	—	107	111	16	108	113	16
	EB			105	117	13	112	117	11
	GTA			100	118	14	110	115	9
	—	900F/8 hr.		162	181	10	165	185	9
		950F/8 hr.		142	163	11	146	165	10
		1000F/8 hr.		132	149	12	136	151	13
	EB	950F/4 hr.		158	165	10	165	173	8
	GTA			162	167	8	152	161	6
	—		EB	132	150	11	122	126	3
			GTA	113	130	10	117	124	6
0.100	—	—	—	110	115	18	112	116	17
	EB			100	112	19	115	116	13
	GTA			102	107	12	108	110	11
	—	950F/8 hr.		153	172	10	158	175	11
		1000F/8 hr.		141	158	14	137	156	12
	EB	950F/4 hr.		153	169	8	156	169	4
		1000F/4 hr.		143	159	9	146	160	9
		1050F/4 hr.		133	152	12	140	153	9
	GTA	950F/4 hr.		166	175	3	169	184	4
		1000F/4 hr.		150	172	6	152	176	7
		1050F/4 hr.		151	162	6	150	168	8

[a] Solution annealed 1450F, 0.33 hour, AC.

Table 4.3.1.2 Effects of fusion welding and heat treatment on sharp notched tensile properties (Ref. 47)

Alloy	Ti-15-3[a]				
Thickness (in)	Weld Type	Age Conditions	NTS[c] (ksi)	Smooth, F_{ty} (ksi)	Ratio NTS/ Smooth F_{ty}
0.050	—	900F/8 hr.	73.1	164.9	.44
		925F/8 hr.	83.8	162.8	.52
	EB	900F/8 hr.	70.6	167.6	.42
		925F/8 hr.	69.2	162.8	.43
	GTA	900F/8 hr.	76.4	171.3	.45
		925F/8 hr.	83.6	171.2	.49
0.100	—	900F/8 hr.	49.4	171.2	.29
		950F/8 hr.	50.1	157.2	.32
	EB	900F/8 hr.	69.4	180.6	.38
		950F/8 hr.	71.3	165.4	.43
	GTA	900F/8 hr.	67.2	173.3	.39
		950F/8 hr.	72.7	156.9	.46
	GTA[b]	900F/8 hr.	59.8	170.2	.35
		950F/8 hr.	63.7	155.0	.41

[a] Solution annealed 1450F, 0.33 hour, AC.

[b] Ti-15-3 filler wire.

[c] Stress concentration factor $K_t > 16$.

Table 4.3.1.3 Effects of heat treatment on fracture toughness of 0.30-inch thick electron beam weldments (Ref. 47)

Alloy	Ti-15-3[a]
Age Conditions	Fracture Toughness[b] (ksi $\sqrt{in}$)
(none)	78.7[c]
900F/8 hr.	42.6
950F/8 hr.	45.6

[a] Solution annealed 1450F, 20 minutes, AC prior to welding.

[b] ASTM E 399 compact tension specimens.

[c] Invalid because of high ductility.

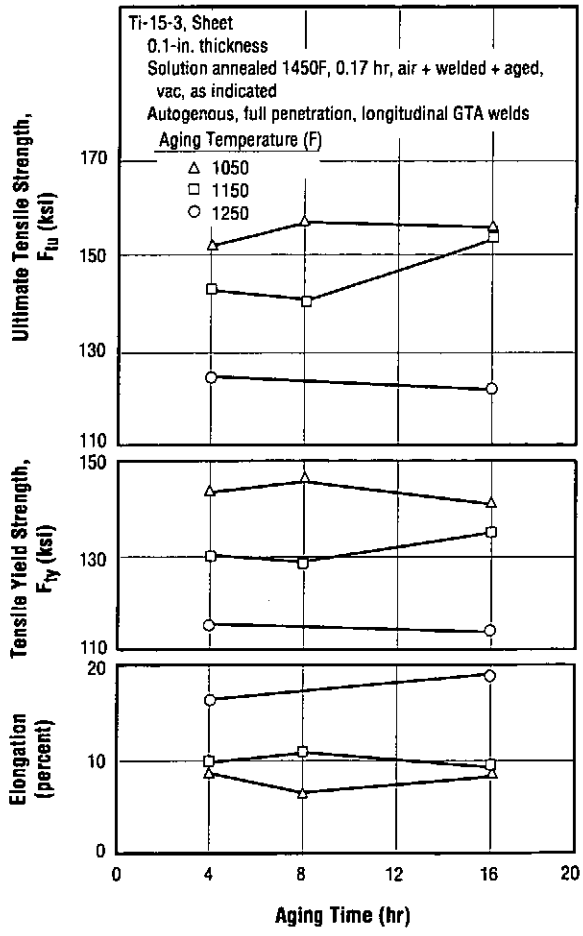


Figure 4.3.1.4 Effects of aging time and temperature on tensile properties of autogenous GTA weldments (Ref. 48)

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NONFERROUS ALLOYS

	Ti
5	Al
2	Sn
2	Zr
4	Mo
4	Cr

Ti – 17

1. GENERAL

Ti-17 may be classified as a "beta-rich" alpha-beta alloy since its beta stabilizer content (Mo + Cr) is slightly higher than that of present commercial alloys. The alloy was developed by the General Electric Company for use in jet engines as a fan and compressor disk material. It can be processed in either the beta or alpha plus beta region and the subsequent heat treatment depends on process history.

The alloy is new and has yet to be adopted on a large scale commercial basis, however, it does appear to have an improved combination of properties relative to other heat-treatable titanium alloys. For example, it can be heat treated to a yield strength level of 150-170 ksi which is similar to that of Ti-6Al-6V-2Sn and 20-30 ksi higher than Ti-6Al-4V. Toughness and ductility properties are higher than for Ti-6Al-6V-2Sn and creep behavior is superior to Ti-6Al-4V. The alloy has hardenability characteristics comparable to some of the beta type alloys, however, it has lower density plus higher modulus and creep strength than the beta alloys.

To date approximately 15 production size ingots (7,000 to 14,000 lbs in weight) have been melted and then converted to billet sizes of 8-12 inch diameter using normal conversion practices. No formability problems have been encountered. Data presented on the alloy are for disk or spool forgings and were generated by the General Electric Company.

1.01 Commercial Designation

Ti-17

1.02 Alternate Designation

1.03 Specifications

1.04 Composition

Table 1.04

1.05 Heat Treatment

The recommended heat treatment for this alloy depends on process history. For alpha-beta processed material the heat treatment consists of a double solution treatment followed by aging. The first solution treatment should be done in the range from 1500 to 1575F for four hours followed by rapid air cooling. The higher temperature, 1575F, produces higher toughness as a result of an increased amount of acicular alpha which precipitates both during cooling and subsequent heat treatment. The second solution treatment is done at 1475F and nucleates additional acicular alpha and produces a beta matrix responsive to subsequent aging. Fan air cooling may be used from the second solution treatment for sections up to 3 in thick, although more consistent and slightly higher strength properties are achieved with a water quench. Heat treatment of beta processed material includes only a single 1475F four-hour solution treatment since acicular alpha is already nucleated or precipitated during cooling from the forging temperature. An aging treatment of 1150-1200F for eight hours is recommended for both the alpha-beta and beta processed material. See Figures 3.0212 and 3.0214 for the effect of solution temperature and aging temperature on the strength properties for both types of processed material.

1.06 Hardness

1.061 Through thickness hardenability of fan air cooled 16 inch diameter x 7 inch thick disk forging, Figure 1.061.

1.062 Through thickness hardenability of water quenched 18 inch diameter x 6 inch thick disk forging, Figure 1.062.

1.063 Through thickness hardenability as a function of cooling rate, Figure 1.063.

1.07 Forms and Conditions Available

1.071 To date alloy has been produced in forging form and can be obtained in alpha-beta or beta processed condition.

1.08 Melting and Casting Practice

Alloy is triple vacuum melted using standard sponge master alloys and melting procedures.

1.09 Special Considerations

1.091 High hardenability is one of the alloy's major attributes. (See Figures 1.061, 1.062 and 1.063).

1.092 Alpha-beta processed material, given conventional solution treatment, usually results in slightly higher yield strength and ductility than beta processing for a given aging treatment. (See Table 3.0218). Beta processing results in higher fracture toughness (see Table 3.02722) Creep resistance and fatigue behavior are unchanged by beta processing (4).

1.093 This alloy has excellent low cycle fatigue behavior and is superior to that of the Ti-6Al-4V alloy (see Figure 3.051).

2. PHYSICAL AND ENVIRONMENTAL EFFECTS

2.01 Thermal Properties

2.011 Melting range.

2.012 Phase changes. Alloy transforms on cooling from beta to alpha + beta at 1600 ± 25F.

2.0121 Time-temperature-transformation diagram, Figure 2.0121.

2.013 Thermal conductivity.

2.014 Thermal expansion, Figure 2.014.

2.015 Specific heat.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density. 0.168 lb per cu in, 4.658 gr per cu cm (1).

2.022 Electrical properties.

2.023 Magnetic properties. Alloy is nonmagnetic.

2.024 Emittance.

2.025 Damping capacity.

2.03 Chemical Environment

2.031 Corrosion resistance. There are no corrosion resistance data yet available on this alloy. However, as is common with all other titanium alloys, it would be expected that this alloy would be susceptible to solid salt stress corrosion at elevated temperatures and exhibit delayed failure of cracked specimens at room temperature in aqueous salt environments.

2.04 Nuclear Environment

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

None

3.02 Mechanical Properties at Room Temperature

3.021 Tension.

3.0211 Stress-strain diagrams.

3.0212 Effect of solution temperature on aged yield strength of beta and alpha-beta processed material, Figure 3.0212.

3.0213 Effect of solution temperature on aged yield and tensile strength of alpha-beta processed material, Figure 3.0213.

3.0214 Effect of aging temperature on the yield strength of beta and alpha-beta processed material, Figure 3.0214.

3.0215 Effect of aging temperature on yield and tensile strength of alpha-beta processed material, Figure 3.0215.

3.0216 Effect of aging temperature on yield strength as a function of quench rate and section thickness in alpha-beta processed condition, Figure 3.0216.

3.0217 Effect of cooling rate from solution treatment on tensile properties of alpha-beta forged material, Table 3.0217.

3.0218 Effect of reduction ratio on the mechanical properties of alpha-beta and beta forged material, Table 3.0218.

3.0219 Tensile properties of beta forged disk, Table 3.0219.

3.022 Compression.

3.0221 Stress-strain diagrams.

	Ti
5	Al
2	Sn
2	Zr
4	Mo
4	Cr

Ti - 17

3.023 Impact.
3.024 Bending.
3.025 Torsion and shear.
3.026 Bearing.
3.027 Stress concentration.
3.0271 Notch properties. (See Table 3.03711).
3.02711 Notch tensile strength of beta processed material as a function of orientation, Table 3.02711.
3.0272 Fracture toughness.
3.02721 Effect of solution temperature on the fracture toughness of alpha-beta processed material, Table 3.02721.
3.02722 Effect of reduction ratio on the fracture toughness of alpha-beta and beta forged material, Table 3.02722.
3.02723 Fracture toughness of beta forged disk, Table 3.02723.
3.028 Combined properties.

3.03 Mechanical Properties at Various Temperatures
3.031 Tension.
3.0311 Stress-strain diagrams.
3.0312 Tensile properties of beta processed material as a function of test temperature, Table 3.0312.
3.0313 Tensile properties of alpha-beta processed material as a function of test temperature, Table 3.0313.
3.032 Compression.
3.0321 Stress-strain diagrams.
3.033 Impact.
3.034 Bending.
3.035 Torsion and shear.
3.036 Bearing.
3.037 Stress concentration.
3.0371 Notch properties.
3.03711 Notch tensile strength of alpha-beta processed material as a function of test temperature, Table 3.03711.
3.0372 Fracture toughness.
3.038 Combined properties.

3.04 Creep and Creep Rupture Properties
3.041 Creep rupture of alpha-beta processed material, Table 3.041.

3.05 Fatigue Properties
3.051 S-N curve for disk forging in alpha-beta processed condition, Figure 3.051.
3.052 Fatigue crack growth rate at RT for specimens from alpha-beta processed forging, Figure 3.052.
3.053 Fatigue crack growth rate at +600F for specimens from alpha-beta processed forging, Figure 3.053.

3.06 Elastic Properties
3.061 Poisson's ratio.
3.062 Modulus of elasticity.
3.0621 Dynamic modulus of elasticity at room and elevated temperatures, Figure 3.0621.
3.063 Modulus of rigidity.
3.064 Tangent modulus.
3.065 Secant modulus.

4. FABRICATION

4.01 Forming
4.011 The alloy has demonstrated superior workability in both open and closed die forging and no cracking has been evidenced during forging operations. Both alpha-beta (1500-1575F) and beta (1650-1700F) forging practice can be used. Press forging appears to be most desirable, since the comparatively low strain rate is more compatible with the lower than usual forging temperature range required for alpha-beta processing than is hammer forging (4).

4.02 Machining and Grinding
Contact Air Force Machinability Data Center,
3980 Rosslyn Drive
Cincinnati, Ohio 45209

4.03 Joining

4.04 Surface Treatment

Source	(1)	
	Weight (percent)	
	Minimum	Maximum
Aluminum	4.5	5.5
Tin	1.5	2.5
Zirconium	1.5	2.5
Molybdenum	3.5	4.5
Chromium	3.5	4.5
Oxygen	0.08	0.13
Nitrogen	-	0.04
Hydrogen	-	0.0125
Iron	-	0.30

TABLE 1.04 COMPOSITION

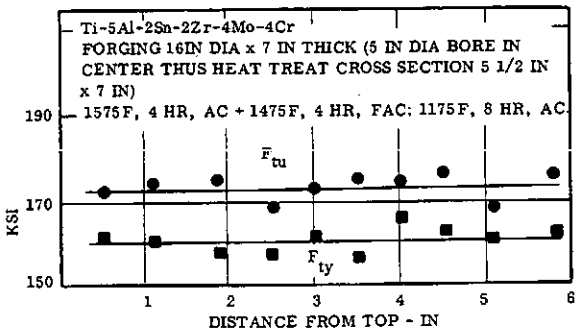


FIG. 1.061 THROUGH THICKNESS HARDENABILITY OF FAN COOLED 16 IN DIAMETER x 7 INCH THICK DISK FORGING. (1)

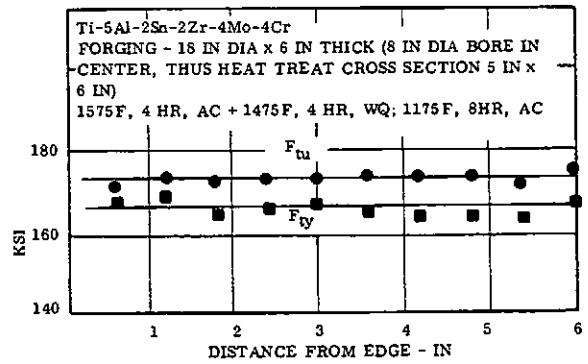


FIG. 1.062 THROUGH THICKNESS HARDENABILITY OF WATER QUENCHED 18 INCH DIAMETER x 6 INCH THICK DISK FORGING. (4)

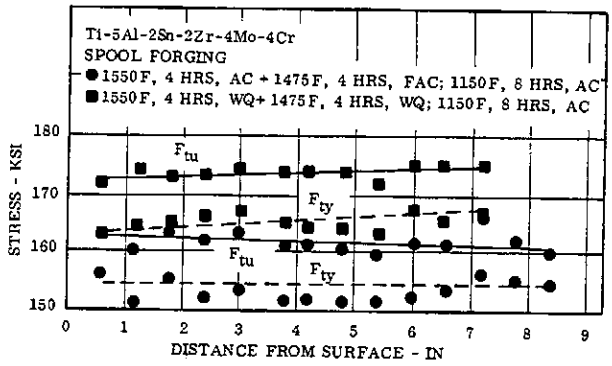


FIG. 1.063 THROUGH THICKNESS HARDENABILITY AS A FUNCTION OF COOLING RATE. (3)

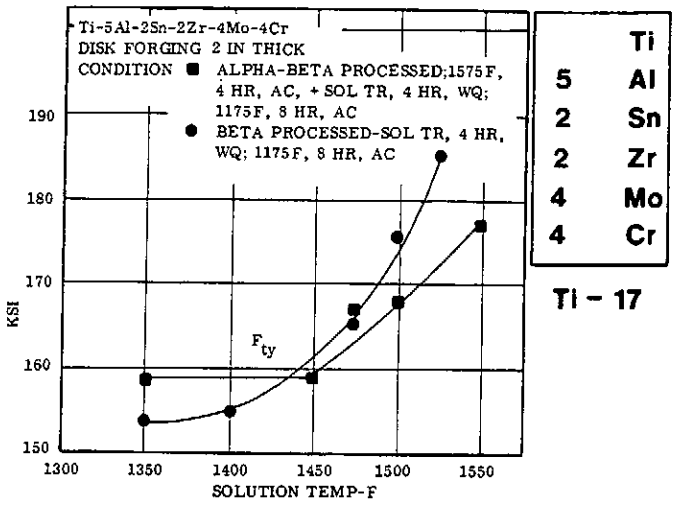


FIG. 3.0212 EFFECT OF SOLUTION TEMPERATURE ON AGED YIELD STRENGTH OF BETA AND ALPHA-BETA PROCESSED MATERIAL. (2)

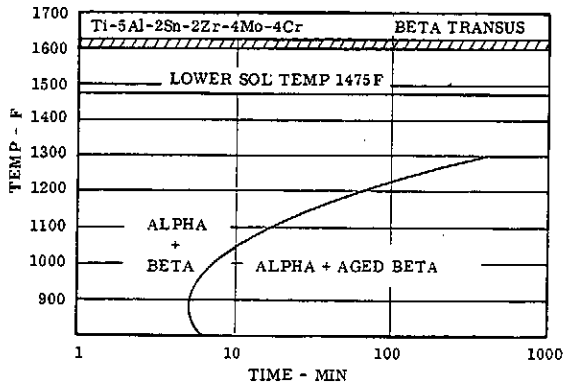


FIG. 2.0121 ISOTHERMAL TRANSFORMATION DIAGRAM. (11)

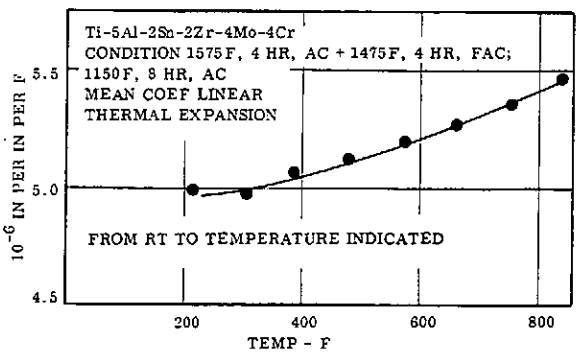


FIG. 2.014 THERMAL EXPANSION. (3)

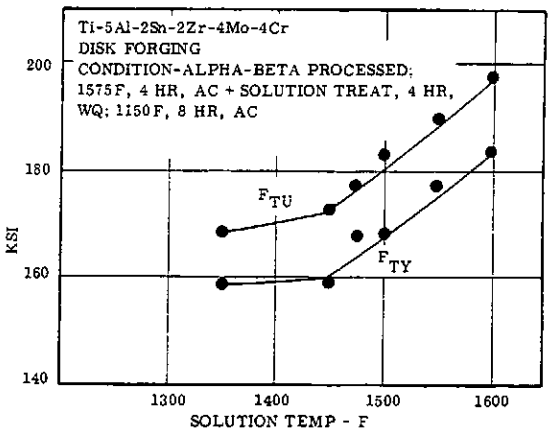


FIG. 3.0213 EFFECT OF SOLUTION TEMPERATURE ON AGED YIELD AND TENSILE STRENGTH OF ALPHA-BETA PROCESSED MATERIAL. (4)

	Ti
5	Al
2	Sn
2	Zr
4	Mo
4	Cr

Ti - 17

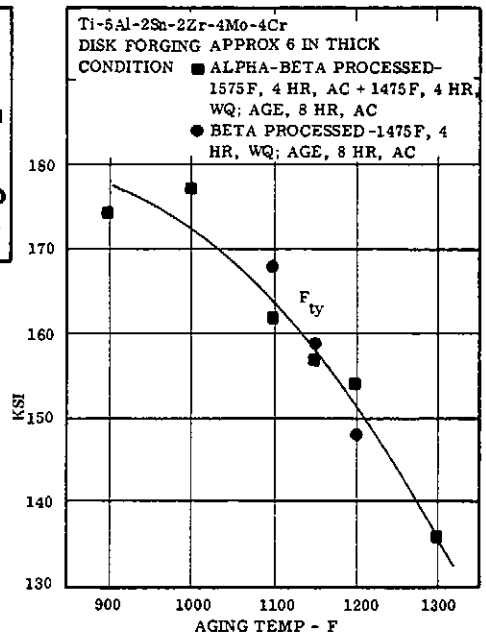


FIG. 3.0214 EFFECT OF AGING TEMPERATURE ON THE YIELD STRENGTH OF BETA AND ALPHA-BETA PROCESSED MATERIAL. (2)

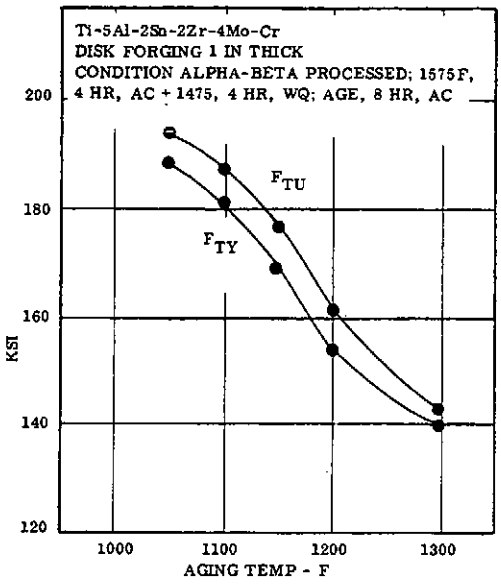


FIG. 3.0215 EFFECT OF AGING TEMPERATURE ON YIELD AND TENSILE STRENGTH OF ALPHA-BETA PROCESSED MATERIAL. (4)

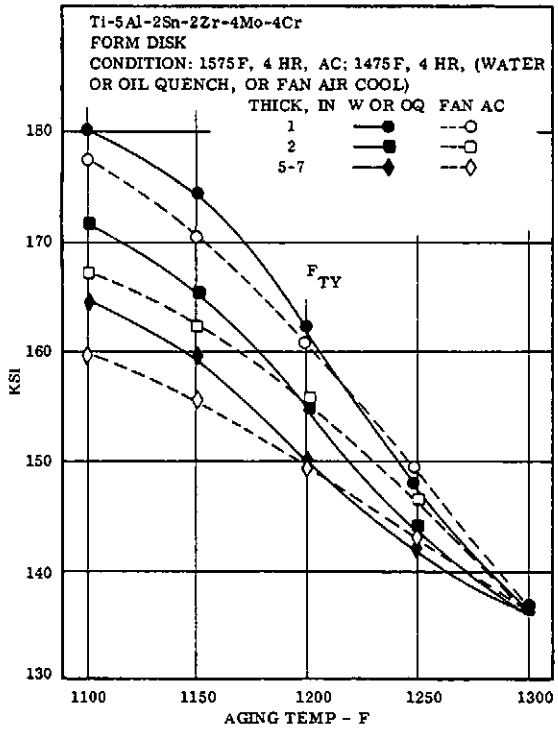


FIG. 3.0216 EFFECT OF AGING TEMPERATURE ON YIELD STRENGTH AS A FUNCTION OF QUENCH RATE AND SECTION THICKNESS IN ALPHA-BETA PROCESSED CONDITION. (3)

	Ti
5	Al
2	Sn
2	Zr
4	Mo
4	Cr

Ti - 17

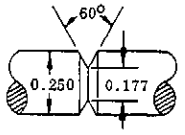
Source	(3)							
Alloy	Ti-5Al-2Sn-2Zr-4Mo-4Cr							
Form	Spool Forging							
Condition	1550F, 4 hrs, ___ + 1475F, 4 hrs, ___; 1150F, 8 hrs, AC							
Cooling Media	AC				WQ			
Distance from Surface (in)	F_{ty} (ksi)	F_{tu} (ksi)	e (2 in) (percent)	RA (percent)	F_{ty} (ksi)	F_{tu} (ksi)	e (2 in) (percent)	RA (percent)
0.6	156	163	10	33	168	172	5	9
1.2	151	160	12	33	169	174	12	36
1.8	155	163	11	30	165	173	9	27
2.4	152	162	10	27	166	173	10	28
3.0	153	163	10	19	167	174	10	35
3.6	151	161	10	28	165	174	9	32
4.2	152	161	11	26	164	174	9	31
4.8	151	160	9	30	164	174	10	24
5.4	151	159	13	32	163	172	6	24
6.0	152	161	12	28	167	175	8	25
6.6	153	161	11	27	165	175	8	23
7.2	156	166	10	19	167	175	10	28
7.8	155	162	11	30				
8.4	154	160	10	26				

TABLE 3.0217 EFFECT OF COOLING RATE FROM SOLUTION TREATMENT ON TENSILE PROPERTIES OF ALPHA-BETA FORGED MATERIAL

Source	(2)				
Alloy	Ti-5Al-2Sn-2Zr-4Mo-4Cr				
Form	Disk Forgings				
Condition	(1550F, 4 hr, AC + 1475F, 4 hr, FAC; 1150F, 8 hr, AC)(a) (1475F, 4 hr, FAC; 1150F, 8 hr, AC) (b)				
Forging Condition	Reduction Ratio	F_{tu} (ksi)	F_{ty} (ksi)	e (2 in) (percent)	RA (percent)
Alpha-beta (a) Forged	2:1	174	167	8.8	24.1
	3:1	171	166	11.1	33.4
	4:1	175	169	9.4	28.8
Beta forged (b)	2:1	175	162	8.1	18.9
	3:1	173	160	10.0	22.6
	4:1	172	161	8.3	19.1

TABLE 3.0218 EFFECT OF REDUCTION RATIO ON THE MECHANICAL PROPERTIES OF ALPHA-BETA AND BETA FORGED MATERIAL

Source	(3)		
Alloy	Ti-5Al-2Sn-2Zr-4Mo-4Cr		
Form	Disk Forging		
Condition	1450F, 4 hrs, FAC; 1150F, 8 hrs, AC		
Orientation	F_{tu} (ksi)	NTS-ksi (K_t = 3.5)	NTS/F_{tu} Ratio
Tang.	171	244	1.43
Radial	172	235	1.37
Axial	169	203	1.20



Notch radius = 0.006 inch

TABLE 3.02711 NOTCH TENSILE STRENGTH OF BETA PROCESSED MATERIAL AS A FUNCTION OF ORIENTATION

Source	(2)				
Alloy	Ti-5Al-2Sn-2Zr-4Mo-4Cr				
Form	Forged disk (21 in dia. x 2-1/4 in. thick)				
Condition	Beta forged + 1475F 4 hr, WQ; 1175F, 8 hr, AC				
Location in Disk	Test Direction	F_{tu} (ksi)	F_{ty} (ksi)	e (2 in) (percent)	RA (percent)
Rim	Tang.	172	162	11	23
Web	Tang.	169	158	10	23
Bore	Radial	172	162	9	22
Data average of two tests.					

TABLE 3.0219 TENSILE PROPERTIES OF BETA FORGED DISK

Source	(2)		
Alloy	Ti-5Al-2Sn-2Zr-4Mo-4Cr		
Form	Disk forging, 18 in dia. x 2 in thick		
Condition	Sol. temp., 4 hr, AC + 1475F, 4 hr, WQ; 1150F, 8 hr, AC		
Sol. Temp.	F_{ty} (a) (ksi)	K_{IC} (b) (ksi$\sqrt{in}$)	
1500	165	25	
1550	163	28	
1575	162	46	
(a) Average of two tests.			
(b) 1 inch thick compact tension specimen.			
Plane strain fracture toughness by ASTM E399-74			

TABLE 3.02721 EFFECT OF SOLUTION TEMPERATURE ON THE FRACTURE TOUGHNESS OF ALPHA-BETA PROCESSED MATERIAL

Ti
5 Al
2 Sn
2 Zr
4 Mo
4 Cr

Ti - 17

Source	(2)			
Alloy	Ti-5Al-2Sn-2Zr-4Mo-4Cr			
Form	Disk Forging			
Condition	Alpha-beta forged 1550F, 4 hr, FAC + 1475F, 4 hr, FAC; 1150F, 8 hr, AC		Beta forged 1475F, 4 hr, FAC; 1150F, 8 hr, AC	
Reduction Ratio	F_{ty} (a) (ksi)	K_{Ic} (b) (ksi$\sqrt{in}$)	F_{ty} (a) (ksi)	K_{Ic} (b) (ksi$\sqrt{in}$)
2:1	167	37.8	162	62.6
3:1	166	32.9	160	55.5
4:1	169	33.9	161	50.2

(a) Average of two tests (see Table 3.0218 for balance of smooth tensile properties).
(b) 1 inch thick compact tension specimen.
TL specimen orientation.
Plane strain fracture toughness by ASTM E399-74.

TABLE 3.02722 EFFECT OF REDUCTION RATIO ON THE FRACTURE TOUGHNESS OF ALPHA-BETA AND BETA FORGED MATERIAL

Source	(2)	
Alloy	Ti-5Al-2Sn-2Zr-4Mo-4Cr	
Form	Forged disk (21 in diameter x 2-1/4 in thick)	
Condition	Beta forged + 1475F, 4 hr, WQ; 1175F 8 hr, AC	
Location in Disk	F_{ty} (a) (ksi)	K_{Ic} (ksi$\sqrt{in}$)
Rim	162	62 (b)(c)
Bore	162	71 (d)

(a)(b) Average of two tests.
(c) TL specimen orientation.
(d) LT specimen orientation.
1 inch thick compact tension specimen.
Plane strain fracture toughness by ASTM E399-74.

TABLE 3.02723 FRACTURE TOUGHNESS OF BETA FORGED DISK

Source	(3)				
Alloy	Ti-5Al-2Sn-2Zr-4Mo-4Cr				
Form	Disk Forging				
Condition	1450F, 4 hrs, FAC; 1150F, 8 hrs, AC				
Test Temp. (F)	Orientation	F_{tu} (ksi)	F_{ty} (ksi)	e (2 in) (percent)	RA (percent)
75	Radial	170	160	9	22
75	Radial	172	162	12	23
75	Axial	168	154	12	23
75	Axial	168	155	13	28
400	Radial	153	132	13	36
400	↓	151	132	13	42
600		143	119	14	41
600		142	118	11	37
800		139	116	17	52
800		139	116	14	51

TABLE 3.0312 TENSILE PROPERTIES OF BETA PROCESSED MATERIAL AS A FUNCTION OF TEST TEMPERATURE

Source	(3)				
Alloy	Ti-5Al-2Sn-2Zr-4Mo-4Cr				
Form	Spool Forging				
Condition	1550F, 4 hrs, AC + 1475F, 4 hrs, FAC; 1150, 8 hr, AC				
Test Temp. (F)	Orientation	F_{tu} (ksi)	F_{ty} (ksi)	e (2 in) (percent)	RA (percent)
75	Radial	172	166	8	26
75	↓	171	162	12	32
75		163	155	11	39
200		156	127	12	36
400		144	122	14	46
600		143	118	12	46
600		137	115	11	49
700		133	108	13	47

TABLE 3.0313 TENSILE PROPERTIES OF ALPHA-BETA PROCESSED MATERIAL AS A FUNCTION OF TEST TEMPERATURE

	Ti
5	Al
2	Sn
2	Zr
4	Mo
4	Cr

Ti - 17

Source	(3)		
Alloy	Ti-5Al-2Sn-2Zr-4Mo-4Cr		
Form	Spool Forging		
Condition	1550F, 4 hr, AC + 1475F, 4 hr, FAC; 1150F, 8 hrs, AC		
Test Temp. (F)	F_{tu} (ksi)	NTS - ksi (K_t = 4)	NTS/F_{tu} Ratio
75	166	213	1.28
200	156	215	1.38
400	141	205	1.45
600	139	190	1.36
700	132	189	1.44
Data average of 3 tests. Notch specimen (see Table 3.02711). Notch radius = 0.0047 inch.			

TABLE 3.03711 NOTCH TENSILE STRENGTH OF ALPHA-BETA PROCESSED MATERIAL AS A FUNCTION OF TEST TEMPERATURE

Source	(3)	
Alloy	Ti-5Al-2Sn-2Zr-4Mo-4Cr	
Form	Spool Forging	
Condition	1550F, 4 hr., AC + 1475F, 4 hr, FAC; 1150F, 8 hr, AC	
Temperature (F)	Stress (ksi)	Time (hours)
400	145	0.01
400	142.5	> 671.9
400	142	> 793.6
600	140	0.1
600	137.5	> 670.5
600	130	> 721.5
800	115	8
900	70	> 140
950	70	≈ 16

TABLE 3.041 CREEP RUPTURE OF ALPHA-BETA PROCESSED MATERIAL

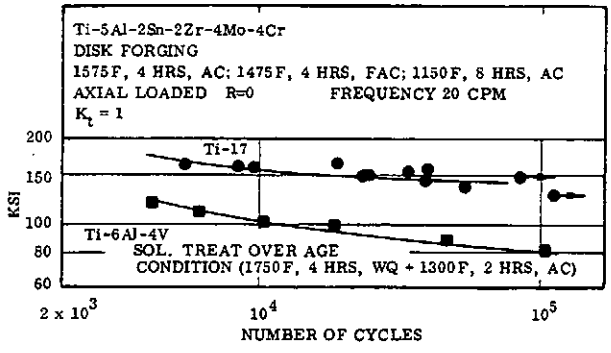


FIG. 3.051 S-N CURVE FOR DISK FORGING IN ALPHA-BETA PROCESSED CONDITION. (2)

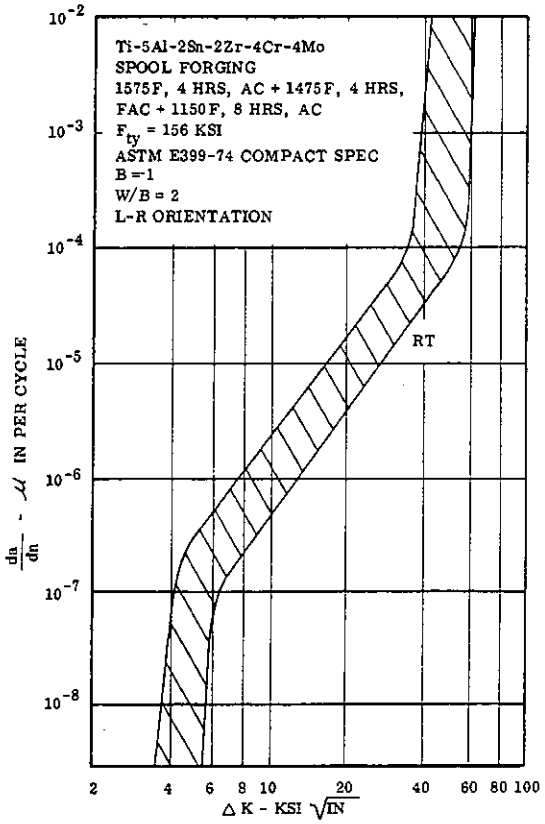


FIG. 3.052 FATIGUE CRACK GROWTH RATE AT ROOM TEMPERATURE FOR SPECIMENS FROM ALPHA-BETA PROCESSED FORGING. (3)

	Ti
5	Al
2	Sn
2	Zr
4	Mo
4	Cr

Ti - 17

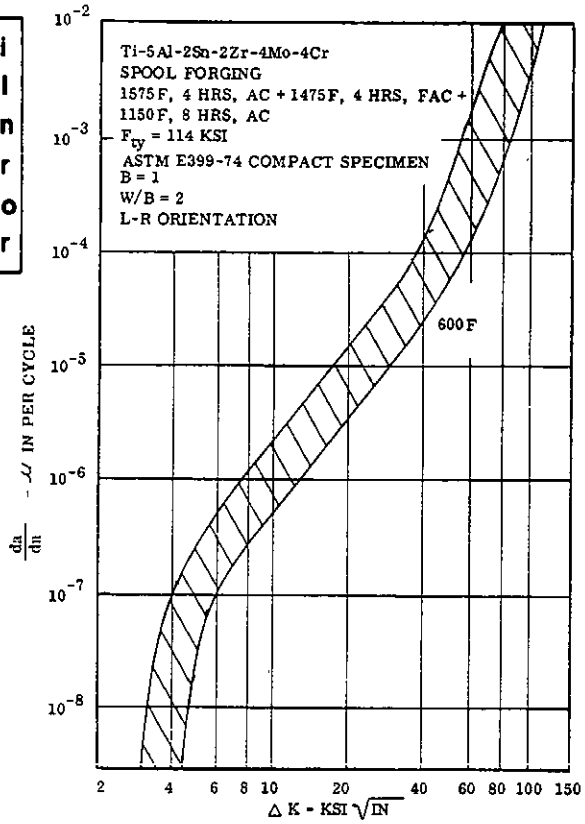


FIG. 3.053 FATIGUE CRACK GROWTH RATE AT +600F FOR SPECIMENS FROM ALPHA-BETA PROCESSED FORGING. (3)

REFERENCES

1. General Electric Co., "Ti-17 Alloy Processing and Properties", AEG-700 (January 1973).
2. Redden, T.K. and Shamblen, C.E., "Effect of Thermo-mechanical Processing and Heat Treatment on the Fatigue and Fracture Behavior of the Ti-17 Alloy", General Electric Co., Presented at AIME Spring Meeting (May 29 - June 1, 1973).
3. Private Communication with Gene E. Best, Manager, Materials Data Unit, General Electric Co., Cincinnati, Ohio (January 16, 1975).
4. "Ti-17 A New High-Strength/Toughness, Deep-Hardenable, Titanium Alloy", Private Communication from Gene E. Best, Manager, Materials Data Unit, General Electric Co., Cincinnati, Ohio (January 16, 1975).

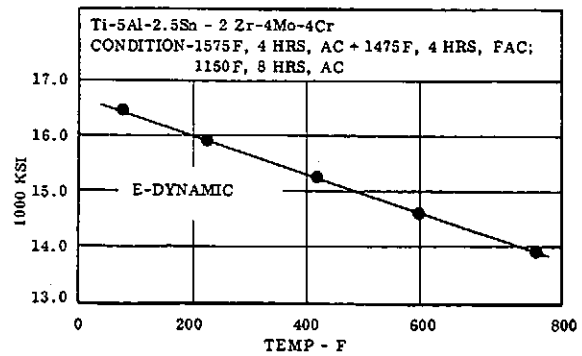


FIG. 3.0621 DYNAMIC MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES. (3)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

1. GENERAL

Ti-679 is a complex super-alpha alloy developed by Imperial Metal Industries of Great Britain and covered by U. S. Patent Number 3,049,425. The alloy is produced and marketed in the United States by the Titanium Metals Corporation of America (TMCA) under license from the British firm. Appearing in 1958, the alloy is currently used for compressor components in British jet engines.

The combination of low-aluminum, medium-zirconium, and high-tin strengthens and stabilizes the alpha phase. Considerable strengthening at all temperatures is derived from the active eutectoid compound Ti_xSi_y. The alloy may be classified as both a weakly stabilized, martensitic alloy and an active eutectoid. It displays the isothermal transformation characteristics of two phase titanium alloys.

For comparable products in the annealed condition, the strength of this alloy from room temperature to 1000F exceeds that of Ti-6Al-4V and Ti-8Al-1Mo-1V and is about equal to Ti-6Al-2Sn-4Zr-2Mo. Its creep strength is superior to Ti-8Al-1Mo-1V and Ti-6Al-4V at all temperatures, but inferior to Ti-6Al-2Sn-4Zr-2Mo at temperatures above 900F. At elevated temperatures, this alloy is less fatigue resistant than Ti-8Al-1Mo-1V and Ti-6Al-2Sn-4Zr-2Mo. The alloy appears to be metallurgically stable up to 850F.

Forgeability and machinability of this alloy are comparable to Ti-8Al-1Mo-1V. Welding of this alloy is not recommended.

1.01 Commercial Designation

Ti-679, IMI-679

1.02 Alternate Designation

1.03 Specifications

Table 1.03

TABLE 1.03

Form	Condition	Specification
Bars, Forgings, Forging Stock	Fully Annealed (in accordance with MIL-H-81200)	MIL-T-9047D (09 June 67)
Bars, Forgings	1650F, 1hr, AC + 930F, 24hrs, AC	AMS-4974 (01 November 67)
Bars, Forgings, Forging Stock	1650F, 1hr, AC + 930F, 24hrs, AC	The Garrett Corporation Airesearch Manufacturing Co EMS-94902 (13 May 66)
Forged Parts	1650F, 1hr, AC or OQ + 930F, 24hrs, AC	General Electric Company 4012158-092 (10 October 63)
Compressor Blades, Vanes	1650F, 1hr, AC + 930F, 24hrs, AC	General Electric Company C50T83-S5 (08 December 66)
Bars, Forgings, Forging Stock	1650F, 1hr, OQ + 930F, 24hrs, AC	General Motors Corporation Allison Division EMS-59034-B (22February 67)
Bars, Forgings, Forging Stock	1650F, 1hr, AC +930F, 24hrs, AC	General Motors Corporation Allison Division EMS-59035-A (29 August 67)
Bars	1650F, 1hr, AC (or faster) + 930F, 24hrs, AC	United Aircraft Corporation Pratt & Whitney Division PWA-1206-A (05 October 65)
Forgings	1650F, 1hr, AC (or faster) + 930F, 24hrs, AC	United Aircraft Corporation Pratt & Whitney Division PWA-1205-A (05 October 65)

1.04 Composition

1.041 Producer's specified composition, Table 1.041.

TABLE 1.041

Source	T.M.C.A.(4)(5)		
	Weight Percent		
	Min.	Max.	Nom.
Tin	10.50	11.500	11.00
Zirconium	4.00	6.000	5.00
Aluminum	2.00	2.500	2.25
Molybdenum	0.80	1.200	1.00
Silicon	0.15	0.270	0.21
Oxygen		0.150	0.10
Iron		0.120	
Carbon		0.040	
Nitrogen		0.040	
Hydrogen		0.008	
Titanium	Balance		

1.042 Users' specified composition, Table 1.042.

TABLE 1.042

Source*	(19)		(20)		(21)		(22)		(23)		(24)		(25)	
	Weight Percent													
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Tin	10.50	11.50	10.50	11.50	10.50	11.50	10.50	11.50	10.50	11.50	10.50	11.50	10.50	11.50
Zirconium	4.00	6.00	4.00	6.00	4.00	6.00	4.00	6.00	4.00	6.00	4.00	6.00	4.50	5.50
Aluminum	2.00	2.50	2.00	2.50	2.00	2.50	2.00	2.50	2.00	2.50	2.00	2.50	2.10	2.90
Molybdenum	.80	1.20	.80	1.20	.80	1.20	.80	1.20	.80	1.20	.80	1.20	.50	1.50
Silicon	.15	.27	.15	.27	.15	.27	.15	.27	.15	.27	.15	.27	.15	.35
Oxygen		.20		.17		.15		.15		.15		.15		.20
Iron		.20		.12		.12		.12		.12		.12		.30
Carbon		.08		.04		.04		.04		.10		.10		.15
Nitrogen		.050		.04		.04		.04		.050		.050		.050
Hydrogen		.009		.010		.015		.0125		.0125		.0125		.0125
Titanium	Balance		Balance		Balance		Balance		Balance		Balance		Balance	

*See Table 1.03 for product forms and conditions.

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

1.05 Heat Treatment

1.051 Stress relief anneal. 900 to 950F, 5 to 10 hours AC, (26)(27)

1.052 Duplex anneal. 1650F, 1 to 2 hours, AC + 930F, 24 hours, AC. (5)(26)(28)
This alloy is used almost exclusively in the duplex annealed condition, claimed to produce optimum mechanical properties (5). The 1650F solution anneal is in the alpha + beta (+compound) field and the 930F stabilization anneal temperature is in the alpha + compound field. Imperial Metal Industries reports (28) that nearly all transformation from beta to alpha occurs during air cooling from the solution temperature (1650F) to approximately 1200F. The 930F treatment only stabilizes the alloy further. This is substantiated by the data of Table 3.0213 which shows only a 7 ksi increase in strength on aging (stabilization annealing). The solution treating temperature of 1650F is not critical (5). A range of 1630 to 1670F should produce identical tensile properties. The same is true of the aging (stabilization anneal) temperature. A range of 910 to 950F should produce identical results for an aging cycle of 24 hours.

1.053 Solution treat and age. 1650F, 1 to 2 hours, OQ or WQ + 930F, 24 hours, AC. (28)(29)
Maximum tensile and creep strength is developed in the solution treated and aged condition (5). As seen from Figure 2.0121, however, relatively rapid cooling from the solution temperature is required to prevent the beta-to-alpha transformation from going to completion. The aging response, therefore, is directly related to the rapidity of the quench.
Table 3.0213 gives the aging response as a function of quench rate. Air cooling produces only limited aging response, and furnace cooled samples do not respond to the aging treatment at all. Water quenching, on the other hand, produces a substantial increase in strength on subsequent aging. The reason for these different responses is apparent in Figure 2.0121 which shows the various cooling rates superimposed on the T-T-T diagram (The "alpha prime transus" shown on the diagram represents a temperature above which alph-beta solution treated material will transform to alpha prime (Martensite) at the M_S temperature on water quenching. Below this temperature the beta is retained on quenching). Table 3.0214 indicates rolled bar oil-quenched from the solution temperature (compared to air cooling) prior to aging is stronger by 19 to 28 ksi depending on the heat treated section size. Additional data (Table 3.0213) show a 32 ksi strengthening due to water quenching from the solution temperature as compared with air cooling for specimens subsequently aged.

1.06 Hardness

1.061 Effect of exposure to elevated temperature on room temperature hardness of bar, Figure 1.061.

1.062 Since hardness is, in general, related to alloy strength characteristics, the variation in strength properties with as-quenched section size provides a useful measure of alloy hardenability. Figure 3.0215 shows the influence of as-quenched section size on the solution treated (water quenched) and aged smooth tensile properties of sections up to 4 inches square. Results from both as-forged sections and sections machined from the largest forged section are presented. As expected, the highest strengths were obtained for the outside location and were nearly constant over the range of sizes investigated. As-forged sections down to 1 inch square exhibit a strength and ductility difference from center to edge. In contrast, a 1 inch square section machined from the 4 inch forging exhibits uniform strength and ductility throughout. The difference between center and edge properties for sections greater than 1 inch square, whether as-forged or machined from the larger forging, increases to as much as 20 ksi as the section size increases to 4 inches square. Results for a small forging water quenched from the solution temperature and subsequently aged (Table 3.0212) agree well with the above bar results (Figure 3.0215) at comparable section sizes.
Table 3.0216 and Figure 3.0322 give the variation in smooth tensile and compressive strengths, respectively, for a heavy ring forging duplex annealed in full section size. As expected, the general strength level is lower than that quoted above for forgings water quenched from the solution temperature prior to aging. However, the tensile properties of the duples annealed forging vary less from center to edge (10 ksi maximum difference in the heaviest section). As shown in Figure 3.0312, this small difference in tensile properties is not exceeded at test temperatures ranging from -110 to +550F and, as shown by the room temperature results of Table 3.02712, is unaltered by 1000 hrs exposure at 550F without load. The heavy section mild-notch (Table 3.02711) and crack-notch (Table 3.03713) tensile properties of the duplex annealed ring forging are uniform throughout. So too are the room temperature ultimate shear strength (Table 3.0352) and room temperature and 550F smooth fatigue strengths (Figure 3.056)

Additional results for duplex annealed hammer-forged (Figure 3.0314) and press-forged (Figure 3.0315) compressor wheels show no greater difference than 10 ksi in tensile strength as a function of forging section size at temperatures ranging from room temperature to 1000F. Where comparisons can be made, exposure to elevated temperature with load does not alter these results, see Tables 3.0217 and 3.0218.

1.07 Forms and Conditions Available
Alloy is commercially available as bar and billet (26)

1.08 Melting and Casting Practice

1.081 Alloy is double consumable electrode vacuum melted.

1.09 Special Considerations

1.091 Silicide segregation. This alloy differs from other alpha-beta alloys in containing 0.21 percent silicon. Investigators in the United States and Great Britain have demonstrated that silicon additions up to 0.5 percent reduce the creep rate of titanium alloys in the range 600 to 1000F (28). However, silicon is benificial only if the melting and processing cycles are controlled to produce a fine uniform dispersion (particle size of one micron or less) of titanium silicide, Ti_5Si_3 (28). Large particles or agglomerations of small particles can result in lower mechanical properties, as shown by the following.
Tensile results (13) from four compressor discs showed low elongations and reductions of area in 7 of 8 tests from the hub area of the wheels. For the seven, elongations ranged from 2.5 to 7.0 percent and reductions of area from 3.9 to 13.0 percent. The eighth specimen showed higher values of ductility, 11.0 percent elongation and 27.8 percent reduction of area. Rim locations of the same discs consistently showed elongations of 13.0 to 15.0 percent and reductions of area of 32.7 to 38.8 percent. Macroscopic examination of the fracture surfaces of the low ductility specimens showed that fractures initiated along bands containing heavy concentrations of silicides. The fact that these segregated areas were apparent only in the center of the parts involved indicates that this condition is probably associated with melting practice.
A later study (14) showed concentrations of heavy, light-etching particles, identified in microprobe analysis as silicides, in the center and mid-radius areas of 6 inch diameter bars. Three tensile blanks were extracted from the mid-radius area of one of the bars, duplex annealed, machined and tested. In contrast to the above results for compressor discs, all three specimens from bar displayed ductilities

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

within the normal range. All fractures, however, originated at segregated bands and in one case fracture took place outside the necked-down area of the specimen. Room temperature low-cycle and high-cycle, axial load fatigue tests have been made of the shaft and hub sections of a 24 inch diameter compressor disc which showed evidence of silicide segregation, but the results were inconclusive (15).

At this writing, no data are available on the possible damaging influence of segregation on the fracture toughness of this alloy. For critical applications where plane strain fracture toughness may be the limiting design consideration, the influence of segregation on this property should be evaluated.

It has been the experience of one forger that segregated areas are limited to the top half and center of affected heats, supporting the conclusion that the problem is probably related to melting practice (15). In this regard, the producer of the alloy points out that eutectoid formers (silicon, copper, iron, etc.) often present a segregation problem until appropriate melting and processing schedules are developed. This, of course, is part of the development of such alloys, and no problems with segregation for the present alloy have been reported by the producer in the past three years (31).

1.092 Stability - General. For certain applications (particularly in commercial aircraft) metallurgical stability is an important design consideration. While no systematic investigations have been made to firmly establish the threshold combinations of stress-time-temperature below which the alloy is metallurgically stable, available data suggest that caution be exercised in the use of this alloy in applications where stability is a requirement.

Alloy stability is usually evaluated by comparing the conventional room temperature tensile properties of specimens with and without prior exposure at stress-time-temperature combinations appropriate to the intended application. Results of this sort for bar and forgings are presented in Figures and Tables 3.0217 through 3.02112. Figure 3.0317 gives the conventional tensile properties of rolled bar exposed without load to elevated temperature and tested at the exposure temperature. The influence of elevated temperature exposure without load on the subsequent room temperature mild-notch and crack-notch tensile properties is reported in Tables 3.02712 and 3.03713, respectively. The effect of prior exposure on room temperature hardness is shown in Figure 1.061. For all stability results reported here, the tested articles were in the duplex annealed condition.

1.093 Stability - 150 hours. 150 hours exposure at temperature-stress combinations ranging from 850F, 65 ksi to 950F, 45 ksi has a small but inconsistent effect on the subsequent room temperature tensile strength and ductility of hammer forged compressor wheels (Table 3.0217). On the other hand, similar press forged wheels exposed 150 hours at 950F, 45 ksi and 1000F, 35 ksi were unchanged in strength but, with only one exception, seriously reduced in ductility (Table 3.0219). For rolled bar, exposure up to 1000F for 10 and 100 hours without load produces no change in room temperature strength and ductility (Figure 3.02112).

1.094 Stability - 300 hours. The room temperature tensile properties of a single compressor wheel forging (Table 3.02110) exposed to temperature-stress combinations of 800F, 75 ksi and 850F, 65 ksi for si for 300 hours were unaffected except for a slightly lower reduction of area value for a single specimen for which 50 - 75 percent of its deformation occured on loading. At 750F, 88 ksi, 300 hours exposure all specimens from this same compressor wheel forging deformed considerably on loading, and low reduction of area fractures were observed in about half of the specimens tested. These low values were associated with what appeared to be stress corrosion cracks. This, of course, is unrelated to metallurgical instability effects.

1.095 Stability - 1000 hours. 1000 hour exposure of hammer forged compressor wheel specimens at 950F, 45 ksi produces very serious losses in tensile ductility with an increase in strength (Table 3.0218). Rolled bar exposed 1000 hours begins to develop an increase in tensile strength with a corresponding loss in reduction of area at 800F (with no load). At 1000F, the gain of strength and loss of ductility for bar is substantial (Figure 3.02112).

The room temperature mild-notch (Table 3.02712) and crack-notch (Table 3.03713) tensile properties of ring forging specimens exposed 1000 hours without load at a moderate temperature (550F) were unaffected by the exposure. Unfortunately these data are scant and one should be aware that a different result might be obtained from cracked specimens exposed at higher temperatures and for longer times.

1.096 Fracture toughness. Alloy is claimed to have relatively poor fracture toughness in sheet form (7, p. 3). No data are available on the fracture toughness of forms other than sheet. For applications where the alloy's fracture toughness may be the limiting design consideration, these data should be developed.

1.097 Stress corrosion. No data are available on the stress corrosion characteristics of this alloy. On the basis of results obtained on other titanium alloys, however, particular attention should be given to the influence of agressive environments in the presence of cracks. Such environments include aqueous chloride solutions and possibly certain organic solvents such as methanol. For some applications, as in jet engines, hot salt stress corrosion characteristics would be necessary design information. The results of Table 3.02110 suggest that stress corrosion cracking in air might warrant consideration.

1.098 Erosion. It has been reported (32) that titanium erodes approximately 40 percent faster than steel in engine-blading applications in jet engines. No data on this relatively unfamiliar characteristic are available at the time of this writing.

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range. Approximately 3100F.

2.012 Phase changes. Beta transus 1730 ± 15F. Alpha prime transus 1600 - 1630F (see 1.053 for definition of alpha prime transus).

2.0121 Time-temperature-transformation diagram, Figure 2.0121.

2.0122 Ti-Si binary phase diagram showing compound formation Ti_5Si_3, Figure 2.0122.

2.013 Thermal conductivity.

2.0131 Thermal conductivity of bar, Figure 2.0131.

2.014 Thermal expansion.

2.0141 Thermal expansion for bar, Figure 2.0141.

2.015 Specific heat.

2.0151 Specific heat for bar, Figure 2.0151.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density. 0.174 lb per cu inch, 4.82 gr per cu cm (26)

2.022 Electrical properties.

2.0221 Electrical resistivity, Figure 2.0221.

2.023 Magnetic properties. Alloy is nonmagnetic.

2.024 Emittance.

2.025 Damping capacity.

2.03 Chemical properties

2.04 Nuclear Properties

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

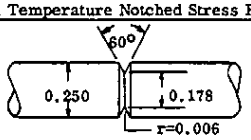
3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 Producer's guaranteed mechanical properties not yet established (29).

3.012 AMS specified mechanical properties, Table 3.012.

TABLE 3.012

Source	AMS (22)							
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si							
Form	Bars and Forgings							
Condition	1650F, 1hr, AC + 930F, 24hrs, AC							
Nominal Diameter or Thickness - Inch	Property Specification							
	Conventional Tensile Properties							
	Room Temperature				800F (1)			
	F_{tu} minimum ksi	F_{ty} minimum ksi	e(2in or 4D) - min percent	RA minimum percent	F_{tu} minimum ksi	F_{ty} minimum ksi	e(2in or 4D) - min percent	RA minimum percent
Bars and Forgings:								
Up to 1.000 Inclusive	145	135	10	20	105	80	15	30
Over 1.000 to 2.000 Inclusive	145	135	10	20	100	80	15	30
Over 2.000 to 3.000 Inclusive (2)	140	130	10	20	95	75	12	25
	Room Temperature Notched Stress Rupture							
Bars under 5 sq. in. cross-sectional area and all forgings @ 165ksi, 5hrs min. (3) Bars 5 sq. in. and over cross-sectional area @ 155ksi, 5hrs min. (3)	 Preferred Specimen (See reference for alternate specimens)							
	1000F Smooth Stress Rupture							
All bars and forgings	@ 70ksi, 23hrs min. life. Test to rupture. RT elong (4D) after rupture shall be ≥ 10 percent (4)							
	Creep Stability							
All forgings	Specimen exposed 100hrs at 800F, 70ksi shall not show more than 0.2 percent creep elongation							

(1) To be held at temperature for thirty minutes before testing.
(2) Over 3.000 inch diameter or distance between parallel sides, tensile properties shall be as agreed upon by purchaser and vendor.
(3) The initial stress may be less than specified and increased to the specified stress in 10 ksi increments at intervals of not less than five hours.
(4) Test stress may exceed 70 ksi, but shall not be changed during test. Time and elongation requirements shall be as specified for 70 ksi applied stress.

Ti	
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

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3.013 Users' specified mechanical properties, Table 3.013.

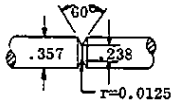
TABLE 3.013

Source	G.E. (25)		G.E. (24)		Pratt and Whitney (21)						Garrett (23)	
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si											
Form	Forged Parts		Compressor Blades and Vanes		Bars < 5 sq in Cross-Sectional Area		Bars ≥ 5 sq in Cross-Sectional Area		Forgings		Bars, Forgings, and Forging Stock	
Condition	1650F, 1hr, AC or OQ+930F,24hrs, AC		1650F, 1hr, AC +930F,24hrs, AC		1650F, 1hr, AC or Faster + 930F, 24hrs, AC						1650F, 1hr, AC + 930F, 24hrs, AC	
Property	Specified Value At :				Specified Value At:						Specified Value At (f):	
	RT	900F	RT	900F	RT	800F(d)	RT	800F(d)	RT	800F(d)	RT	900F
F_{tu} - ksi min.	140	95	140	95	145	105	130	95	145	105	140	95
F_{ty} - ksi min.	130	75	130	75	130	77	120	70	130	77	130	75
e(4D) - % min.	10	10	10	10	10	12	10	12	10	12	10	10
RA - % min.	20	20	20	20	25	30	25	30	25	30	20	20
RT Notch Stress Rupture (See Table 3.012 for Specimen Drawing)	@150ksi, 5hrs min life (a)		@160ksi, 5hrs min life (c)		@165ksi, 5hrs min life (c)		@155ksi, 5hrs min life (c)		@165ksi, 5hrs min life (c)		@160ksi, 5hrs min life (c)	
Smooth Stress Rupture	@60ksi, 950F,35hrs min life (b)		not specified		@ 1000F, 70ksi (e), 23hrs min. life. Test to rupture. RT elong (4D) after rupture shall be ≥ 10 percent						@60ksi, 950F, 35hrs min life (b)	
Creep Stability	Shall meet RT tensile properties above after 100hrs exposure at 900F, 48ksi				not specified						Shall meet RT tensile properties above after 100hrs exposure @ 900F, 48ksi (g)	
Hardness	not specified				Shall not exceed RC-40						not specified	

(a) Initial stress may be less than 150 ksi and increased to 150ksi in 10 ksi increments at intervals of not less than 5 hours. If no failure in 5 hours at 150ksi, stress shall be increased in 10ksi increments at 5 hour intervals until failure or 200ksi, 5 hours, is obtained.
(b) Test to rupture or 70 hours.
(c) Initial stress may be less than specified and increased to specified stress in 10ksi increments at intervals of not less than 5 hours.
(d) Specimens to be held at temperature for 30 minutes before testing.
(e) Test stress may exceed 70ksi, but shall not be changed during test. Time and elongation requirements shall be specified for 70ksi applied stress.
(f) Specimen taken from any location of bars, forgings, and forging stock up to 2 1/4 inch minimum section thickness, and from mid-radius location of sections over 2 1/4 inch minimum thickness.
(g) Not a requirement for acception or rejection of material.

3.014 Users' specified mechanical properties, Table 3.014.

TABLE 3.014

Source	Allison (20)	Allison (30)	
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form	Bars and Forgings		
Condition	1650F, 1hr, AC + 930F, 24hrs, AC	1650F, 1hr, OQ + 930F, 24hrs, AC	
Property	Specified Value at 850F(a)	Specified Value(b)at: RT	840F(a)
F_{tu} - ksi min.	100	161	119
F_{ty} - ksi min.	80	139	80
e(4D) - % min.	12	10	12
RA - % min.	30	20	
Creep Stability	Specimen exposed 100hrs, 750F, 70ksi shall not exceed 0.1% creep strain	Specimen exposed 100hrs, 840F, 56ksi shall not exceed 0.1% creep strain	
Mild-notch tensile		≥1.3 times smooth tensile strength	
 (Preferred specimen, see reference for alternate specimens)			

(a) Specimen to be held at temperature 30 minutes before testing.
(b) For section sizes up to 1 inch in diameter or distance between parallel sides.

3.02 Mechanical Properties at Room Temperature
3.021 Tension (see also 3.031).
3.0211 Effect of solution temperature on solution treated tensile properties of forged bar, Table 3.0211.

TABLE 3.0211

Source	(5, p.5)			
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si			
Form	1 1/8 inch square forging*			
Condition	Solution Treated, 1hr, WQ			
Solution Temp.-F	RT Tensile Properties			
	F_{tu} ksi	F_{ty} ksi	e percent	RA percent
1700	194.6	169.0	6.0	23.7
1675	186.9	168.3	----	----
1650	176.8	151.5	12.0	43.0
1600	176.2	152.0	12.0	41.0
1575	154.8	118.1	19.0	41.8
1550	155.8	104.7	18.0	39.1

*Machined to 1/2 inch round, then solution treated.

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

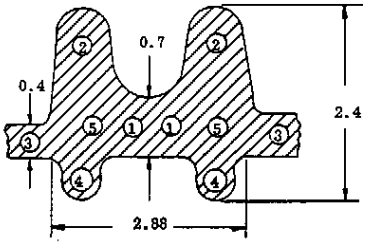
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3.0212 Effect of aging cycle and specimen location on tensile properties of forging, Table 3.0212.

TABLE 3.0212

Source	(5)			
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si			
Form	Forging			
Condition	1650F, 1hr, WQ + age, AC (in full section)			
	Aging Cycles			
	930F, 1hr	930F, 12hrs	930F, 24hrs	1050, 24hrs
F_{tu}, ksi	176.8 (1)	179.6 (1)	178.8 (1)	178.0 (1)
	188.5 (3)	191.9 (3)	192.9 (3)	179.2 (3)
	162.9 (5)	167.8 (5)	173.9 (5)	175.1 (5)
F_{ty}, ksi	154.4 (1)	158.0 (1)	158.0 (1)	161.0 (1)
	165.1 (3)	169.4 (3)	170.9 (3)	156.0 (3)
	139.8 (5)	145.2 (5)	151.7 (5)	154.6 (5)
e, percent	12.0 (1)	12.0 (1)	11.0 (1)	10.0 (1)
	12.0 (3)	11.0 (3)	10.0 (3)	16.0 (3)
	14.0 (5)	18.0 (5)	10.0 (5)	12.0 (5)
RA, percent	41.0 (1)	40.0 (1)	40.0 (1)	33.5 (1)
	45.3 (3)	41.4 (3)	35.3 (3)	42.1 (3)
	48.0 (5)	47.0 (5)	42.0 (5)	32.2 (5)

See drawing below for specimen location



Cross-section of 12 inch long Navajo forging used for quenching studies.

3.0213 Aging response of forged bar quenched at various rates from the solution temperature, Table 3.0213.

TABLE 3.0213

Source	(5, p.13)				
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si				
Form	1 1/8 in Square Forging*				
Quench Rate From 1650F Solution Treatment	Aging Treatment	F_{tu} ksi	F_{ty} ksi	e %	RA %
As Forged		151.2	136.5	14.0	49.9
Furnace Cooled	930F, 24hrs, AC	143.7	132.1	11.0	23.1
Furnace Cooled	None	143.8	133.0	11.0	25.8
Air Cooled	930F, 24hrs, AC	167.3	149.6	17.5	44.4
Air Cooled	None	159.8	142.8	16.0	47.4
Water Quenched	930F, 24hrs, AC	199.6	180.0	10.0	32.9
Water Quenched	None	176.8	151.5	12.0	43.0

*Heat treated in full section size.

3.0214 Effect of quenching rate from the solution temperature on the tensile properties of solution treated and aged bar of various sizes, Table 3.0214.

TABLE 3.0214

Source	(11)							
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si							
Form	Rolled Bar							
Condition	1650F, 1hr min., AC +930F, 24hrs, AC				1650F, 1hr min., OQ+930F, 24hrs, AC			
Heat Treated Section Size (1) Inch	F_{tu} ksi	F_{ty} ksi	e percent	RA percent	F_{tu} ksi	F_{ty} ksi	e percent	RA percent
3(edge)	151.0	-----	21	42	170.0	142.0	18	40
3(center)	150.5	127.5	18	34	169.0	139.0	16	34
2	158.5	131.5	16	31	174.0	145.0	14	32
1 1/2	160.0	135.5	17	29	179.5	147.0	18	33
1	160.0	134.0	17	31	182.0	150.0	14	31
1/2	166.0	147.0	17	30	194.0	163.0	12	29
(1) Originally 3 1/2 inches diameter								

3.0215 Effect of heat treated section size on the tensile properties of forged bar, Figure 3.0215.

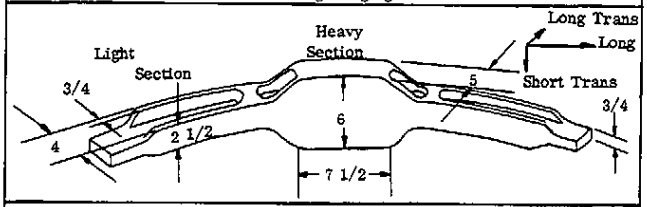
3.0216 Variation in room temperature tensile properties of large ring forgings as a function of specimen location and orientation, Table 3.0216.

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

TABLE 3.0216

Source		(9, pp.53-54 and 58-59)			
Alloy		Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si			
Form		Large Ring Forging			
Condition		1650F, 1hr, fan cool + 930F, 24hrs, AC(1)			
Specimen Location	Specimen Orientation	RT Tensile Properties (2)(3) F_{tu} ksi	F_{ty} ksi	e(1 in) ksi	RA percent
Forging Heavy Section					
Edge	Long	149.7	134.5	13.3	33.7
		(146.5)	(133.2)	(14.7)	(39.7)
Mid-Radius	"	144.8	130.3	14.7	35.0
Center	"	143.3	128.8	14.0	35.0
		(142.0)	(128.0)	(15.7)	(40.3)
Edge	Long Trans	147.0	133.8	13.7	40.3
Mid-Radius	" "	142.5	127.7	13.3	40.3
Center	" "	139.6	124.7	14.0	42.3
		(139.2)	(124.8)	(17.0)	(44.0)
Edge	Short Trans	148.2	133.8	14.0	40.0
		(149.8)	(135.3)	(15.0)	(41.3)
Mid-Radius	" "	144.3	129.8	14.7	41.0
Center	" "	138.4	123.7	13.0	38.3
		(144.2)	(129.3)	(14.0)	(37.7)
Forging Light Section					
Flange	Short Trans	149.6	135.3	16.0	41.0
Ring Forging					



(1) Heat treated in full section size
(2) Each value average of three tests.
(3) Unbracketed values - Forging No. 2
Braketed values - Forging No. 1
Both from same ingot

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

3.0217 Effect of 150 hours exposure to elevated temperature with load on the room temperature tensile properties of hammer forged compressor wheels, Table 3.0217.

TABLE 3.0217

Source	(17, pp. 12, 13, 15, and 16)							
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si							
Form	24in diameter hammer forged compressor wheels							
Condition	1650F, 1hr, AC + 930F, 24hrs, AC							
	Creep Exposure Conditions				Subsequent RT Tensile Properties			
Location - Direction	Temp F	Stress ksi	Time hr	Total Creep percent	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
Hammer Forged Compressor Wheel "A" (See Fig. 3.0314)								
Web - Tang	Unexposed				152.8	137.1	15.0	34.2
Web - Tang	850	65	165	0.160	145.7	133.0	15.0	36.0
Web - Tang	900	55	166	0.210	148.2	136.6	11.0	38.6
Rim - Tang	Unexposed				149.8	135.0	13.8	33.9
Rim - Tang	850	65	150	0.144	166.1	151.0	14.0	36.2
Rim - Tang	900	55	150	0.164	157.2	142.0	12.0	22.6
Rim - Tang	950	45	166	0.185	153.5	140.3	11.0	26.5
Web-Radial	Unexposed				144.6	125.6	14.0	37.0
Web-Radial	950	45	150	0.240	156.4	140.6	14.0	32.3
Hammer Forged Compressor Wheel "B" (See Fig. 3.0314)								
Web - Tang	Unexposed				155.1	138.2	12.5	32.3
Web - Tang	900	55	150	0.164	157.2	142.0	12.0	22.6
Rim - Tang	Unexposed				159.8	145.6	13.0	33.1
Rim - Tang	850	65	150	0.144	166.1	151.0	14.0	36.2
Web-Radial	Unexposed				154.0	139.1	13.8	41.7
Web-Radial	950	45	150	0.240	156.4	140.0	14.0	32.3
Both wheels from same heat. 0.250 inch diameter specimens.								

3.0218 Effect of 1000 hours exposure to elevated temperature with load on the room temperature tensile properties of hammer forged compressor wheels, Table 3.0218.

TABLE 3.0218

Source	(17, pp. 12, 13, 15, 16)							
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si							
Form	24in diameter hammer forged compressor wheels							
Condition	1650F, 1hr, AC+930F, 24hrs, AC							
	Creep Exposure Conditions				Subsequent RT Tensile Properties			
Location - Direction	Temp F	Stress ksi	Time hr	Total Creep percent	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
Hammer Forged Compressor Wheel "A" (See Fig. 3.0314)								
Rim - Tangential	Unexposed				149.8	135.0	13.8	33.9
Rim - Tangential	850	65	1000	0.408	156.0	145.3	14.0	28.9
Rim - Tangential	900	55	1000	0.364	156.8	142.1	15.0	28.9
Web - Radial	Unexposed				144.6	125.6	14.0	37.0
Web - Radial	950	45	1000	1.668	149.2	135.5	6.0	8.7
0.250 inch diameter specimens								

3.0219 Effect of 150 hours exposure to elevated temperature with load on the room temperature tensile properties of press-forged compressor wheels, Table 3.0219

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

TABLE 3.0219

Source	(17, pp.18,19,21,and 22)							
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si							
Form	22in diameter press forged compressor wheels							
Condition	1650F, 1hr, AC + 930F, 24hrs, AC							
Location - Direction	Creep Exposure Conditions				Subsequent RT Tensile Properties			
	Temp F	Stress ksi	Time hr	Total Creep - %	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
Press Forged Compressor Wheel "A" (See Fig. 3.0315)								
Coupling-Axial		Unexposed			148.5	133.5	13.0	34.8
Coupling-Axial	900	55	150	0.256	150.3	137.2	14.0	31.0
Coupling-Axial	950	45	150	0.679	149.4	133.3	12.0	17.7
Coupling-Tang		Unexposed			152.0	138.8	15.0	35.1
Coupling-Tang	1000	35	150	0.880	147.4	135.4	7.0	13.2
Rim-Tangential		Unexposed			154.0	139.0	14.5	32.7
Rim-Tangential	850	65	150	0.152	152.9	141.0	13.0	29.5
Rim-Tangential	900	55	150	0.196	154.2	141.0	12.0	25.4
Rim-Tangential	950	45	150	0.264	154.4	141.0	10.0	19.8
Press Forged Compressor Wheel "B" (See Fig. 3.0315)								
Coupling-Axial		Unexposed			150.5	133.1	14.0	38.8
Coupling-Axial	900	55	150	0.212	149.0	134.7	14.0	36.2
Coupling-Axial	950	45	150	0.372	151.5	137.6	9.0	13.9
Coupling-Tang		Unexposed			153.8	138.0	15.0	40.8
Coupling-Tang	1000	35	150	0.340	151.5	139.6	5.0	9.4
Rim-Tangential		Unexposed			155.8	139.9	14.5	37.3
Rim-Tangential	850	65	150	0.128	156.4	142.5	12.0	29.5
Rim-Tangential	900	55	150	0.156	154.2	140.0	13.0	27.5
Rim-Tangential	950	45	150	0.160	155.0	140.5	14.0	28.8
Wheels from different heats. 0.250 inch diameter specimens.								

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

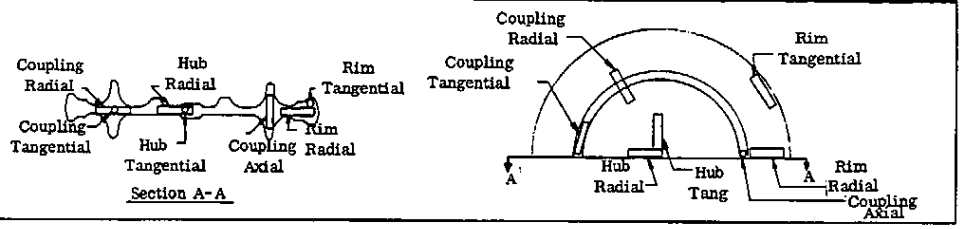
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3.02110 Effect of 300 hours exposure to elevated temperature with load on room temperature tensile properties of compressor wheel forgings, Table 3.02110.

TABLE 3.02110

Source		(12)						
Alloy		Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si						
Form		24 1/2 inch diameter compressor wheel forging						
Condition		1650F, 1hr, AC + 930F, 24hrs, AC						
		300 hr Exposure At:			Subsequent RT Tensile Properties *			
Location	Direction	Temp F	Stress ksi	Deformation %	F_{ty} ksi	F_{tu} ksi	e(1 in) percent	RA percent
Rim	Tangential	750	88	.419**	145.0	149.0	11.1	24.6***
Rim	Radial	750	88	.476**	142.5	145.0	16.3	36.0
Coupling	Tangential	750	88	.330**	142.3	145.8	12.9	10.9***
Coupling	Radial	750	88	.385**	140.0	141.0	13.2	29.4
Coupling	Axial	750	88	.500**	139.5	140.6	12.3	29.4
Hub	Tangential	750	88	.333**	141.3	145.0	13.0	18.8***
Hub	Radial	750	88	.374**	140.0	143.8	17.0	36.0
Rim	Tangential	800	75	.195	140.5	148.0	15.9	39.2
Rim	Tangential	800	75	.178	142.0	150.5	17.0	36.0
Rim	Tangential	850	65	.154	139.0	149.0	17.1	39.2
Rim	Radial	850	65	.192	136.0	144.0	18.9	42.3
Coupling	Tangential	850	65	.161	136.0	145.2	18.5	36.0
Coupling	Radial	850	65	.283	132.0	141.0	15.6	36.0
Coupling	Axial	850	65	.191	129.0	137.3	11.4	22.7
Hub	Tangential	850	65	.227	137.0	148.5	12.2	18.8***
Hub	Radial	850	65	.235	134.0	145.0	17.6	36.0
Rim	Tangential		None		135.6	150.2	14.5	40.1
Rim	Radial		None		133.6	150.4	14.0	42.5
Coupling	Tangential		None		137.6	154.8	14.5	43.7
Coupling	Radial		None		130.0	147.8	11.5	30.5
Coupling	Axial		None		134.4	151.4	14.5	41.4
Hub	Tangential		None		136.0	152.2	15.0	40.1
Hub	Radial		None		132.4	148.6	13.5	38.8

*Tests made after creep exposure without surface conditioning.
**Approximately 50 to 75 percent of plastic deformation occurred on loading.
***Fracture originated at what is thought to be stress corrosion crack.

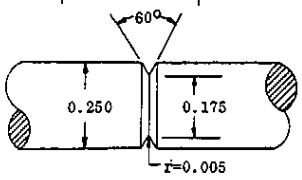


3.02111 Effect of 0.1 percent creep prestrain on the room temperature tensile properties of forgings, Figure 3.02111.
3.02112 Effect of exposure to elevated temperature on room temperature tensile properties of bar, Figure 3.02112.
3.02113 Typical room temperature tension stress-strain curve for large ring forging, Figure 3.02113.
3.022 Compression (see also 3.032).
3.0221 Stress-strain diagram (see also 3.0321).
3.023 Impact (see also 3.033).
3.024 Bending.
3.025 Torsion and shear (see also 3.035).
3.026 Bearing (see also 3.036).
3.027 Stress concentration (see also 3.037).
3.0271 Notch properties (see also 3.0371).

3.02711 Room temperature mild notch strength of large ring forging, Table 3.02711.

TABLE 3.02711

Source	(9, pp.58-59 and 63)		
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form	Large Ring Forging		
Condition	1650F, 1hr, Fan Cool + 930F,24hrs,AC(1)		
Specimen Location	Specimen Orientation	F_{ty}(3) ksi	Mild Notch Strength(4) - ksi
Forging Heavy Section Properties (2)			
Edge	Long	134	208
Center	Long	129	205
Edge	Long Trans	134	207
Mid-Radius	Long Trans	128	203
Edge	Short Trans	134	204
Mid-Radius	Short Trans	130	201



K_t = 3.9

(1) Heat treated in full section size.
(2) See Table 3.0216 for forging configuration and size.
(3) Each value average of three tests.
(4) Each value average of two tests.

3.02712 Effect of exposure to elevated temperature on room temperature smooth and mild-notch tensile properties of large forging, Table 3.02712.

TABLE 3.02712

Source			(9, pp. 53,63, and 90-91)				
Alloy			Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si				
Form			Large Ring Forging				
Condition			1650F, 1hr, Fan Cool + 930F, 24hrs, AC(1)				
Exposure Time/ Temp	Specimen Location	Specimen Orientation	Subsequent RT Properties				
			F_{tu} ksi	F_{ty} ksi	e(1in) percent	RA percent	Mid-Notch(2) Strength- ksi
Forging Heavy Section Properties (3) (4)							
None	Center	Long	142	128	15.7	40.3	
1000hrs/550F	Center	Long	142	129	13.0	39.0	
None	Edge	Long	146	133	14.7	39.7	207
1000hrs/550F	Edge	Long	150	137	15.0	35.5	203

(1) Heat treated in full section size.
(2) See Table 3.02711 for specimen drawing.
(3) See Table 3.0216 for forging configuration and size.
(4) Each value average of two tests.

3.0272 Fracture toughness.
3.028 Combined properties.

3.03 Mechanical Properties at Various Temperatures
3.031 Tension.
3.0311 Effect of test temperature on tensile properties of bar, Figure 3.0311.
3.0312 Variation in large ring forging heavy section tensile properties as a function of specimen location, orientation, and test temperature, Figure 3.0312.
3.0313 Variation in large ring forging light section tensile properties as a function of specimen location, orientation, and test temperature, Figure 3.0313.
3.0314 Effect of test temperature on tensile properties of hammer forged compressor wheels, Figure 3.0314.
3.0315 Effect of test temperature on tensile properties of press forged compressor wheels, Figure 3.0315.
3.0316 Effect of test temperature on tensile properties of forgings, Figure 3.0316.
3.0317 Effect of exposure to elevated temperature on tensile properties of bar at the exposure temperature, Figure 3.0317.
3.032 Compression (see also 3.022).
3.0321 Effect of test temperature on compressive yield strength of bar, Figure 3.0321.
3.0322 Effect of test temperature on compressive yield strength of large ring forgings, Figure 3.0322.
3.0323 Typical compressive stress-strain curves for large ring forging at room temperature and 550F, Figure 3.0323.
3.033 Impact.
3.0331 Effect of test temperature on standard Charpy-V impact energy for bar, Figure 3.0331.
3.034 Bending.
3.035 Torsion and shear.
3.0351 Effect of test temperature on ultimate shear strength of bar, Figure 3.0351.

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

3.0352 Ultimate shear strength of large ring forging at room temperature and 550F, Table 3.0352.

TABLE 3.0352

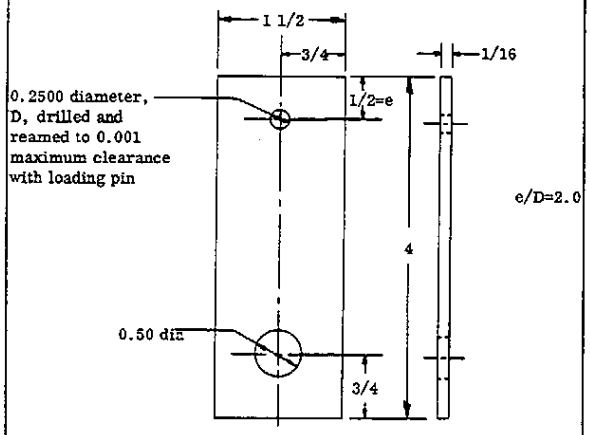
Source	(9, p.74)		
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form	Large Ring Forging		
Condition	1650F, 1hr, Fan Cool+930F, 24hrs, AC(1)		
Specimen Location (2)	Specimen Orientation (2)	Test Temp-F	F_{su} (3) ksi
Edge or Center	Long	RT	100.9
Edge or Center	Long	550	71.2

(1) Heat treated in full section size.
(2) Specimens 1.000 inch long by 0.250 inch in diameter taken from forging heavy section (see Table 3.0216 for forging configuration and size).
(3) Each value average of duplicate tests.

3.036 Bearing.
3.0361 Bearing strength of large ring forging at room temperature and 550F, Table 3.0361.

TABLE 3.0361

Source		(9, p.75)		
Alloy		Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form		Large Ring Forging		
Condition		1650F, 1hr, Fan Cool+930F, 24hrs, AC(1)		
Specimen Location	Specimen Orientation	Test Temp F	F_{bry}(3) ksi	F_{bru}(3) ksi
Web(2)	Long(2)	RT	231.4	305.8
Flange	Long	550	176.7	231.0



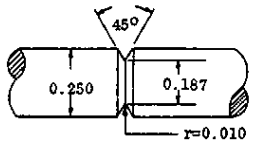
(1) Heat treated in full section size (see table 3.0216 for forging configuration and size).
(2) See Fig. 3.0313 for detail of forging light section.
(3) Each value average of duplicate tests.

3.037 Stress concentration (see also 3.027).
3.0371 Notch properties (see also 3.0271).

3.03711 Effect of test temperature on mild-notch strength of bar, Table 3.03711.

TABLE 3.03711

Source	(7, pp. 293 and 297)		
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form	1/2x1 1/8 inch rolled bar		
Condition	1650F, 2hrs, AC + 930F, 24hrs, AC		



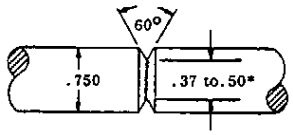
	Test Temperature - F		
	70	400	800
F_{ty}* - ksi	138.6	100.3	83.1
NTS** -ksi	218.7	175.6	164.8

*Each value average of ten tests.
**Each value average of duplicate tests.

3.03712 Effect of test temperature on mild-notch strength of forging, Figure 3.03712.
3.03713 Smooth and crack-notch tensile properties of large ring forging as a function of specimen location and test temperature in both unexposed and exposed (1000 hours, 550F) conditions, Table 3.03713.

TABLE 3.03713

Source		(9, pp.53-54 and 79)		
Alloy		Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form		Large Ring Forging		
Condition		1650F, 1hr, Fan Cool+930F, 24hrs, AC(1)		
Specimen Location	Specimen Orientation	Heavy Section Properties(2) Test Temp F	F_{ty} ksi	Crack Notch Strength-ksi
Unexposed				
Edge	Short Trans	-110	158	88
Center	Short Trans	-110	---	93
Edge	Short Trans	RT	135	103
Center	Short Trans	RT	129	104
Exposed				
Edge	Short Trans	RT	135	107
Center	Short Trans	RT	129	109



Pre-cracked Round Bar
*Starter notch net dia 0.6in; net dia reduced from 0.6in to value shown by fatigue cracking

(1) Heat treated in full section size.
(2) See Table 3.0216 for forging configuration and size.
(3) Specimens exposed 1000 hrs at 550F (unstressed) and tested without surface treatment.

3.0372 Fracture toughness.
3.038 Combined properties.

3.04 Creep and Creep Rupture Properties

3.041 Creep deformation curves for bar at 800F, Figure 3.041.

3.042 Creep deformation curves for bar at 900F, Figure 3.042.

3.043 Creep deformation curves for bar at 1000F, Figure 3.043.

3.044 Minimum creep rate curves for bar at 800, 900 and 1000F, Figure 3.044.

3.045 0.1 percent creep curves for forgings, Figure 3.045.

3.046 Time to 0.1 percent and 0.2 percent creep deformation for compressor wheel forging, Table 3.046.

TABLE 3.046

Source		(12)		
Alloy		Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form		24 1/2in dia Compressor Wheel Forging		
Condition		1650F, 1hr, AC + 930F, 24hrs, AC		
Location*	Direction	Creep Exposure	Time to 0.1% Creep hrs	Time to 0.2% Creep hrs
Rim	Tangential	750F - 88 ksi	125	---
Rim	Radial	"	183	---
Coupling	Tangential	"	70	---
Coupling	Radial	"	380**	---
Coupling	Axial	"	65	380**
Hub	Tangential	"	195	---
Hub	Radial	"	140	---
Rim	Tangential	800F - 75 ksi	35	292
Rim	Tangential	"	50	385**
Rim	Tangential	850F - 65 ksi	50	---
Rim	Radial	"	15	345**
Coupling	Tangential	"	62	---
Coupling	Radial	"	6	62
Coupling	Axial	"	44	335**
Hub	Tangential	"	12	155
Hub	Radial	"	16	148

*See Table 3.02110 for specimen locations within wheel forging
**Extrapolated

3.047 300 hours creep deformation for compressor wheel forging, Table 3.047

TABLE 3.047

Source		(12)		
Alloy		Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form		24 1/2in dia Compressor Wheel Forging		
Condition		1650F, 1hr, AC + 930F, 24hrs, AC		
Location*	Direction	Plastic Deformation on Loading--Percent	300hrs Creep Deformation--Percent	Total 300hrs Plastic Deformation--Percent
		750F - 88 ksi		
Rim	Tangential	0.279	0.140	0.419
Rim	Radial	0.348	0.128	0.476
Coupling	Tangential	0.174	0.156	0.330
Coupling	Radial	0.304	0.081	0.385
Coupling	Axial	0.322	0.178	0.500
Hub	Tangential	0.210	0.123	0.333
Hub	Radial	0.241	0.133	0.374
		800F - 75 ksi		
Rim	Tangential	0.000	0.195	0.195
Rim	Tangential	0.000	0.178	0.178
		850F - 65 ksi		
Rim	Tangential	0.000	0.154	0.154
Rim	Radial	0.000	0.192	0.192
Coupling	Tangential	0.000	0.161	0.161
Coupling	Radial	0.000	0.283	0.283
Coupling	Axial	0.000	0.191	0.191
Hub	Tangential	0.000	0.227	0.227
Hub	Radial	0.000	0.235	0.235

* See Table 3.02110 for specimen location within wheel forging

3.048 Master creep curves for compressor wheel forgings, Figure 3.048.

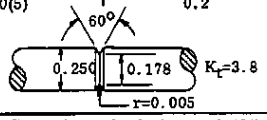
3.049 Room temperature mild-notch creep rupture properties of compressor wheel forgings, Table 3.049

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

TABLE 3.049

Source	(17, pp.14,16,19, and 22)	
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si	
Form	Compressor Wheel Forgings	
Condition	1650F, 1hr, AC + 930F, 24hrs, AC	
	RT Mild-Notch Creep Rupture Properties	
Location - Direction	Stress at Failure ksi	Time to Failure hrs
Hammer Forged Compressor Wheel "A" (1)		
Web-Radial	190(2)	5.1
Web-Radial	190(2)	4.8
Web-Tangential	190(2)	0.4
Web-Tangential	190(2)	0.4
Hammer Forged Compressor Wheel "B" (1)		
Rim-Axial	180(3)	5.3
Rim-Axial	200(3)	0.2
Rim-Tangential	210(3)	0.2
Web-Radial	200(3)	1.6
Press Forged Compressor Wheel "A" (4)		
Rim-Radial	190(5)	3.8
Rim-Radial	190(5)	0.6
Coupling-Tangential	190(5)	4.9
Coupling-Tangential	190(5)	4.6
Press Forged Compressor Wheel "B" (4)		
Rim-Radial	190(5)	0.3
Rim-Radial	190(5)	0.1
Coupling-Tangential	180(5)	5.2
Coupling-Tangential	190(5)	0.2



(1) See Fig. 3.0314 for wheel configuration; wheels "A" and "B" from same heat.
(2) Stress increased from 150 ksi in 10 ksi increments approximately every 5 hrs.
(3) Stress increased from 170 ksi in 10 ksi increments approximately every 5 hrs.
(4) See Fig. 3.0315 for wheel configuration; wheels "A" and "B" from different heats.
(5) Stress increased from 180 ksi in 10 ksi increments approximately every 5 hrs.

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

3.0410 Creep rupture properties of compressor wheel forging at 800 and 900F, Table 3.0410.

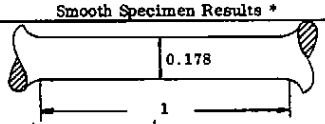
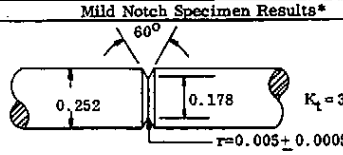
TABLE 3.0410

Source	(12)		
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form	24 1/2in dia Compressor Wheel Forging		
Condition	1650F, 1hr, AC + 930F, 24hrs, AC		
	Creep Exposure		Time to
Location - Direction*	Stress ksi	Temp F	Rupture hrs
Rim-Tangential	85	800	1171.8
Rim-Tangential	90	800	1001.0
Rim-Tangential	110	800	0.1
Rim-Tangential	95	900	73.8
Rim-Radial	80	900	1670.6
Rim-Radial	95	900	226.9
Rim-Radial	100	900	137.0
Rim-Radial	100	900	195.0
Coupling-Axial	100	800	1491.0**
Coupling-Axial	105	800	743.0**
Coupling-Axial	110	800	0.8
Coupling-Axial	90	900	191.7

* See Table 3.02110 for specimen locations within wheel forging.
** Test still in progress.

3.0411 Smooth and mild-notch creep rupture properties of forging at various temperatures, Table 3.0411.

TABLE 3.0411

Source		(16)		
Alloy		Ti-11Sn-5Ar-2.25Al-1Mo-0.21Si		
Form		15 in diameter x 1.3 in thick Hammer Forging***		
Condition		1650F, 1 hr, AC + 930F, 24 hrs, AC		
Temp F	Stress ksi	Test Duration hrs	e(1 in) percent	RA percent
Smooth Specimen Results *				
				
750	108	332.6	No Rupture - Test Discontinued	
750	85	550.1	No Rupture - Test Discontinued	
850	100	184.5	No Rupture - Test Discontinued	
850	80	407.5	No Rupture - Test Discontinued	
950	90	183.7	No Rupture - Test Discontinued	
950	75	321.6	17.7	38.0
Mild Notch Specimen Results*				
				
70	150	5.0	No Rupture - Stress Raised 10ksi**	
	160	17.1	No Rupture - Stress Raised 10ksi	
	170	5.0	No Rupture - Stress Raised 10ksi	
	180	19.2	No Rupture - Stress Raised 10ksi	
	190	5.5	No Rupture - Stress Raised 10ksi	
	200	17.5	No Rupture - Stress Raised 10ksi	
	210	0.2	Rupture	

*Specimens from edge location, tangential direction.
**Stress increased from 150ksi in 10ksi increments if no failure in times shown; notch rupture data all from a single specimen.
***Forging "A", Fig. 3.0316.

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

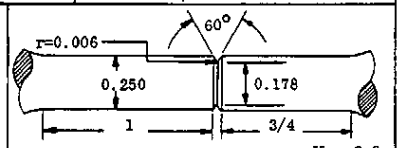
Ti-679

3.0412 Creep rupture properties of hammer forged and press forged compressor wheels at various temperatures using a combination specimen, Table 3.0412.

TABLE 3.0412

Source			(17, pp.13,15,18,and 21)		
Alloy			Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form			Compressor Wheel Forgings		
Condition			1650F, 1hr, AC + 930F, 24hrs, AC		
Stress Rupture Properties					
Temp F	Stress ksi	Specimen Location - Direction	Time to Rupture hrs	e(1 in) percent	Location of Failure
Hammer Forged Compressor Wheel "A"*					
950	80.0	Web-Radial	236.9	21.6	Smooth Section
1000	65.0	Web-Radial	190.0	29.6	Smooth Section
Hammer Forged Compressor Wheel "B"*					
950	80.0	Web-Radial	198.8	22.6	Smooth Section
1000	65.0	Web-Radial	107.5	27.9	Smooth Section
Press Forged Compressor Wheel "A"**					
950	60.0	Rim-Tangential	726.8	23.9	Smooth Section
950	60.0	Rim-Radial	879.1	22.6	Smooth Section
950	80.0	Rim-Tangential	152.7	21.3	Smooth Section
950	80.0	Rim-Radial	33.8	14.6	Smooth Section
1000	65.0	Rim-Tangential	123.5	27.9	Smooth Section
		Rim-Radial	89.2	----	Notched Section
Press Forged Compressor Wheel "B"**					
950	60.0	Rim-Tangential	1468.0	17.3	Smooth Section
950	60.0	Rim-Radial	1631.5	29.9	Smooth Section
950	80.0	Rim-Tangential	215.2	19.9	Smooth Section
950	80.0	Rim-Radial	198.6	25.3	Smooth Section
1000	65.0	Rim-Tangential	154.4	17.3	Smooth Section
1000	65.0	Rim-Radial	151.1	27.9	Smooth Section

*See Fig. 3.0314 for wheel configuration. Wheels "A" and "B" from same heat.
**See Fig. 3.0315 for wheel configuration. Wheels "A" and "B" from different heats.



Combination - Bar Specimen

3.05 Fatigue Properties

3.051 Axial load smooth and mild-notch fatigue properties for bar at 70F, Figure 3.051.

3.052 Axial load smooth and mild-notch fatigue properties for bar at 400F, Figure 3.052.

3.053 Axial load smooth and mild-notch fatigue properties for bar at 800F, Figure 3.053.

3.054 Constant-life fatigue diagram for bar at several temperatures (smooth specimens), Figure 3.054.

3.055 Constant-life fatigue diagram for bar at several temperatures (mild-notch specimens), Figure 3.055.

3.056 Axial tension smooth and mild-notch fatigue properties of large ring forging at room temperature and 550F, Figure 3.056.

3.057 Mild-notch fatigue strength of forgings at 70 and 800F, Figure 3.057.

3.06 Elastic Properties

3.061 Static tensile modulus of elasticity at room and elevated temperatures for bar, Figure 3.061.

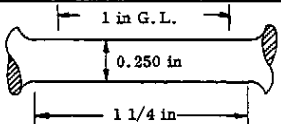
3.062 Dynamic modulus of elasticity at room and elevated temperatures for bar, Figure 3.062.

3.063 Static compressive modulus of elasticity at room and elevated temperatures for bar, Figure 3.063

3.064 Comparison of precision and conventional room temperature static tensile moduli of elasticity for bar, Table 3.064.

TABLE 3.064

Source		(18, p.15)			
Alloy		Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si			
Form		2 1/4 in dia Rolled Bar			
Condition		1650F, 1hr, AC + 930F, 24hrs, AC			
E(1) (Precision) 10^3 ksi	E(2) (Conventional) 10^3 ksi	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
15.6	15.4	145.5	130.0	23.0	48.1
15.8	15.4	149.5	134.0	21.0	45.1



(1) Tuckerman strain measuring system used, measurement sensitive to 2 x 10^{-6} inch per inch.
(2) Conventional Riehle extensometer used.

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

3.065 Precision static tensile and compressive room temperature moduli of elasticity for large ring forging, Table 3.065.

TABLE 3.065

Source	(9, pp. 93-94)		
Alloy	Ti-11Sn-5Zr-2.25Al-1Mo-0.21Si		
Form	Large Ring Forging (1)		
Condition	1650F, 1hr, Fan Cool+930F, 24hrs, AC(2)		
Test Direction	Specimen Location	Specimen Orientation	Precision Static Elastic Modulus (3) 1000 ksi
Tension	Edge	Long	E=15.7
Tension	Edge	Long Trans	E=16.1
Compression	Edge	Long	E_c=16.1
Compression	Edge	Long Trans	E_c=16.5

(1) Specimens extracted from heavy section of forging. See Table 3.0216 for forging configuration and size.
(2) Heat treated in full section size.
(3) Tuckerman Optical Strain measuring system used. Each value average of three tests on same specimen.

4. FABRICATION

4.01 Formability

4.011 Forging

To develop the best combination of mechanical properties, this alloy is forged at 1650F. During final forging, the entire piece must be worked below 1730F, the beta transus temperature. Large amounts of forging work (by reductions of 8:1 or 9:1 in upsetting, for instance) produce 135-140 ksi yield strength for the duplex annealed condition (28).

The forgeability of this alloy is good, being, in terms of cracking resistance, about the same as Ti-8Al-1Mo-1V but not as good Ti-6Al-4V or Ti-6Al-6V-2Sn (10, p. 14).

The forgeability of an alloy is not only concerned with the amount of plastic deformation it can withstand without cracking but also the energy needed to deform the material and the allowable forging temperature range. This alloy is compared with other titanium alloys with respect to these variables in Table 4.0111.

4.0111 Forging characteristics of Ti-679 and other titanium alloys, Table 4.0111.

TABLE 4.0111

Source			(10, p. 14)			
Alloy	Type	Alpha Transus ± 25° F	Beta Transus ± 25° F	Die Forging Range, F	Required Pressure[a] 1000psi	Resistance to Cracking
Commercially Pure	Alpha	1660	1760	1550-1700	65-75	
Ti-5Al-2.5Sn	Alpha	1735	1900	1775-1850	75-85	Good
Ti-8Al-1Mo-1V	Alpha-Beta	1700	1900	1775-1850	75-85	Fair-Good
Ti-5Al-5Sn-5Zr	Alpha	1715	1815	1700-1800	75-85	Poor-Fair
Ti-7Al-12Zr	Alpha	1710	1825	1700-1800	75-85	Fair
IMI-679	Alpha-Beta	----	1750	1650-1725	75-85	Fair-Good
Ti-6Al-4V	Alpha-Beta	----	1820	1650-1800	75-85	Good-Excellent
Ti-6Al-4V-ELI	Alpha-Beta	----	1820	1650-1800	75-85	Good-Excellent
Ti-6Al-6V-2Sn	Alpha-Beta	----	1735	1575-1675	65-75	Excellent
Ti-7Al-4Mo	Alpha-Beta	----	1840	1680-1825	75-85	Good
Ti-4Al-4Mn	Alpha-Beta	----	1700	1500-1650	65-75	Good
Ti-13V-11Cr-3Al	Beta	----	1325	1600-1800	85-100	Excellent

[a] For forging in hydraulic press; approximately 50 percent more energy should be added to these figures for hammer forgings as titanium alloys are strain rate sensitive.

4.02 Machining and Grinding

Machining this alloy is somewhat difficult due to its high rate of work hardening (16). Machining is accomplished with the same general techniques and degree of difficulty as other titanium alloys (16).

4.03 Welding

4.05 Heat Treatment

4.05 Surface Treatment

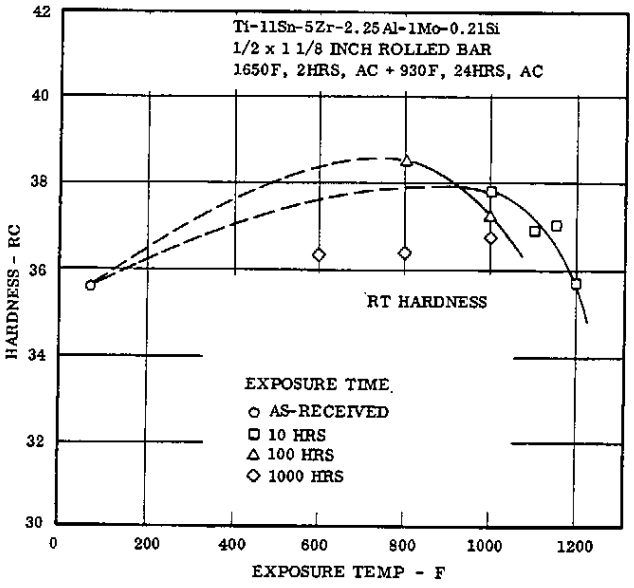


FIG. 1.061 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ROOM TEMPERATURE HARDNESS OF BAR. (7, p. 302)

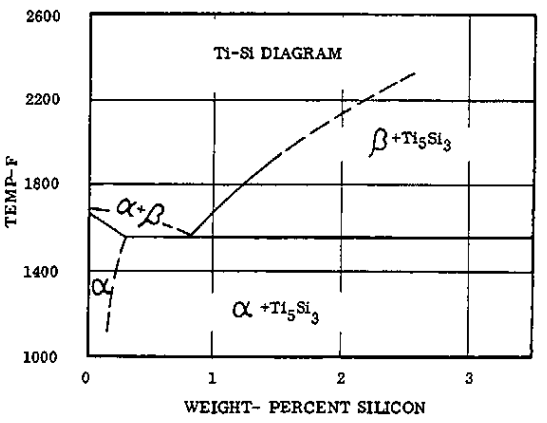


FIG. 2.0122 Ti-Si BINARY PHASE DIAGRAM SHOWING COMPOUND FORMATION Ti_5Si_3 (5, p.8)

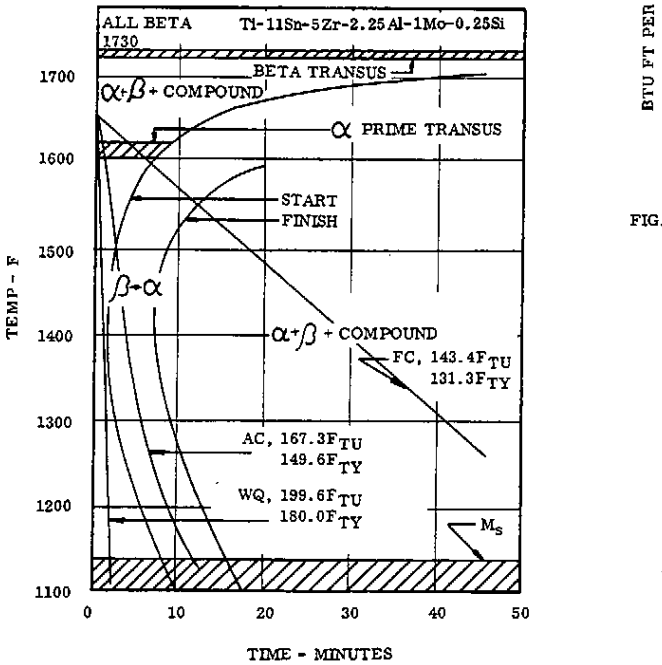


FIG. 2.0121 TIME-TEMPERATURE-TRANSFORMATION DIAGRAM (STRENGTH VALUES SHOWN ARE IN UNITS OF KSI AND ARE FOR SPECIMENS SOLUTION TREATED AS SHOWN AND AGED 930F, 24 HRS, AC) (5, p. 13)

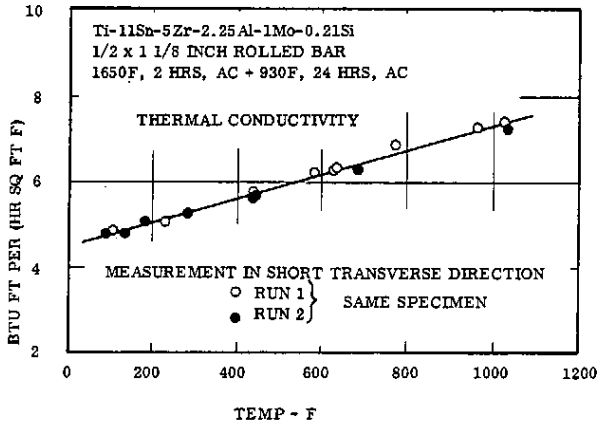


FIG. 2.0131 THERMAL CONDUCTIVITY OF BAR (7, p. 321)

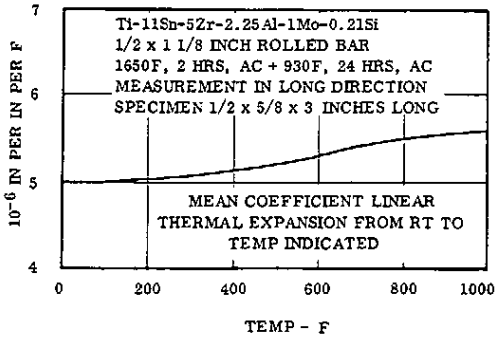


FIG. 2.0141 THERMAL EXPANSION FOR BAR (7, p.329)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

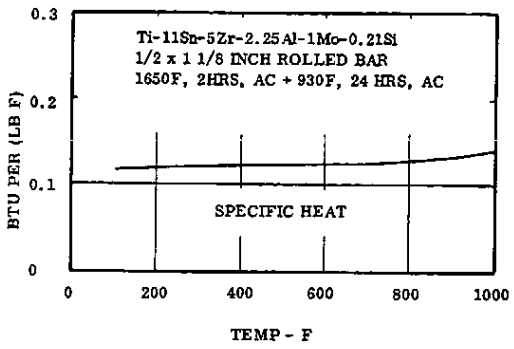


FIG. 2.0151 SPECIFIC HEAT FOR BAR (7, p.218)

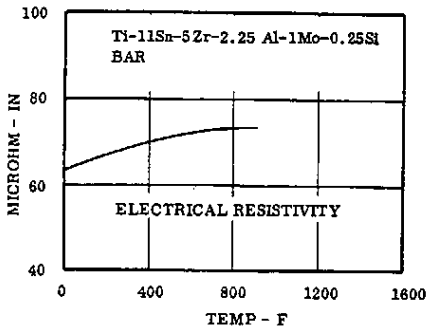


FIG. 2.0221 ELECTRICAL RESISTIVITY (4, p.2)(5, p.4)

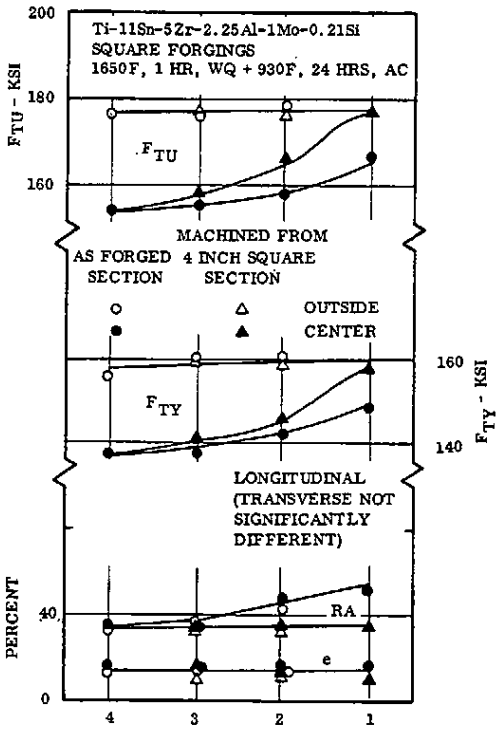


FIG. 3.0215 EFFECT OF HEAT TREATED SECTION SIZE ON THE TENSILE PROPERTIES OF FORGED BAR (8)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

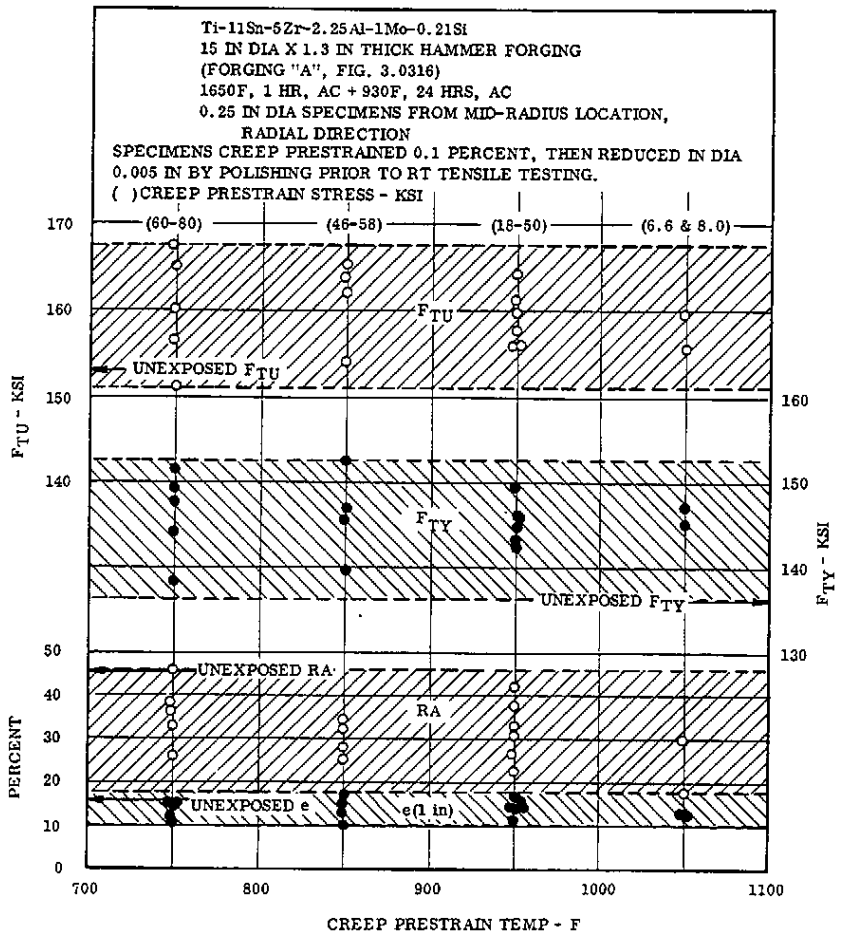


FIG. 3.02111 EFFECT OF 0.1 PERCENT CREEP PRESTRAIN ON ROOM TEMPERATURE TENSILE PROPERTIES OF FORGING (16)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

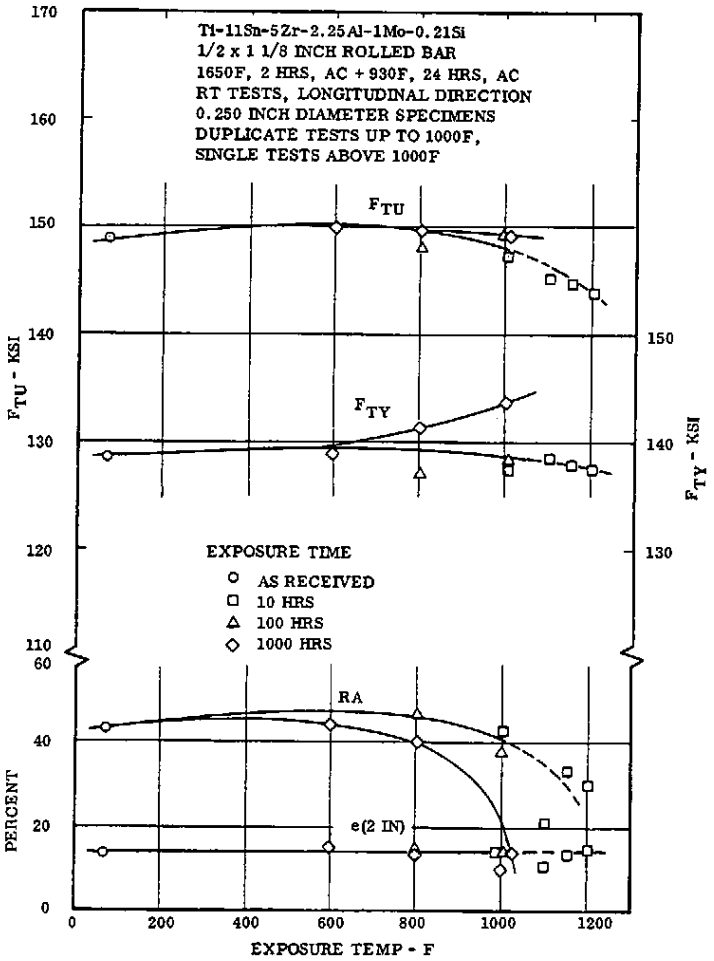


FIG. 3.02112 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF BAR (7, pp. 305-306)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

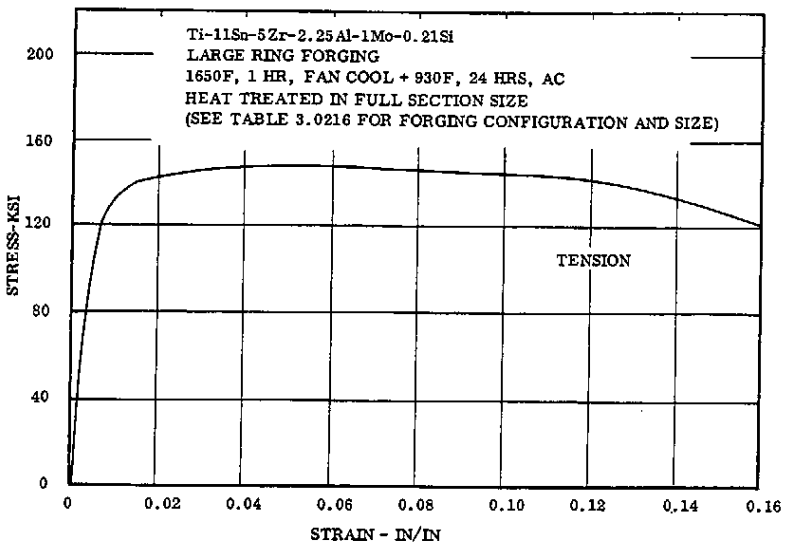


FIG. 3.02113 TYPICAL ROOM TEMPERATURE TENSION STRESS - STRAIN CURVE FOR LARGE RING FORGING (9, p. 45)

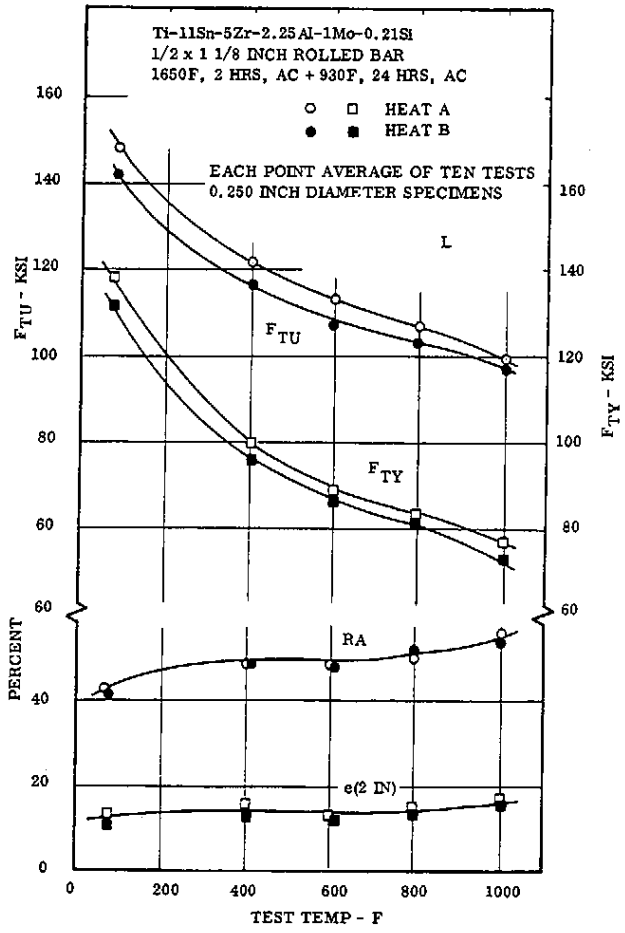


FIG. 3.0311 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF BAR (7, pp. 293-296)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

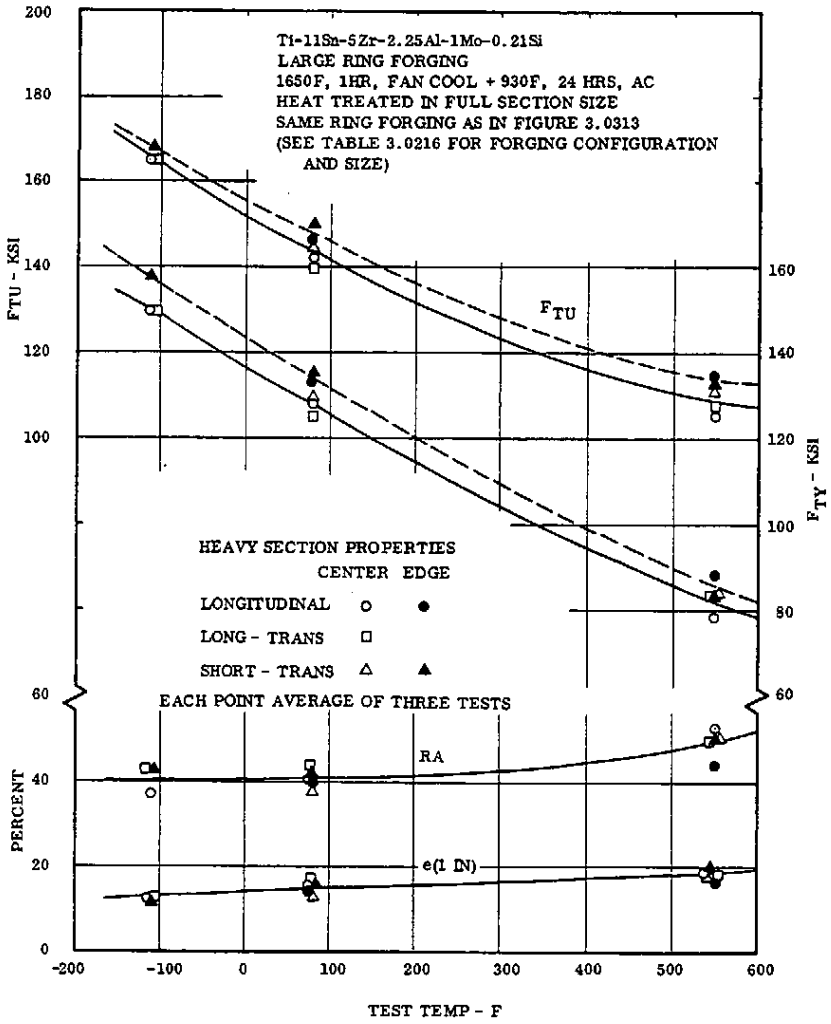


FIG. 3.0312 VARIATION IN LARGE RING FORGING HEAVY-SECTION TENSILE PROPERTIES AS A FUNCTION OF SPECIMEN LOCATION, ORIENTATION, AND TEST TEMPERATURE (9, pp.53-55)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

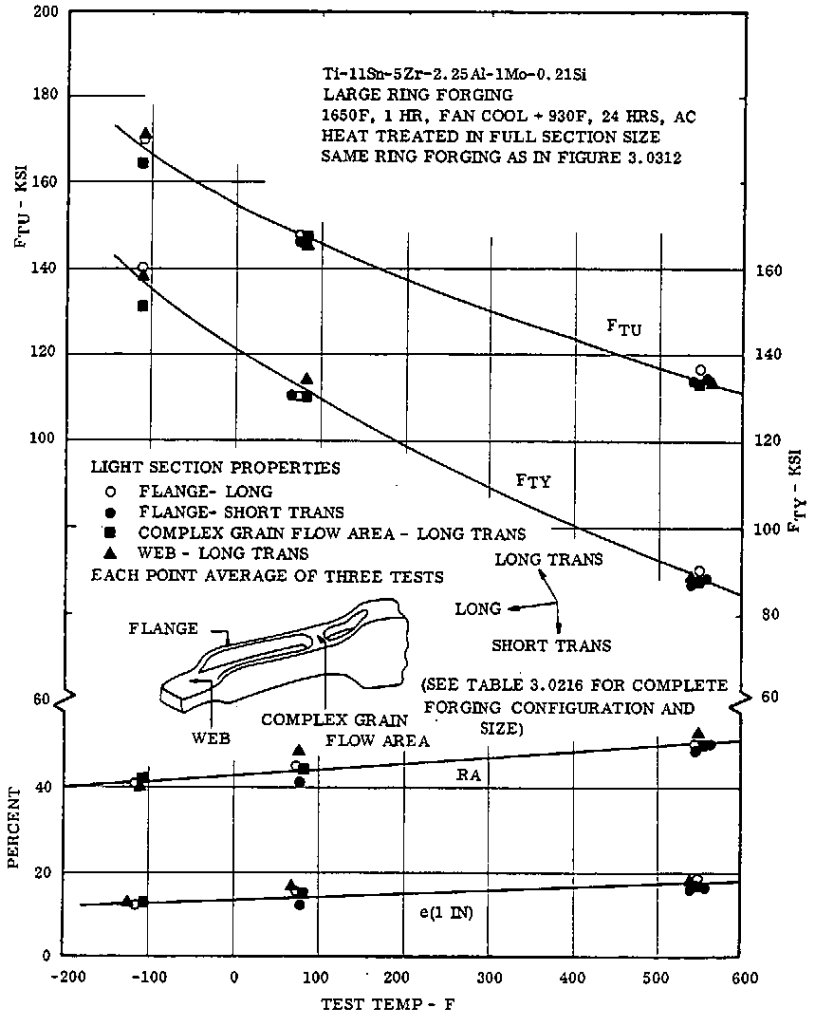


FIG. 3.0313 VARIATION IN LARGE RING FORGING LIGHT-SECTION TENSILE PROPERTIES AS A FUNCTION OF SPECIMEN LOCATION, ORIENTATION, AND TEST TEMPERATURE (9. pp. 56-57)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

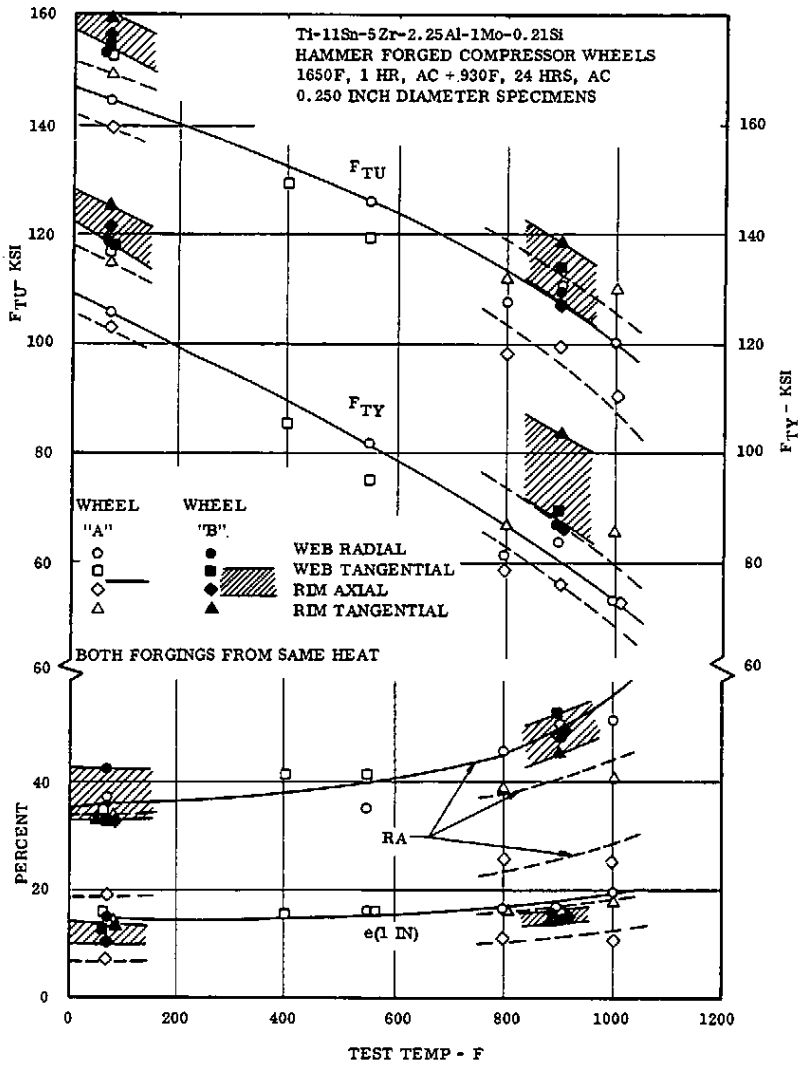
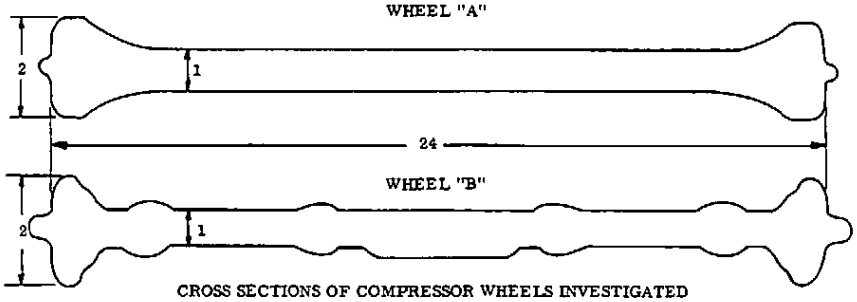


FIG. 3.0314 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF HAMMER FORGED COMPRESSOR WHEELS (17, pp.12 and 15)



CROSS SECTIONS OF COMPRESSOR WHEELS INVESTIGATED

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

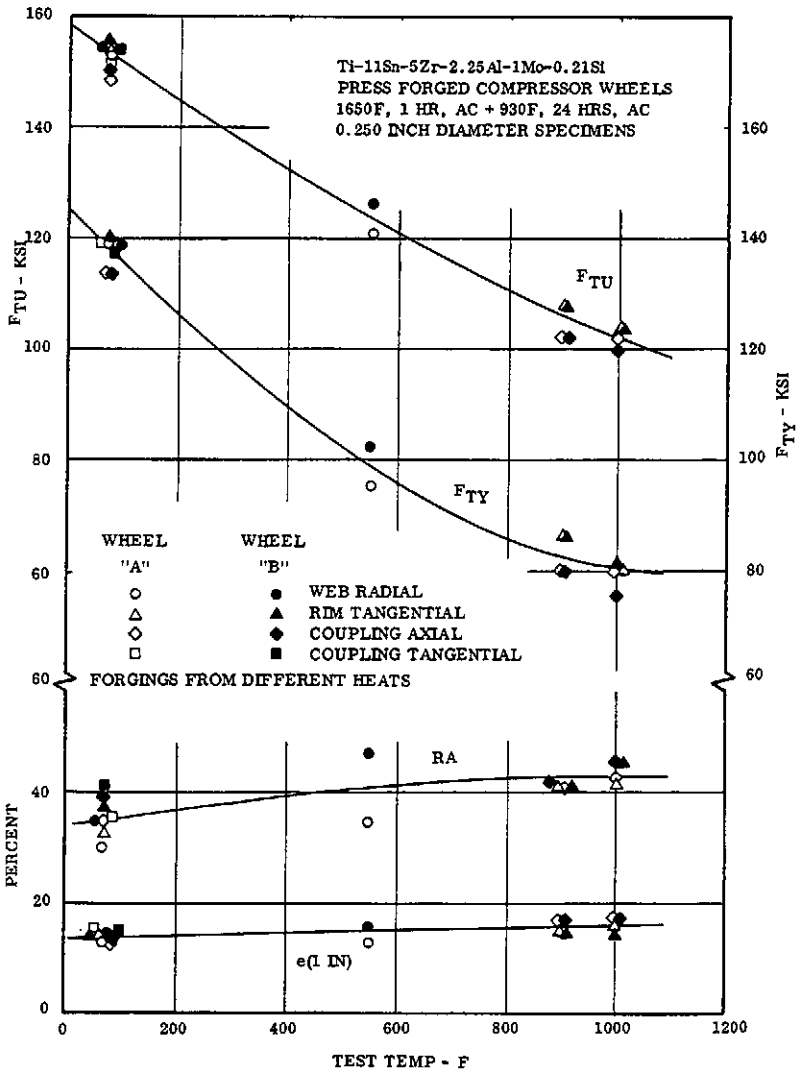
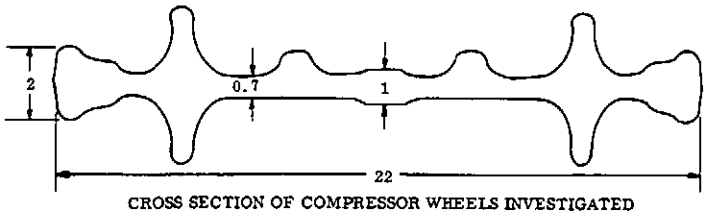


FIG. 3.0315 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF PRESS FORGED COMPRESSOR WHEELS. (17, pp. 18 and 21)



CROSS SECTION OF COMPRESSOR WHEELS INVESTIGATED

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

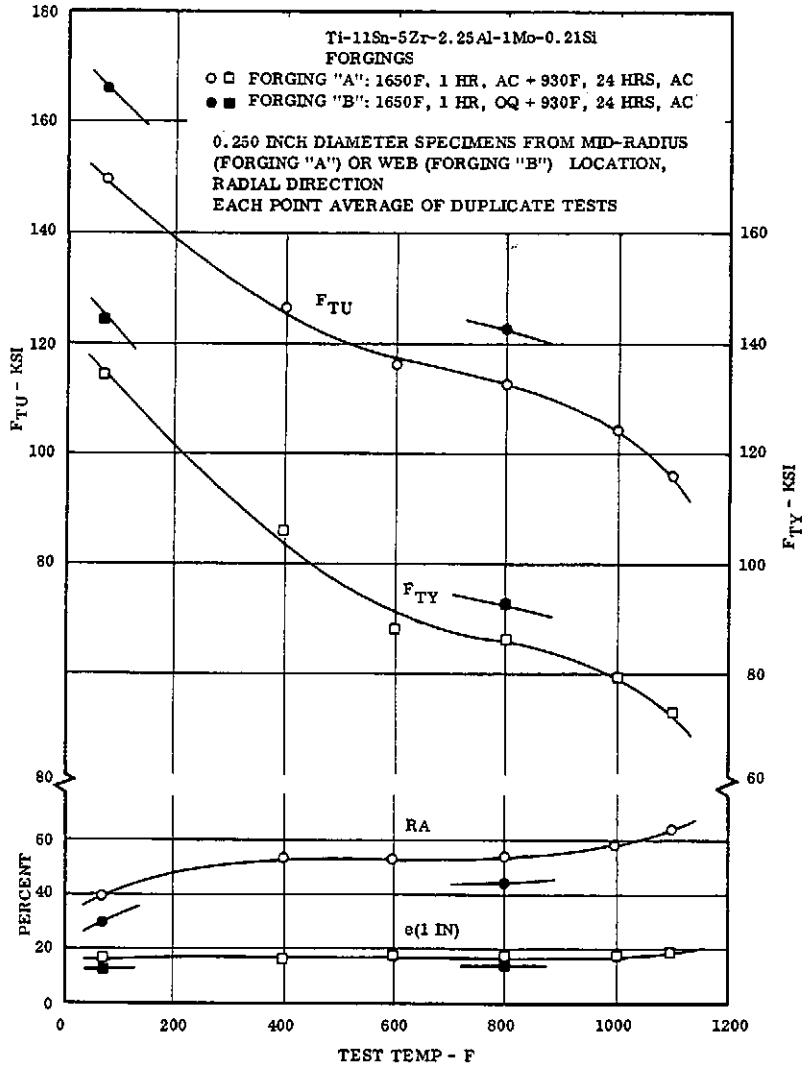
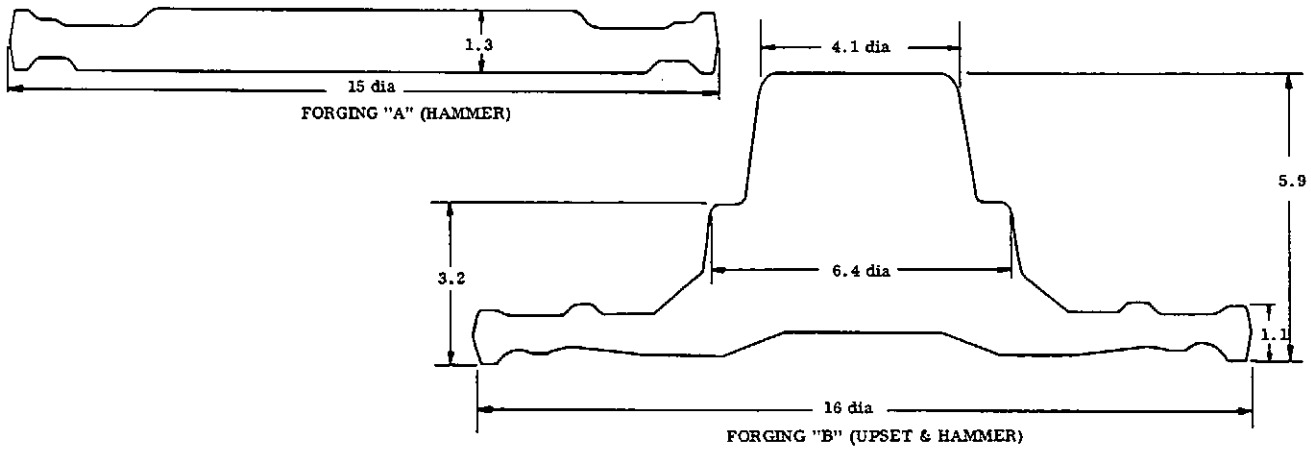


FIG. 3.0316 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF FORGINGS (16)



	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

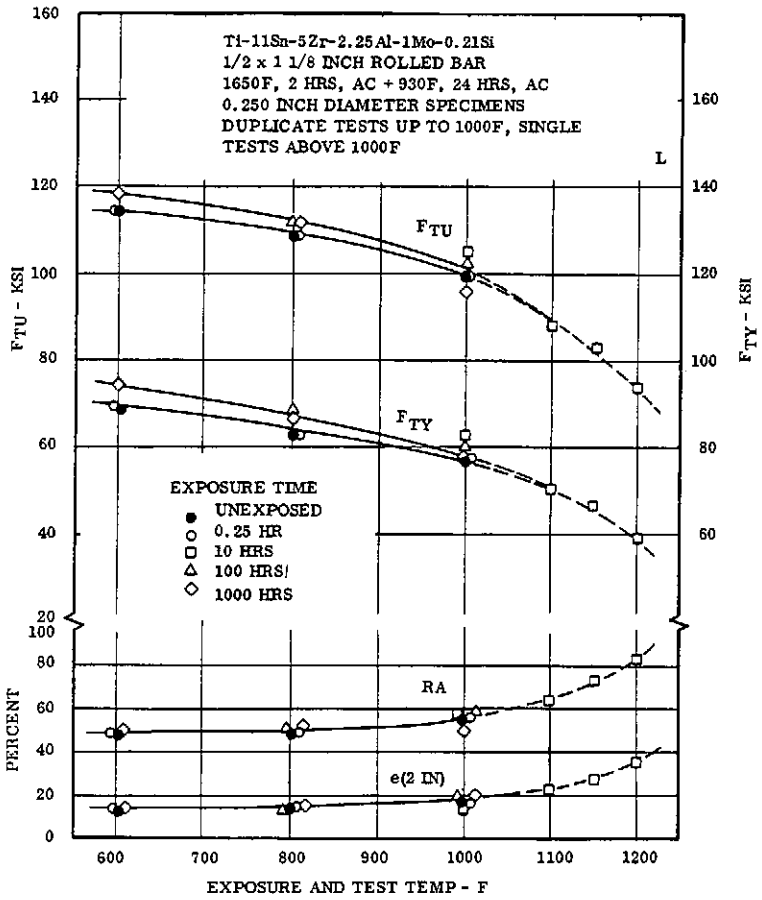


FIG. 3.0317 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF BAR AT THE EXPOSURE TEMPERATURE. (7, pp. 146 and 305-306)

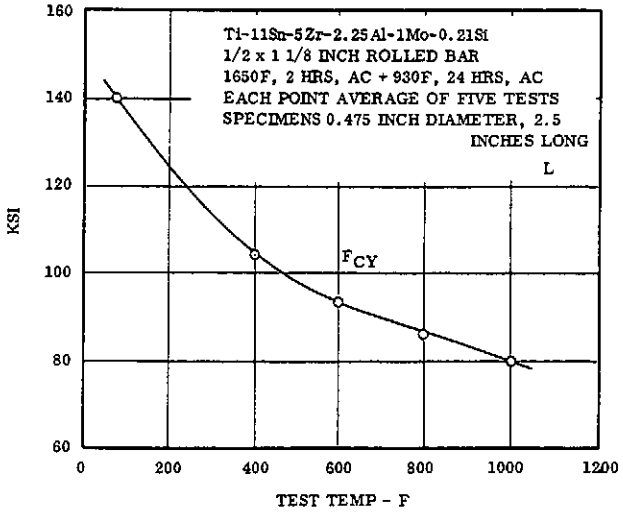


FIG. 3.0321 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF BAR. (7, p. 299)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

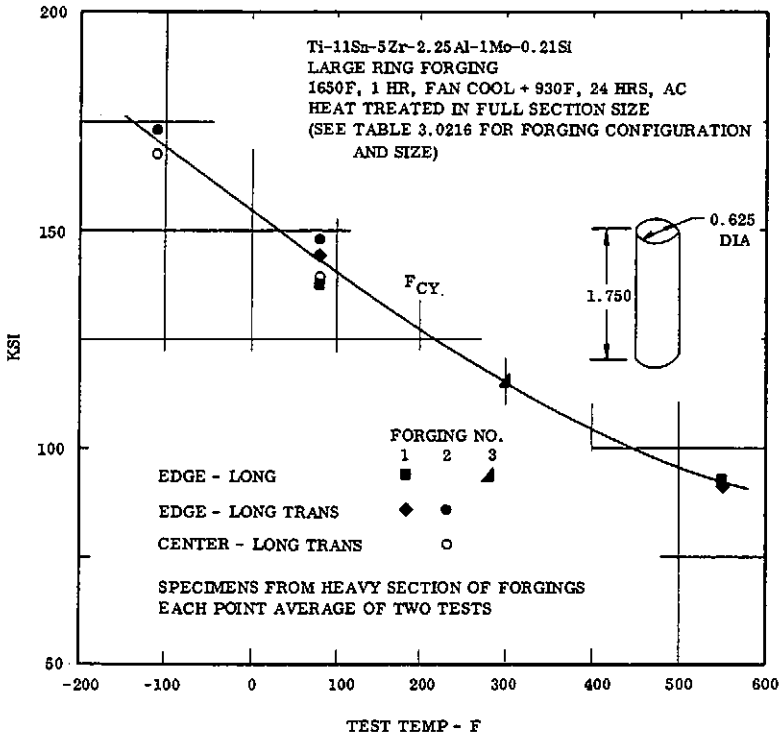


FIG. 3.0322 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF LARGE RING FORGINGS (9, pp.71-72)

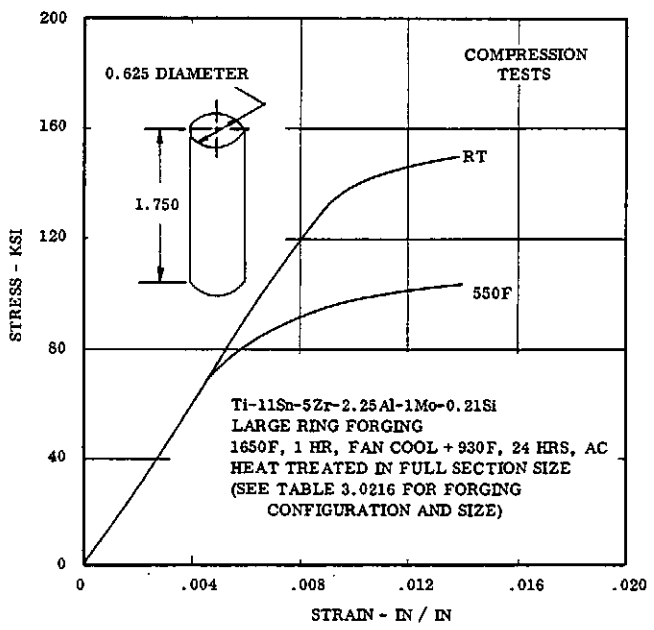


FIG. 3.0323 TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR LARGE RING FORGING AT ROOM TEMPERATURE AND 550F (9, pp.67-68)

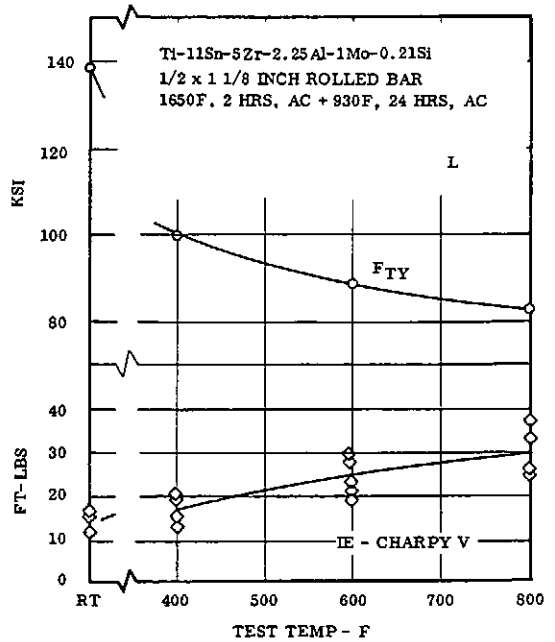
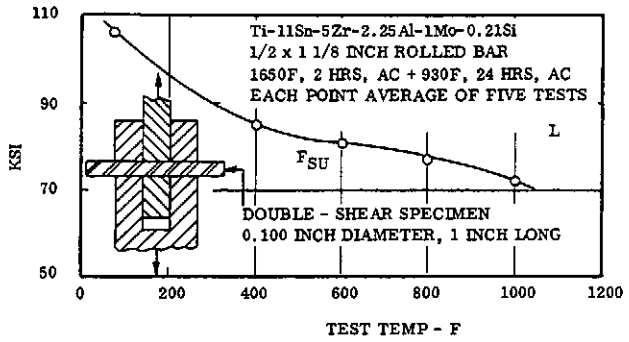


FIG. 3.0331 EFFECT OF TEST TEMPERATURE ON STANDARD CHARPY V IMPACT ENERGY FOR BAR (7, pp. 146 and 309)



	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

FIG. 3.0351 EFFECT OF TEST TEMPERATURE ON ULTIMATE SHEAR STRENGTH OF BAR (7, p.301)

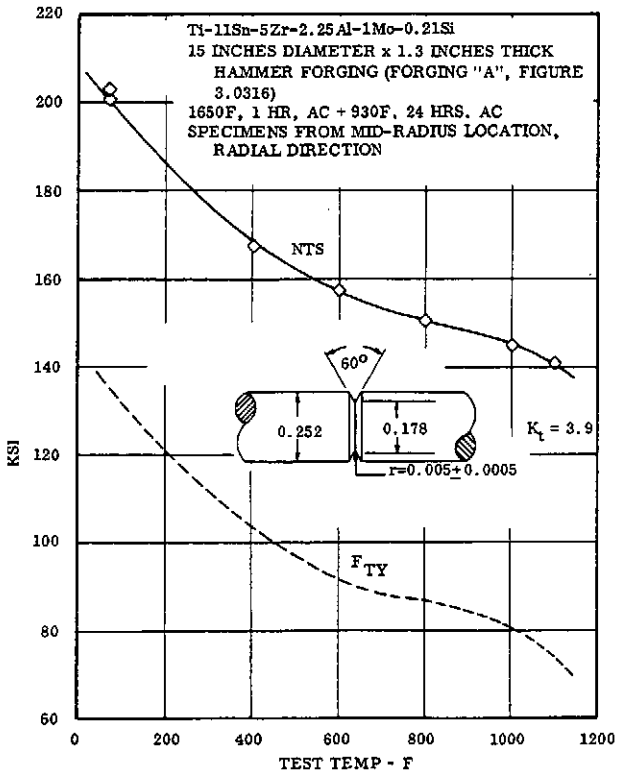


FIG. 3.03712 EFFECT OF TEST TEMPERATURE ON MILD-NOTCH STRENGTH OF FORGING (16)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

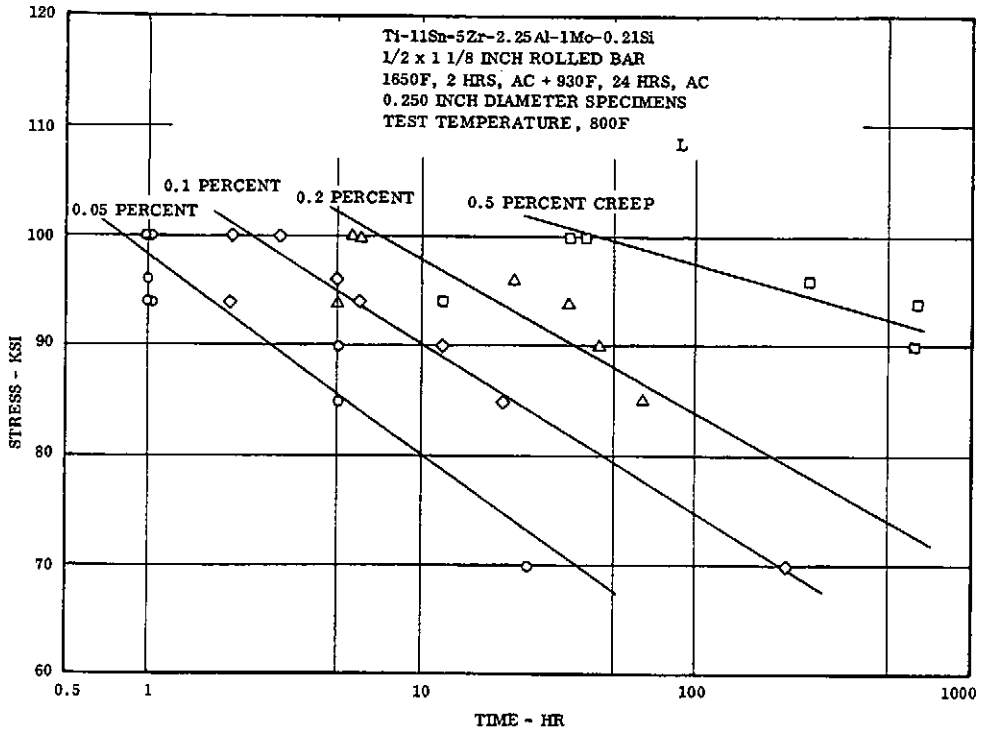


FIG. 3.041 CREEP DEFORMATION CURVES FOR BAR AT 800F (7, p. 308)

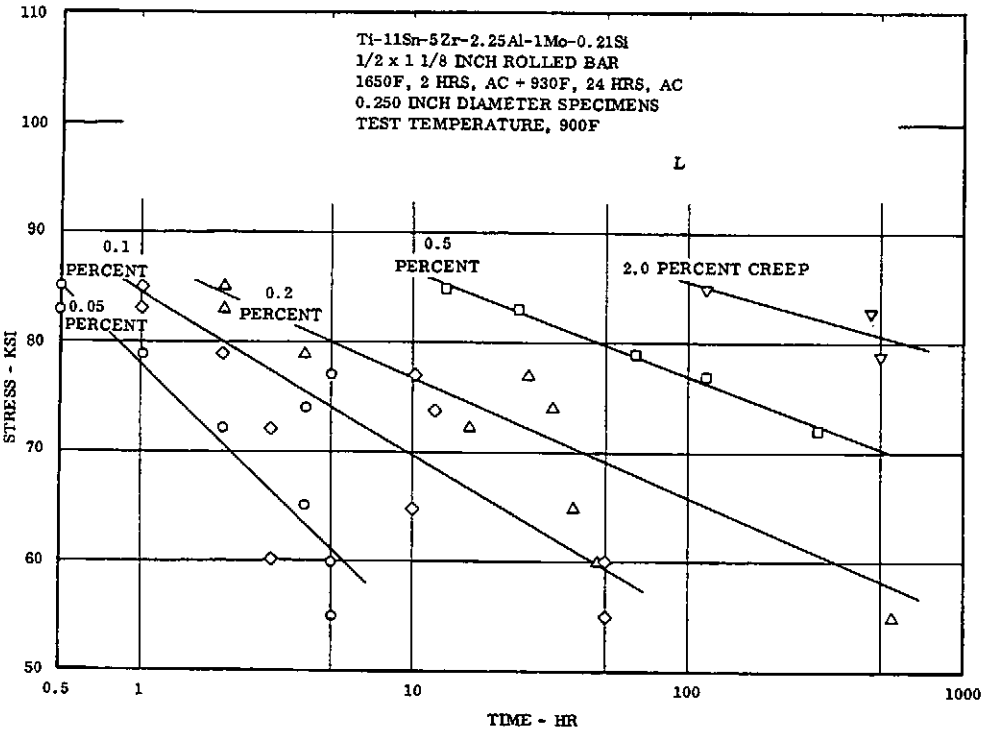


FIG. 3.042 CREEP DEFORMATION CURVES FOR BAR AT 900F (7, p. 308)

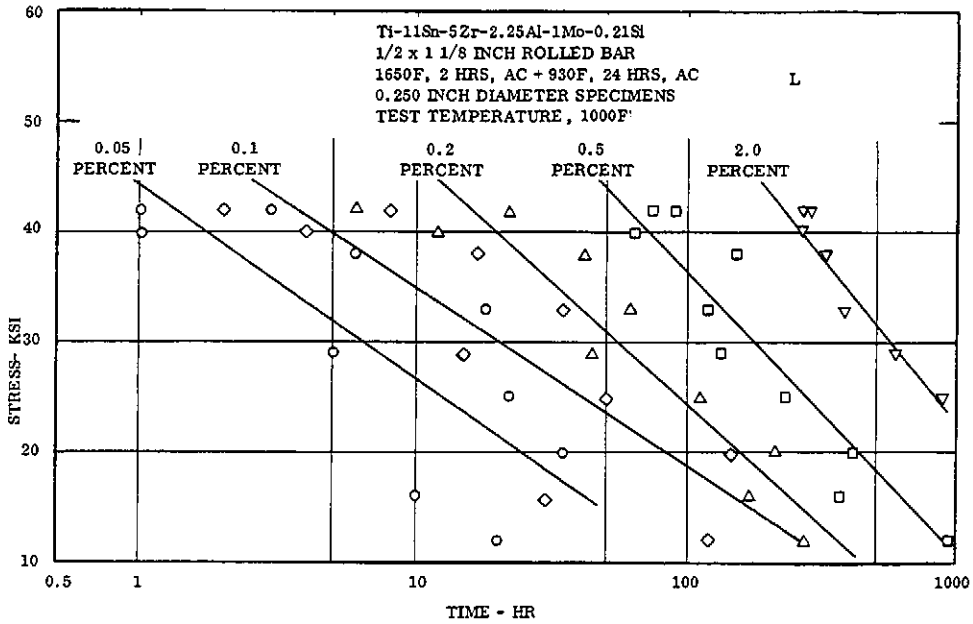


FIG. 3.043 CREEP DEFORMATION CURVES FOR BAR AT 1000F (7, p.308)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

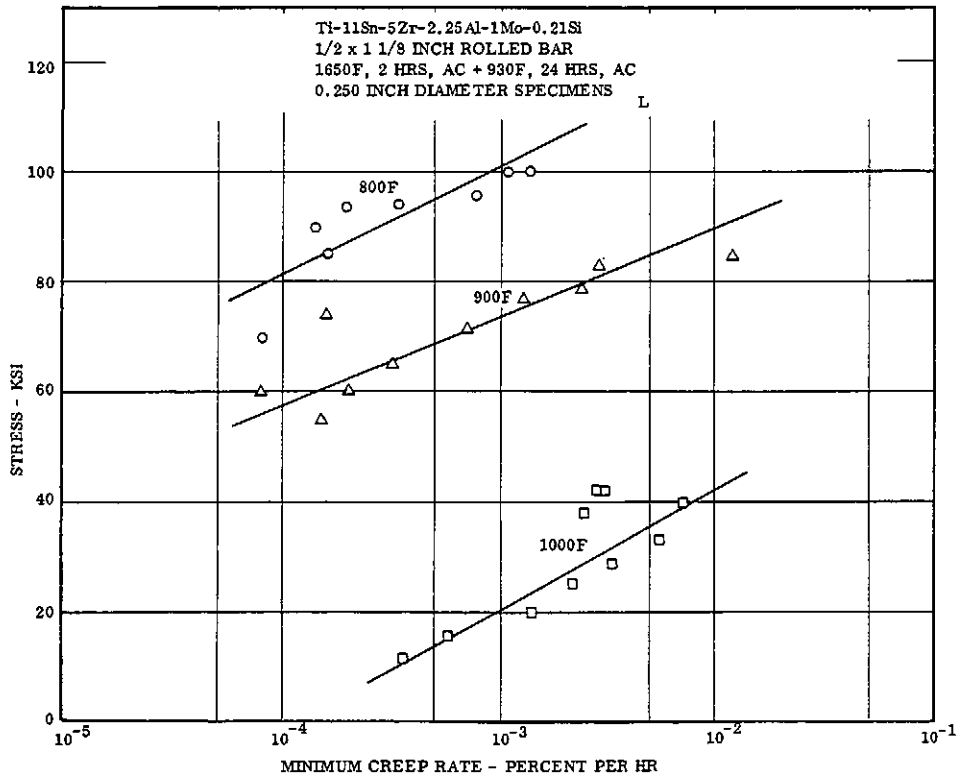


FIG. 3.044 MINIMUM CREEP RATE CURVES FOR BAR AT 800, 900, AND 1000F (7, p.308)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

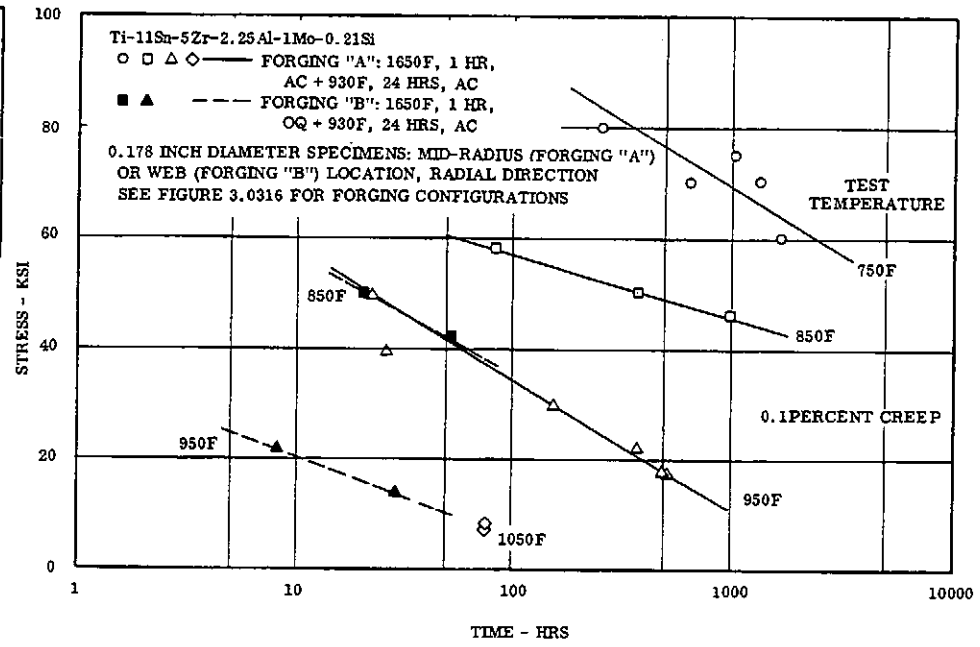


FIG. 3.045 0.1 PERCENT CREEP CURVES FOR FORGINGS (16)

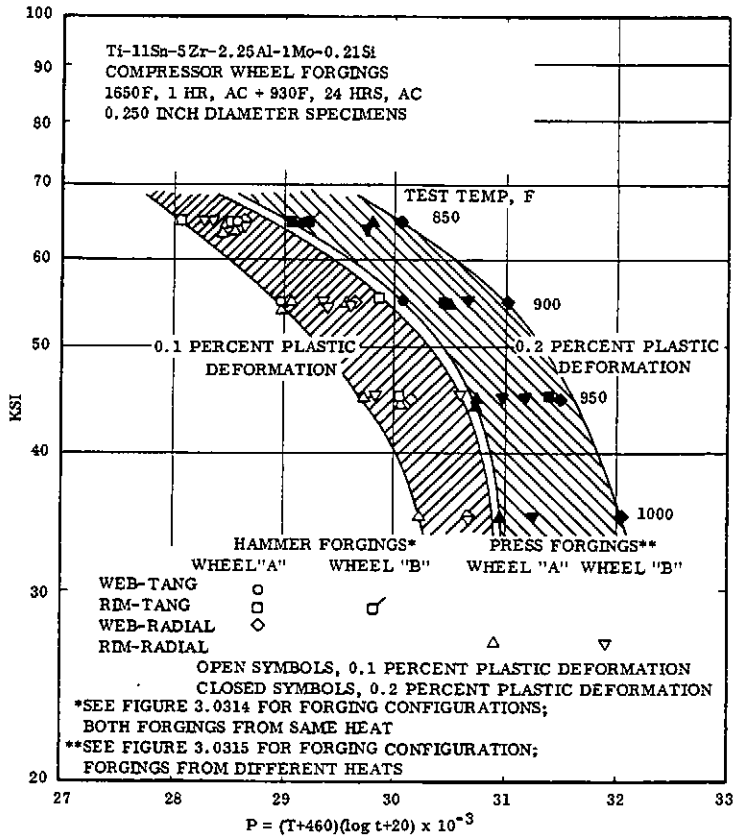


FIG. 3.048 MASTER CREEP CURVES FOR COMPRESSOR WHEEL FORGINGS (17, pp.13,16,19, and 22)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

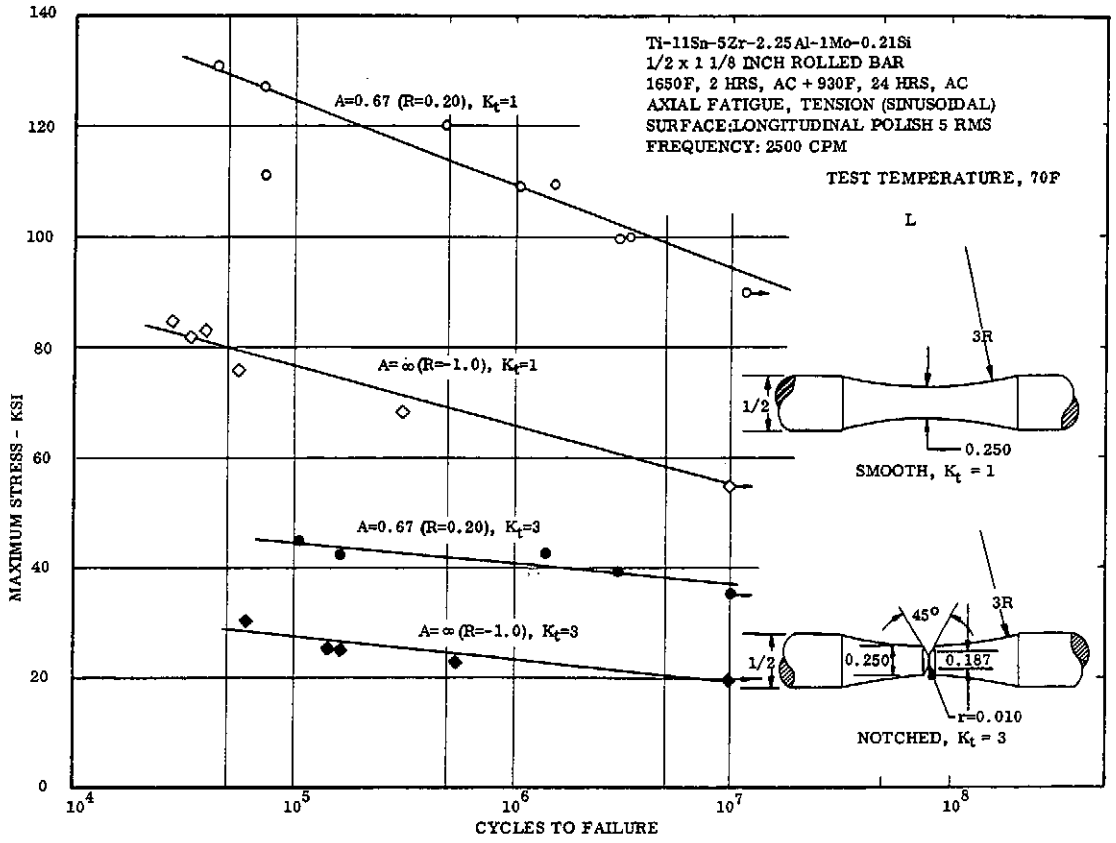


FIG. 3.051 AXIAL LOAD SMOOTH AND MILD-NOTCH FATIGUE PROPERTIES FOR BAR AT 70F (7, pp.312-313)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

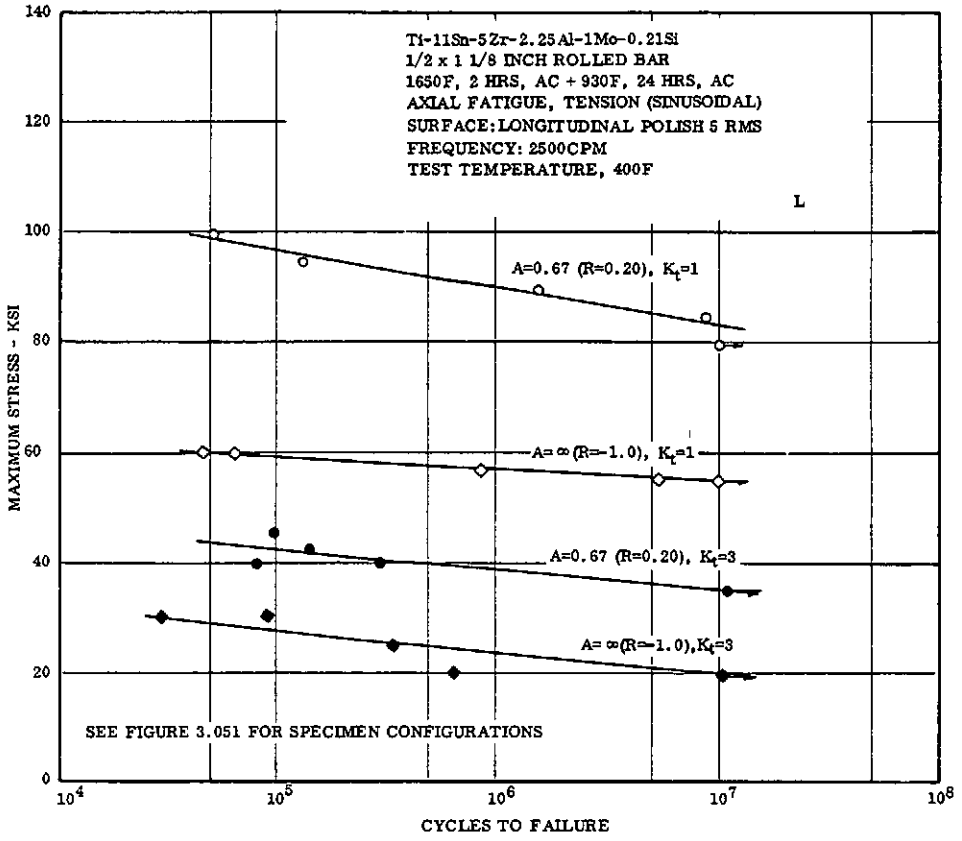
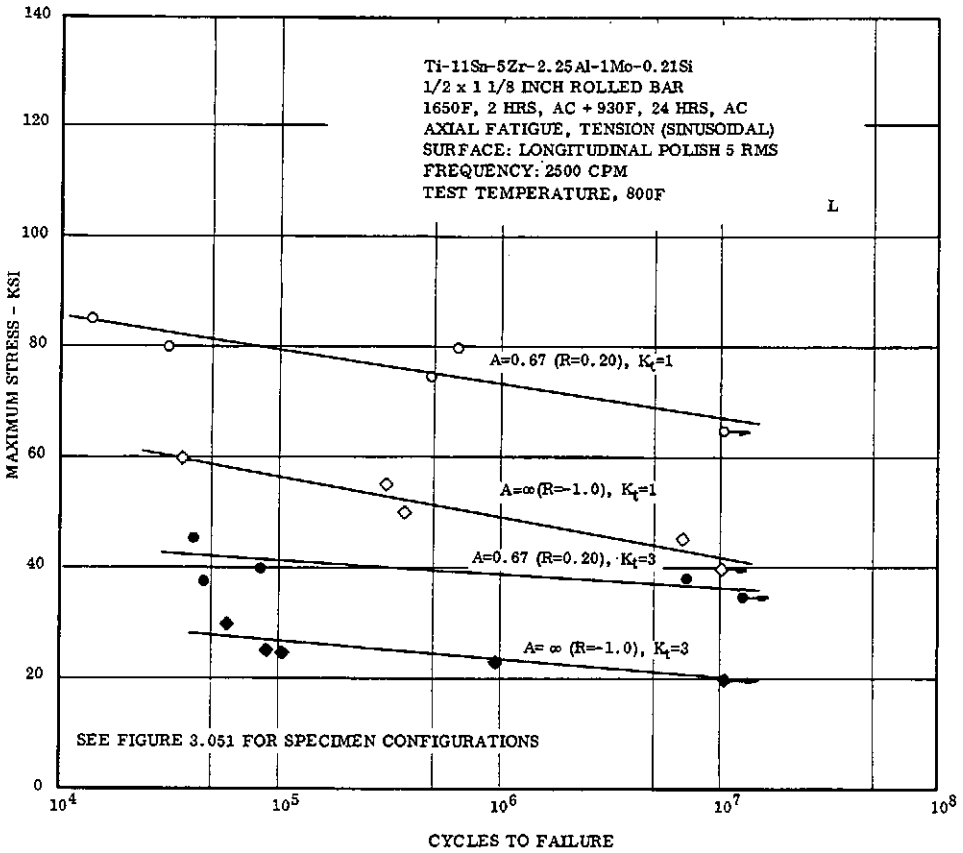


FIG. 3.052 AXIAL LOAD SMOOTH AND MILD-NOTCH FATIGUE PROPERTIES FOR BAR AT 400F(7, pp. 312-313)



	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

FIG. 3.053 AXIAL LOAD SMOOTH AND MILD-NOTCH FATIGUE PROPERTIES FOR BAR AT 800F (7, pp.312-313)

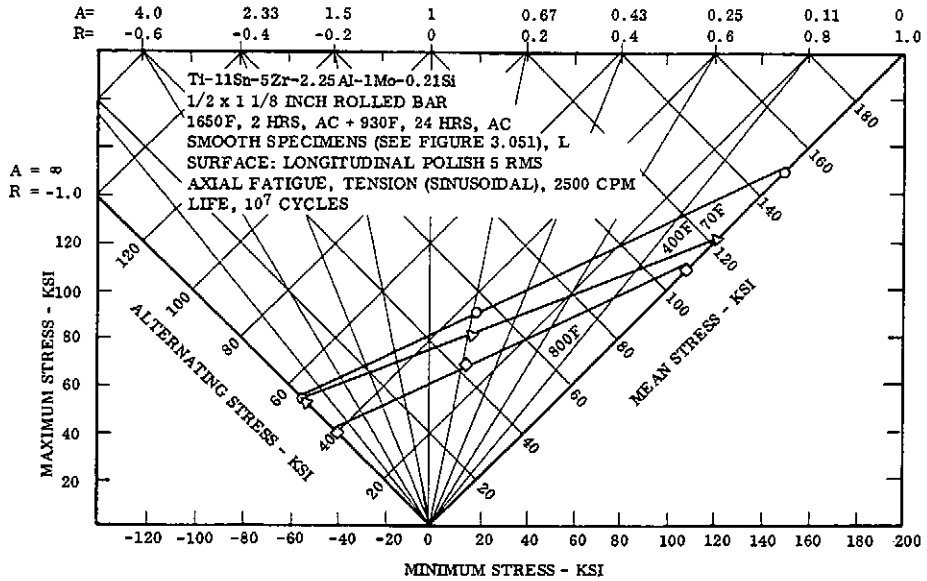


FIG. 3.054 CONSTANT-LIFE FATIGUE DIAGRAM FOR BAR AT SEVERAL TEMPERATURES (SMOOTH SPECIMENS) (7, pp. 192, 312)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

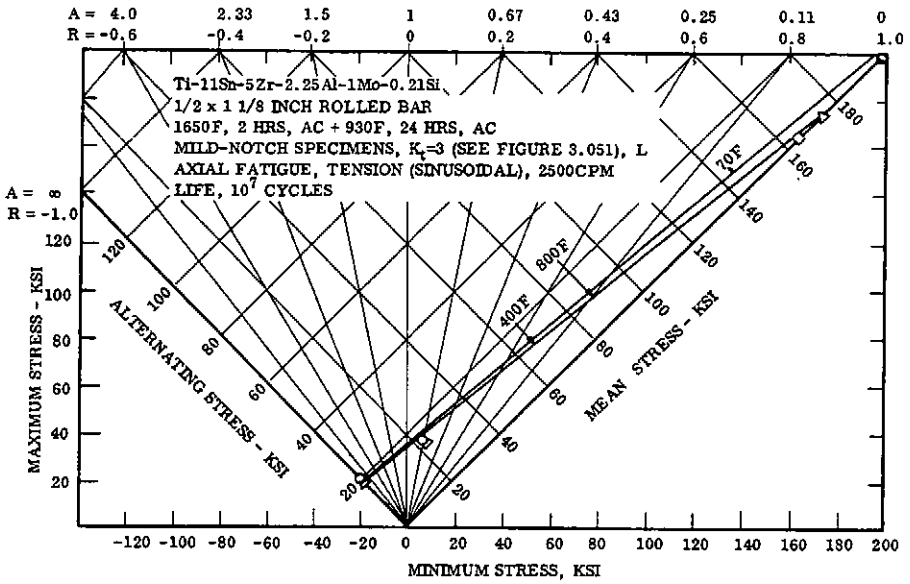


FIG. 3.055 CONSTANT-LIFE FATIGUE DIAGRAM FOR BAR AT SEVERAL TEMPERATURES (MILD-NOTCH SPECIMENS, K_t=3) (7, pp. 193, 313)

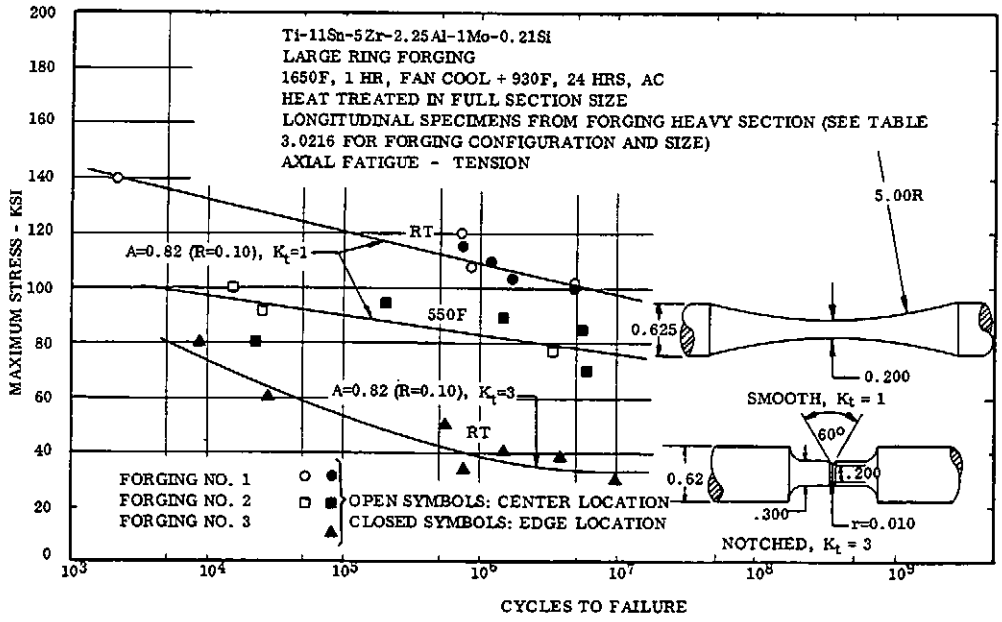


FIG. 3.056 AXIAL TENSION SMOOTH AND MILD-NOTCH FATIGUE PROPERTIES OF LARGE RING FORGING AT ROOM TEMPERATURE AND 550F. (9, pp. 87-88)

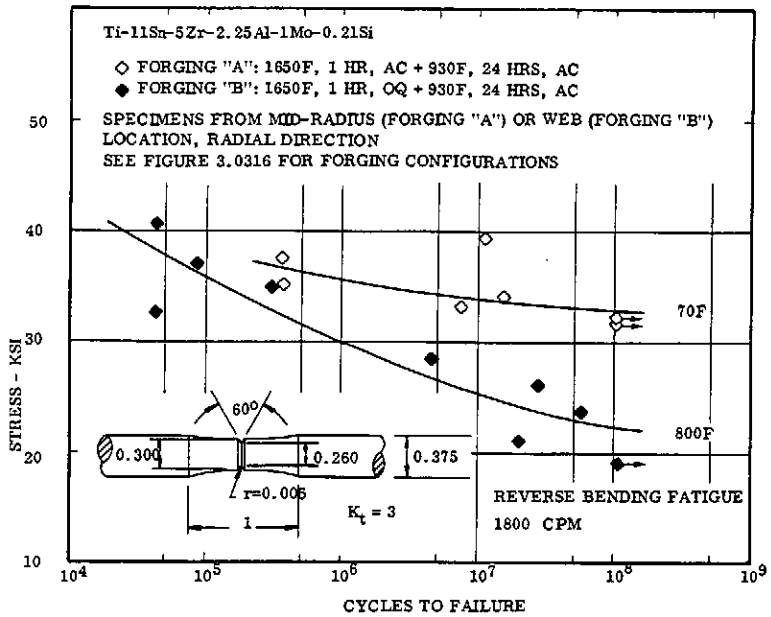


FIG. 3.057 MILD-NOTCH FATIGUE STRANGTH OF FORGINGS AT 70 AND 800F (16)

	Ti
11	Sn
5	Zr
2.5	Al
1	Mo
0.25	Si

Ti-679

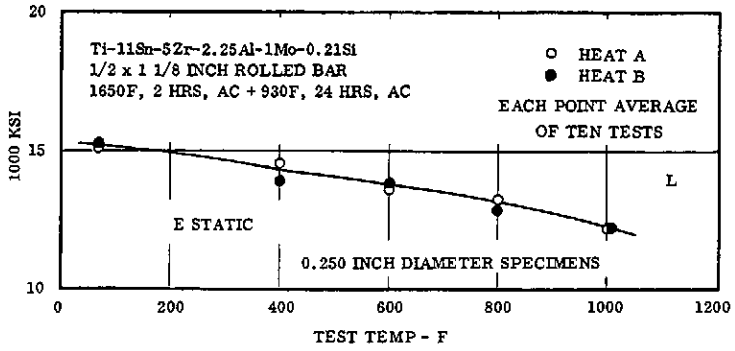


FIG. 3.061 STATIC TENSILE MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES FOR BAR (7, pp. 293-296)

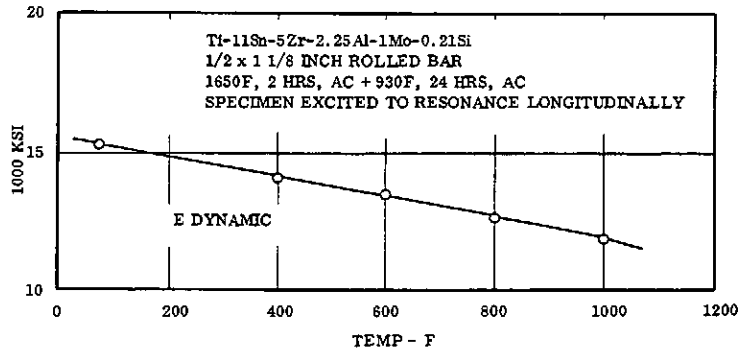


FIG. 3.062 DYNAMIC MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES FOR BAR (7, p.196)

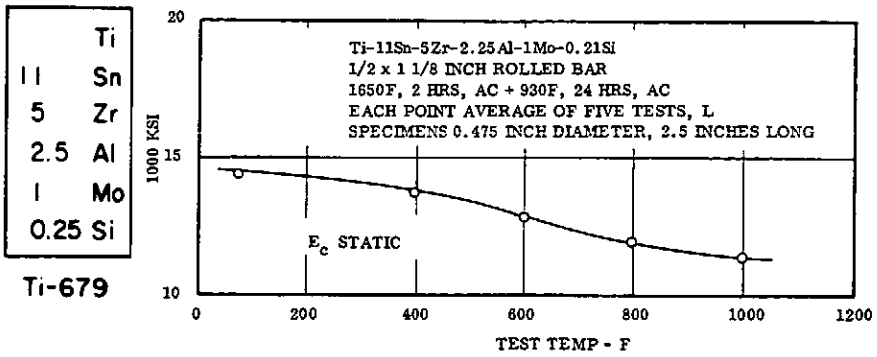


FIG. 3.063 STATIC COMPRESSIVE MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES FOR BAR (7, p.299)

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22. Aerospace Material Specifications, AMS-4974 (Nov. 1, 1967)
23. The Garrett Corporation, Airesearch Manufacturing Company, Specification EMS-94902 (May 13, 1966)
24. General Electric Company, Specification C50T83-S5 (December 8, 1966)
25. General Electric Company, Specification 4012158-092 (October 10, 1963)
26. "How to Use Titanium - Properties and Fabrication of Titanium Mill Products," TMCA
27. D.J. Maykuth, "Residual Stresses, Stress Relief, and Annealing of Titanium and Titanium Alloys," DMIC Report S-23 (July 1, 1968)
28. V.J. Erdeman, "A Titanium Alloy for Use at Elevated Temperatures," Metal Progress (Feb. 1966)
29. Private Communication with S. Jones, TMCA, West Caldwell, New Jersey.
30. General Motors Corporation, Allison Division, Specification EMS-59034-B (February 22, 1967)
31. Private Communication with R. Broadwell, TMCA, West Caldwell, New Jersey.
32. L.P. Jahnke, "Titanium in Jet Engines, "Aircraft Engine Technology Division, General Electric Company Cincinnati, Ohio, paper presented at the International Conference on Titanium, London, England (May 21-24, 1968) referenced by R.A. Wood and D.J. Maykuth, "Titanium and Titanium Alloys," Review of Recent Developments, Battelle Memorial Institute (August 23, 1968)

1. GENERAL

Commercially pure titanium is used where high ductility associated with moderate strength, high corrosion resistance and good weldability are desired. It is available in various degrees of purity, characterized mainly by different oxygen contents, and, consequently, with different mechanical properties. In 1959 three major grades were preferred with minimum yield strengths of 40 ksi, 55 ksi and 70 ksi, although other grades having yield strengths from 35 to 80 ksi are also widely used.

1.01 Commercial Designations. Commercially pure titanium, Ti-40, Ti-55, Ti-70.

1.02 Alternate Designations.

F_{ty}, min = 40 ksi. Ti (40,000 psi), A-40, MST-40, RS-40, Ti-55A.

F_{ty}, min = 55 ksi. 99 + Ti, Ti(55,000 psi), A-55, MST-55, RS-55, Ti-65A.

F_{ty}, min = 70 ksi. 99 Ti, Ti(70,000 psi), A-70, MST-70, RS-70, Ti-75A.

F_{ty}, min = 80 ksi. Ti-100A.

1.03 Specifications. Table 1.03.

TABLE 1.03

AMS	F_{ty}, min	Form	Military
4902	40 ksi	Sheet, strip, plate	MIL-T-9046 Cl 5
4941		Tubing, welded	
4951		Wire, welding	
4900A	55 ksi	Sheet, strip, plate	MIL-T-9046 Cl 7
4901B	70 ksi	Sheet, strip, plate	MIL-T-9046 Cl 6
4921A		Bar, forgings, and forging stock	MIL-T-9047 Cl 1

1.04 Composition. Table 1.04.

TABLE 1.04

Source	AMS (1) (2)	AMS (3)	AMS (4)	AMS (5)	AMS (6)
F_{ty}, min - ksi	40		55	70	
	Percent Max	Percent Max	Percent Max	Percent Max	Percent Max
Carbon	0.20	0.10	0.20	0.20	0.20
Nitrogen	0.07 (b)	0.07	-	-	0.07
Oxygen (a)	-	0.15	-	-	0.40
Hydrogen	0.015	0.015	0.015	0.015	0.0125
Iron	-	0.30	-	-	-
Manganese	-	0.20	-	-	-
Other	0.60	-	0.60	0.80	0.80 (c)
Titanium	Balance	Balance	Balance	Balance	Balance

(a) If determined
(b) AMS 4941 only
(c) Need not be reported

1.05 Heat Treatment

1.051 Anneal 1000 F, 1 hr to 1300 F, 2 hr, depending upon degree of restoration of yield strength desired. Effect of annealing temperature on yield strength of cold rolled Ti-55, Fig. 1.051.

1.052 Stress relief to avoid distortions due to residual stresses. 1000 F, 1/2 hr to 1 hr, 900 F, 2 to 4 hr or 800 F, 8 hr.

1.06 Hardenability. All grades can be hardened only by cold work.

1.07 Forms and Conditions Available

1.071 Alloy is available in the full commercial range of sizes for sheet, strip, plate, bar, billet, wire, forgings, extrusions and seamless and welded tubing, all in the annealed condition.

1.072 Special products which are available on a commercial basis are cold worked flat products and wire and castings.

1.08 Melting and Casting Practice. Consumable electrode double vacuum melt.

1.09 Special Considerations

1.091 Hydrogen pickup during pickling or heating may lead to hydrogen embrittlement.

1.092 Oxygen and nitrogen contamination during hot forming or heat treating may result in a brittle skin and difficulties on further forming operations.

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting temperature. 3000 to 3040 F. Melting point of high purity (iodide) titanium is between 3020 and 3055 F.

2.012 Phase changes. Alloy transforms from beta phase to alpha phase on cooling. Transformation temperature range (beta transus). Table 2.012.

TABLE 2.012

Grade	Iodide	Ti-55	Ti-70
Transformation range, F	1621	1650 to 1685	1665 to 1740

2.013 Thermal conductivity, Fig. 2.013.

2.014 Thermal expansion, Fig. 2.014.

2.015 Specific heat, Fig. 2.015.

2.02 Other Physical Properties

2.021 Density. 0.163 lb per cu in. 4.51 gr per cu cm.

2.022 Electrical resistivity, Fig. 2.022.

2.023 Magnetic properties. Alloy is nonmagnetic. Permeability, 1.00005 to 1.0001 at 20 oersteds.

2.03 Chemical Properties

2.031 Corrosion resistance

2.0311 General. Titanium and its alloys possess outstanding corrosion resistance to most media, as summarized in Table 2.0311.

TABLE 2.0311

Medium	Corrosion Resistance
Nitric Acid	Excellent for all concentrations and to boiling point. Titanium has pyrophoric tendencies in red fuming nitric acid below 2 percent water and 10 to 20 percent nitrogen dioxide contents.
Sulfuric, Hydrochloric and Phosphoric Acids	Resists attack in dilute solutions at low temperatures. At higher temperatures and concentrations, inhibitors allow effective application.
Hydrofluoric Acid	Rapidly attacked.
Organic Salts	Generally good. Borderline passivity in formic and trichloroacetic acids.
Inorganic Salts	Outstanding, particularly to pitting attack of chloride solutions (sea water), exception aluminum chloride.
Alkalies	Excellent for all concentrations and to boiling point, except boiling concentrated potassium hydroxide.

2.0312 Stress corrosion may occur in commercially pure titanium in dry red fumic acid. Stress corrosion may also occur in some titanium alloys, but not in pure titanium, if chloride salts have been deposited on the surface of stressed material which is then subjected to high temperatures.

2.0313 Galvanic corrosion of many metals is promoted by contact with titanium and its alloys, which are at the noble end of the galvanic series, next to nickel base alloys.

2.0314 Hydrogen embrittlement is a major problem with titanium and its alloys. Hydrogen is readily absorbed from hydrogenating solutions at room temperature and from the atmosphere at elevated temperatures. Hydrogen embrittlement of titanium alloys may assume one of two forms. First, common for alpha alloys, is a reduction in ductility and slight increase in strength. This is associated with a decrease in impact strength at temperatures below 200 F and a shift in the temperature range where the change from duc-

tile to brittle behavior is observed. Second, similar to the embrittlement of steels, is an embrittlement at slow speeds of testing and under constant or "sustained" loads as usually demonstrated by such tests on notched specimens. This type of embrittlement generally becomes evident only above a certain strength level and it is observed particularly in alpha-beta type alloys at room and moderately elevated temperatures. In general, the hydrogen tolerance of titanium alloys is specified at 0.015 percent for bar products, but it may vary depending upon the alloy and its condition. If the tolerance limit is maintained, hydrogen embrittlement is practically absent.

2.032 Oxidation resistance

2.0321 Scaling of titanium and its alloys starts at about 900 F. Light scale formed during exposure at temperatures up to 1000 F for long times has no detrimental effect on the properties.

2.0322 Heating to temperatures above 1000 F under oxidizing conditions results in increasingly severe surface scaling as well as in diffusion of oxygen. Diffusion results in hard brittle surface layers difficult to distinguish from the base metal. This contaminated layer is brittle and must be removed, therefore, by mechanical or chemical means prior to forming parts or application in stressed components.

2.04 Nuclear Properties

2.041 The thermal neutron absorption cross section of titanium is 5.6 barns.

2.042 The mechanical properties of Ti-70 are affected by irradiation as follows.

2.0421 The hardness is increased by exposure at 3 to 20 x 10^{19} nvt slow and 200 to 540 F from about 200 to 230 BHN.

2.0422 Irradiation at 180 F raises the yield strength considerably, the tensile strength to a lesser extent and reduces the ductility, both at room temperature and at 212 F. A yield point was observed when tested at 390 F.

2.0423 The impact strength appears unaffected by irradiation, according to limited data.

2.043 Physical properties of Ti-70 are affected by irradiation as follows.

2.0431 The density remained constant after irradiation.

2.0432 No dimensional changes were observed.

2.0433 The electrical resistivity decreased by exposure at 2 to 7 x 10^{20} nvt slow and 180 F.

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 AMS specified mechanical properties, Table 3.011.

TABLE 3.011

Source	AMS (1)	AMS (2)	AMS (3)	AMS (4)	AMS (5)	AMS (6)
Alloy	Ti-40			Ti-55	Ti-70	
Form	Sheet, strip, plate	Tubing, welded	Wire, welding	Sheet, strip, plate	Sheet, strip, plate	Bar, forgings stock
Condition	Ann					
F_{tu}, min - ksi	50	50	50	65	80	80
max - ksi	-	-	80	-	-	-
F_{ty}, min - ksi	40	40	-	55	70	70
max - ksi	65	65	-	80	95	-
e(2 in), min-percent	20	20	-	18	15	(4D) 15*
RA, min -percent	-	-	-	-	-	30*

* Thickness ≤3 in

3.02 Mechanical Properties at Room Temperature. See 3.03 also.

3.021 Typical hardness values, Table 3.021.

TABLE 3.021

Alloy	Ti-40	Ti-55	Ti-70
Hardness			
RB, min	88	95	-
max	92	99	-
RC, min	-	-	23
max	-	-	29

3.022 Effect of exposure to elevated temperatures with load on tensile properties of Ti-70 bar, Table 3.022.

TABLE 3.022

Source	(7, p. C-17)					
Alloy	Ti-70					
Form	Bar					
Condition	Ann					
1100 hr exposure at	Tested at RT					
Temp F	Load ksi	Creep percent	F_{tu} ksi	F_{ty} ksi	e percent	RA percent
RT	65	10.6	107	97	15	45
400	40	3.6	97	89	20	53
600	35	5.8	106	98	20	33
800	12.5	6.5	93	76	20	33
1000	4	10.8	83	66	17	31

3.023 Effect of strain rate on tensile properties of Ti-55 and Ti-70 sheet, Fig. 3.023.

3.024 Compressive yield strength, $F_{cy} = 1.04\ F_{ty}$.

3.025 Commercially pure titanium is not notch sensitive at room temperature, as evidenced for bar by a constant notch strength ratio over a wide range of stress concentrations or notch sharpnesses. Effect of notch sharpness on the notch strength ratio of bar at room temperature, Fig. 3.025.

3.026 Sheet specimens, provided with notches of various sharpnesses, also show lack of notch sensitivity at room temperature, evidenced by linear increase in notched strength ratio with notch depth. Effect of notch depth on the notch strength ratio of sheet, Fig. 3.026.

3.03 Mechanical Properties at Various Temperatures

3.031 Short time tension properties

3.0311 Stress strain curves for Ti-55 and Ti-70 sheet at room and elevated temperatures, Fig. 3.0311.

3.0312 Effect of test temperature on tensile properties of various grades of titanium bar and sheet, Fig. 3.0312.

3.0313 Effect of test temperature on tensile properties of Ti-70 sheet, Fig. 3.0313.

3.0314 Effect of test temperature on tensile properties of annealed and of cold worked 0.064 in Ti-55 sheet, Fig. 3.0314.

3.0315 Effect of test temperature on tensile strength of annealed and of cold worked 0.187 in Ti-55 sheet, Fig. 3.0315.

3.0316 Effects of test temperature, holding time and strain rate on tensile properties of Ti-70 sheet, Fig. 3.0316.

3.032 Short time properties other than tension

3.0321 Stress strain curves in compression for Ti-55 at room and elevated temperatures, Fig. 3.0321.

3.0322 Effect of test temperature on compressive yield strength of Ti-55 sheet, Fig. 3.0322.

3.0323 Effect of test temperature on bearing properties of Ti-55 sheet, Fig. 3.0323.

3.0324 Effect of test temperature on shear strength of Ti-55 sheet, Fig. 3.0324.

3.0325 Effects of test temperature and strain rate on torsion strength of Ti-70 bar, Fig. 3.0325.

3.0326 Effect of test temperature on impact strength of various grades of titanium, Fig. 3.0326.

3.033 Static stress concentration effects

3.0331 Effects of notch depth and low test temperatures on the notch strength ratio of Ti-70 bar, Fig. 3.0331.

3.04 Creep and Creep Rupture Properties

3.041 Total strain curves for Ti-70 sheet at 600 to 1200 F, Fig. 3.041.

3.042 Creep rupture curves for Ti-55 and Ti-70 at room temper-

ature to 1000 F, Fig. 3.042.

3.05 Fatigue Properties

3.051 Fatigue properties of Ti-55 bar, Table 3.051.

TABLE 3.051

Source	(8, p. 34)					
Alloy	Ti-55					
Form	Bar					
Condition	Ann					
Temp F	Method	Stress Ratio A	Stress Ratio R	Stress Concentration	Fatigue Strength - ksi at Cycles 10^6	Fatigue Strength - ksi at Cycles 10^7
-312	Rev bend	∞	-1	Smooth K = 1	-	100
				Notched K = 2.7	-	46
RT				Smooth K = 1	42	41
				Notched K = 2.7	-	35
600				Smooth K = 1	22	21

3.052 Fatigue properties of Ti-70 sheet and bar at room temperature, Table 3.052.

TABLE 3.052

Source	(7, p. C-15)						
Alloy	Ti-70						
Condition	Ann						
Form	Method	Stress Ratio A	Stress Ratio R	Stress Concentration	Fatigue Strength - ksi at Cycles 10^5	Fatigue Strength - ksi at Cycles 10^6	Fatigue Strength - ksi at Cycles 10^7
Bar	Rot beam	∞	-1	Smooth K = 1	75	68	62
				Notched K = 2.7	42	38	36
Sheet	Direct Stress	0.25	0.6	Smooth K = 1	-	-	78

3.06 Elastic Properties

3.061 Modulus of elasticity at various temperatures, Fig. 3.061.

3.062 Modulus of rigidity at room and elevated temperatures, Fig. 3.062.

3.063 Poisson's ratio, 0.34 to 0.405.

3.064 Tangent modulus curves in compression at room and elevated temperatures, Fig. 3.064.

FABRICATION

4.01 Forming and Casting

4.011 Commercially pure titanium is formed only to a limited extent at room temperature. Many forming operations require heating to 400 to 1200 F. The ease of forming decreases as the strength increases. Burrs should be removed by filing to prevent edge cracking.

4.012 Bend radii of 3.5t can be obtained at room temperatures using a lubricant. Smaller radii can be formed at temperatures above 300 F.

4.013 Flanges can be rubber or die formed and sections can be contoured by stretch forming at room temperature. Preferably, the part is formed in two operations with an intermediate anneal.

4.014 Elevated temperatures are used for various forming operations as follows: Drop hammer forming, 800 to 1000 F, spinning and deep drawing, about 800 F, rubber forming and die forming flanges, 400 to 800 F.

4.015 Shearing and blanking require the same techniques and pressures as 1/4 hard austenitic stainless steels.

4.016 Forging. Starting temperature 1700 F maximum, finishing temperature 1200 F minimum. To obtain optimum properties, forging equivalent to 25 to 40 percent reduction should be performed below the transformation temperature (beta to alpha + beta) in the final forging operation. Subsequent reheating such as required for sizing operations, should not exceed 1500 F or, generally, about 200 F below the beta to alpha plus beta temperature.

4.017 Castings having properties comparable to those of wrought products can be produced in commercially pure titanium using consumable or nonconsumable electrode melting techniques. The metal is poured in vacuum into special mold materials such as machined graphite.

4.02 Machining

4.021 Commercially pure titanium has machining characteristics similar to those of austenitic stainless steels. Titanium alloys, because of their higher hardness, are somewhat more difficult to machine, but the same general rules apply. Sharp tools, rigid setups, heavy feeds slow speeds and an abundance of soluble oil coolant are the basic rules for successful machining. Titanium requires low forces and demonstrates a complete absence of "built up edge" It can be machined to very high surface finishes.

4.022 Sawing is best performed with high speed friction saws running at a linear speed of 4000 to 4500 fpm. The feed should be positive. Hack and hand sawing is also possible. High speed steel blades, heavy feeds and slow speeds should be used. Surface scale and contaminated surfaces will result in excessive blade wear if not removed.

4.023 Grinding should be performed only as a finishing operation. Light feed rates should be maintained. Silicon carbide wheels are satisfactory for conventional speed grinding. Maximum grinding ratios are maintained at 3,000 to 5,000 feet per minute surface speed. Parts should be stress relieved after grinding to remove residual stresses.

4.03 Welding

4.031 General. Commercially pure titanium is readily welded by suitable techniques. Welds possess excellent flow characteristics, high strength and ductility and a corrosion resistance equal to that of the parent metal.

4.032 Fusion welding to 100 percent efficiency is accomplished by using gas shielded arc welding techniques. In open fusion welding, shielding can be effected by a sufficient supply of helium or argon, or preferably a 50/50 mixture of both, whereby any air contact with surface areas heated to 1800 F or higher is prevented. Alternatively, inert gas filled chambers are used. Back up support is essential. The edges must be deburred by filing and the metal must be very clean where welded. Stress relief at 800 to 1000 F in a furnace, or at about 1200 F with a gas torch is recommended after welding.

4.033 Resistance welding. Spot and seam welding is done without protective atmosphere, using electrode pressures welding currents and time cycles similar to those used with austenitic stainless steels.

4.04 Heating and Heat Treating

4.041 Electric furnaces are preferred for heating and heat treating. If gas fired furnaces are used, these should be of the muffle type and the atmosphere should be oxidizing. Direct flame impingement should be avoided to prevent severe localized oxidation and contamination.

4.042 Contact with scale or dirt should be prevented.

4.043 The heating and heat treating time should be kept at a minimum, after uniform temperature is reached.

4.044 Direct resistance heating of sheet or other thin sections may alternately be used where extremely short heat up and total heating times are desired on nearly finished surfaces to minimize surface oxidation.

4.05 Surface Treating

4.051 Cleaning. Oxidation at temperatures in excess of 1100 F is detrimental to forming and machining operations and can rarely be tolerated in finished parts. Scale may be removed preferably in oxidizing molten salt baths although under certain conditions sodium hydride type baths can be used if hydrogen pickup is minimized. It may also be removed mechanically by grit or vapor blasting or by grinding. Grinding should be followed by stress relief. After scale removal, the subsurface high oxygen layer should be removed by pickling in a 20 to 35 percent nitric acid - 2 to 5 percent hydrofluoric acid solution at 130 to 160 F. A nitric to hydrofluoric acid ratio of 10:1 or greater should be maintained to prevent hydrogen pickup.

4.052 Light discolorations obtained by heating at 1000 to 1100 F may be removed by pickling in the nitric acid-hydrofluoric acid solution.

4.053 Surface hardening, to minimize wear of reciprocating parts can be accomplished by nitriding to surface hardnesses in excess of 600 KHN.

4.054 Galling of bolts or in forming of parts, can be eliminated by anodic or phosphate base chemical conversion type coatings. Oxides developed at 1200 to 1400 F also prevent galling and serve as a base for lubricants.

4.055 Electroplating with copper or nickel can be applied to titanium.

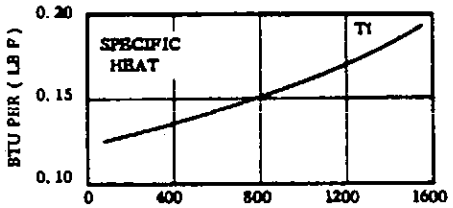


FIG. 2.015 SPECIFIC HEAT

(10, p. 4)

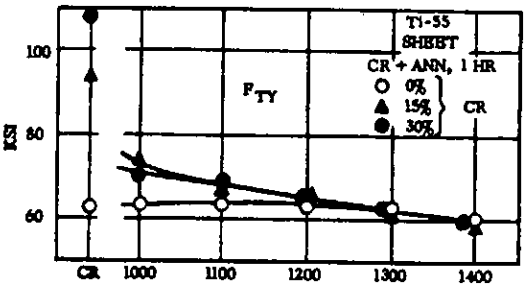


FIG. 1.051 EFFECT OF ANNEALING TEMPERATURE ON YIELD STRENGTH OF COLD ROLLED Ti-55 SHEET

(9, p. 108)

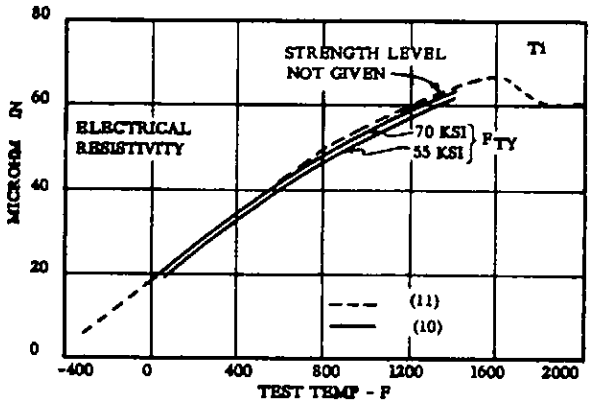


FIG. 2.022 ELECTRICAL RESISTIVITY

(10, p. 3)(11, p. 44)

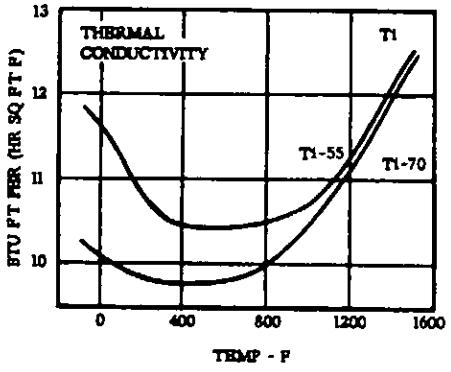


FIG. 2.013 THERMAL CONDUCTIVITY

(10, p. 3)

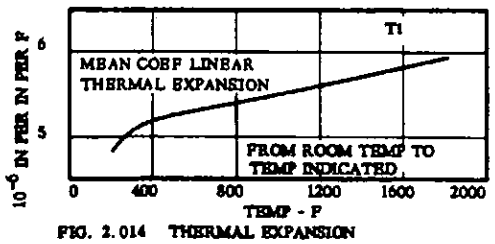


FIG. 2.014 THERMAL EXPANSION

(10, p. 3)

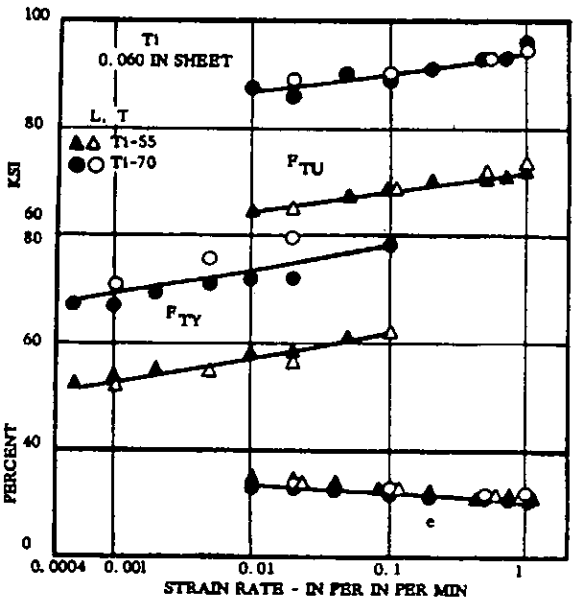


Fig. 3.023 EFFECT OF STRAIN RATE ON TENSILE PROPERTIES OF Ti-55 AND Ti-70 SHEET

(9, p. 100, 101)

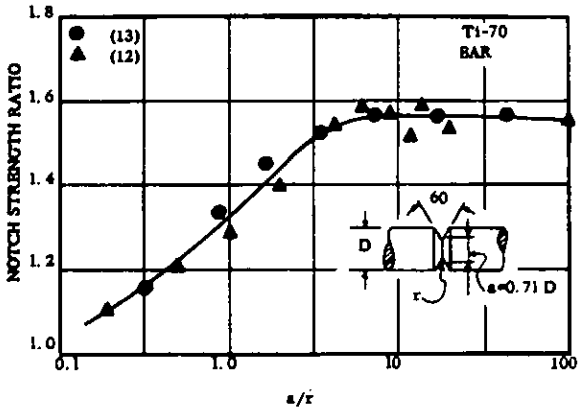


FIG. 3.025 EFFECT OF NOTCH SHARPNESS ON THE NOTCH STRENGTH RATIO OF BAR AT ROOM TEMPERATURE

(12, p. 15)(13, p. 17)

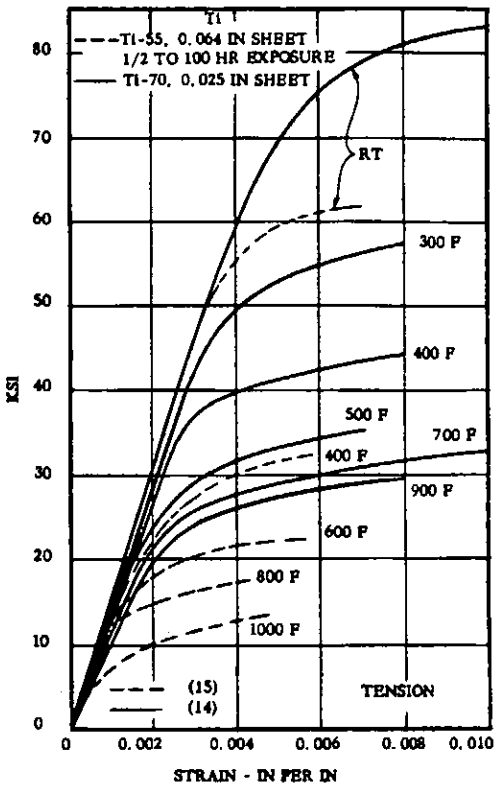


FIG. 3.0311 STRESS STRAIN CURVES FOR Ti-55 AND Ti-70 SHEET AT ROOM AND ELEVATED TEMPERATURES

(14)(15, p. 67, 68)

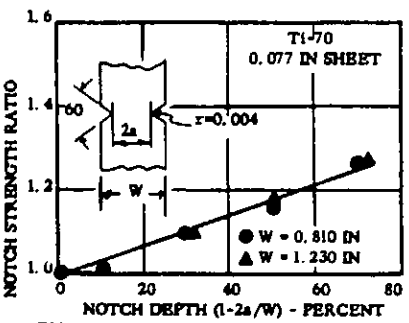


FIG. 3.026 EFFECT OF NOTCH DEPTH ON THE NOTCH STRENGTH RATIO OF SHEET

(21)

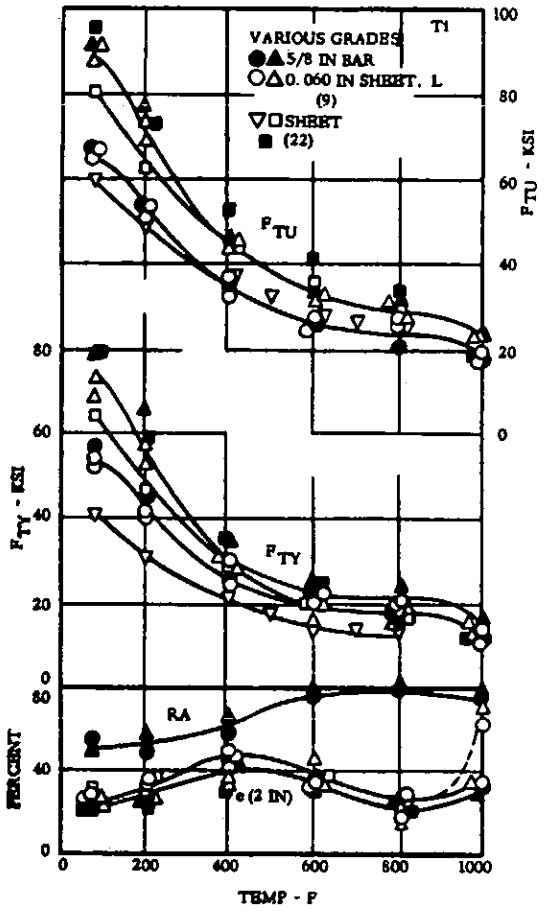


FIG. 3.0312 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF VARIOUS GRADES OF TITANIUM BAR AND SHEET (9, p. 102-107) (22, p. 4-6)

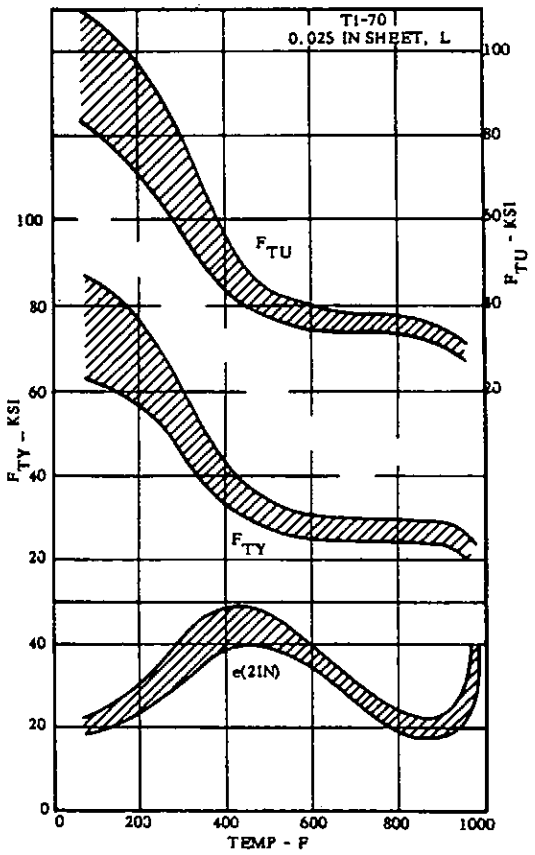


FIG. 3.0313 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF Ti-70 SHEET (14)

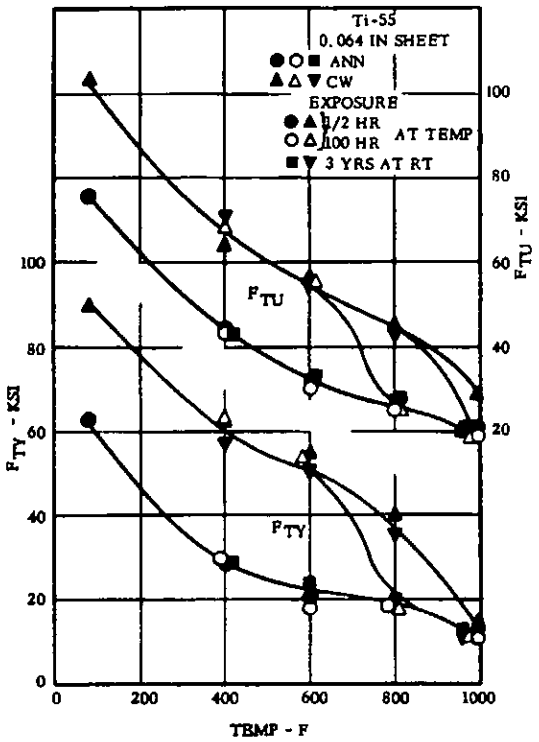


FIG. 3.0314 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED AND OF COLD WORKED 0.064 IN TI-55 SHEET

(17), (19, p. 31)

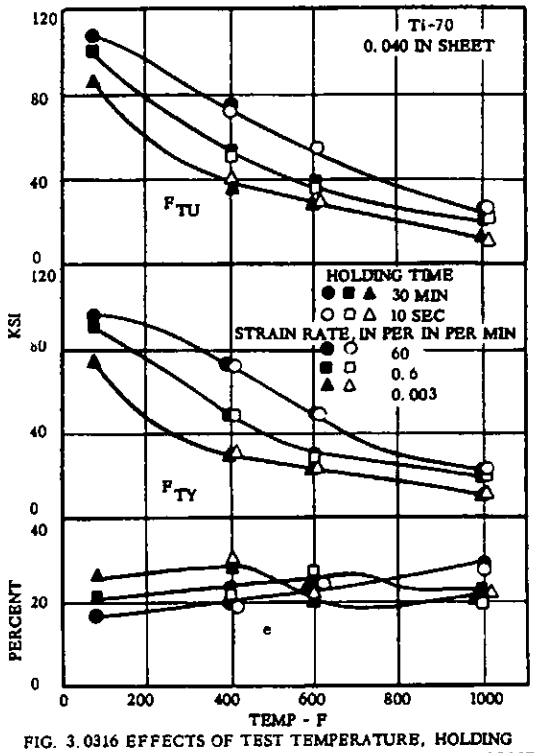


FIG. 3.0316 EFFECTS OF TEST TEMPERATURE, HOLDING TIME AND STRAIN RATE ON TENSILE PROPERTIES OF TI-70 SHEET

(16, p. 102-107)

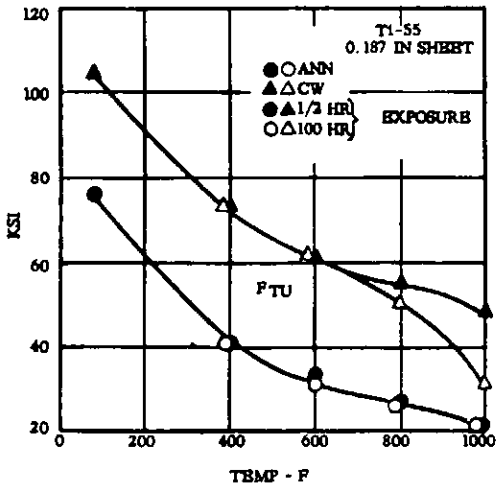


FIG. 3.0315 EFFECT OF TEST TEMPERATURE ON TENSILE STRENGTH OF ANNEALED AND OF COLD WORKED 0.187 IN TI-55 SHEET

(17, p. 168, 177)

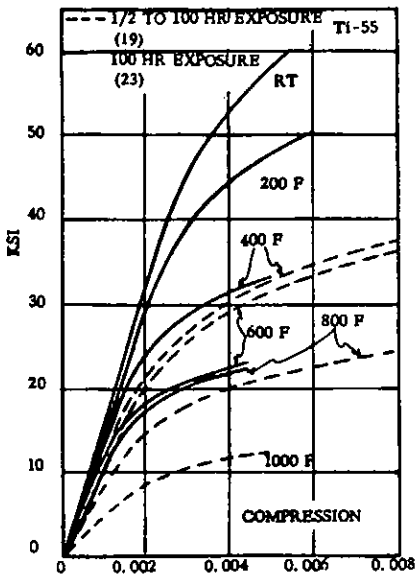


FIG. 3.0321 STRESS STRAIN CURVES IN COMPRESSION FOR TI-55 AT ROOM AND ELEVATED TEMPERATURES

(19, p. 55) (23)

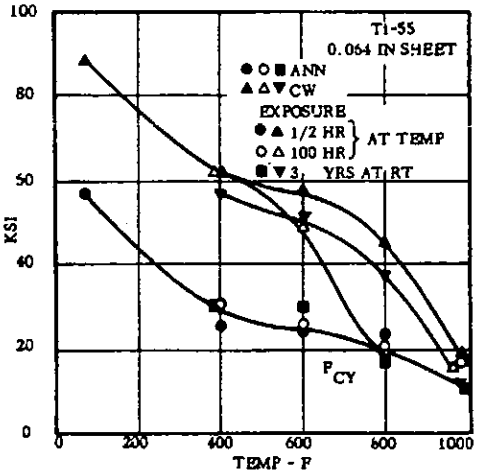


FIG. 3.0322 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF Ti-55 SHEET (17, p. 163, 172)(19, p. 28)

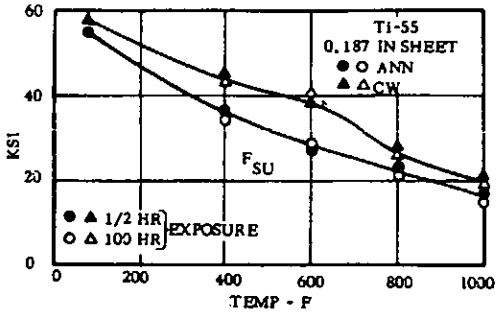


FIG. 3.0324 EFFECT OF TEST TEMPERATURE ON SHEAR STRENGTH OF Ti-55 SHEET (17, p. 167, 176)

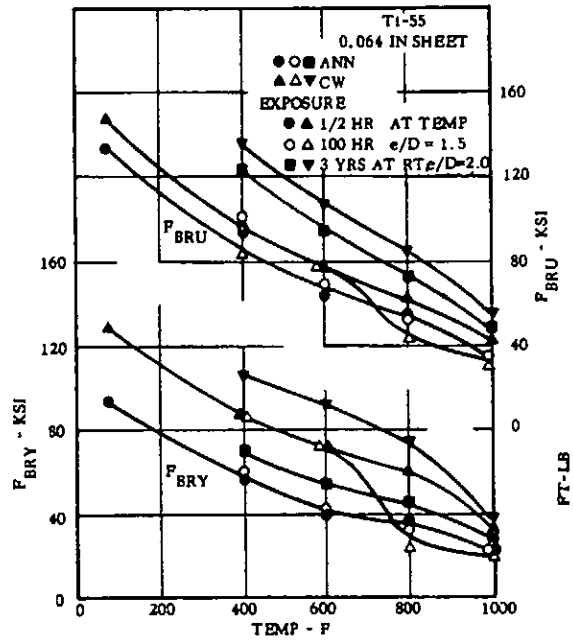


FIG. 3.0323 EFFECT OF TEST TEMPERATURE ON BEARING PROPERTIES OF Ti-55 SHEET (17) (19, p. 26)

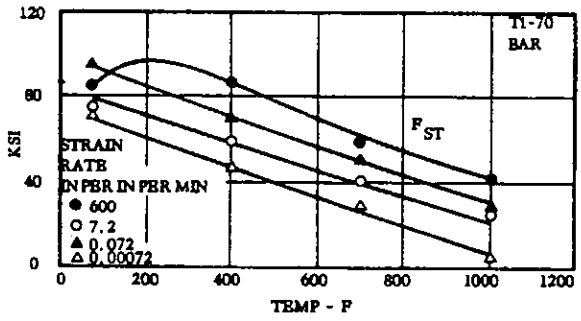


FIG. 3.0325 EFFECTS OF TEST TEMPERATURE AND STRAIN RATE ON TORSION STRENGTH OF Ti-70 BAR (18, p. 103)

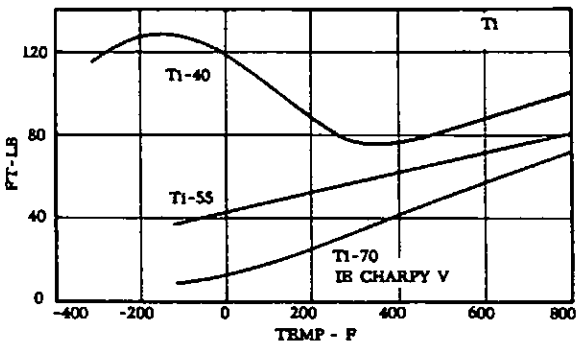


FIG. 3.0326 EFFECT OF TEST TEMPERATURE ON IMPACT STRENGTH OF VARIOUS GRADES OF TITANIUM (22)

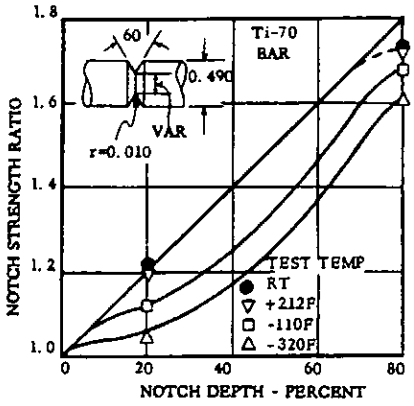


FIG. 3.0331 EFFECTS OF NOTCH DEPTH AND LOW TEST TEMPERATURES ON THE NOTCH STRENGTH RATIO OF Ti-70 BAR (13, TBL. B-7)

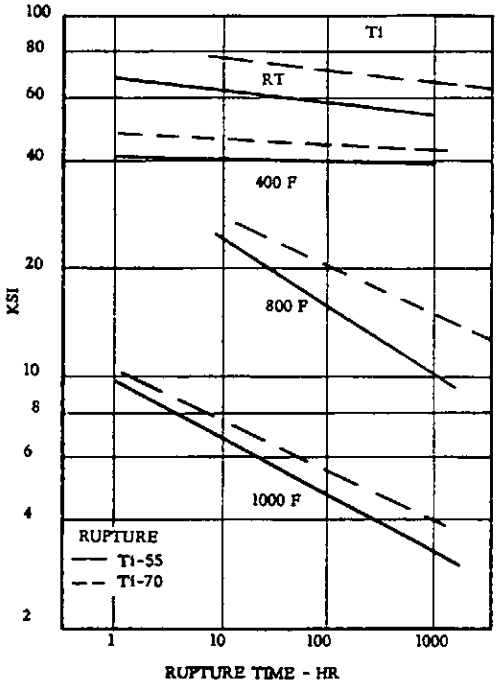


FIG. 3.042 CREEP RUPTURE CURVES FOR Ti-55 AND Ti-.70 AT RT TO 1000 F (7)

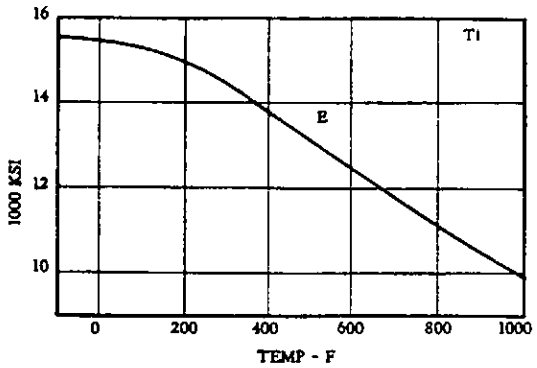


FIG. 3.061 MODULUS OF ELASTICITY AT VARIOUS TEMPERATURES (7)

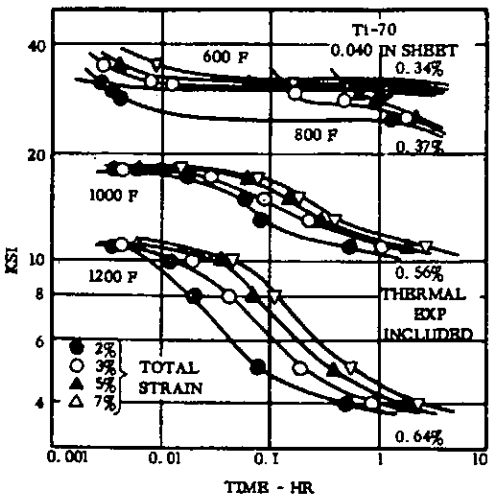


FIG. 3.041 TOTAL STRAIN CURVES FOR Ti-70 SHEET AT 600 TO 1200 F (20, p. 34, 35)

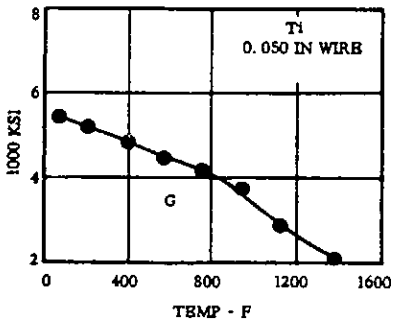


FIG. 3.062 MODULUS OF RIGIDITY AT ROOM AND ELEVATED TEMPERATURES (23)

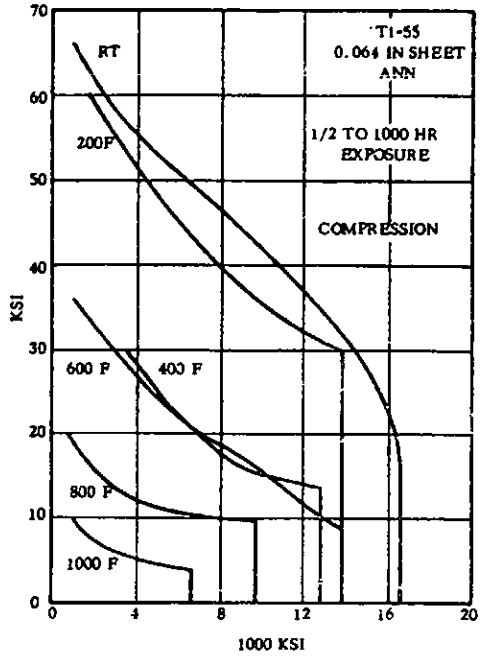


FIG. 3.064 TANGENT MODULUS CURVES IN COMPRESSION AT ROOM AND ELEVATED TEMPERATURES (19, p. 86, 87)

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AUTHOR: C. F. HICKEY, JR.

NONFERROUS ALLOYS

	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

38-6-44

1. GENERAL

This alloy, sometimes referred to as Beta C or more often by combinations of the nominal composition 38-6-44, is an age hardenable, metastable beta alloy. It was developed by the RMI Company (formerly Reactive Metals, Inc.) in 1969. The alloy is formulated by depressing the beta transus with the beta isomorphous elements, molybdenum and vanadium, and the sluggish beta eutectoid element, chromium. It is slightly more beta stabilized than Ti-11.5Mo-6Zr-4.5Sn (Beta III) and less beta stabilized than Ti-13V-11Cr-3Al.

Beta phase is retained on cooling from above the beta transus (1460F). The alloy can then be heat treated to high strength levels, up to 200 ksi, by aging between 900 to 1100F. Large variations in tensile strength can be obtained by varying the aging temperature and time. A portion of the beta phase transforms to a finely dispersed alpha during aging. It is reported that unlike some of the other beta alloys, 38-6-44 does not develop the brittle omega phase during heat treatment. Also, the alloy does not grain coarsen as rapidly as other beta alloys when heat treated or worked at temperatures above the beta transus.

The alloy exhibits excellent cold working characteristics, thus it can be manufactured as sheet, foil, tubing, and cold drawn wire and bar with a combination of high strength and ductility. It may be easily hot worked and is through-hardenable in sections up to six inches. The available information indicates it is quite resistant to sustained load crack growth in 3.5 percent NaCl solution. Potential applications include fasteners, springs, torsion bars, and foil to heavy section parts.

1.01 Commercial Designation

3Al-8V-6Cr-4Mo-4Zr Titanium Alloy.

1.02 Alternate Designation

RMI-3Al-8V-6Cr-4Mo-4Zr.
Tel-Ti-3Al-8V-6Cr-4Mo-4Zr.
Ti-3Al-8V-6Cr-4Mo-4Zr.
38-6-44.
Beta C.

1.03 Specifications

None

1.04 Composition

1.041 Producers specified composition, Table 1.041.

1.042 The relationship between composition, transformation kinetics, and microstructure has been reviewed (10). The alloy has a total of 18 percent beta stabilizer additions plus 3 percent aluminum, an alpha stabilizer, and 4 percent zirconium, generally a neutral element. In this alloy Zr appears to act more like a beta stabilizer and it is believed to be a constituent of a second phase which is formed upon cooling from above the beta transus (1460 ± 25F) (1). To date this second phase has not been identified, however, it has been established that it is not $TiCr_2$. It appears as a randomly dispersed, fine precipitate in the solution annealed microstructure, and possibly may exist at elevated temperatures. It is felt that this second phase inhibits beta grain growth during exposure above the beta transus, thus acting as a ductility enhancer.

Quenching or air cooling from above the beta transus to room temperature results in the retention of beta in a metastable condition. Recrystallization occurs after short-time annealing at or above the beta transus. The ductile annealed metastable beta phase transforms partially to alpha upon subsequent aging. The alpha phase precipitates both intergranularly and intragranularly when aged over the 800 - 1300F temperature range. This alloy does not develop omega, a brittle phase, during heat treatment.

1.05 Heat Treatment

1.051 Solution treating and annealing are the same for this alloy. 1500 to 1700F, hold from 15 to 30 minutes, either air cool or water quench (see Tables 1.062 and 1.063). The 1700F temperature is generally recommended for plate or bar, whereas 1500 - 1600F can be used for thin products such as wire, foil, and sheet. The effect of annealing temperature on the tensile properties of cold drawn fastener stock, plate and tubing are shown in Figures 1.0641, 3.0213 and 3.0214. Lower annealing temperatures, specifically 1250F, result in an increase in tensile strength, however a drastic decrease in ductility (see Figure 3.0214).

1.052 Age. 900 to 1100F, with higher strengths obtainable at the lower temperatures within this range (see Figure 3.0215 to 3.0218).

1.053 The selection of aging time for an alloy depends on the combination of properties desired. For this alloy, aging at times beyond 8 hours has an insignificant effect on strength and ductility. Based on a strength-ductility criterion one producer (1) recommends an aging temperature of 900F for 8 hours as offering the best combination of properties (see Figure 3.0217). No information is available on the influence of aging temperature or time on toughness properties.

1.06 Hardness

1.061 The alloy is sufficiently beta stabilized to exhibit deep hardenability. Uniform strength levels in sections up through 6 inches thickness have been reported for both the solution annealed and solution annealed plus aged condition (see Tables 1.062 and 1.063).

1.062 Effect of quench rate and specimen location on full section room temperature tensile properties for 6 inch diameter billet in the solution annealed condition. Table 1.062.

1.063 Effect of quench rate and specimen location on full section room temperature tensile properties for 6 inch diameter billet in the solution annealed plus aged condition, Table 1.063.

1.064 The alloy has excellent cold working characteristics, thus it is possible to manufacture the alloy as foil, sheet, tubing, cold drawn wire and bar with a combination of high strength and ductility. Results (1) from the Olsen cup test show that it has superior formability to numerous titanium alloys. Beta III and Ti-8Mo-8V-2Fe-3Al were not included in this comparison. Cold working prior to aging also enhances the final aged properties.

1.0641 Effect of annealing temperature on tensile properties of 0.312 in round cold drawn fastener stock, Figure 1.0641.

1.0642 Effect of cold work on tensile properties of fastener stock in two solution annealed conditions, Figure 1.0642.

1.0643 Effect of various aging treatments on the mechanical properties of cold drawn fastener bar, Table 1.0643.

1.0644 Effect of aging on mechanical properties of fastener stock cold drawn various percentages, Figure 1.0644.

1.0645 Effect of aging temperature on tensile properties of cold worked tubing. Figure 1.0645.

1.07 Forms and Conditions Available

Plate, sheet, foil, tubing, and cold drawn wire and bar.

1.08 Melting and Casting Practice

1.081 The composition of the metastable beta alloy Ti-3Al-8V-6Cr-4Mo-4Zr was designed to meet certain specific requirements. The alloy was planned so it would have not only an attractive combination of properties but also that it would be easy to produce using conventional melting practices and readily available raw materials. This alloy can be melted without difficulty when the commercially available master alloys for vanadium (15Al-85V) and molybdenum (30Al-70Mo) are used. Chromium and zirconium can be added in their elemental forms but elemental vanadium is not recommended because of its high cost. Unalloyed molybdenum should not be added because this element (having both a relatively high melting temperature and density) is very difficult to melt into titanium and consistently obtain a

	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

38-6-44

homogeneous alloy (12).

1.082 Titanium castings have not been widely used to date because of processing problems which have both limited the quality and resulted in high production costs. In an attempt to enhance the quality of titanium castings, recent efforts (11) have been directed at demonstrating the use of pyrolytic graphite coated ceramic molds. Results indicate that these molds are suitable for use with alpha-beta titanium alloys in the manufacture of precision investment castings, but not for beta titanium alloys. Casting fluidity of the alpha-beta Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo is superior to the beta alloys, Beta III and Ti-3Al-8V-6Cr-4Zr-4Mo. The tensile properties of the alpha-beta alloys were acceptable in strength, ductility and notch toughness. The beta alloys showed excellent strength but low ductility, which was caused by the formation of a carbide phase during melting (see Figures 1.083 and 1.084). Thus, induction melting in graphite crucibles is recommended for alpha-beta alloys, however, not for beta titanium alloys.

1.083 Tensile properties of various cast titanium alloys at room temperature, Figure 1.083.

1.084 Tensile properties of various cast titanium alloys at 600F, Figure 1.084.

1.09 Special Considerations

1.091 The alloy exhibits good to excellent fabrication characteristics in both the cold and hot worked conditions.

1.092 Results of a recent investigation (14) show that the beta alloys Ti-3Al-8V-6Cr-4Mo-4Zr, Ti-8Mo-8V-2Fe-3Al, and Beta III are candidate materials for core applications in titanium honeycomb panels. To date only commercially pure titanium, Ti-3Al-2.5V, and Ti-6Al-4V have been used as core materials. The beta alloys offer significant cost reduction potential because of their lower processing costs and a significant increase in strength due to their age hardening characteristics. The 38-6-44 exhibits higher strength properties than the other two beta alloys after various thermal treatments (see Figure 3.0219).

1.093 Unlike Beta III, this alloy may be immune to salt water stress corrosion cracking at room temperature (8)(9). (See 2.033).

1.094 The alloy is susceptible to rapid hydrogen diffusion during heating, pickling, or chemical milling operations (13). However, because of the much higher solubility of hydrogen in the beta phase (BCC) than in the alpha phase (HCP) of titanium, this alloy has a higher tolerance to hydrogen embrittlement than the alpha or alpha-beta alloys.

1.095 Hardenability and quench rate effect. Tables 1.062 and 1.063 show the effect of quench rate and specimen location on full section room temperature tensile properties for 6 inch diameter billet in the solution annealed and solution annealed and aged condition. Uniform strength properties are exhibited by edge, mid radius, and center location specimens for both conditions. Quench rate has no significant effect on strength properties for either condition, however, it does appear to have an effect on ductility for the solution annealed condition.

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range.

2.012 Phase change. Beta transus 1460 ± 25F (See 1.042).

2.0121 Time-temperature-transformation diagrams.

2.013 Thermal conductivity.

2.014 Thermal expansion, Figure 2.014.

2.015 Specific heat.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density. 0.174 lb per cu in, 4.824 gr per cu cm.

2.022 Electric properties.

2.023 Magnetic properties. Alloy is nonmagnetic.

2.024 Emissivity.

2.025 Damping capacity.

2.03 Chemical Properties

2.031 Corrosion resistance. General. Based upon results by Hagemeyer and Gordon (8), this alloy, unlike Beta III, is apparently immune to salt water stress corrosion cracking at room temperature. This immunity has also been found by Czyrklis and Levy (9), who further report that methanolic solutions provide an extremely aggressive environment for room temperature stress corrosion cracking. No data are available as to its susceptibility to solid salt stress corrosion at elevated temperatures.

2.032 Stress corrosion cracking. Results (8) of aging specimens of this alloy at 1050, 1150, and 1250F show no growth of the fatigue precrack after more than 2000 hours submergence in a 3.5 percent sodium chloride solution at a crack tip stress intensity, K_{Ii}, equal to the fracture toughness value (see Table 2.0321).

2.0321 Effect of aging temperature on stress corrosion cracking in a 3.5 percent sodium chloride environment, Table 2.0321.

2.033 Czyrklis and Levy (9) used the cantilever beam test to determine the alloy's degree of susceptibility to stress corrosion cracking when exposed to various environments. Results are plotted in Figure 2.0331 and can be summarized as follows: (1) The alloy in the aged condition (875F) does not exhibit sustained load crack growth in 3.5 percent NaCl in 166 hours. (If susceptible, failure time for titanium alloys is usually within this time frame), (2) Methanolic solutions provide extremely aggressive environments for SCC and susceptibility is markedly increased in CH_3OH + HCl solution and (3) the addition of sodium nitrate to the CH_3OH + HCl solution significantly improves the resistance to SCC. Values for exposure to the various environments are:

Environment	K_{ISCC} - $KSI\sqrt{in}$ (166 hrs. exposure).
3.5 percent NaCl	34.5
CH_3OH	16
CH_3OH + 0.5 percent HCl	6
CH_3OH + 0.5 percent HCl + 0.5 percent Na Na_3	30

2.0331 Effect of testing environment on resistance to stress corrosion cracking of plate in the solution treated plus aged condition, Figure 2.0331.

2.034 Fractographic analysis of the stress corroded specimens showed that crack extension in all environments cited in 2.033 was transgranular. The alloy exhibits fractographic ductile characteristics (dimple rupture) in air, 3.5 percent NaCl and inhibited CH_3OH + HCl environments (9).

3. MECHANICAL PROPERTIES

3.01 Specific Mechanical Properties

3.011 Producers guaranteed minimum mechanical properties for solution annealed condition, Table 3.011.

3.012 Producers guaranteed minimum mechanical properties for solution treated plus aged condition, Table 3.012.

3.02 Mechanical Properties at Room Temperature

3.021 Tension-stress/strain diagrams - tension properties.

3.0211 Longitudinal stress-strain curves (see Figure 3.0311).

3.0212 Transverse stress-strain curves (see Figure 3.0312).

3.0213 Effect of annealing temperature on tensile properties of 1 inch thick hot rolled plate, Figure 3.0213.

3.0214 Effect of annealing temperature on the tensile properties of tubing, Figure 3.0214.

3.0215 Effect of aging temperature on the tensile properties of plate in the solution annealed condition, Figure 3.0215.

3.0216 Effect of aging temperature on tensile properties of annealed tubing, Figure 3.0216.

3.0217 Effect of time at various aging temperatures on the tensile properties of forgings, Figure 3.0217.

3.0218 Effect of aging temperature on the tensile properties of beta alloys in foil form, Table 3.0218.
3.0219 Effect of thermal exposure treatments prior to aging on the tensile properties of beta alloys in foil form, Figure 3.0219.
3.022 Compression-stress/strain diagrams - compression properties.
3.0221 Typical longitudinal compressive stress-strain curve for solution treated plus aged condition (see Figure 3.0321).
3.0222 Typical transverse compressive stress-strain curve for solution treated plus aged condition (see Figure 3.0322).
3.023 Impact.
3.024 Bending.
3.025 Torsion and shear.
3.0251 Effect of solution temperature on the torsion and tensile properties of aged bar, Table 3.0251.
3.0252 Effect of aging treatment on the torsion and tensile properties of aged bar, Table 3.0252.
3.026 Bearing.
3.027 Stress concentration.
3.0271 Notch properties.
3.0272 Fracture toughness.
3.02721 Plane strain fracture toughness properties for the solution treated plus aged condition, Table 3.02721.
3.028 Combined properties.

3.03 Mechanical Properties at Various Temperatures
3.031 Tension-stress/strain diagrams - tension properties.
3.0311 Longitudinal stress-strain curves at elevated temperatures for the solution treated plus aged condition, Figure 3.0311.
3.0312 Transverse stress-strain curves at elevated temperatures for the solution treated plus aged condition, Figure 3.0312.
3.0313 Effect of test temperature on tensile properties of bar in the solution annealed condition, Figure 3.0313.
3.0314 Effect of test temperature on tensile properties of bar in the solution treated plus aged condition, Figure 3.0314.
3.0315 Effect of test temperature on tensile properties of billet in the solution treated plus aged condition, Figure 3.0315.
3.0316 Effect of test temperature on the tensile properties of various size tubing, Table 3.0316.
3.032 Compression-stress/strain diagrams. Compression properties.
3.0321 Longitudinal compressive stress-strain and tangent modulus curves at elevated temperatures for the solution treated plus aged condition, Figure 3.0321.
3.0322 Transverse compressive stress-strain and tangent modulus curves at elevated temperatures for the solution treated plus aged condition, Figure 3.0322.
3.0323 Effect of test temperature on compressive yield strength of forging in the solution treated plus aged condition, Figure 3.0323.
3.033 Impact.
3.034 Bending.
3.035 Torsion and shear (See Table 3.044)
3.036 Bearing.
3.037 Stress concentration.
3.0371 Notch properties.
3.0372 Fracture toughness.
3.038 Combined properties.

3.04 Creep and Creep Rupture Properties
3.041 Creep rupture curves for billet at 500, 700 and 900F in the solution annealed plus aged condition, Figure 3.041.
3.042 Thermal and creep stability data for cold drawn, solution annealed and solution annealed plus aged bar, Table 3.042.
3.043 Effect of thermal exposure on tensile properties of various size tubing, Table 3.043.
3.044 Effect of various heat treatments on the thermal stability of tensile and shear properties of bar, Table 3.044.

3.05 Fatigue Properties
3.051 S-N curves at elevated temperatures for smooth and notched specimens in the solution treated plus aged condition at a stress ratio of R = 0.1, Figure 3.051.

3.06 Elastic Properties
3.061 Poisson's ratio.
3.062 Modulus of elasticity (Reference 1).

Orientation	Annealed Condition	STA Condition
Tension	14×10^3 ksi	15.4×10^3 ksi
Compression	-	14.8×10^3 ksi

3.0621 Effect of test temperature on the modulus of elasticity in tension and compression of billet in the solution treated plus aged condition, Figure 3.0621.
3.063 Modulus of rigidity.
3.0631 Effect of solution treatment on modulus of rigidity of bar, Table 3.0631.
3.0632 Effect of aging treatment on modulus of rigidity of bar, Table 3.0632.
3.064 Tangent Modulus.
3.0641 Longitudinal tangent modulus at elevated temperatures for the solution treated plus aged condition, Figure 3.0641.
3.0642 Transverse tangent modulus at elevated temperatures for the solution treated plus aged condition, Figure 3.0642.
3.065 Secant modulus.

4. FABRICATION

4.01 Formability
(See 1.064).
4.011 General. The alloy has good hot and cold workability and is highly resistant to cracking during hot working. Hot working is accomplished in the temperature range of 1500F to 1800F with relative insensitivity to workability or subsequent mechanical property variation. Because of its good cold working characteristics, it is possible to manufacture the alloy as sheet, foil, tubing, cold drawn wire and bar with a combination of high strength and ductility.

4.02 Machining and Grinding
Contact Air Force Machinability Data Center, 3980 Rosslyn Drive, Cincinnati, Ohio, 45209.

4.03 Welding
Limited data (1) indicate that the alloy can be welded in the solution annealed condition, but not after solution treating and aging. Welds can be strengthened by aging, however, there is a significant loss in ductility.
4.031 Mechanical properties of sheet and plate weldments, Table 4.031.

4.04 Heat Treatment

4.05 Surface Treatment
The cleaning procedures established for the first commercial beta alloy, Ti-13V-11Cr-3Al, are particularly applicable for this alloy (13). In addition, even though the beta alloys have a high tolerance to hydrogen embrittlement, caution should be exercised in any chemical cleaning operation which is capable of imparting hydrogen to the metal.

	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

38-6-44

	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

38-6-44

Source	(1)	
	Weight Percent	
Element	Minimum	Maximum
Aluminum	3.0	4.0
Vanadium	7.5	8.5
Chromium	5.5	6.5
Molybdenum	3.5	4.5
Zirconium	3.5	4.5
Iron		0.30
Nitrogen		0.03
Carbon		0.05
Oxygen		0.12
Hydrogen		0.020
Other Elements: Each		0.10
Total		0.40

TABLE 1.041 PRODUCERS SPECIFIED COMPOSITION

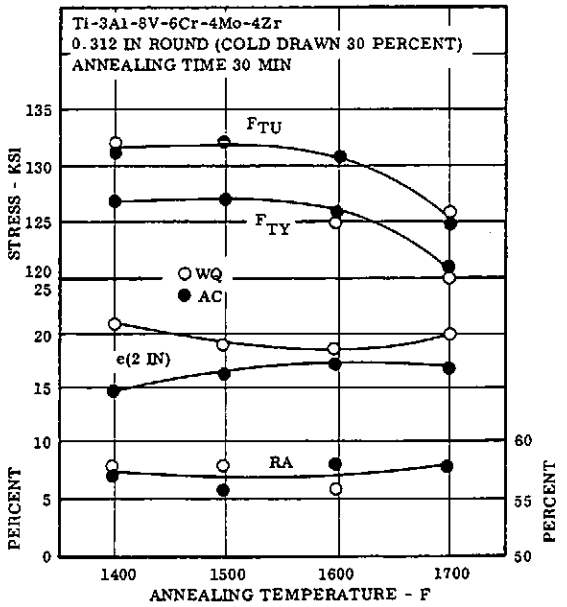


FIG. 1.0641 EFFECT OF ANNEALING TEMPERATURE ON TENSILE PROPERTIES OF 0.312 IN ROUND COLD DRAWN FASTENER STOCK. (1)

Source	(2)					
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr					
Form	6 in diameter x 6 in long					
Condition	1500F, 15 Min, WQ			1500F, 15 Min. AC		
Location	Edge	Mid Radius	Center	Edge	Mid Radius	Center
F_{tu} (ksi)	120	120	117	118	120	120
F_{ty} (ksi)	114	113	111	112	113	113
e (1 in) (percent)	16	10	12	15	15	14
RA (percent)	42	22	25	36	31	33
Longitudinal tests. Data average of two tests.						

TABLE 1.062 EFFECT OF QUENCH RATE AND SPECIMEN LOCATION ON FULL SECTION ROOM TEMPERATURE TENSILE PROPERTIES FOR 6 IN DIAMETER BILLET IN THE SOLUTION ANNEALED CONDITION.

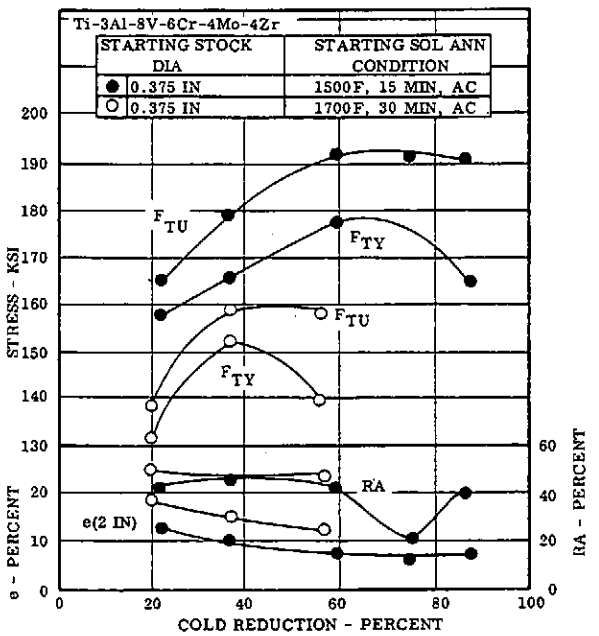


FIG. 1.0642 EFFECT OF COLD WORK ON TENSILE PROPERTIES OF FASTENER STOCK IN TWO SOLUTION ANNEALED CONDITIONS. (3)

Source	(2)					
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr					
Form	6 in diameter x 6 in long					
Condition	1500F, 15 Min., WQ; 1050F, 12 hrs., AC			1500F, 15 Min., AC; 1050F, 12 hrs., AC		
Location	Edge	Mid Radius	Center	Edge	Mid Radius	Center
F_{tu} (ksi)	176	173	174	173	175	178
F_{ty} (ksi)	165	163	164	167	167	168
e (1 in) (percent)	9	10	9	9	9	9
RA (percent)	18	20	18	18	17	16
Longitudinal tests. Data average of two tests.						

TABLE 1.063 EFFECT OF QUENCH RATE AND SPECIMEN LOCATION ON FULL SECTION ROOM TEMPERATURE TENSILE PROPERTIES FOR 6 IN DIAMETER BILLET IN THE SOLUTION ANNEALED PLUS AGED CONDITION.

Source	(1)				
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr				
Form	Bar				
Size (in)	Condition	F_{tu} (ksi)	F_{ty} (ksi)	e (2 in) (percent)	RA (percent)
0.330	AS CD - 22.5 percent	165	157	13	43
	CD + 800F, 6 hr, AC	242	228	5	17
	CD + 800F, 12 hr, AC	246	234	1	12
	CD + 900F, 6 hr, AC	229	215	5	16
	CD + 900F, 12 hr, AC	223	205	7	18
	CD + 1000F + 6 hr, AC	191	177	12	18
0.510	AS CD - 30 percent	168	160	8	25
	CD + 900F, 6 hr, AC	238	222	5	6
	CD + 950F, 6 hr, AC	228	211	5	6
	CD + 1000F, 4 hr, AC	201	185	10	24

TABLE 1.0643 EFFECT OF VARIOUS AGING TREATMENTS ON THE MECHANICAL PROPERTIES OF COLD DRAWN FASTENER BAR.

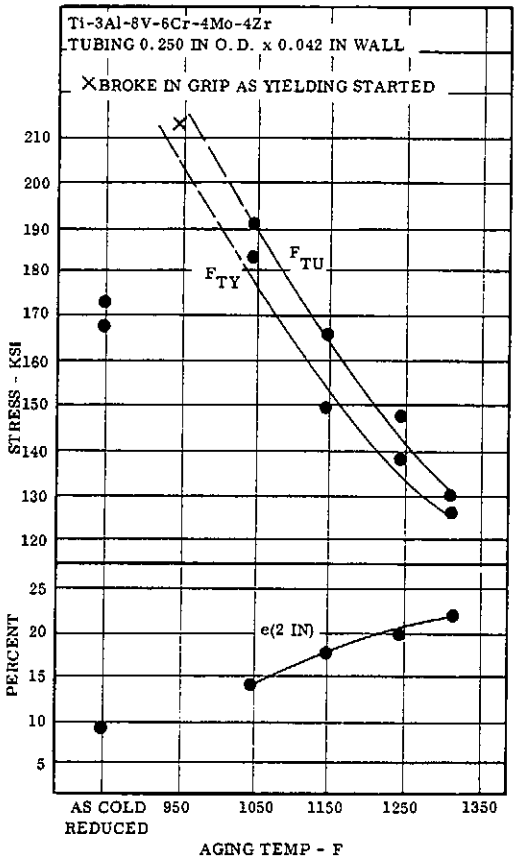


FIG. 1.0645 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF COLD WORKED TUBING. (5)

	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

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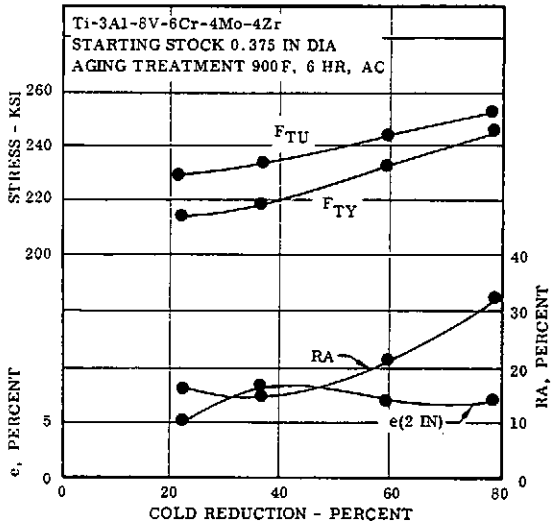


FIG. 1.0644 EFFECT OF AGING ON MECHANICAL PROPERTIES OF FASTENER STOCK COLD DRAWN VARIOUS PERCENTAGES. (3)

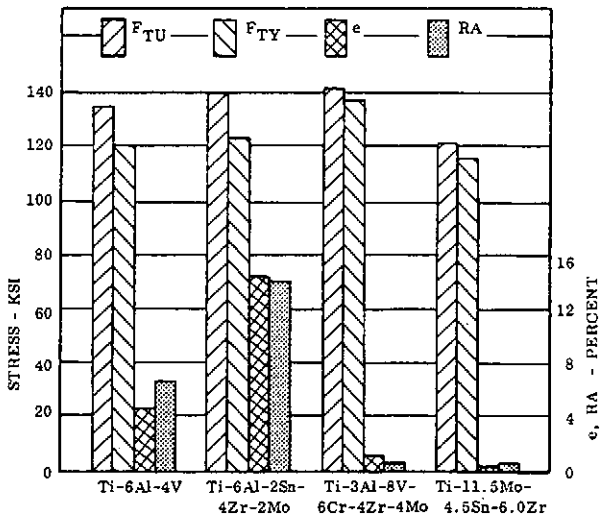


FIG. 1.083 TENSILE PROPERTIES OF VARIOUS CAST TITANIUM ALLOYS AT ROOM TEMPERATURE. (11)

	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

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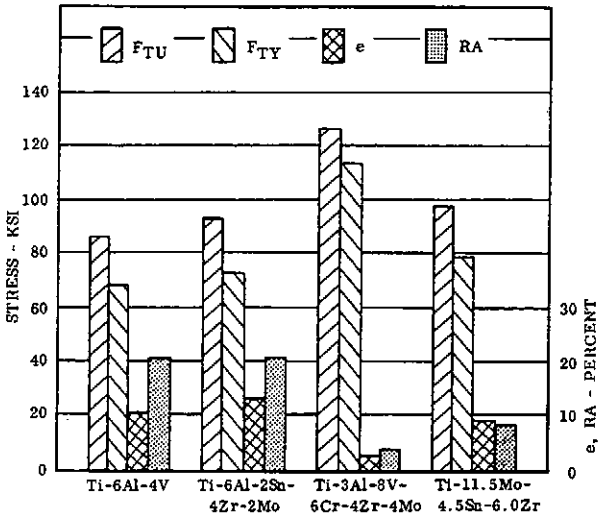


FIG. 1.084 TENSILE PROPERTIES OF VARIOUS CAST TITANIUM ALLOYS AT 600F. (11)

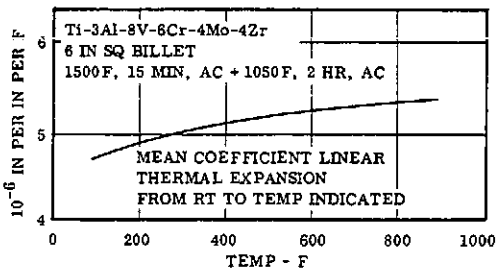


FIG. 2.014 THERMAL EXPANSION. (6)

Source	(8)
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr
Form	1.25 in thick plate
Condition	1700F, 1 hr, AC, age 8 hr, VAC
Environment	3.5 percent NaCl in distilled water
Aging Temperature (F)	Stress Corrosion Cracking K_{ISCC} Ksi$\sqrt{in}$
1050	> 47 (a)
1150	> 55 (a)
1250	> 50 (a)

(a) No crack growth took place, thus the value of K_{ISCC} is reported as being greater than maximum value of K_I tested. Specimens used were a bolt loaded, constant deflection WOL type, containing a fatigue crack W of 2.55 in and B of 0.80 in. Orientation L-T.

TABLE 2.0321 EFFECT OF AGING TEMPERATURE ON STRESS CORROSION CRACKING IN A 3.5 PERCENT SODIUM CHLORIDE ENVIRONMENT.

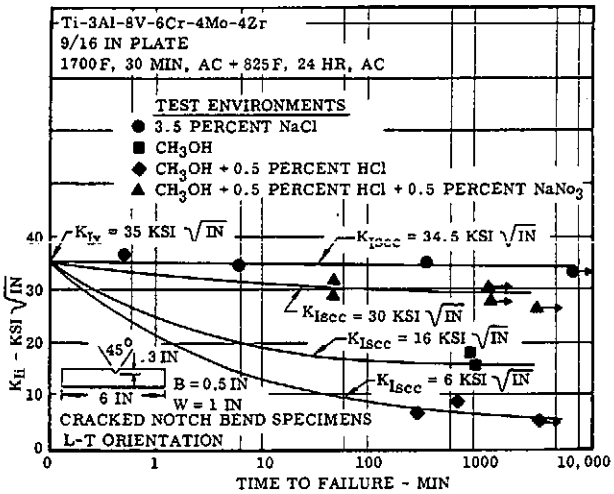


FIG. 2.0331 EFFECT OF TESTING ENVIRONMENT ON RESISTANCE TO STRESS CORROSION CRACKING OF PLATE IN THE SOLUTION TREATED PLUS AGED CONDITION. (9)

NOTE: K_{Ix} EQUALS THE AIR VALUE.

Source	(2)						
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr						
Condition	Sol. ann - 1500F, 15 - 30 min, AC						
Form	Sheet and Strip		Plate		Bar and Forged Billet		
Thickness-in.	to 0.070	>0.070 to 0.187	to 2	>2 to 4	0.50 to 1.50	>1.50 to 3.00	>3.00 to 9.00
F_{tu} (ksi)	125	125	125	120	125	120	125
F_{ty} (ksi)	120	120	120	115	120	115	120
e (2 in) (percent)	8 (a)	8	10	8	10	10	10 (d)
				6 (b)		8(b)	
				3 (c)			
RA (percent)					30	25	25
						20(b)	

(a) Gauges < 0.030 inch
(b) Transverse Direction
(c) Short transverse direction
(d) Results based on forged samples 3:1 minimum upset

TABLE 3.011 PRODUCERS GUARANTEED MINIMUM MECHANICAL PROPERTIES FOR SOLUTION ANNEALED CONDITION.

Source	(2)						
Type	Ti-3Al-8V-6Cr-4Mo-4Zr						
Condition	STA: Sol. ann 1500 - 1700F, 1 hr., AC; Age 850 to 1000F, 24 hr, AC						
Form	Sheet and Strip	Plate		Bar and Billet			
Thickness - in	All gauges	to 2	>2 to 4	0.50 to 1.50	>1.50 to 3.00	>3.00 to 6.00	>3.00 to 9.00(a)
F_{tu} (ksi)	180	180	180	190	180	170	180
F_{ty} (ksi)	170	170	170	180	170	160	170
e (2 in) (percent)	6	8	8	8	8	6	10
			6(b)		6(b)	3(b)	
RA (percent)				15	15	15	20
					15(a)	5(b)	

(a) Results based on forged samples 3:1 minimum upset.
(b) Transverse direction.

TABLE 3.012 PRODUCERS GUARANTEED MINIMUM MECHANICAL PROPERTIES FOR SOLUTION TREATED PLUS AGED CONDITION.

	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

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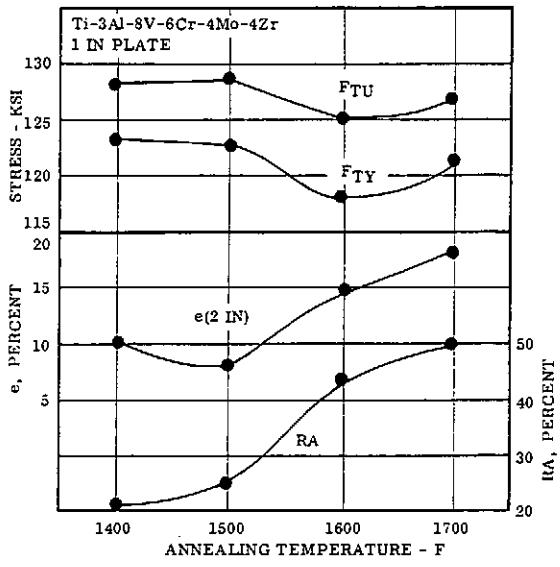


FIG. 3.0213 EFFECT OF ANNEALING TEMPERATURE ON TENSILE PROPERTIES OF 1 IN THICK HOT ROLLED PLATE. (1)

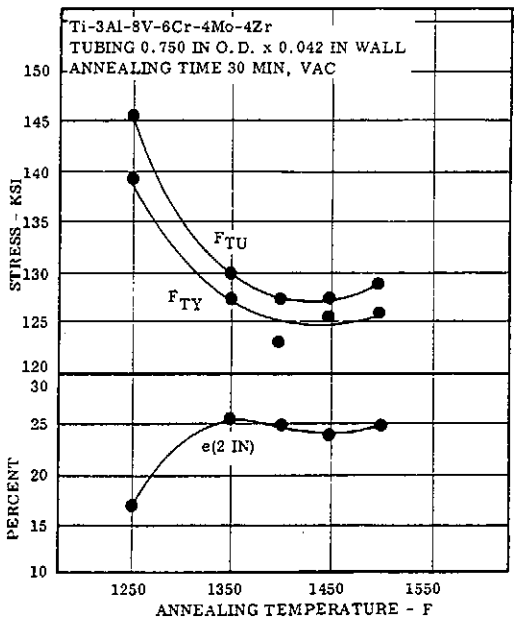


FIG. 3.0214 EFFECT OF ANNEALING TEMPERATURE ON THE TENSILE PROPERTIES OF TUBING. (5)

	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

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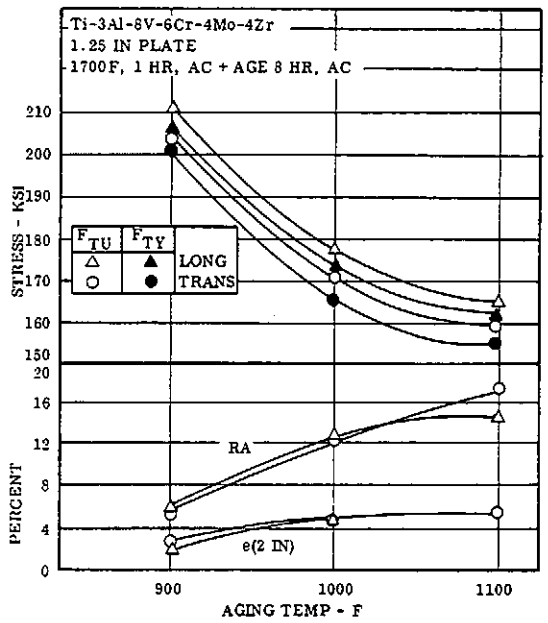


FIG. 3.0215 EFFECT OF AGING TEMPERAURE ON THE TENSILE PROPERTIES OF PLATE IN THE SOLUTION ANNEALED CONDITION. (8)

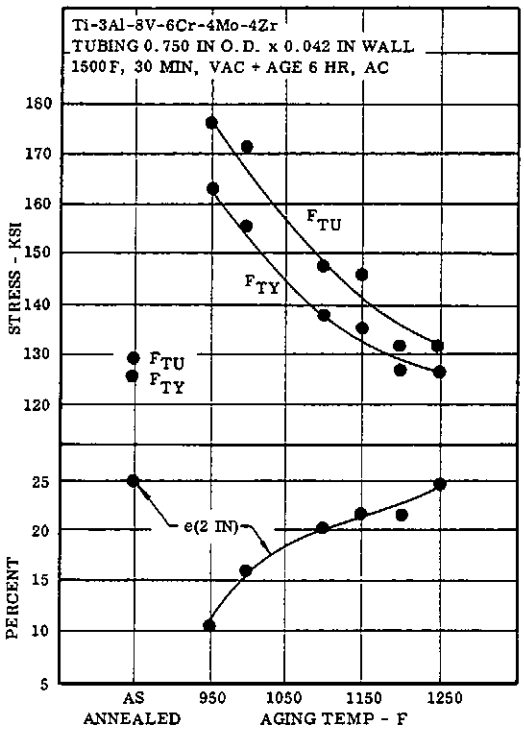


FIG. 3.0216 EFFECT OF AGING TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED TUBING. (5)

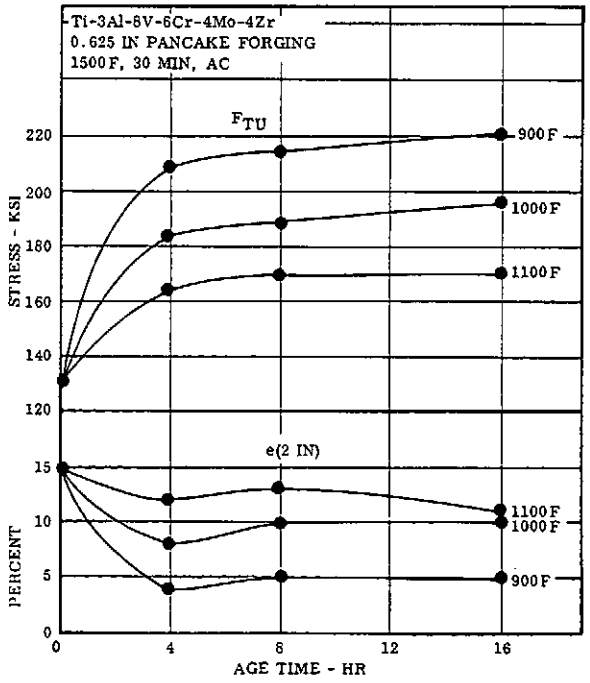


FIG. 3.0217 EFFECT OF TIME AT VARIOUS AGING TEMPERATURES ON THE TENSILE PROPERTIES OF FORGING. (1)

Source	(14)					
Form	0.003 in. Foil					
Condition	1500F, 15 min, FC + age, 8 hr, AC					
Alloys	Ti-3Al-8V-6Cr-4Mo-4Zr		Ti-11.5Mo-4.5Sn-6.0Zr		Ti-8Mo-8V-2Fe-3Al	
Aging Temperature	950F	1000F	950F	1000F	950F	1000F
F_{tu} (ksi)	193	174	187	180	193	182
F_{ty} (ksi)	180	163	172	166	175	-
e (2 in.) (percent)	6.9	3.4	5.0	3.0	5.0	4.0

TABLE 3.0218 EFFECT OF AGING TEMPERATURE ON THE TENSILE PROPERTIES OF BETA ALLOYS IN FOIL FORM.

	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

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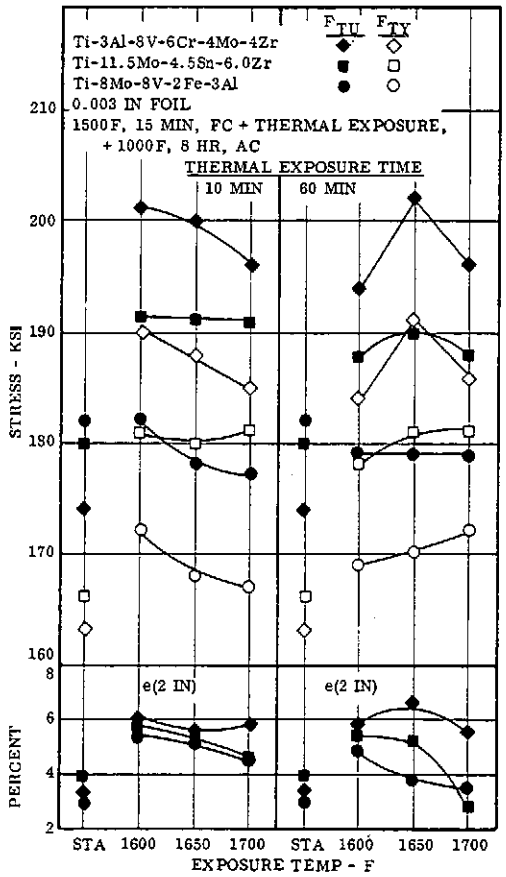


FIG. 3.0219 EFFECT OF THERMAL EXPOSURE TREATMENTS PRIOR TO AGING ON THE TENSILE PROPERTIES OF BETA ALLOYS IN FOIL FORM. (14)

Ti
3 Al
8 V
6 Cr
4 Mo
4 Zr

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Source	(12)									
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr									
Form	2.625 in diameter bar									
Solution Treatment (c)	Torsion Properties(d)		Long Tensile Properties				45° Tensile Properties			
	F_{st} (ksi)	F_{sty} (ksi)	F_{tu} (ksi)	F_{ty} (ksi)	e (percent)	RA (percent)	F_{tu} (ksi)	F_{ty} (ksi)	e (percent)	RA (percent)
1400F, 30 min. AC (a)	148	134	214	205	6	13	211	201	2	3
1500F, 30 min. AC (a)	160	140	212	203	7	15	213	202	3	5
	164	140	212	203	7	15	213	202	3	5
1700F, 30 min, AC + 1500F, 30 min, AC(a)	166	133	211	200	4	6	209	197	4	4
	162	132	204	194	4	6	200	190	5	8
1700F, 30 min, AC + 1500F, 30 min, AC(b)	171	138	204	192	5	7	213	205	5	8

(a) Laboratory heat treatment.
(b) Production heat treatment
(c) Solution treatment followed by aging at 900F, 24 hours, AC.
(d) Based on gage dimensions of 1.375 in diameter and 9.5 in length.

TABLE 3.0251 EFFECT OF SOLUTION TEMPERATURE ON THE TORSION AND TENSILE PROPERTIES OF AGED BAR.

Source	(12)					
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr					
Form	2.625 in diameter bar					
Condition	Production Anneal 1700F, 30 min, AC; 1500F, 30 min, AC + age					
Aging Treatment	Torsion Properties(a)		45° Tensile Properties			
	F_{st} (ksi)	F_{sty} (ksi)	F_{tu} (ksi)	F_{ty} (ksi)	e (percent)	RA (percent)
900F, 12 hr, AC	162	132	206	192	4	6
900F, 24 hr, AC	167	134	205	191	5	7
925F, 8 hr, AC	162	129	205	192	4	6
950F, 8 hr, AC	159	127	200	187	5	6

(a) See (d) Table 3.0251

TABLE 3.0252 EFFECT OF AGING TREATMENT ON THE TORSION AND TENSILE PROPERTIES OF AGED BAR.

Source	(6)(7)	
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr	
Condition	STA: 1500F, 15 min, AC + 1050F, 12 hr, AC	
Test temp.	RT	
Form	Billet (6) (F_{ty} = 167 ksi) 6 in sq.	Forging (7) (F_{ty} = 168 ksi) 4 in thick
Orientation	Plane strain fracture toughness K_{Ic} - ksi$\sqrt{in}$	
L-T	58(a)	-
L-T	60(b)	-
L-T	-	53

Bend specimen - 3 point loading
Data average of three or more tests
Thickness, B = 0.50 inch (6)
B = 0.75 inch (7)
Testing procedure and data conform to ASTM E399

(a) Specimens from outside location of billet.
(b) Specimens from middle location of billet.

TABLE 3.02721 PLANE STRAIN FRACTURE TOUGHNESS PROPERTIES FOR THE SOLUTION TREATED PLUS AGED CONDITION.

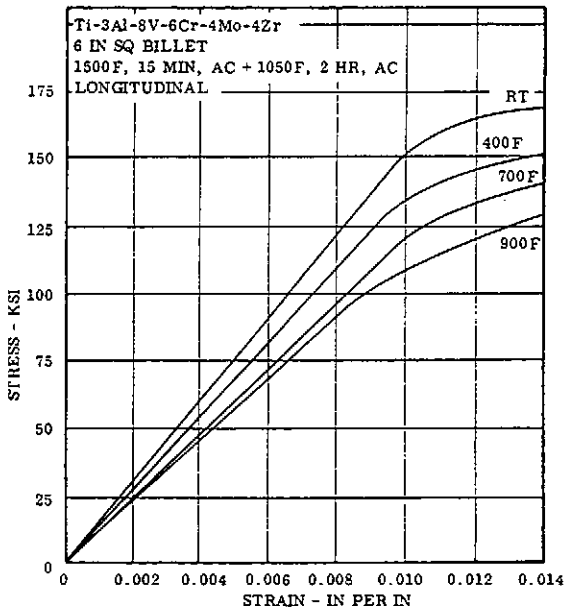


FIG. 3.0311 LONGITUDINAL STRESS-STRAIN CURVES AT ELEVATED TEMPERATURES FOR THE SOLUTION TREATED PLUS AGED CONDITION. (6)

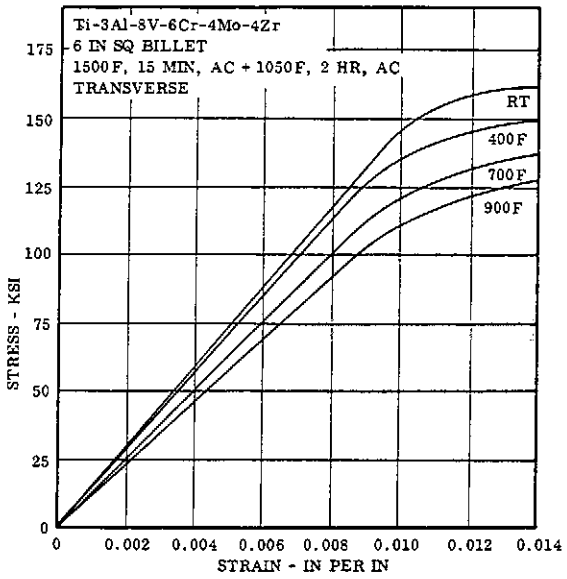
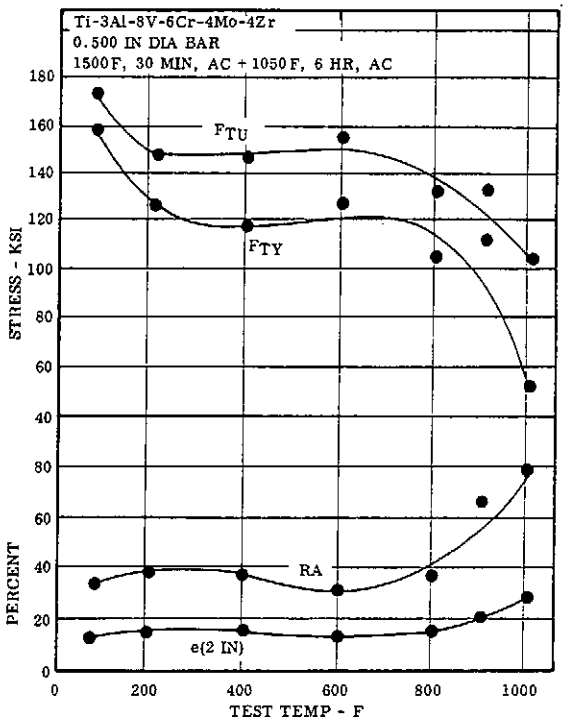


FIG. 3.0312 TRANSVERSE STRESS-STRAIN CURVES AT ELEVATED TEMPERATURES FOR THE SOLUTION TREATED AGED CONDITION. (6)



	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

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FIG. 3.0314 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF BAR IN THE SOLUTION TREATED PLUS AGED CONDITION. (1)

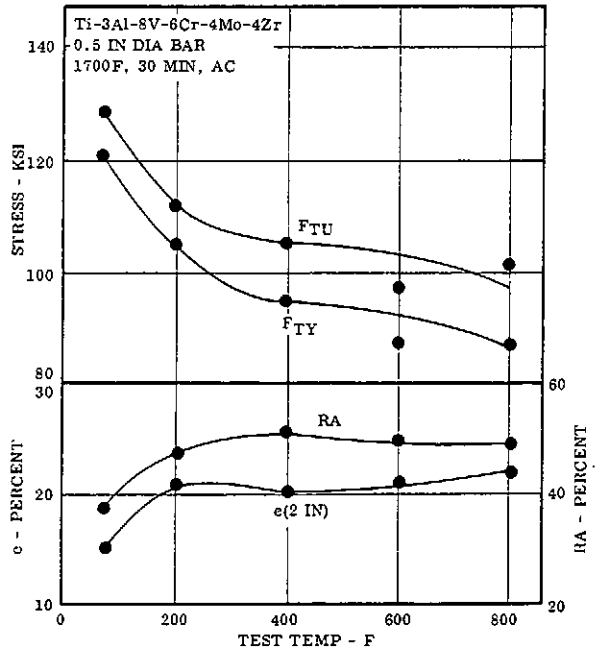


FIG. 3.0313 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF BAR IN THE SOLUTION ANNEALED CONDITION. (1)

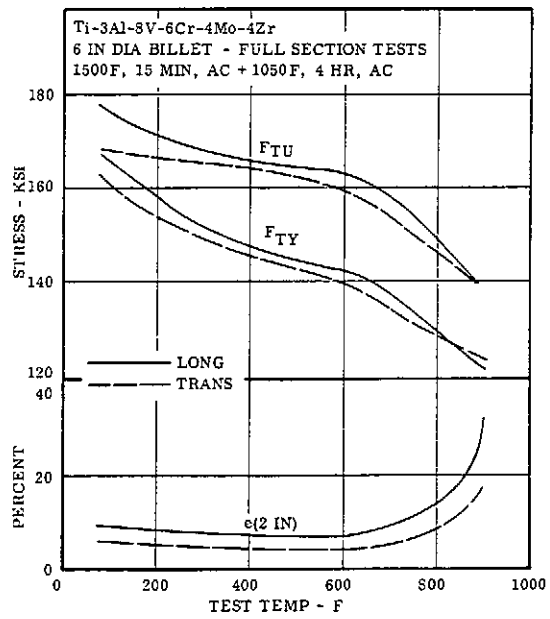


FIG. 3.0315 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF BILLET IN THE SOLUTION TREATED PLUS AGED CONDITION. (1)

Ti
3 Al
8 V
6 Cr
4 Mo
4 Zr

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Source	(5)			
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr			
Form	Tubing			
Condition	Sol. ann. 1500F - 1.5 hr - vacuum cooled			
Tubing size (in)	Test temp (F)	F_{tu} (ksi)	F_{ty} (ksi)	e (2 in) (percent)
0.750 OD x 0.042 wall	RT	127	122	20
	450	107	103	34
	650	103	91	31
0.540 OD x 0.030 wall	RT	129	125	18
	450	105	100	28
	650	99	88	30
0.375 OD x 0.025 wall	RT	137	130	14
	450	108	100	16
	650	102	90	21
Data are average of two tests				

TABLE 3.0316 EFFECT OF TEST TEMPERATURE ON THE TENSILE PROPERTIES OF VARIOUS SIZE TUBING

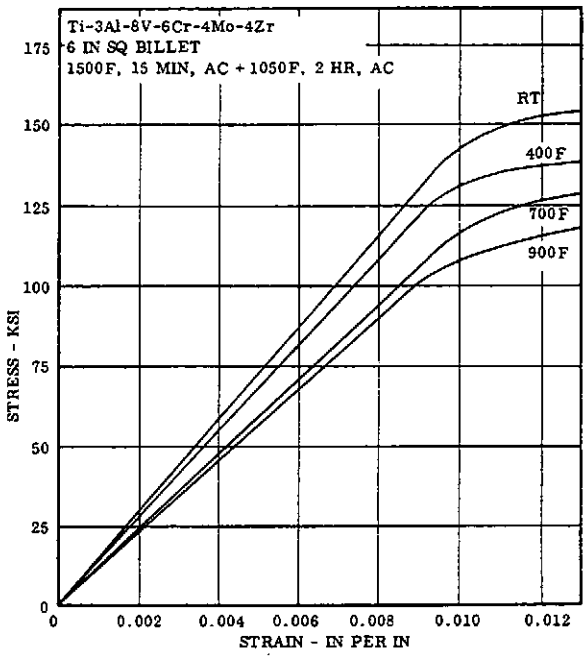


FIG. 3.0322 TRANSVERSE COMPRESSIVE STRESS-STRAIN CURVES AT ELEVATED TEMPERATURES FOR THE SOLUTION TREATED PLUS AGED CONDITION. (6)

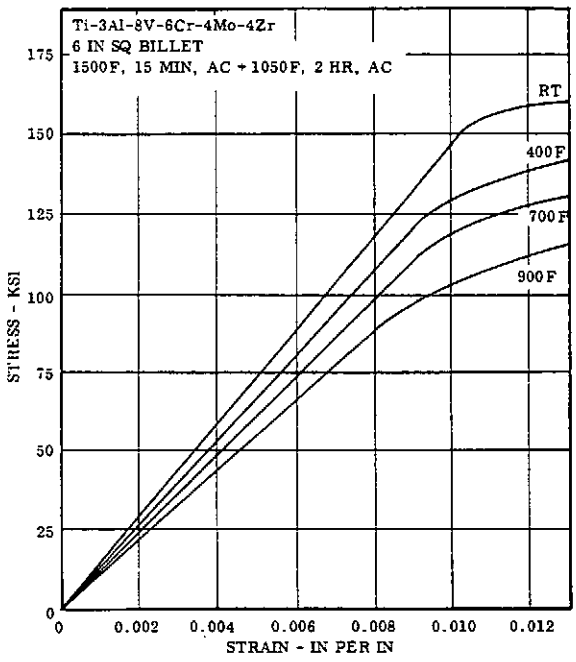


FIG. 3.0321 LONGITUDINAL COMPRESSIVE STRESS-STRAIN CURVES AT ELEVATED TEMPERATURES FOR THE SOLUTION TREATED PLUS AGED CONDITION. (6)

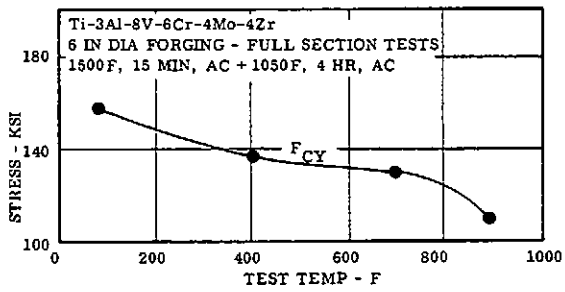


FIG. 3.0323 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF FORGING IN THE SOLUTION TREATED PLUS AGED CONDITION. (1)

	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

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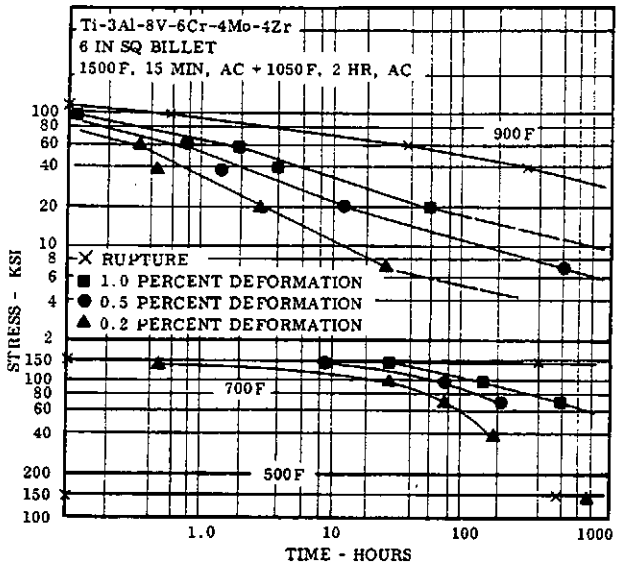


FIG. 3.041 CREEP RUPTURE CURVES FOR BILLET AT 500, 700 AND 900F IN THE SOLUTION ANNEALED PLUS AGED CONDITION. (6)

Source	(3)(4)								
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr								
Form	Bar								
			Tensile Properties						
			Before Exposure				After Exposure			
Bar Dia. (in)	Condition	Thermal Exposure	F_{tu} (ksi)	F_{ty} (ksi)	e (2 in) (percent)	RA (percent)	F_{tu} (ksi)	F_{ty} (ksi)	e (2 in) (percent)	RA (percent)
0.330	As CD - 22.5 percent	500F-40 ksi-100 hr.	165	157	13	43	164	151	12	50
0.330	As Sol Ann -1550F	500F-0 ksi-25 hr.	130	128	16	49	131	129	19	47
		500F-0 ksi-100 hr.					131	128	16	49
		500F-40 ksi-25 hr.					132	129	19	48
		500F-40 ksi-100 hr.					133	128	18	50
		500F-40 ksi-200 hr.					130	127	18	48
		600F-40 ksi-100 hr.					138	133	23	48
0.500	As Sol ann 1500F; Age 1050F, 6 hr.	600F-80 ksi-1107 hr(a)	174	160	13	35	174	162	14	31
		700F-75 ksi-212 hr(b)					180	166	12	30
		800F-30 ksi-72 hr (c)					181	165	15	29

(a) Total creep deformation 0.126 percent.
(b) Total creep deformation 0.234 percent.
(c) Total creep deformation 0.250 percent.

TABLE 3.042 THERMAL AND CREEP STABILITY DATA FOR COLD DRAWN, SOLUTION ANNEALED AND SOLUTION ANNEALED PLUS AGED BAR.

Source	(5)					
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr					
Form	Tubing					
Condition	Sol. ann. 1500F - 1.5 hr - vacuum cooled					
Thermal Exposure	500F - 0 ksi - 100 hr.					
	Tensile Properties					
	Before Exposure			After Exposure		
Tubing Size (in)	F_{tu} (ksi)	F_{ty} (ksi)	e (2 in) (percent)	F_{tu} (ksi)	F_{ty} (ksi)	e (2 in) (percent)
0.750 OD x 0.042 wall	127	122	20	128	125	18
0.540 OD x 0.030 wall	129	125	18	124	121	15
0.375 OD x 0.025 wall	137	130	14	135	132	17

TABLE 3.043 EFFECT OF THERMAL EXPOSURE ON TENSILE PROPERTIES OF VARIOUS SIZE TUBING.

	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

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Source	(3)									
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr									
Form	0.312 in diameter bar									
Exposure Condition	550F - no stress - 500 hr.									
	Room Temp. Tensile and Shear Properties									
	Before Exposure					After Exposure				
Condition before Exposure	F_{tu} (ksi)	F_{ty} (ksi)	e (2 in) (percent)	RA (percent)	Shear (ksi)	F_{tu} (ksi)	F_{ty} (ksi)	e (2 in) (percent)	RA (percent)	Shear (ksi)
1500F-15 min-AC	131	130	16	49	92	136	130	15	39	95
	129	127	16	49	91	136	129	15	44	95
1500F-15 min-AC;	220	208	8	17	127	227	210	7	10	125
800F-6 hrs, AC	216	204	8	18	123					125
1500F-15 min-AC;	210	187	7	21	121	212	198	8	17	124
900F-6 hr-AC					119	209	197	9	16	124
1500F-15 min-AC;	178	162	15	38	111	172	157	15	41	110
1000F-6 hr-AC	180	167	16	40	110	173	159	17	37	110
1500F-15 min-AC;	163	151	15	50	104	160	149	20	42	105
1050F-6 hr-AC	161	153	13	49	102	161	147	20	44	105
1500F-15 min-AC;						147	139	21	45	100
1150F -6 hr-AC						149	138	20	46	99
1500F-15 min-AC;	135	129	18	48	91	134	127	20	46	91
1250F-6 hr-AC	136	130	16	49	92	138	131	13	39	92

TABLE 3.044 EFFECT OF VARIOUS HEAT TREATMENTS ON THE THERMAL STABILITY OF TENSILE AND SHEAR PROPERTIES OF BAR.

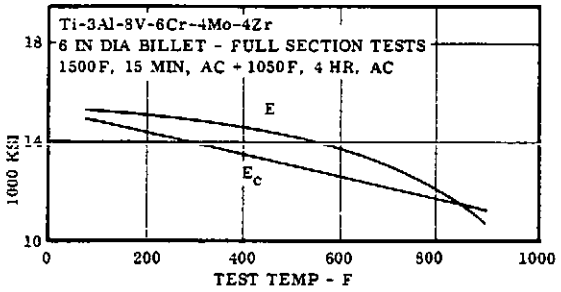


FIG. 3.0621 EFFECT OF TEST TEMPERATURE ON THE MODULUS OF ELASTICITY IN TENSION AND COMPRESSION OF BILLET IN THE SOLUTION TREATED PLUS AGED CONDITION. (1)

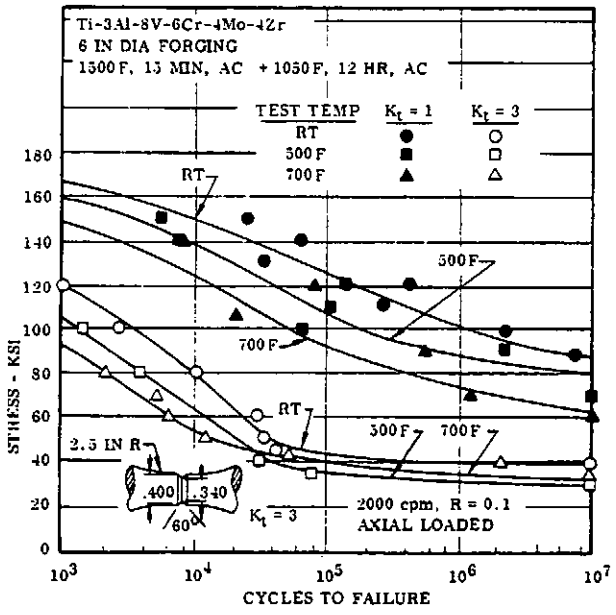


FIG. 3.051 S-N CURVES AT ELEVATED TEMPERATURES FOR SMOOTH AND NOTCHED SPECIMENS IN THE SOLUTION TREATED PLUS AGED CONDITION AT A STRESS RATIO OF R = 0.1. (6)

Source	(12)	
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr	
Form	2.625 in diameter bar	
Solution Treatment	Modulus of Rigidity, G x 10^6 psi	
	(a)	(b)
1400F, 30 min, AC (c)	6.08	6.04
1500F, 30 min, AC (c)	5.94	5.82
		6.37
1700F, 30 min, AC +	6.05	6.30
1500F, 30 min, AC (c)		6.30
1700F, 30 min, AC +		6.25
1500F, 30 min, AC (d)		

(a) Determined by ultrasonic pulse-echo technique
(b) Statically determined from torsion test data
(c) Laboratory heat treatment
(d) Production heat treatment

TABLE 3.0631 EFFECT OF SOLUTION TREATMENT ON MODULUS OF RIGIDITY OF BAR.

Source	(12)
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr
Form	2.625 in diameter bar
Condition	Production anneal 1700F, 30 min, AC; 1500F, 30 min, AC + age

Aging Treatment	Modulus of Rigidity G x 10^6 psi (a)
900F-12 hr-AC	5.95
900F-24 hr-AC	6.28
925F-8 hr-AC	5.91
950F-8 hr-AC	6.04

(a) Statistically determined from torsion test data

TABLE 3.0632 EFFECT OF AGING TREATMENT ON MODULUS OF RIGIDITY OF BAR.

	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

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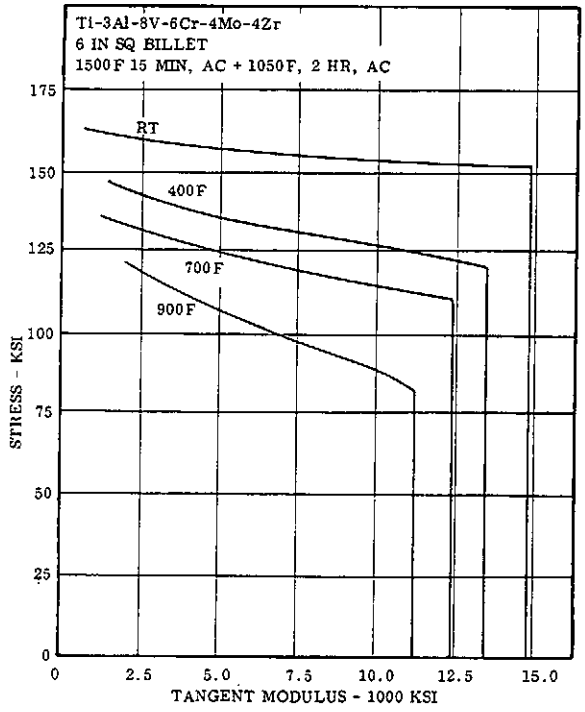


FIG. 3.0641 LONGITUDINAL TANGENT MODULUS AT ELEVATED TEMPERATURES FOR THE SOLUTION TREATED PLUS AGED CONDITION. (6)

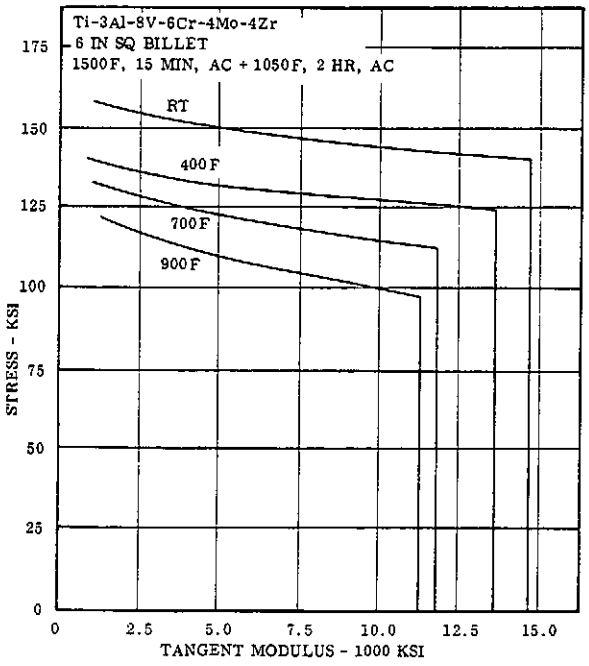


FIG. 3.0642 TRANSVERSE TANGENT MODULUS AT ELEVATED TEMPERATURES FOR THE SOLUTION TREATED PLUS AGED CONDITION. (6)

Source	(1)									
Alloy	Ti-3Al-8V-6Cr-4Mo-4Zr									
Form	Sheet - 0.085 inch and Plate - 0.500 inch									
	F_{tu} (ksi)		F_{ty} (ksi)		e (percent)		RA (percent)		Failure Site	
Condition	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
1500F, 15 min, AC	126	-	118	-	13	-	-	-		
1500F, 15 min, AC + weld	119	119	113	109	7	10	-	28	WM	WM
1500F, 15 min, AC + weld + 1100F, 2 hr, AC	-	152	-	144	-	6	-	9	-	WM

(a) Sheet
(b) Plate
Gas tungsten-arc (GTA) weld process.
Ti-3Al-8V-6Cr-4Mo-4Zr filler metal used.
WM - weld metal.
Data average of two tests.

TABLE 4.031 MECHANICAL PROPERTIES OF SHEET AND PLATE WELDMENTS.

	Ti
3	Al
8	V
6	Cr
4	Mo
4	Zr

38-6-44

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REVISED: MARCH 1966

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NONFERROUS ALLOYS

	Ti
13	V
11	Cr
3	Al

B 120 VCA

1. GENERAL

B 120 VCA is a heat treatable body-centered cubic metastable beta alloy which is formable in the solution treated condition and can be aged to yield strengths of 170 to 200 ksi. Extreme cold working prior to aging has produced tensile strengths as high as 300 ksi in small section specimens. The alloy has more than 25 percent alloy content and stabilizes in a body-centered cubic form down to 275F with moderately rapid cooling. This structure is retained down to room temperature. In this condition the alloy can be strengthened by reheating above 600F where precipitation of the alpha phase (close-packed hexagonal structure) and of the compound $TiCr_2$ occurs. The solution treating temperature is of particular importance in its influence on toughness, and temperatures below those commonly used may be employed to advantage in this respect. A desirable characteristic of the alloy is that it can be air cooled from a low solution treatment temperature (1400 to 1450F) and yet exhibit good aging response, (1, p. 4)(4)(16)(38, p. 8, 9).

1.01 Commercial Designation

B 120 VCA Titanium Alloy.

1.02 Alternate Designations

Crucible B 120 VCA,
Republic RS 120B,
Ti-13V-11Cr-3Al,
Beta Ti.

1.03 Specifications

AMS 4917, sheet, strip and plate.
MIL-T-9046, sheet, strip and plate.

1.04 Composition

Table 1.04.

TABLE 1.04

Source	Crucible (5)		TMCA(2, p. 8)		AMS (20)	
	Percent		Percent		Percent	
	Min	Max	Min	Max	Min	Max
Aluminum	2.50	4.00	2.50	3.50	2.5	4.0
Carbon	-	0.10	-	0.05	-	0.10
Chromium	10.00	12.00	10.00	12.00	10.0	12.0
Iron	-	0.35	-	-		0.35
Vanadium	12.50	14.00	12.50	14.50	12.5	14.5
Nitrogen	-	0.05	-	0.08	-	0.05
Hydrogen (Sheet and Wire)	-	-	-	0.02	-	0.02
Hydrogen (Bar and Billet)	-	-	-	0.015	-	-
Oxygen	-	-	-	0.20	-	0.17
Titanium	Balance		Balance		Balance	

1.05 Heat Treatment

1.051 Solution treat. 1400 to 1450F, 10 to 30 minutes, air cool, (4).

1.0511 Anneal. Same as solution treat, 1.051. The terms anneal and solution treat can be used interchangeably for this alloy as both terms designate one material condition, (2, p. 8).

1.052 Stress relief. 900F during aging. If aging is not employed, 15 minutes at 1000F is recommended, (2, p. 10).

1.053 Age. Normally a full age is used, 900F, 72 hours. However, the mechanical properties are a function of aging time and temperature and for special applications other aging treatments can be developed, (4)(16).

1.06 Hardness

1.061 Effect of solution annealing temperature on room temperature hardness of sheet, Fig. 1.061.

1.062 Effect of aging time on room temperature hardness of cold rolled sheet, Fig. 1.062.

1.063 Effect of reduction by shear forming on hardness of alloy, Fig. 1.063.

1.064 Effect of low temperature on hardness of solution treated and aged sheet, Fig. 1.064.

1.07 Forms and Conditions Available

1.071 The alloy is available in a wide range of sizes in the solution treated, fully aged, or solution treated and cold rolled conditions as sheet, strip, plate and foil. Barstock and large billets are supplied in the annealed condition for further forging. Small bar, fastener-stock and wire is generally supplied in the solution treated condition, but is also available in the aged condition. Producers are developing production of this alloy as extrusions and welded and seamless tubing, (1, p. 2)(2, p. 11).

1.08 Melting and Casting Practice

Consumable electrode double-vacuum melting, (2, p. 8).

1.09 Special Consideration

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range

2.012 Phase changes

2.0121 Time-temperature-transformation diagram for alloy, Fig. 2.0121.

2.0122 Phase diagram of alloy with variable chromium content, Fig. 2.0122.

2.0123 Phase diagram of alloy with variable aluminum content, Fig. 2.0123.

2.013 Thermal conductivity, Fig. 2.013.

2.014 Thermal expansion, Fig. 2.014.

2.015 Specific heat, Fig. 2.015.

2.016 Thermal diffusivity

2.02 Other Physical Properties

2.021 Density. 0.175 lb per cu in, 4.85 gr per cu cm, room temperature, (1, p. 2).

2.022 Electrical resistivity
RT Ann, 60.2 microhms-in,
RT STA, 55.8 microhms-in, (25, p. 29).

2.023 Magnetic properties

2.024 Emissivity

2.025 Damping capacity

2.03 Chemical Properties

2.031 Corrosion resistance. This alloy exhibits excellent resistance to sea water and chloride solutions and is also resistant to corrosion by both gaseous and liquid fluorine at temperatures below 220F. It is susceptible to stress corrosion cracking in uninhibited hydrochloric acid, (1, p. 30)(11, p. 7).

2.032 Oxidation resistance

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 Producer's specified mechanical properties, Table 3.011.

Ti
13 V
11 Cr
3 Al

B120 VCA

TABLE 3.011

Source	Crucible (1, p.3)		TMCA (2, p.12)					
Alloy	Ti-13V-11Cr-3Al							
Form	Sheet		Sheet and strip			Foil	Bar, billet, forging and fastener stock	
Condition	ST	STA (c)	ST	STA	CR + Aged	STCR	ST	STA
Thickness - in						< 0.008		
F_{tu}, min - ksi	125	190	125	190	220	230	125	185
F_{ty}, min - ksi	120	170	120	170	200	220	120	170
e (2 in), min - percent	10	6	10	4 (a), 3 (b)	3	2	-	-
e (4 D), min - percent	-	-	-	-	-	-	10	4
Bend factor (radius-t)	3 t	6 t - 8 t	3 t (d), 3.5 t(e)	-	-	-	-	-
RA, max - percent	40 (c)	10-20	-	-	-	-	-	-

(a) > 0.020 in thick
(b) < 0.020 in thick
(c) Typical properties
(d) < 0.071 in thick
(e) > 0.071 in thick

3.012 AMS specified mechanical properties, Table 3.012.

TABLE 3.012

Source	(20)	
Alloy	Ti-13V-11Cr-3Al	
Condition	ST	Precipitation HT
Form	Sheet, strip, and plate	
Strain rate	0.003 to 0.007 in/in/min (a)	
Thickness-in	> < 0.250	
F_{tu}, min-ksi	130	190
F_{ty}, min-ksi	120	170
e(2in), min-percent	8	5
>0.250 in	10	-
Hardness, RC	36	-

(a) Through yield strength and then increase to produce failure in approx. one minute

3.013 Design mechanical properties of sheet, strip and plate, Table 3.013.

TABLE 3.013

Source	(39)	
Alloy	B120 VCA	
Form	Sheet, strip and plate	
Condition	Ann	ST and aged
Thickness - in	-	≤ 0.250
Basis	MIL-T-9046 Type IV	
F_{tu}, -ksi	125	170
F_{ty}, -ksi	120	160
F_{cy}, -ksi	120	162
F_{su}, -ksi	92	105
F_{bru}, (e/D=1.5) - ksi	207	248
(e/D=2.0) - ksi	270	313
F_{bry}, (e/D=1.5) - ksi	169	217
(e/D=2.0) - ksi	200	247
e(2 in) -percent	10 (a)	4 (b)

(a) Thickness of 0.025 and greater
(b) Thickness of 0.025 and greater; 3 percent below 0.025 inch

3.02 Mechanical Properties at Room Temperature

3.021 Tension
3.0211 Stress-strain diagrams. See 3.0311
3.0212 Effect of heat treatment on tensile properties.
3.02121 Effect of solution treat temperature on room temperature tensile properties of aged sheet, Fig. 3.02121.
3.02122 Effect of aging temperature and time on room temperature tensile properties of sheet, Fig. 3.02122.
3.02123 Effect of aging time on room temperature tensile properties of cold drawn wire, Fig. 3.02123.
3.02124 Effect of aging time on room temperature tensile properties of sheet, cold rolled various amounts after solution treating, Fig. 3.02124.
3.0213 Effect of pre-strain on tensile properties.
3.02131 Effect of stretching after solution treatment on room temperature tensile properties of subsequently aged sheet, Fig. 3.02131.
3.02132 Effect of reduction by shear forming on tensile properties of alloy, Fig. 3.02132.
3.02133 Effect of cold work on room temperature tensile properties of solution treated sheet, Fig. 3.02133.
3.0214 Effect of exposure on tensile properties.
3.02141 Effect of exposure stress and temperature on room temperature tensile properties of sheet in solution treated condition, Fig. 3.02141.
3.02142 The effect of exposure time on room temperature tensile properties at various temperatures for sheet, Fig. 3.02142.
3.0215 Effect of strain rate on room temperature properties of sheet in solution treated condition, Fig. 3.0215.
3.0216 Design tensile properties at room temperature. See Table 3.013.
3.022 Compression
3.0221 Stress-strain diagrams. See 3.0321.
3.0222 Room temperature compressive yield strength for 0.040 inch sheet aged 900F, 60 hours,
F_{cy}, L = 207.7 ksi,
F_{cy}, T = 214.3 ksi, (26, p. 1.A.3.5.1).
3.0223 Effect of stretching in solution treated condition on room temperature compressive yield strength of aged sheet, (Bauschinger Effect), Fig. 3.0223.
3.0224 Design compressive properties at room temperature, see Table 3.013.
3.023 Impact, see Section 3.033.
3.024 Bending, see Section 4.031.
3.025 Torsion and shear
3.0251 Effect of reduction by shear forming on ultimate shear strength of alloy, Fig. 3.0251.
3.0252 Design shear properties at room temperature, see Table 3.013.
3.026 Bearing, see Section 3.034.
3.0261 Design bearing properties at room temperature, see Table 3.013.
3.027 Stress concentration
3.0271 Notch properties
3.02711 Effect of stress concentration on tensile strength of aged sheet, Fig. 3.02711.
3.02712 Effect of exposure temperature and time on room temperature notch strength of alloy in solution treated condition, Fig. 3.02712.
3.02713 Effect of thickness on room temperature notch strength of aged sheet, Fig. 3.02713.
3.02714 Effect of aging temperature and time on notched and unnotched room temperature properties of sheet, Fig. 3.02714.
3.02715 Effect of stress concentration factor on room temperature notch strength properties of sheet, Fig. 3.02715.
3.0272 Fracture toughness
3.02721 Effect of solution annealing temperature on room temperature net fracture stress and fracture toughness of sheet, Fig. 3.02721.
3.02722 Effect of aging time on room temperature net fracture stress and fracture toughness of sheet, Fig. 3.02722.
3.028 Combined properties

3.03 Mechanical Properties at Various Temperatures
3.031 Tension

3.0311	Stress-strain diagrams
3.03111	Stress-strain curves for solution treated and aged sheet in tension, Fig. 3.03111.
3.03112	Stress-strain curves in tension for solution treated sheet at various temperatures, Fig. 3.03112.
3.03113	Stress-strain curves for alloy at very high temperatures, Fig. 3.03113.
3.03114	Stress-strain curves at room and low temperatures for solution treated bar in tension, Fig. 3.03114.
3.03115	Stress-strain curves at room and low temperatures for solution treated and aged sheet in tension, Fig. 3.03115.
3.0312	Effect of test temperature on tensile properties of solution treated sheet and bar, Fig. 3.0312.
3.0313	Effect of test temperature on tensile properties of several heats of aged sheet, Fig. 3.0313.
3.0314	Effect of test temperature on tensile properties of different gage sheet, Fig. 3.0314.
3.0315	Effect of test temperature on tensile properties of sheet, Fig. 3.0315.
3.0316	Effect of time of exposure at 550F on tensile properties at room temperature and -110F for 0.040 in sheet, Fig. 3.0316.
3.0317	Effect of exposure time at 550F on tensile properties at room temperature and -110F for 0.064 in sheet, Fig. 3.0317.
3.0318	Effect of low test temperature on tensile properties of sheet, Fig. 3.0318.
3.032	Compression
3.0321	Stress-strain diagrams
3.03211	Stress-strain curves in compression for solution treated and aged sheet of various thicknesses and test temperatures, Fig. 3.03211.
3.0322	Effect of test temperature on compressive yield strength of sheet at room and elevated temperatures, Fig. 3.0322.
3.0323	Effect of room and elevated temperature on compressive yield strength of various sheet thicknesses, Fig. 3.0323.
3.0324	Effect of test temperature on compressive yield strength of different gage sheet, Fig. 3.0324.
3.033	Impact
3.0331	Effect of test temperature on impact strength of bar, Fig. 3.0331.
3.034	Bending
3.035	Torsion and shear
3.0351	Effect of test temperature on double shear strength of bar and sheet, Fig. 3.0351.
3.0352	Effect of test temperature on shear strength of sheet, Fig. 3.0352.
3.0353	Effect of low temperature on shear strength of sheet, Fig. 3.0353.
3.036	Bearing
3.0361	Effect of test temperature on bearing yield strength of aged sheet at low and elevated temperatures, Fig. 3.0361.
3.0362	Effect of test temperature on bearing properties of sheet for e/D = 1.5, Fig. 3.0362.
3.0363	Effect of test temperature on bearing properties for sheet for e/D = 2.0, Fig. 3.0363.
3.037	Stress concentration
3.0371	Notch properties
3.03711	Effect of test temperature on notch strength of aged sheet, Fig. 3.03711.
3.03712	Effect of test temperature and aging time on notch strength ratio for sheet at low and elevated temperatures, Fig. 3.03712.
3.03713	Effect of test temperature and thickness on sharp edge notch and smooth tensile strength of solution treated sheet, Fig. 3.03713
3.03714	Effect of exposure time at 550F on notch strength at room temperature and -110F for sheet, Fig. 3.03714.
3.03715	Effect of exposure time at 550F on notch strength at room temperature and -110F for sheet, Fig. 3.03715.
3.03716	Effect of low test temperature on notch strength of sheet, Fig. 3.03716.
3.03717	Effect of test temperature on net fracture stress of center notch sheet specimens, Fig. 3.03717.
3.0372	Fracture toughness
3.03721	Effect of test temperature on net fracture stress and plane strain fracture toughness of bar and sheet, Fig. 3.03721.
3.038	Combined properties

	Ti
13	V
11	Cr
3	Al

B120VCA

3.04	Creep and Creep Rupture Properties
3.041	Creep rupture curves for aged sheet at 800F, Fig. 3.041.
3.042	Creep curves for aged sheet at 600 and 700F, Fig. 3.042.
3.05	Fatigue Properties
3.051	S-N curves for solution treated bar, Fig. 3.051.
3.052	S-N curves for solution treated and aged sheet at room and low temperatures, Fig. 3.052.
3.06	Elastic Properties
3.061	Poisson's ratio at room and elevated temperatures, Fig. 3.061.
3.062	Modulus of elasticity
3.0621	Modulus of elasticity at low and elevated temperatures, Fig. 3.0621.
3.0622	Effect of test temperature on modulus of elasticity for sheet in compression, Fig. 3.0622.
3.0623	Modulus of elasticity for 0.040 in sheet aged at 600F in compression, 60 hours, $E_c = 16.3 \times 10^3$ ksi, (26, p. 1. A.3.5.1).
3.063	Modulus of rigidity at room temperature, 6.2×10^3 ksi, (25, p. 29).
3.064	Tangent modulus
3.0641	Tangent modulus curves in tension for solution treated and aged sheet at room and elevated temperatures, Fig. 3.0641.
3.0642	Tangent modulus curves at room and elevated temperatures for solution treated and aged sheet in compression, Fig. 3.0642.
3.065	Secant modulus curves at room and elevated temperatures for solution treated and aged sheet in compression, Fig. 3.065.

4. FABRICATION

4.01 Formability

4.011 General.

Although requiring higher work forces, this alloy in the solution treated condition is more amenable to cold forming than any other of the high strength titanium alloys and it has good cold heading properties. In very severe cold forming such as spinning or deep drawing, intermediate anneals may be advisable. Forming by all conventional methods is possible, (1, p. 20).

4.0111 Effect of test temperature on bend properties of solution treated sheet at room and elevated temperatures, Fig. 4.0111.

4.012 Forging. Hot forging temperature 1850F. Warm forging below 1400F promotes more rapid aging and results in a stronger and more ductile alloy after aging. Reductions up to 50 percent are possible between anneals in open and closed die forgings, (1, p. 20)(13, p. 76).

4.0121 Effect of aging after forging at two temperatures, Fig. 4.0121.

4.013 Splitting limits for brake forming at 1000F and 1200F, Fig. 4.013.

4.014 Limit curve for deep drawing at 1200F, Fig. 4.014.

4.015 Limit curves for linear stretch at 500F, Fig. 4.015.

4.02 Machining

This alloy is somewhat more difficult to machine than other titanium alloys. Sulfurized oils can be used as cutting fluids with high speed steel tools. Maintain slow speeds and coarse feeds for all machining operations. Grind wet to minimize fire hazard, using aluminum oxide wheels, (4).

	Ti
13	V
11	Cr
3	Al

B120 VCA

4.03 Welding

This alloy can be satisfactorily welded using inert gas shielded tungsten arc method without filler, or using B-120 VCA as a filler. Consumable electrode welding may be accomplished with B120 VCA wire as filler. Resistance, seam, spot or flash welding methods are also applicable, (1, p. 24).

4.031 Room temperature bend properties (single point) of weld joints, Table 4.031.

TABLE 4.031

Source	(14, p. 10)			
Alloy	Ti-13V-11Cr-3Al			
Form and Condition	Sheet * solution treated and aged 900 F, 25 hr			
Filler wire	ST, welded and aged		ST, welded and aged	
	Fract defl, in	Rupture modulus, ksi	Fract defl, in	Rupture modulus, ksi
Unwelded base alloy	1.70	286.3	1.70	286.3
Ti-75A	1.46	247.7	1.55	227.9
Ti-3Al	1.54	268.1	1.66	239.4
Ti-6Al-4V	1.28	270.1	1.70	210.4
RS-140	1.30	292.2	1.52	248.5
Ti-4Al-3Mo-1V	1.54	267.9	1.62	225.0
Ti-2.5Al-16V	1.02	278.6	1.59	215.4
A-110AT	1.28	286.5	1.60	230.6
Ti-3Al-6Mo	1.04	267.1	1.58	235.8
Ti-13V-11Cr-3Al	1.28	231.2	1.58	230.8

* Sheet specimen 1 1/2 in wide x 4 1/2 in long. Punch nose radius 0.125 in, 105° Anvil

4.032 Weldability is excellent in annealed condition, but weld metal ages at different rate than bare metal resulting in low joint efficiencies. Large grain size and micro-segregation of alloying constituents develop at weld-metal grain boundaries during the fusion process. These adversely effect the properties of the joint after aging. The ductility and toughness of aged weldments are generally low when large grains and grain boundary precipitates are present, (38, p. 9).

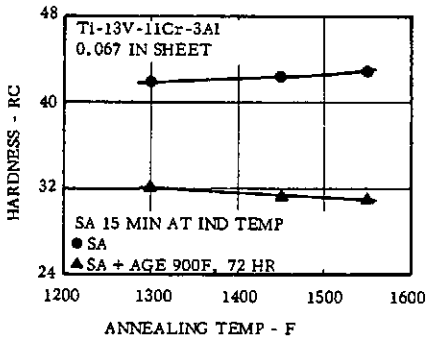


FIG. 1.061 EFFECT OF SOLUTION ANNEALING TEMPERATURE ON ROOM TEMPERATURE HARDNESS OF SHEET (24, p. 154)

4.04 Heat Treatment

Before heat treatment remove all hydrocarbons, carbonaceous materials, chloride cleaner residuals. Final cleaning using light acid pickle is recommended. Heating in air at temperatures above about 800F contaminates the surface. If inert atmosphere cannot be used the contaminated layer must be removed by surface treatment, (1, p. 30).

4.05 Surface Treatment

4.051 Scale removal can be accomplished by oxidizing molten salt baths, by grinding, by grit and vapor blasting and by pickling in 20 to 30 percent nitric acid plus 2 percent hydrofluoric acid at 130F, (1, p. 30).

4.052 Brightening dip by immersion in 10 percent nitric acid plus 1/4 percent hydrofluoric acid, (4).

4.053 Finger stains are removed by most detergents, (4).

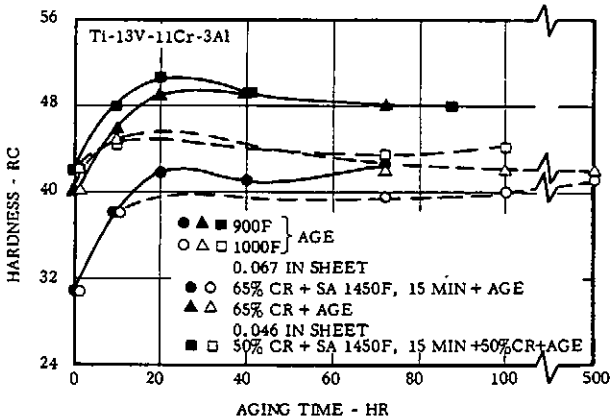


FIG. 1.062 EFFECT OF AGING TIME ON ROOM TEMPERATURE HARDNESS OF COLD ROLLED SHEET (24, p. 160, 177)

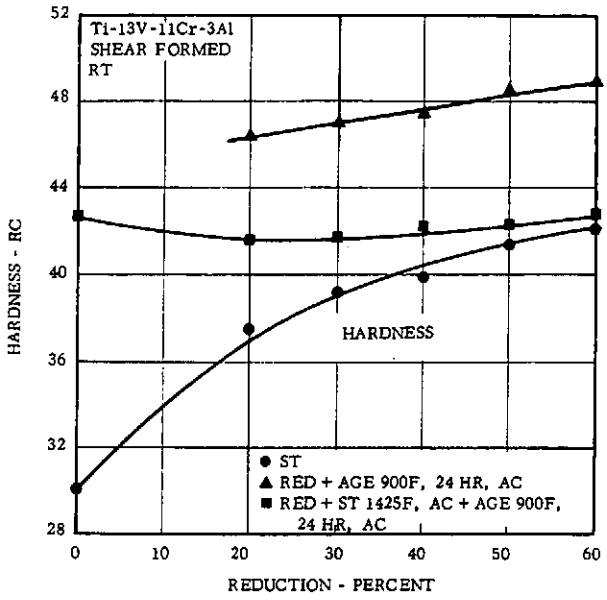
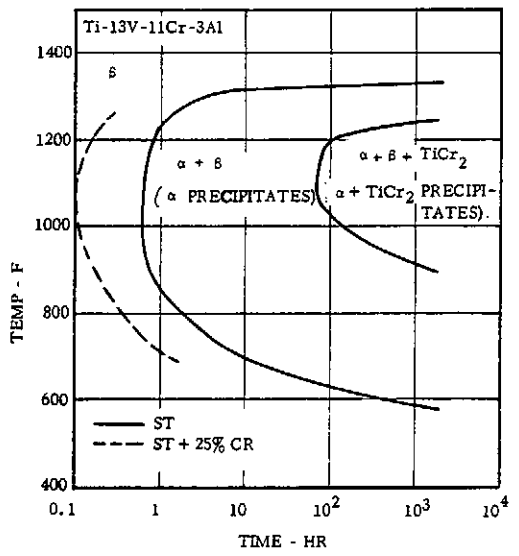


FIG. 1.063 EFFECT OF REDUCTION BY SHEAR FORMING ON HARDNESS OF ALLOY (27, p. 217-221)



	Ti
13	V
11	Cr
3	Al

B120 VCA

FIG. 2.0121 TIME-TEMPERATURE-TRANSFORMATION DIAGRAM FOR ALLOY (3)

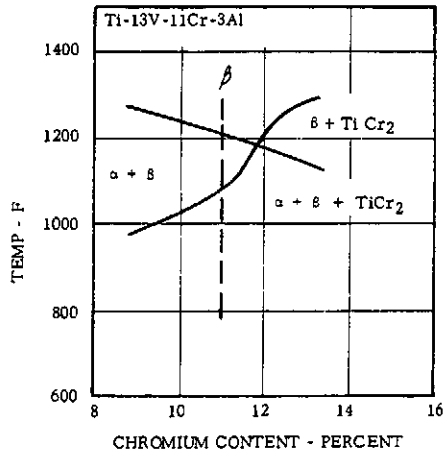


FIG. 2.0122 PHASE DIAGRAM OF ALLOY WITH VARIABLE CHROMIUM CONTENT (3, p. 11)

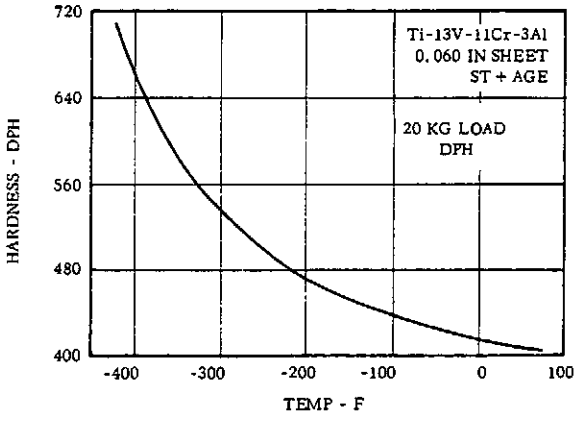


FIG. 1.064 EFFECT OF LOW TEMPERATURES ON HARDNESS OF SOLUTION TREATED AND AGED SHEET (37, p. C.8.k)

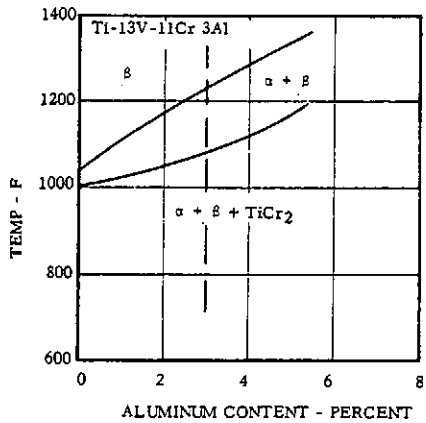


FIG. 2.0123 PHASE DIAGRAM OF ALLOY WITH VARIABLE ALUMINUM CONTENT (3, p. 12)

	Ti
13	V
11	Cr
3	Al

B120 VCA

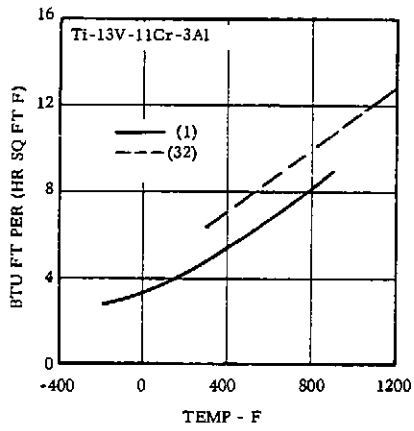


FIG. 2.013 THERMAL CONDUCTIVITY
(1, p. 2)(32, p. 65)

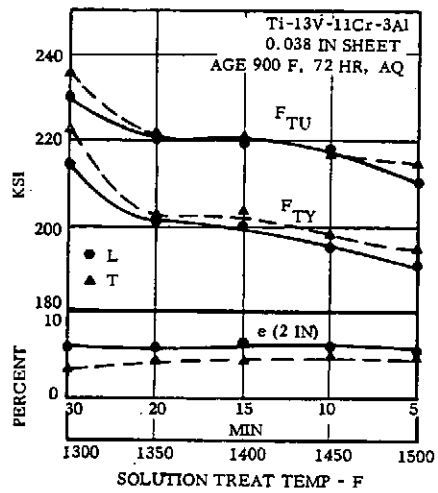


FIG. 3.02121 EFFECT OF SOLUTION TREAT TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF AGED SHEET
(1, p. 3)

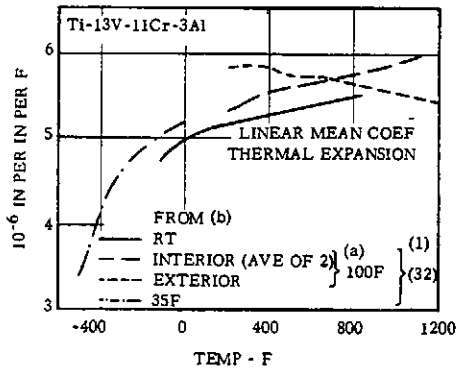


FIG. 2.014 THERMAL EXPANSION (1, p. 2)(32, p. 63, 64)

(a) Location of test specimen
(b) To temperature indicated

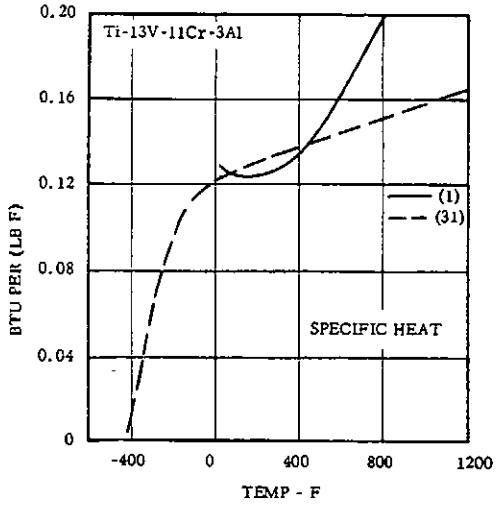


FIG. 2.015 SPECIFIC HEAT (1, p. 2)(31, p. 236)

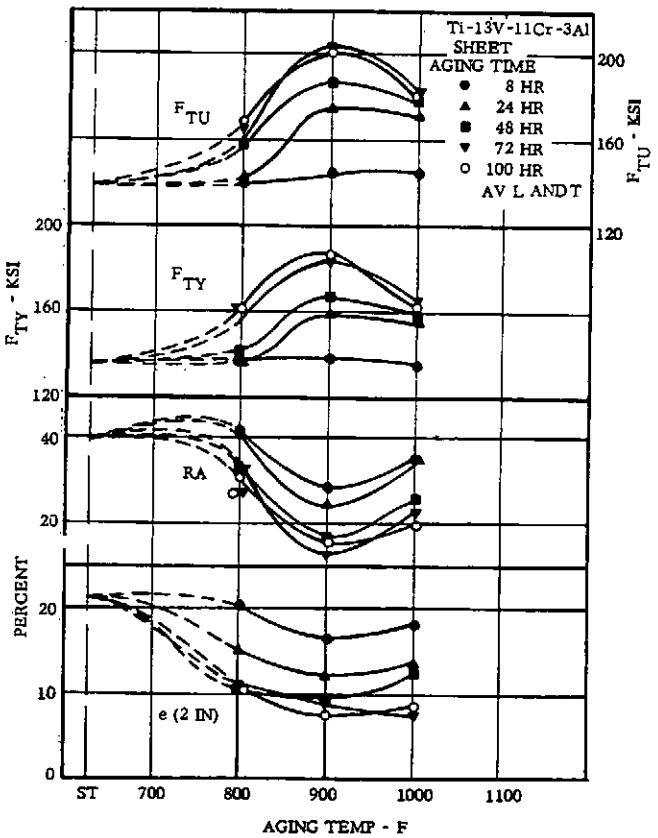


FIG. 3.02122 EFFECT OF AGING TEMPERATURE AND TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF SHEET
(3, p. 27)

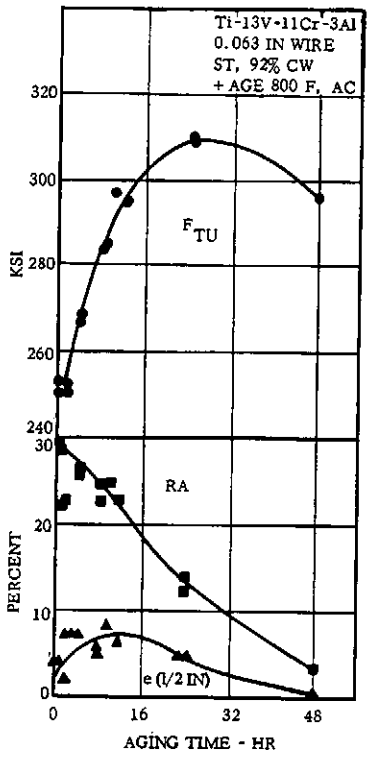
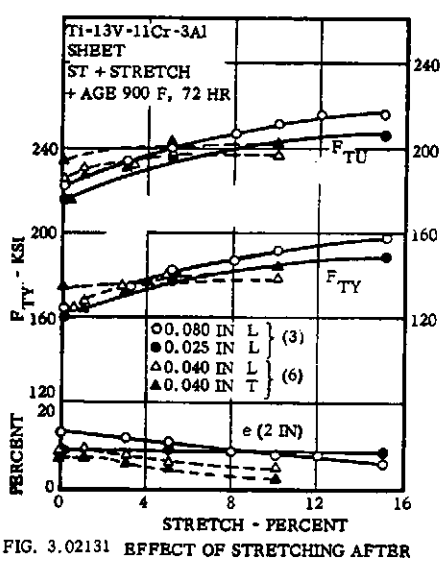


FIG. 3.02123 EFFECT OF AGING TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF COLD DRAWN WIRE (1, p. 20)



	Ti
13	V
11	Cr
3	Al

B120VCA

FIG. 3.02131 EFFECT OF STRETCHING AFTER SOLUTION TREATMENT ON ROOM TEMPERATURE TENSILE PROPERTIES OF SUBSEQUENTLY AGED SHEET (3, p. 41) (6, p. 513)

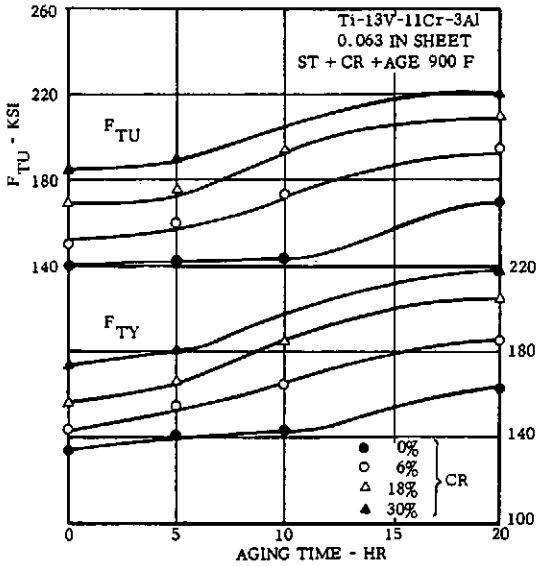


FIG. 3.02124 EFFECT OF AGING TIME ON ROOM TEMPERATURE TENSILE PROPERTIES FOR SHEET COLD ROLLED VARIOUS AMOUNTS AFTER SOLUTION TREATING (16)

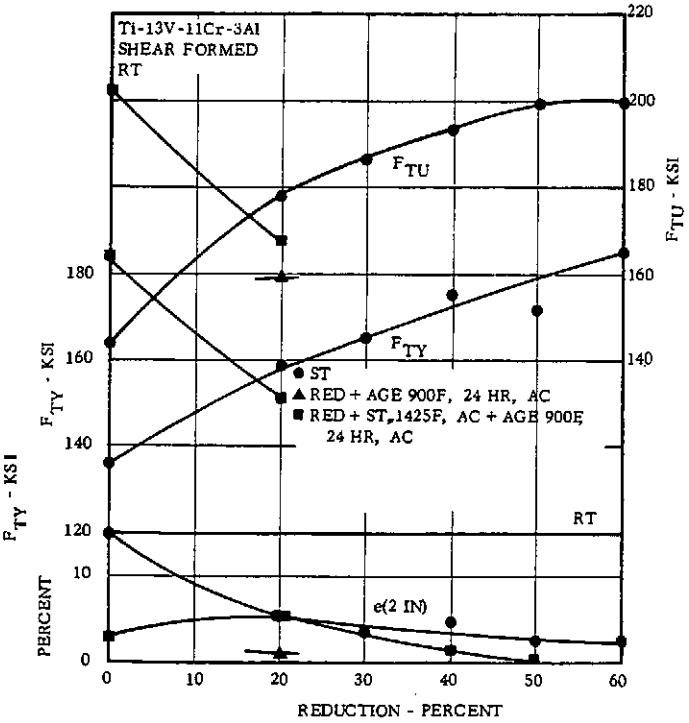


FIG. 3.02132 EFFECT OF REDUCTION BY SHEAR FORMING ON TENSILE PROPERTIES OF ALLOY (27, p. 217-221)

	Ti
13	V
11	Cr
3	Al

B120 VCA

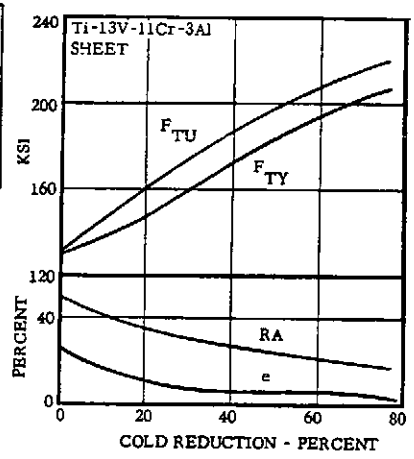


FIG. 3.02133 EFFECT OF COLD WORK ON ROOM TEMPERATURE TENSILE PROPERTIES OF SOLUTION TREATED SHEET (1, p. 23)

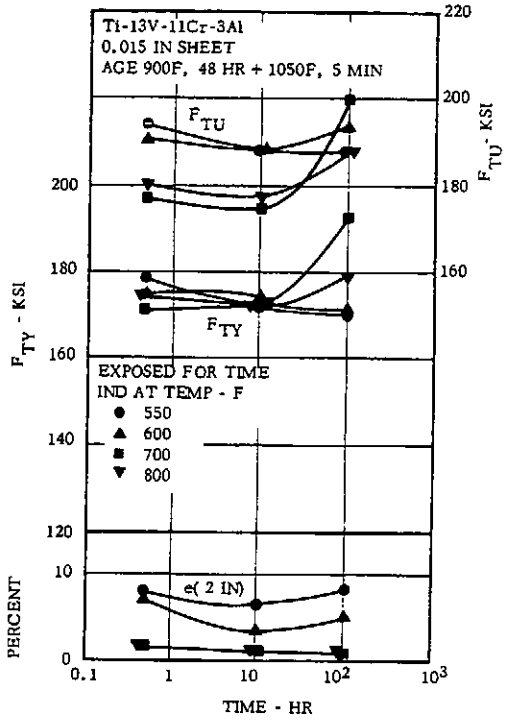


FIG. 3.02142 THE EFFECT OF EXPOSURE TIME ON ROOM TEMPERATURE TENSILE PROPERTIES AT VARIOUS TEMPERATURES FOR SHEET (26, p. 1.A.3.5.1)

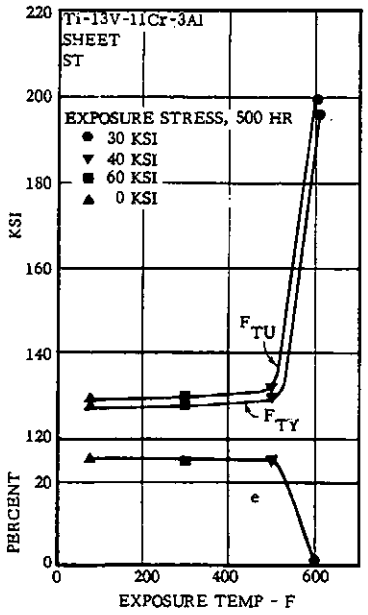


FIG. 3.02141 EFFECT OF EXPOSURE STRESS AND TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF SHEET IN SOLUTION TREATED CONDITION (3, p. 94)

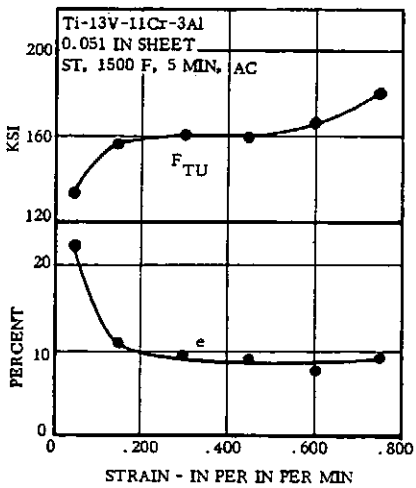


FIG. 3.0215 EFFECT OF STRAIN RATE ON ROOM TEMPERATURE PROPERTIES OF SHEET IN SOLUTION TREATED CONDITION (1, p. 5)

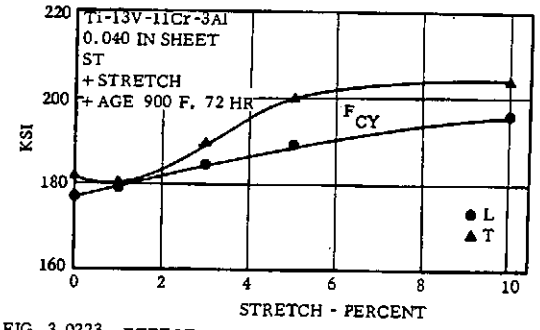
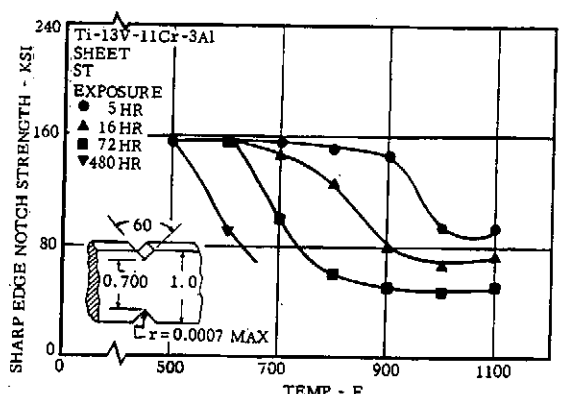


FIG. 3.0223 EFFECT OF STRETCHING IN SOLUTION TREATED CONDITION ON ROOM TEMPERATURE COMPRESSIVE YIELD STRENGTH OF AGED SHEET (BAUSCHINGER EFFECT) (6, p.512-514)



	Ti
13	V
11	Cr
3	Al

B120 VCA

FIG. 3.02712 EFFECT OF EXPOSURE TEMPERATURE AND TIME ON ROOM TEMPERATURE NOTCH STRENGTH OF ALLOY IN SOLUTION TREATED CONDITION (19, p.11)

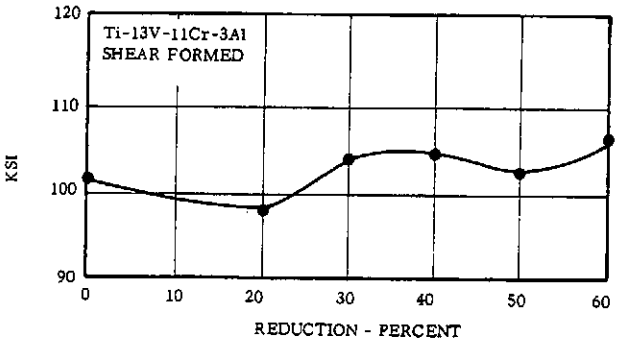


FIG. 3.0251 EFFECT OF REDUCTION BY SHEAR FORMING ON ULTIMATE SHEAR STRENGTH OF ALLOY (27, p. 302-307)

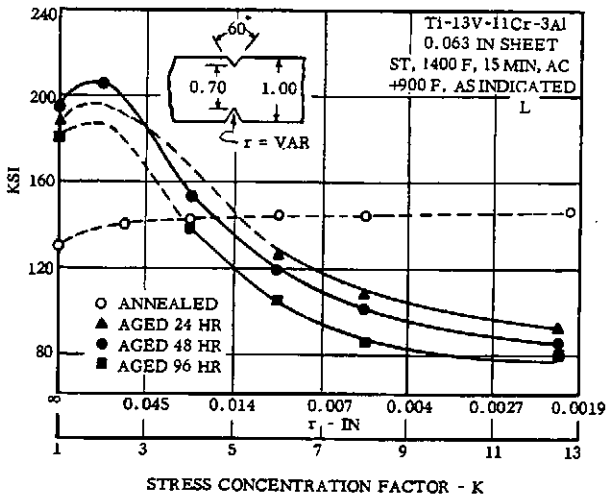


FIG. 3.02711 EFFECT OF STRESS CONCENTRATION ON TENSILE STRENGTH OF AGED SHEET (7, p. 20, 21)

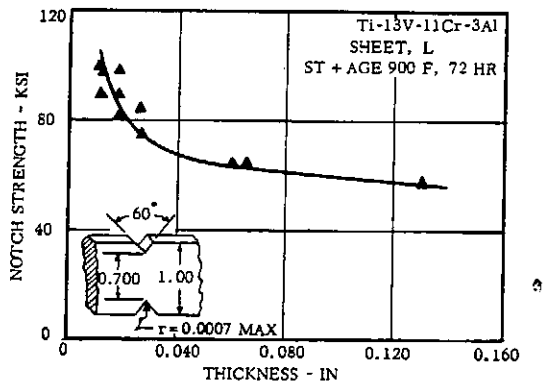


FIG. 3.02713 EFFECT OF THICKNESS ON ROOM TEMPERATURE NOTCH STRENGTH OF AGED SHEET (18, p.7)

	Ti
13	V
11	Cr
3	Al

B120 VCA

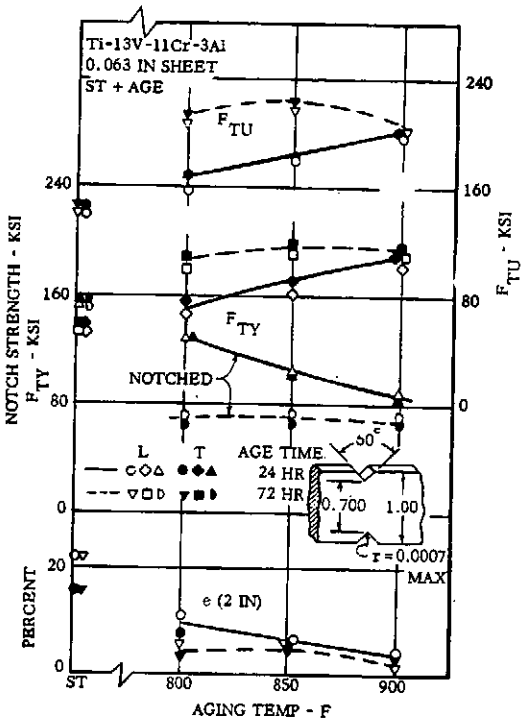


FIG. 3.02714 EFFECT OF AGING TEMPERATURE AND TIME ON NOTCHED AND UNNOTCHED ROOM TEMPERATURE TENSILE PROPERTIES OF SHEET (17, p. 81)

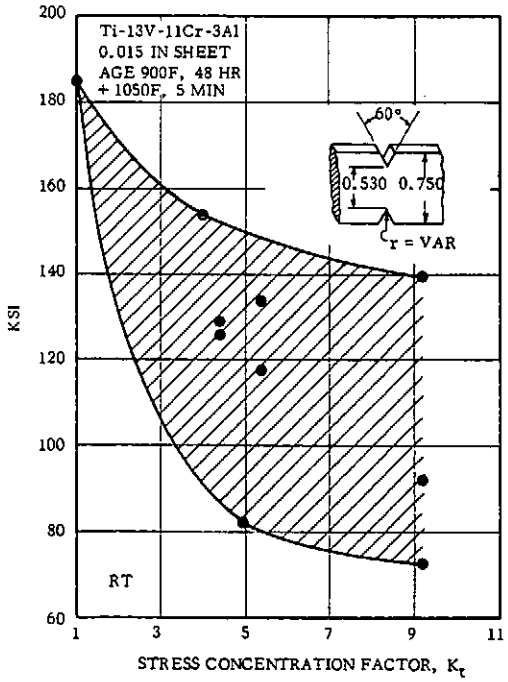


FIG. 3.02715 EFFECT OF STRESS CONCENTRATION FACTOR ON ROOM TEMPERATURE NOTCH STRENGTH PROPERTIES OF SHEET (26, p. 1.A.3.5.1)

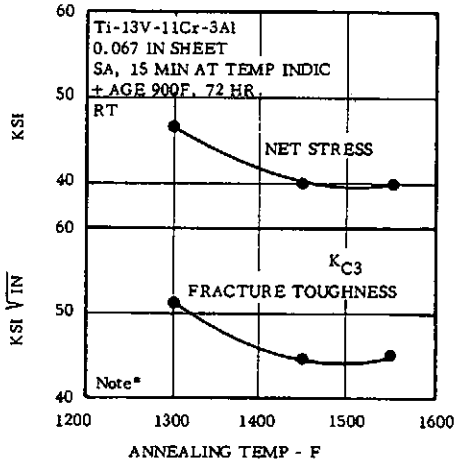


FIG. 3.02721 EFFECT OF SOLUTION ANNEALING TEMPERATURE ON ROOM TEMPERATURE NET FRACTURE STRESS AND FRACTURE TOUGHNESS OF SHEET (24, p. 154)

* Center notched by spark discharge machining fatigue cracked 0.7 inch long by tension-tension cycling.

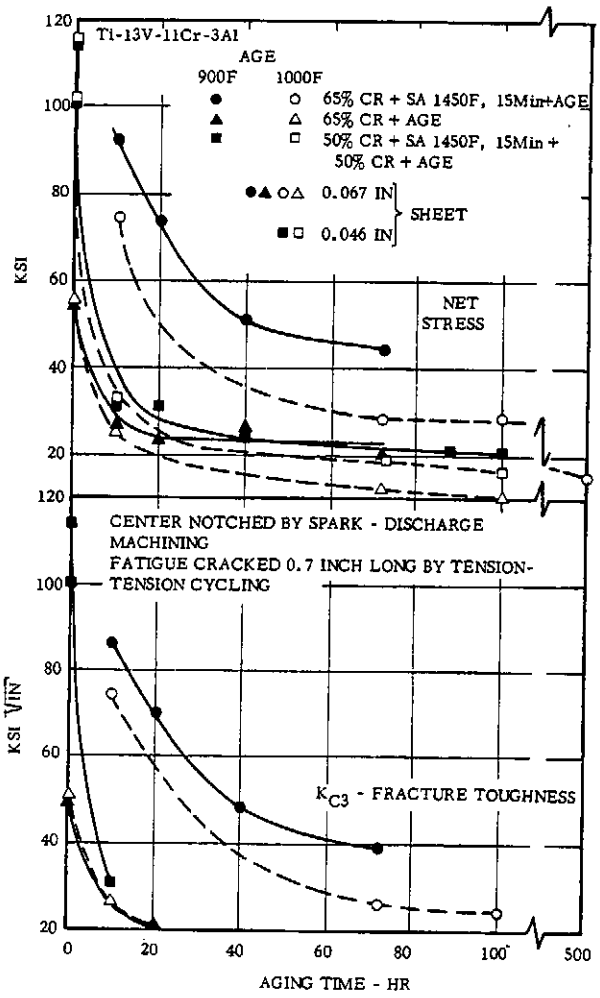


FIG. 3.02722 EFFECT OF AGING TIME ON ROOM TEMPERATURE NET FRACTURE STRESS AND FRACTURE TOUGHNESS OF SHEET (24, p. 160, 177)

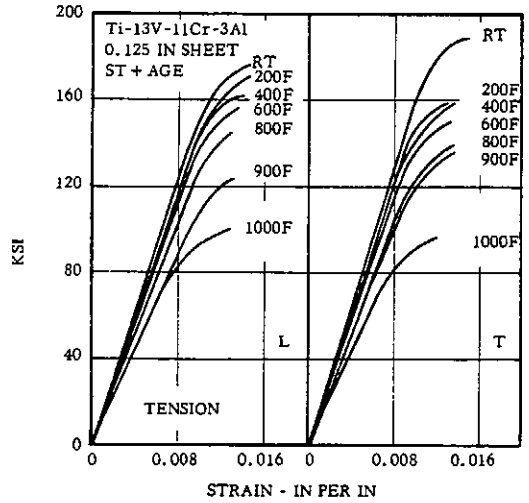


FIG. 3.03111 STRESS-STRAIN CURVES FOR SOLUTION TREATED AND AGED SHEET IN TENSION (33, p. 128-130)

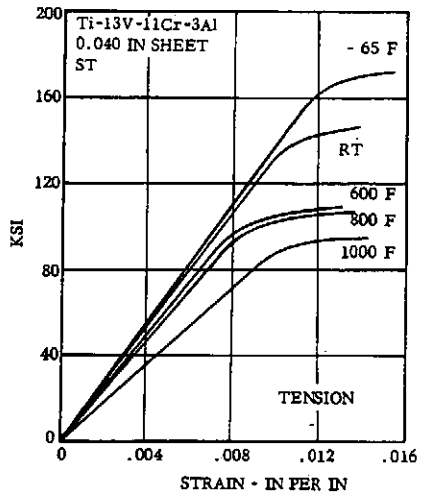


FIG. 3.03112 STRESS STRAIN CURVES IN TENSION FOR SOLUTION TREATED SHEET AT VARIOUS TEMPERATURES (1, p. 5)

Ti	
13	V
11	Cr
3	Al

B120 VCA

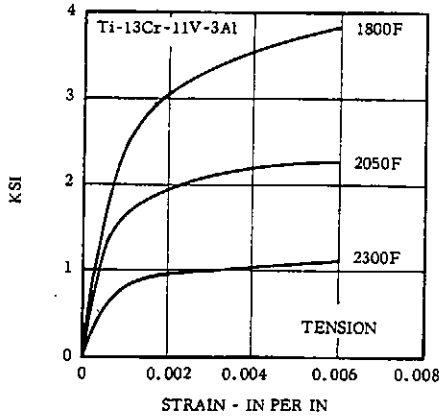


FIG. 3.03113 STRESS-STRAIN CURVES FOR ALLOY AT VERY HIGH TEMPERATURES (34, p. 15-17)

	Ti
13	V
11	Cr
3	Al

B120 VCA

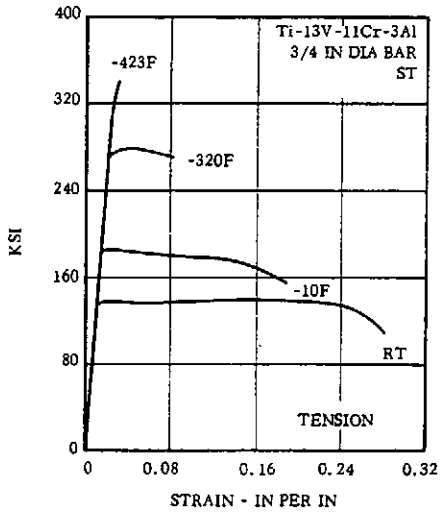


FIG. 3.03114 STRESS-STRAIN CURVES AT ROOM AND LOW TEMPERATURES FOR SOLUTION TREATED BAR IN TENSION (37, p. C.8.h)

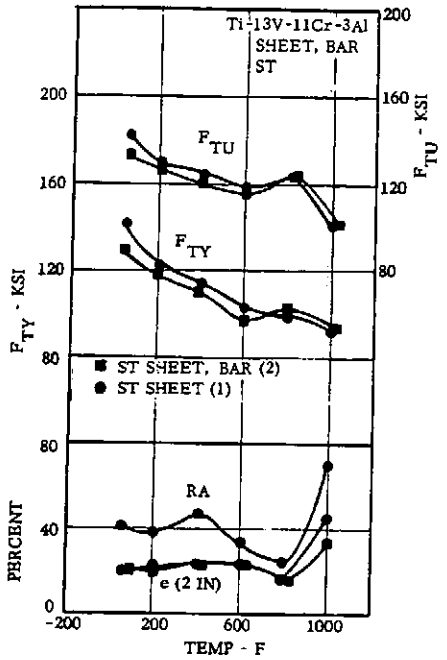


FIG. 3.0312 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION TREATED SHEET AND BAR (1, p. 5) (2, p. 13)

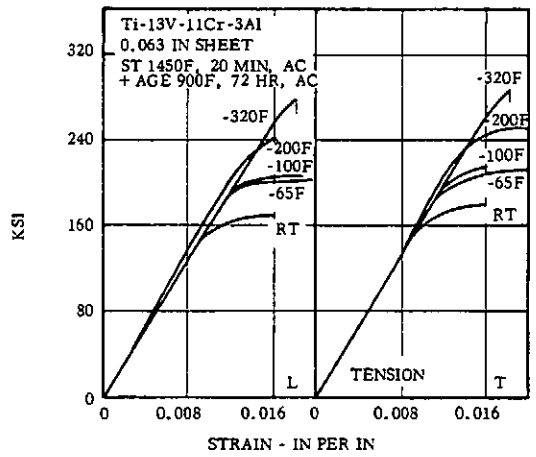


FIG. 3.03115 STRESS-STRAIN CURVES AT ROOM AND LOW TEMPERATURES FOR SOLUTION TREATED AND AGED SHEET IN TENSION (31, p. 232, 233)

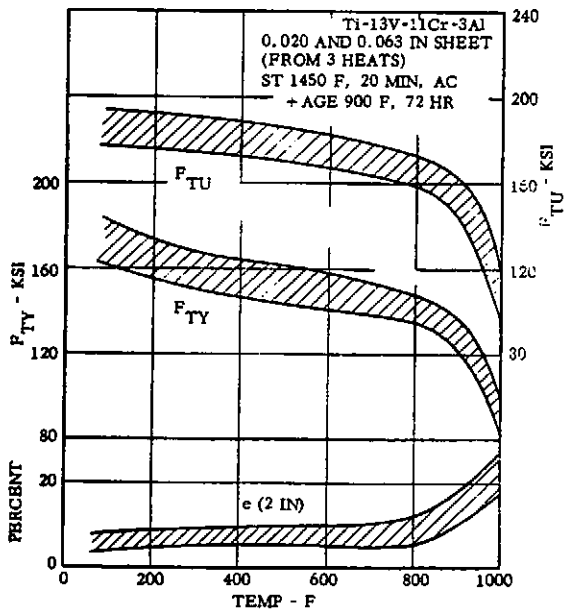


FIG. 3.0313 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SEVERAL HEATS OF AGED SHEET (8, p. 8, 8A) (9, p. A3-A12) (10, p. A3-A16)

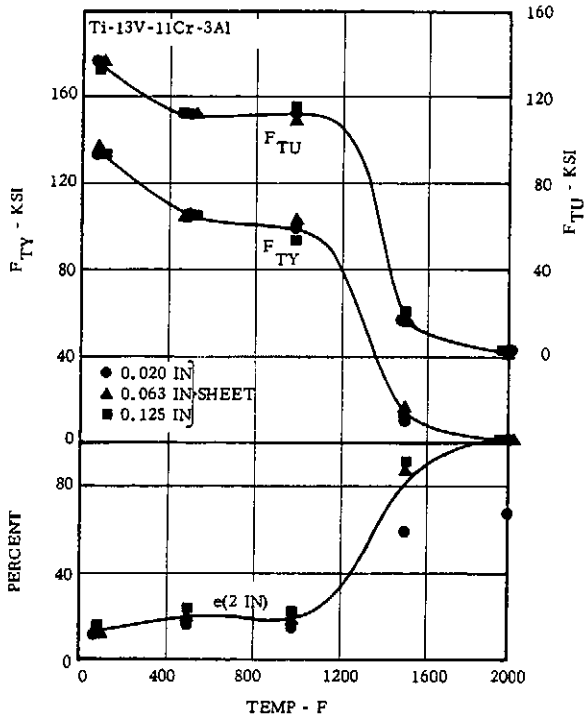
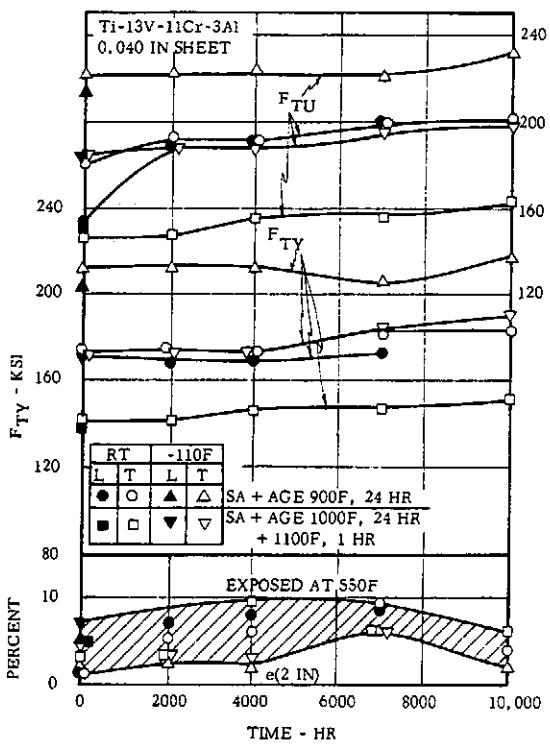


FIG. 3.0314 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF DIFFERENT GAGE SHEET (29, p. 61, 26, 29, 70)



Ti	
13	V
11	Cr
3	Al

B120 VCA

FIG. 3.0316 EFFECT OF EXPOSURE TIME AT 550F ON TENSILE PROPERTIES AT ROOM TEMPERATURE AND -110F FOR SHEET (21, p. 26, 27)

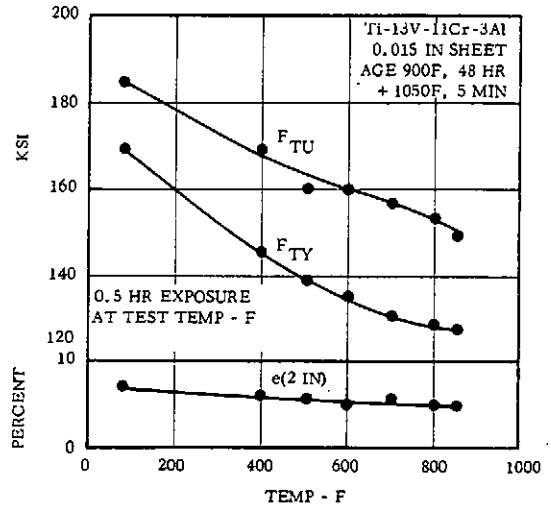


FIG. 3.0315 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SHEET (26, p. 1.A.3.5)

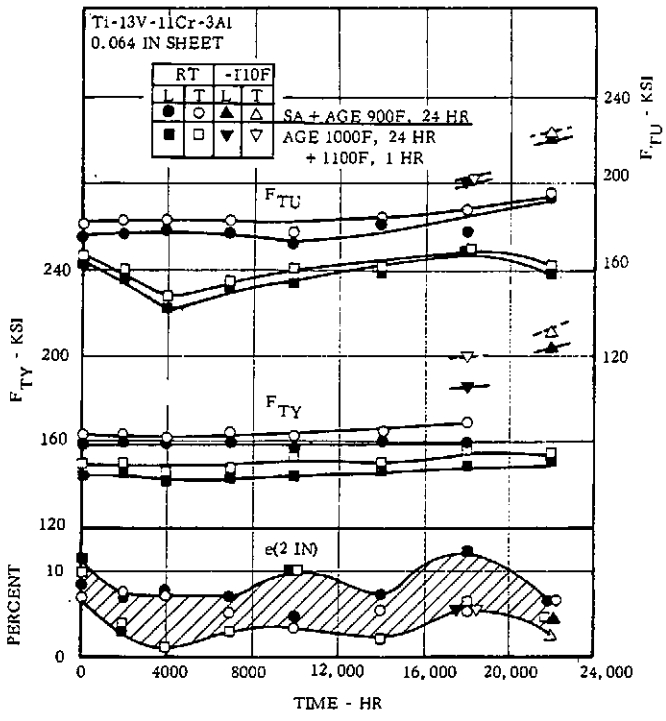


FIG. 3.0317 EFFECT OF EXPOSURE TIME AT 550F ON TENSILE PROPERTIES AT ROOM TEMPERATURE AND -110F FOR 0.064 IN SHEET (21, p. 24, 25)

	Ti
13	V
11	Cr
3	Al

B120 VCA

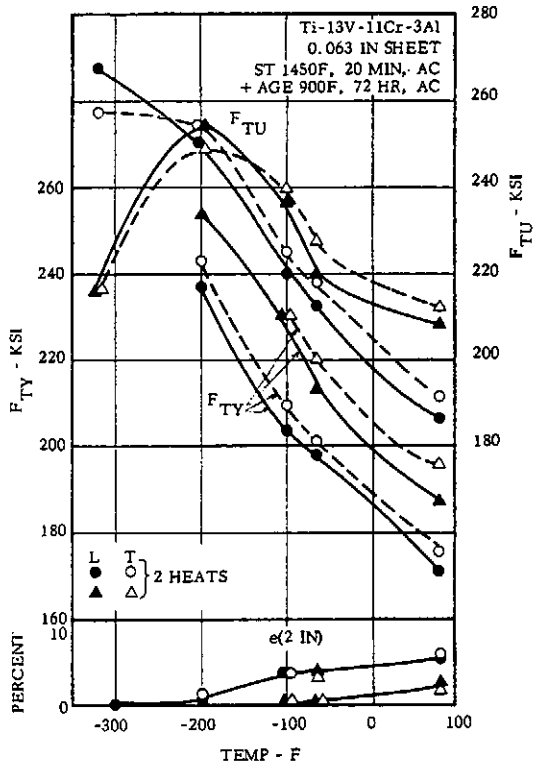


FIG. 3.0318 EFFECT OF LOW TEST TEMPERATURES ON TENSILE PROPERTIES OF SHEET
(32, p. 61, 62)

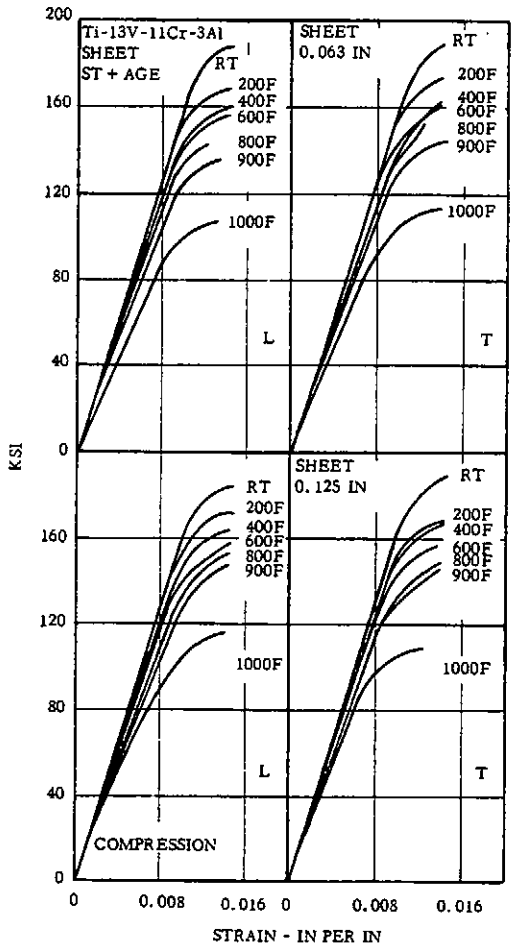


FIG. 3.03211 STRESS-STRAIN CURVES IN COMPRESSION FOR SOLUTION TREATED AND AGED SHEET OF VARIOUS THICKNESS AND TEST TEMPERATURES
(33, p. 131-132)

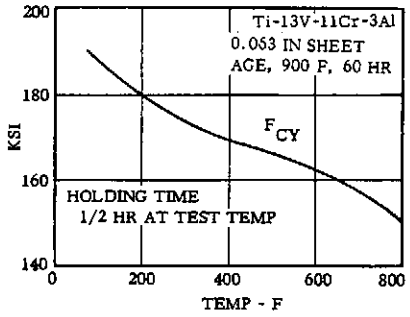


FIG. 3.0322 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF SHEET AT ROOM AND ELEVATED TEMPERATURES (2, p. 13)

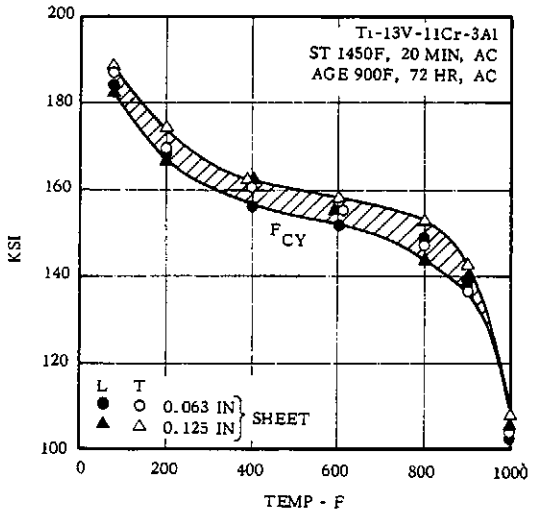
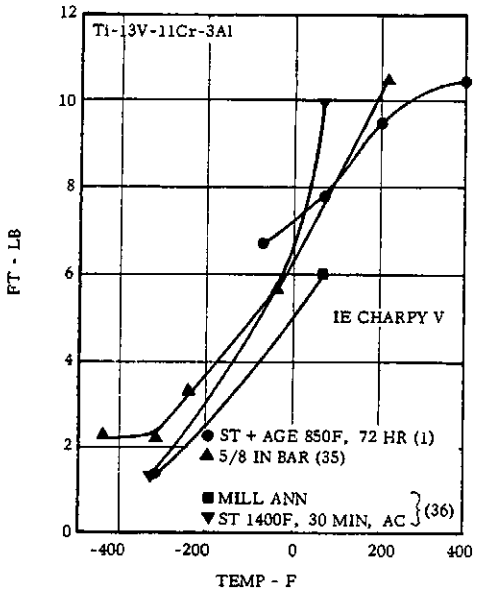


FIG. 3.0323 EFFECT OF ROOM AND ELEVATED TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF VARIOUS SHEET THICKNESSES (32, p. 15-20)



Ti	
13	V
11	Cr
3	Al

B120 VCA

FIG. 3.0331 EFFECT OF TEST TEMPERATURE ON IMPACT STRENGTH OF BAR (1, p. 18, 19)(35, p. 4)(36, p. 32)

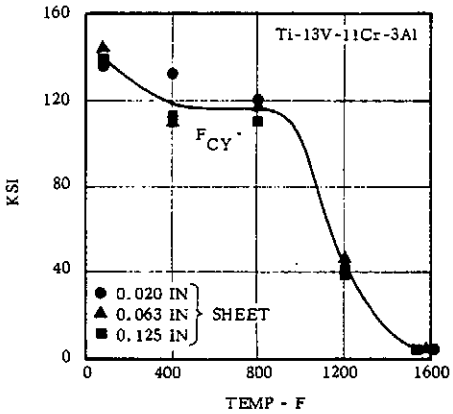


FIG. 3.0324 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF DIFFERENT GAGE SHEET (28, p. 79)

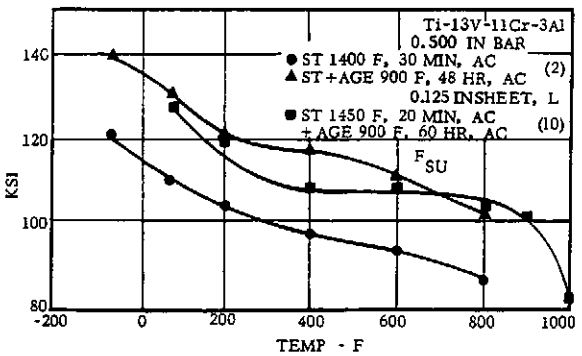


FIG. 3.0351 EFFECT OF TEST TEMPERATURE ON DOUBLE SHEAR STRENGTH OF BAR AND SHEET (2, p. 14) (10, p. A35-A37)

	Ti
13	V
11	Cr
3	Al

B 120 VCA

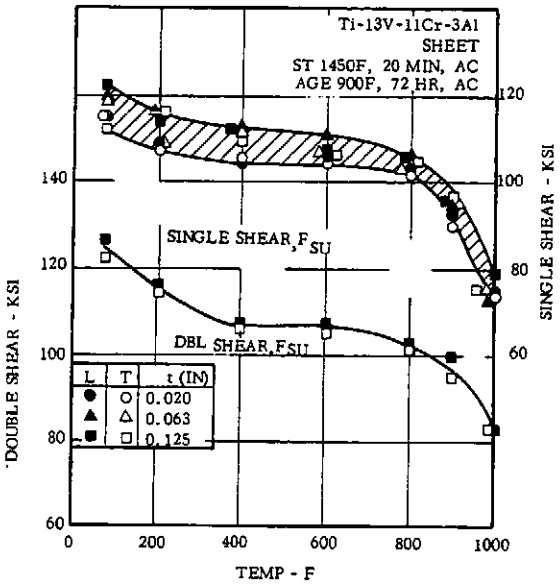


FIG. 3.0352 EFFECT OF TEST TEMPERATURE ON SHEAR STRENGTH OF SHEET (32, p. 51-54)

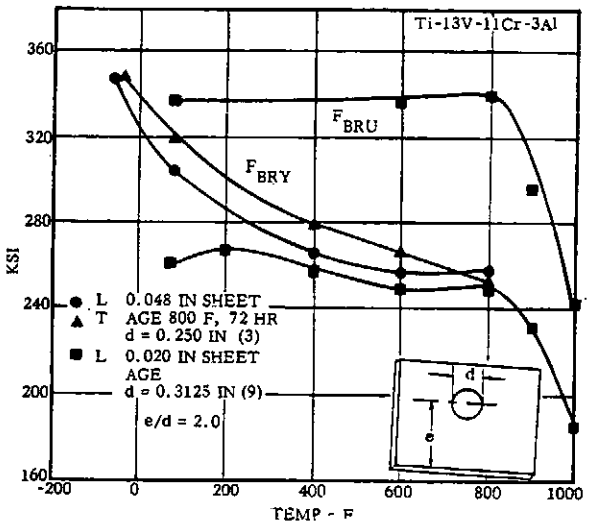


FIG. 3.0361 EFFECT OF TEST TEMPERATURE ON BEARING YIELD STRENGTH OF AGED SHEET AT LOW AND ELEVATED TEMPERATURES (3, p. 86) (9, p. A33-A35)

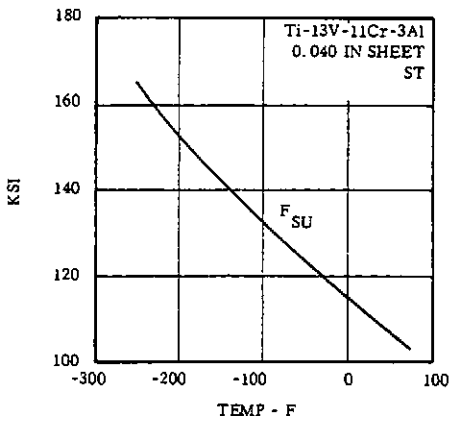


FIG. 3.0353 EFFECT OF LOW TEMPERATURES ON SHEAR STRENGTH OF SHEET (37, p. C.8.p)

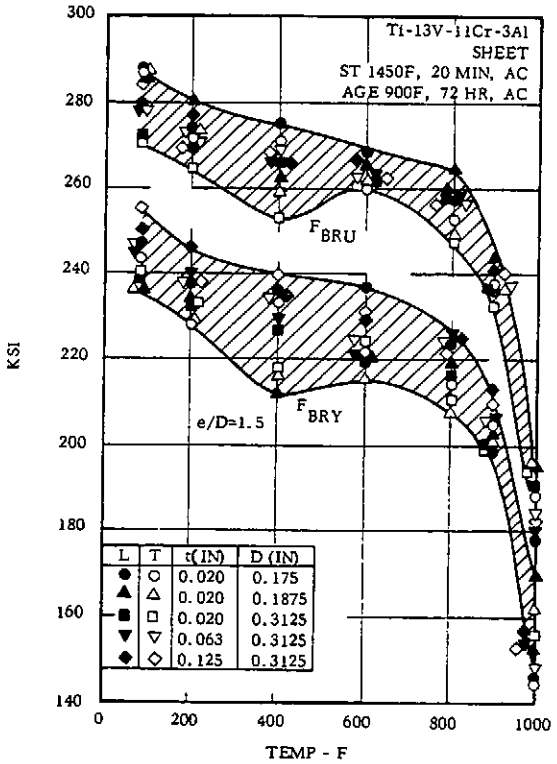


FIG. 3.0362 EFFECT OF TEST TEMPERATURE ON BEARING PROPERTIES OF SHEET FOR e/D = 1.5 (32, p. 21-35)

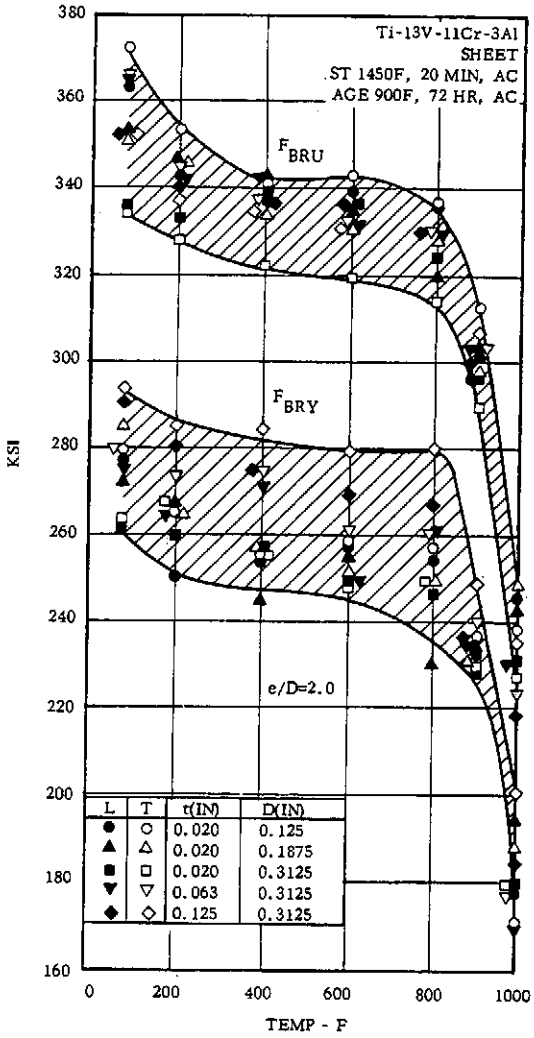


FIG. 3.0363 EFFECT OF TEST TEMPERATURE ON BEARING PROPERTIES OF SHEET FOR e/D = 2.0

(32, p. 36-50)

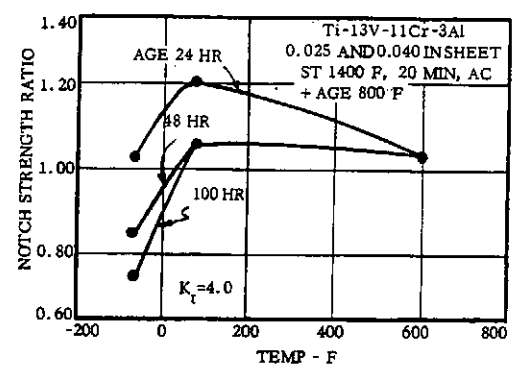


FIG. 3.03712 EFFECT OF TEST TEMPERATURE AND AGING TIME ON NOTCH STRENGTH RATIO FOR SHEET AT LOW AND ELEVATED TEMPERATURES

(4)

	Ti
13	V
11	Cr
3	Al

B120 VCA

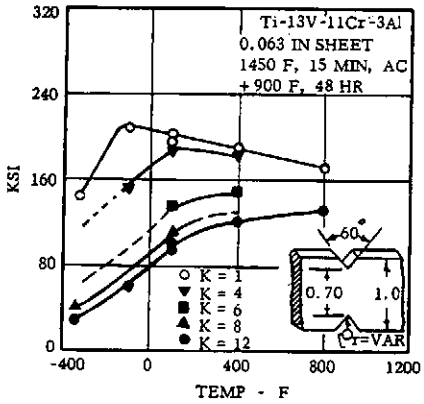


FIG. 3.03711 EFFECT OF TEST TEMPERATURE ON NOTCH STRENGTH OF AGED SHEET

(7, p. 26)

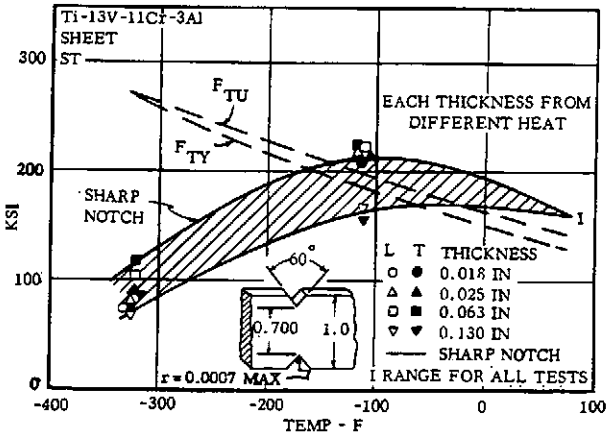


FIG. 3.03713 EFFECT OF TEST TEMPERATURE AND THICKNESS ON SHARP EDGE NOTCH AND SMOOTH TENSILE STRENGTH OF SOLUTION TREATED SHEET

(18, p.15)

	Ti
13	V
11	Cr
3	Al

B120 VCA

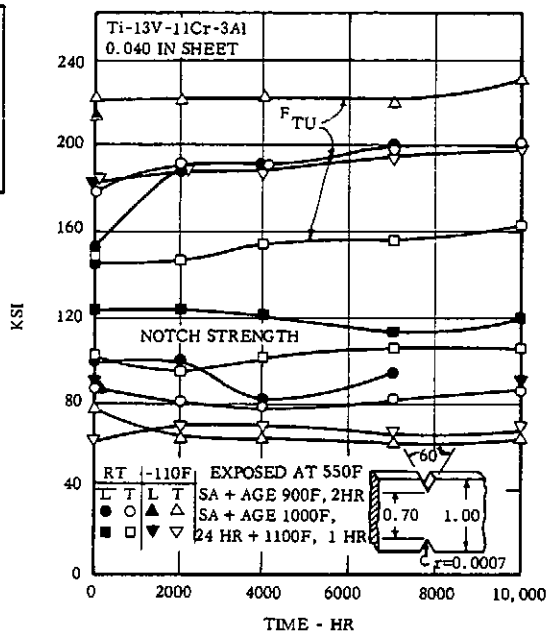


FIG. 3.03714 EFFECT OF EXPOSURE TIME AT 550F ON NOTCH STRENGTH AT ROOM TEMPERATURE AND -110F FOR SHEET (21, p. 26, 27)

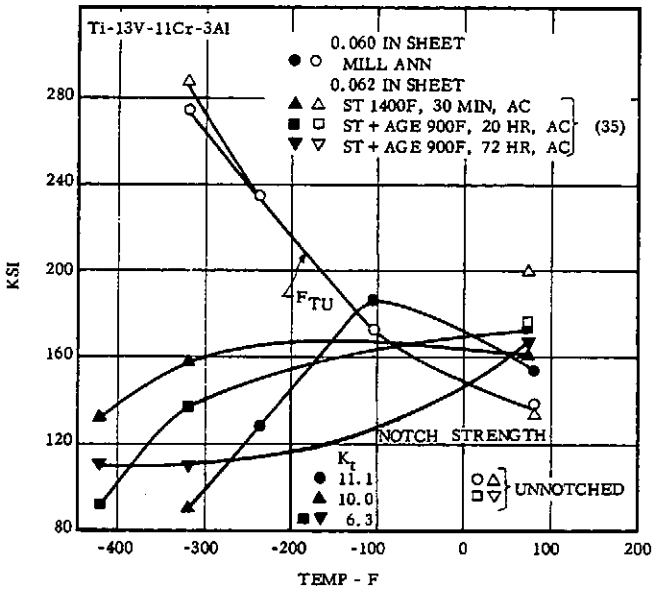


FIG. 3.03716 EFFECT OF LOW TEST TEMPERATURE ON NOTCH STRENGTH OF SHEET (34, p. 5)(35, p. 30, 31)

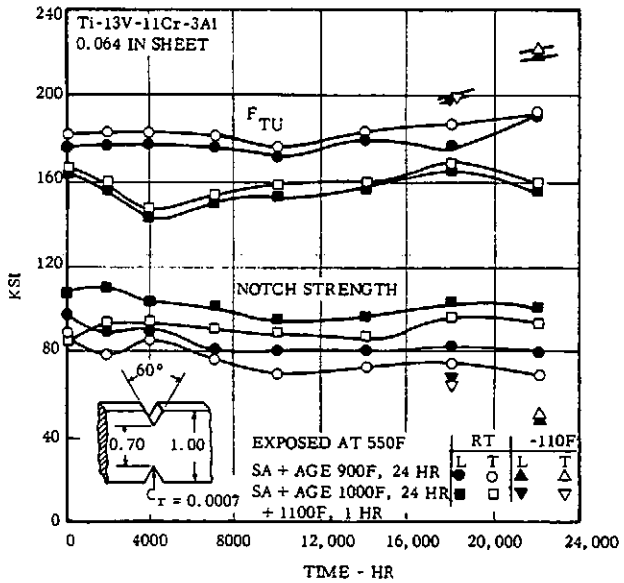


FIG. 3.03715 EFFECT OF EXPOSURE TIME AT 550F ON NOTCH STRENGTH AT ROOM TEMPERATURE AND -110F FOR SHEET (21, p. 24, 25)

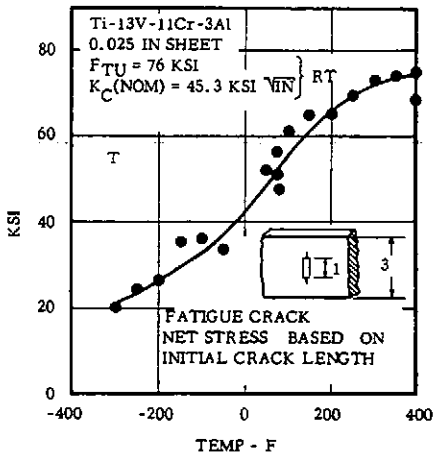


FIG. 3.03717 EFFECT OF TEST TEMPERATURE ON NET FRACTURE STRESS OF CENTER NOTCH SHEET SPECIMENS (22, Tbl. 26)

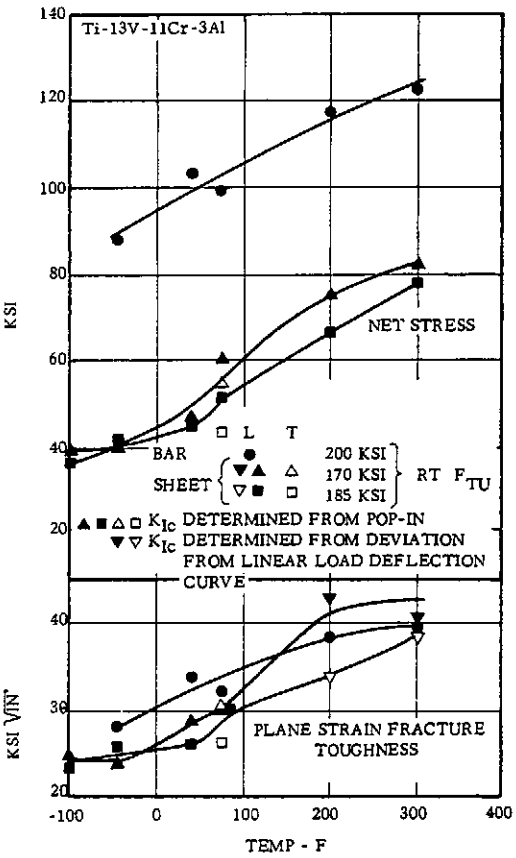
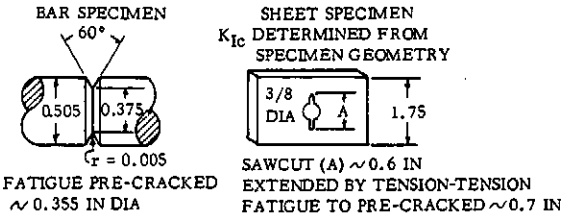


FIG. 3.03721 EFFECT OF TEST TEMPERATURE ON NET FRACTURE STRESS AND PLANE STRAIN FRACTURE TOUGHNESS OF BAR AND SHEET (28, Tbls. 33-35)



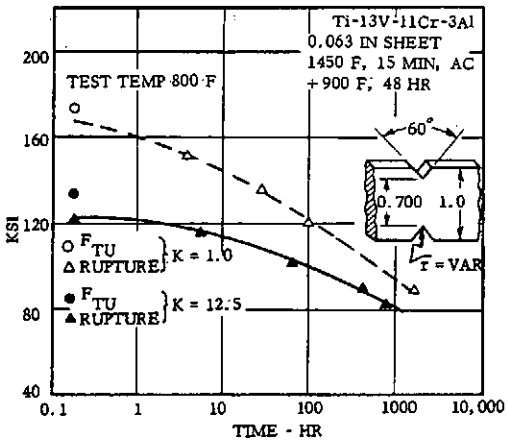


FIG. 3.041 CREEP RUPTURE CURVES FOR AGED SHEET AT 800 F (7, p. 29)

	Ti
13	V
11	Cr
3	Al

B120 VCA

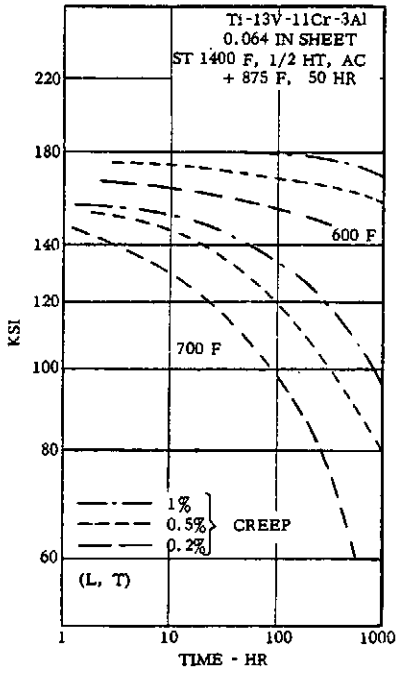


FIG. 3.042 CREEP CURVES FOR AGED SHEET AT 600 AND 700 F (15, p. 28-32)

	Ti
13	V
11	Cr
3	Al

B120 VCA

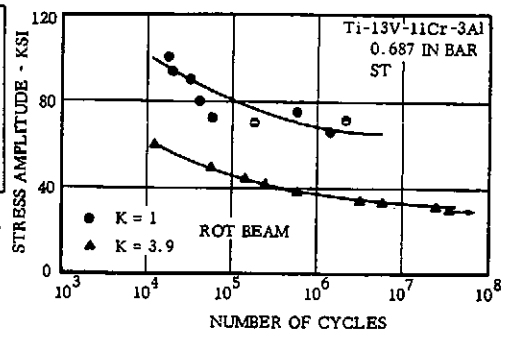


FIG. 3.051 S-N CURVES FOR SOLUTION TREATED BAR (1, p. 19)

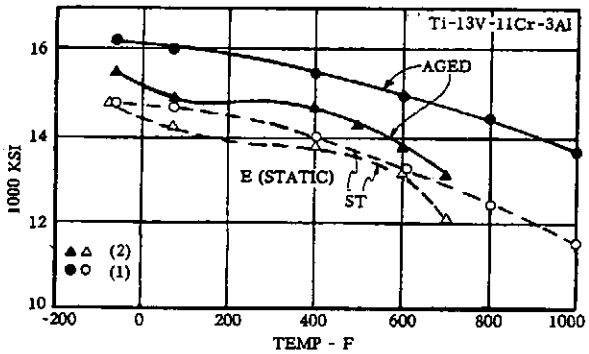


FIG. 3.0621 MODULUS OF ELASTICITY AT LOW AND ELEVATED TEMPERATURES (1, p. 2) (2, p. 8)

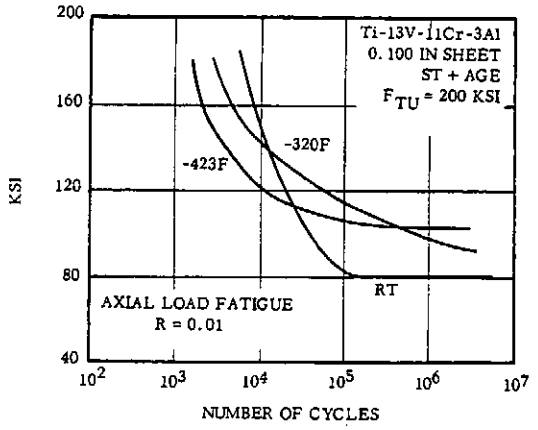


FIG. 3.052 S-N CURVE FOR SOLUTION TREATED AND AGED SHEET AT ROOM AND LOW TEMPERATURES (37, p. C.8.o)

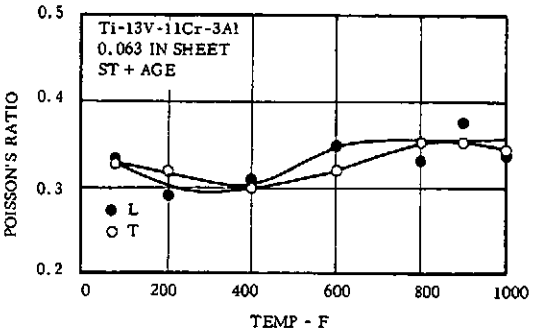


FIG. 3.061 POISSON'S RATIO AT ROOM AND ELEVATED TEMPERATURE (31, p. 181)

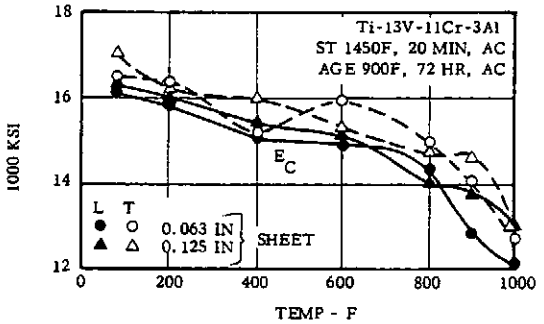


FIG. 3.0622 EFFECT OF TEST TEMPERATURE ON COMPRESSION MODULUS OF ELASTICITY FOR SHEET (32, p. 15-20)

	Ti
13	V
11	Cr
3	Al

B120 VCA

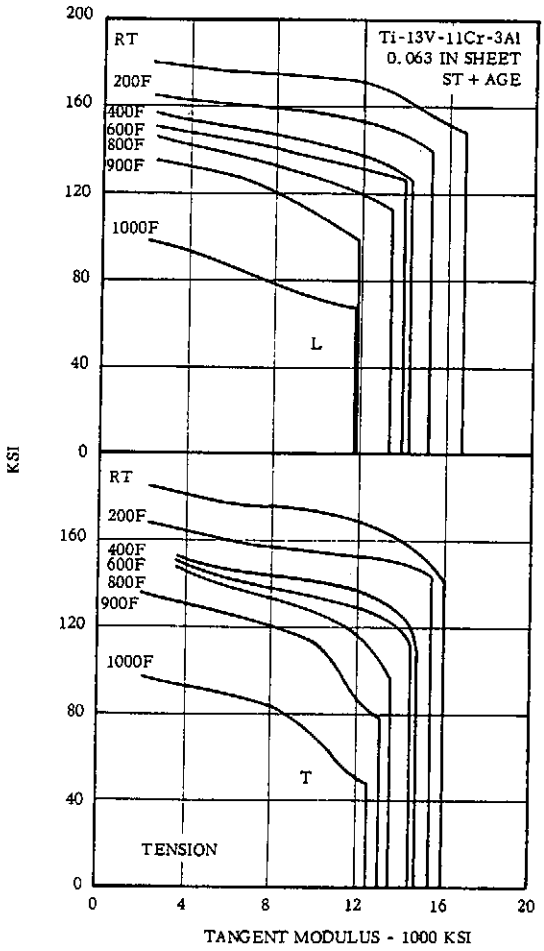


FIG. 3.0641 TANGENT MODULUS CURVES AT ROOM AND ELEVATED TEMPERATURES FOR SOLUTION TREATED AND AGED SHEET IN TENSION
(23, p. 122)

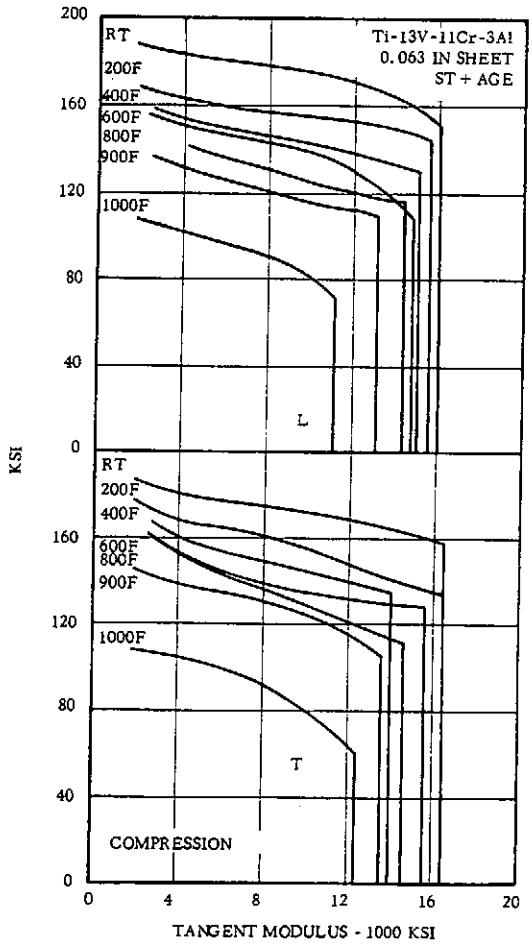


FIG. 3.0642 TANGENT MODULUS CURVES AT ROOM AND ELEVATED TEMPERATURES FOR SOLUTION TREATED AND AGED SHEET IN COMPRESSION
(33, p. 124)

	Ti
13	V
11	Cr
3	Al

B120 VCA

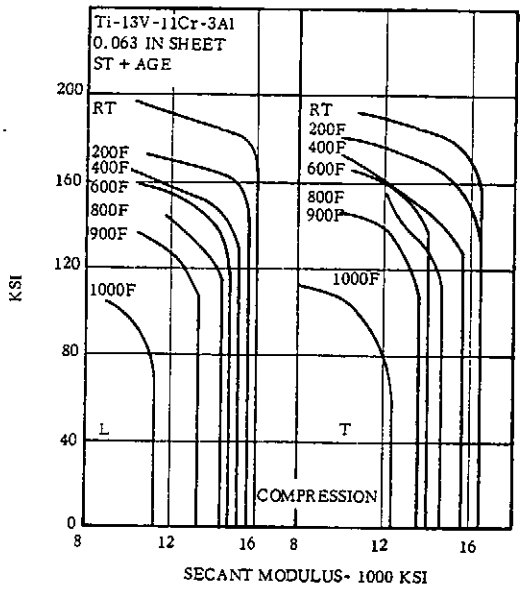


FIG. 3.065 SECANT MODULUS CURVES AT ROOM AND ELEVATED TEMPERATURES FOR SOLUTION TREATED AND AGED SHEET IN COMPRESSION (33, p. 126)

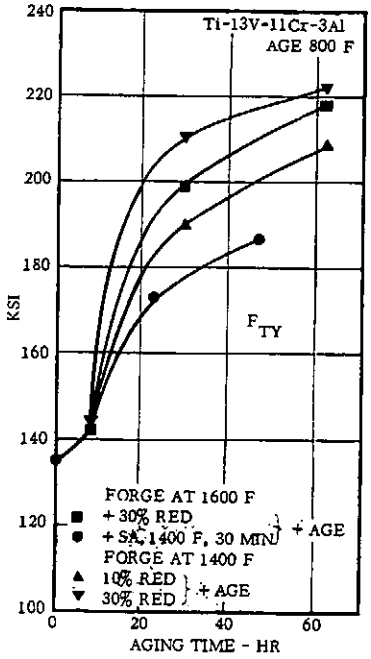


FIG. 4.0121 EFFECT OF AGING AFTER FORGING AT TWO TEMPERATURES (13, p. 77)

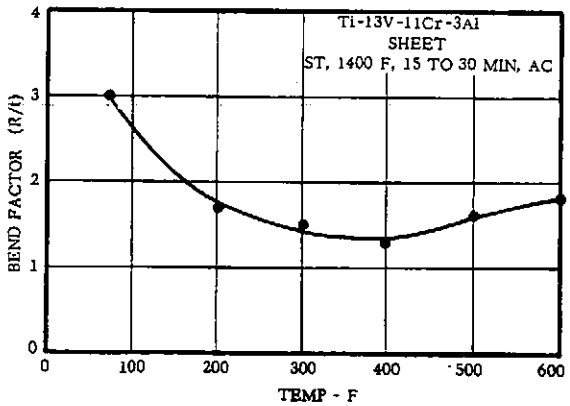


FIG. 4.0111 EFFECT OF TEST TEMPERATURE ON BEND PROPERTIES OF SOLUTION TREATED SHEET AT ROOM AND ELEVATED TEMPERATURES (12, p. 4)

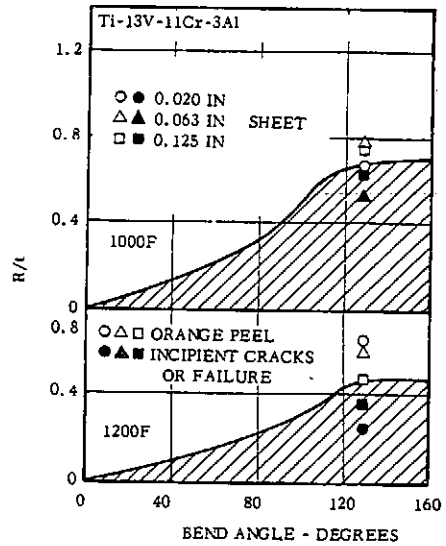


FIG. 4.013 SPLITTING LIMITS FOR BRAKE FORMING AT 1000F AND 1200F (29, p. 93-95)

	Ti
13	V
11	Cr
3	Al

B 120 VCA

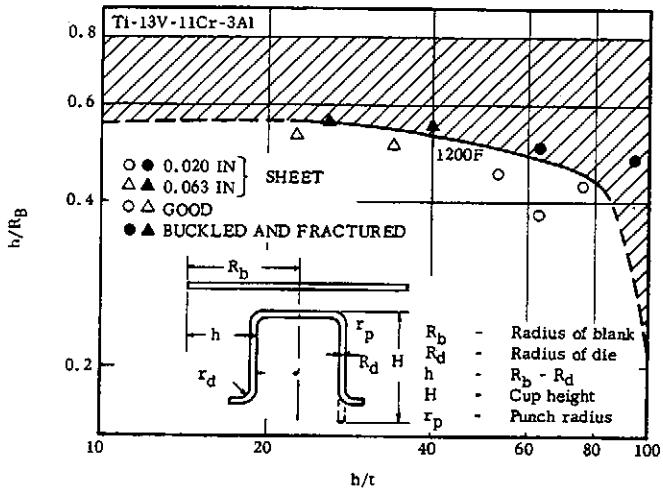


FIG. 4.014 LIMIT CURVE FOR DEEP DRAWING AT 1200F

(29, p. 121, 122)

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	Ti
13	V
11	Cr
3	Al

B120 VCA

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NONFERROUS ALLOYS

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

1. GENERAL

This alloy is an age hardenable, metastable beta alloy developed by Crucible Steel Division of Colt Industries under partial sponsorship of the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio (Air Force Contract No. AF33(615)-2742). It has exceptional workability and high strength capability. It may be readily hot or cold worked and is through-hardenable in sections up to six inches. Actual and potential applications include fasteners, sheet metal parts, tubing and heavy section parts.

Beta phase is retained on quenching from above 1400F. Omega phase, which also forms on quenching, is stable up to 800F. Yield strengths of up to 220 ksi have been measured in beta + omega structures, the strength level being dependent on the size and volume fraction of the omega phase. Plane strain fracture toughness reaches a minimum value of about 20 ksi$\sqrt{in}$ when the omega particle size exceeds 100 A°. Beta + alpha structures show good combinations of strength (up to F_{ty} = 170 ksi) and fracture toughness (up to K_{Ic} = 60-70 ksi$\sqrt{in}$). Unfortunately, the best combinations are susceptible to stress-corrosion cracking in aqueous solutions containing halide ions. The alloy is castable and weldable.

1.01 Commercial Designation

Beta III Titanium Alloy.

1.02 Alternate Designation

Ti-11.5Mo-6Zr-4.5Sn.

1.03 Specifications

AMS-4977, Bars and Wire (fastener stock)
AMS-4980, Bars and Wire
MIL-T-9047E, Bars and Forging Stock.

1.04 Composition

1.041 AMS and military specified compositions, Table 1.041.

1.05 Heat Treatment

1.051 Solution treat. 1275 to 1450F, hold briefly at temperature (several minutes), cool rapidly. Lower temperatures are used for maximum aging response, higher temperatures for maximum hardenability and solution treated formability. Liquid quenching is generally used, though air cooling is often adequate when solution treated properties are not important. The effect of quench rate from solution temperature on solution treated tensile properties is shown in Figure 3.02136 and Table 3.02125.

1.052 Age. 900 to 1100F, with higher strengths obtainable at the lower temperatures within this range.

1.053 The selection of aging time will depend on the combination of properties desired. At 900F, little additional strengthening is obtained by aging beyond eight hours (see Figure 3.02137), but the best combination of strength and fracture toughness is obtained by aging beyond thirty-two hours (see Section 3.0272). No information is available on the influence of aging time on strength and toughness at higher aging temperatures.

Section 1.06 discusses the aging kinetics as related to hardness. The influence of heatup time on heavy section hardenability is discussed in Section 1.091.

Elevated temperature stability is affected by aging time, as discussed in Section 1.092. When elevated temperature stability is required, eight-hour aging appears adequate in the upper portion of the recommended aging temperature range; times near thirty-two hours may be needed at 900 to 950F.

Aging time has a complicated influence on the stress corrosion cracking susceptibility of this alloy (see Section 2.03).

1.06 Hardness

1.061 The transformation kinetics and associated mechanical behavior of this alloy have been studied by Feeney and Blackburn (15). At aging temperatures below 800F, hardening (or strengthening) is caused by the precipitation of ω-phase (see TTT diagram, Figure 2.0121). The variation of hardness with aging time at 400, 550 and 700F is shown in Figure 1.064. At low aging temperatures, e.g. 400F, the hardness increase is slight and occurs after a rather long initial incubation period (about 120 minutes at 400F). In contrast, aging at temperatures between 500 to 700F commences with a very short (< 2 minutes) incubation period, and a large increase in hardness occurs.

At aging temperatures above 800F, α-phase precipitation is responsible for strengthening. The effect of aging time at 850, 1000 and 1150F on hardness is shown in Figure 1.066. The curves are classical in shape with lower peak hardness at shorter times the higher the aging temperature. Slight overaging is also apparent at each aging temperature. At 1150F, however, there is a marked increase in hardness at times over 100 hours. This secondary hardening far exceeds the initial peak hardness occurring between 5 and 10 minutes.

In the narrow temperature range 800F ± 10F, the α-phase and ω-phase grow simultaneously. Figure 1.065 shows the 800F aging curve bracketed by the 700F and 850F aging curves. It is seen that the aging characteristics at 800F are an apparent compromise between those at the two other aging temperatures.

The influence of prior deformation on the aging response at 700 and 1000F is shown in Figures 1.064 and 1.066, respectively. At the outset of 700F aging the hardness level of deformed stock far exceeds that of undeformed material. The hardness of both increases with aging time and, near peak hardness, the two curves tend to merge. The aging time to achieve peak hardness at 700F is slightly reduced by prior deformation.

As shown in Figure 1.066, the hardness of deformed stock does not increase with aging time at 1000F, but decreases. This contrasts with the response of deformed stock aged at 700F. Further, although the hardness curves for deformed and undeformed stock aged at 1000F merge at longer aging times, there is still a difference of 35 DPN at the peak hardness of the undeformed stock.

1.062 AMS specified hardness for bars and wire, Table 1.062.

1.063 AMS specified hardness for bars and wire for fastener application, Table 1.063.

1.064 Effect of aging time on hardness of specimens aged below 800F, Figure 1.064.

1.065 Effect of aging time on hardness of specimens aged at 800F, Figure 1.065.

1.066 Effect of aging time on hardness of specimens aged above 800F, Figure 1.066.

1.07 Forms and Conditions Available

1.071 The alloy is available in all mill product forms, including foil. Extrusions and tubing are presently available only on a pilot production basis (7).

1.08 Melting and Casting Practice

1.081 Molybdenum is difficult to add to large heats of titanium because of the combined effect of its high melting temperature and density. Zirconium, however, forms a relatively low-melting, low-density master alloy with molybdenum. Attempts to produce this alloy by master-alloy techniques have proven cost-prohibitive. The alloy is now produced using a proprietary vacuum arc melting technique developed by Crucible. Some early production ingots showed evidence of unmelted molybdenum. Modifications to the proprietary melting technique have subsequently been made and ingots are now being produced completely free of unmelted material (4).

1.082 Triple vacuum-arc melted material smooth strength properties are no different than those of double vacuum-arc melted stock (4).

	Ti
11.5	Mo
6	Zr
4.5	Sn

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1.083 Tensile properties of cast-to-size specimens, Table 1.083.

1.09 Special Considerations

1.091 Section size and directionality. Tables 3.0214 thru 3.0216 show the influence of as-quenched section size on the solution treated (water quenched) and aged smooth tensile properties of forged sections up to 6 inches square. The tin content of the bars tested was higher than the normal specification in order to enhance uniform hardenability. The results, however, agree with those for forgings of specified composition in Tables 3.0212 and 3.0213. While the alloy is through-hardenable in 6 inch section (Tables 3.0214 thru 3.0216), an anomaly exists in that higher strengths were obtained in 6 inch section than in 3 or 4 inch section. It is believed that this behavior is related to the effect of heatup time to aging, similar to behavior noted for Ti-13V-11Cr-3Al (14) - the longer the heatup time for a given section, the higher the strength level.

Generally, the reduction in area is observed to decrease with increasing section size. In Table 3.0214 it is noticed that the transverse ductility for bars aged at 900F were particularly low compared with the longitudinal direction. Overaging at 950 or 1000F did not improve this situation (see Tables 3.0215 and 3.0216). Cross forging lessens this directionality, as shown in Table 3.0217 (the edge properties reported should not be weighed heavily because of the limited amount of cold work imparted to those areas).

1.092 Stability. Omega phase forms when solution treated material is aged in the 400 to 800F temperature range (see T-T-T diagram in Figure 2.0121). When well developed, omega phase embrittles the alloy. Stability considerations therefore limit the service temperature for solution treated material to 350 to 400F maximum.

Alpha phase precipitates upon aging at temperatures above 800F, apparently without prior formation of omega. When high strength and/or elevated temperature stability is required, the alloy is aged in the 900 to 1100F range to a stable alpha-beta dispersion. Omega then does not form in subsequent service at lower temperatures. Eight hour aging time is adequate in the upper portion of the recommended range. Times near thirty-two hours may be needed for aging at 900 to 950F. Experience has shown that aging above 1100F leads to instability during subsequent exposure in the omega formation range, e.g. 700F. This is due to the large amount of relatively alloy-lean beta produced at higher aging temperatures (4).

1.093 Composition. Increases in beta stabilizer (Mo and Zr) content above nominal cause modest strength reductions for a given heat treatment (see Table 3.02138). Decreases below nominal may produce creep instability in the maximum strength condition (4).

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range. Approximately 3200 to 3300F (7).

2.012 Phase changes. Beta transus approximately 1400F (7).

2.0121 Time-temperature-transformation diagram, Figure 2.0121.

2.013 Thermal conductivity.

2.014 Thermal expansion, Figure 2.014.

2.015 Specific heat.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density. 0.183 lb per cu in. 5.10 gr per cu cm (4).

2.022 Electrical properties.

2.0221 Electrical resistivity. 61.3 microhms-inch at 74F for Ti-11.4Mo-5.9Zr-4.3Sn-0.11O.

2.023 Magnetic properties.

2.024 Emittance.

2.025 Damping capacity.

2.03 Chemical Properties

2.031 Corrosion resistance. General. In common with other titanium alloys, Ti-11.5Mo-6Zr-4.5Sn is susceptible to solid salt stress corrosion at elevated temperatures and exhibits delayed failure of cracked specimens at room temperature in aqueous salt environments. No data are available on the stress corrosion cracking susceptibility in organic solvents such as methanol.

2.032 Salt water stress corrosion cracking. According to recent studies by Feeney and Blackburn (15)(21)(22), the as-quenched and omega-phase-strengthened structures (aging between 400 and 800F) appear to be immune to stress corrosion cracking in aqueous halide solutions. This is in contrast to beta + alpha structures (aging above 800F) which show stress corrosion cracking susceptibility the degree to which is dependent upon the aging temperature, applied stress, strain rate, environment and applied electric potential. Figure 2.033 shows the delayed failure characteristics in 3.5 percent NaCl solution of cracked bend specimens aged 100 hours at 900F and tested under open circuit conditions. The data indicate a threshold stress intensity factor of 26 ksi$\sqrt{\text{in.}}$. The investigators found no environmental failures under the same conditions for specimens aged at 1150F. This is consistent with the results in Figure 2.034 which show for specimens immersed in 0.6 M KCl at an applied electric potential of -500 mv that the lower the aging temperature (within the beta + alpha field), the lower the threshold stress intensity factor and the higher the subsequent crack growth velocity. Aging time has a complicated influence on the threshold stress intensity factor and subsequent crack growth velocity as shown in Figure 2.035 for specimens aged at 900F and tested in 0.6M KCl at an applied electric potential of -500 mv.

The influence of applied electric potential on the threshold stress intensity factor for specimens immersed in 0.6M KCl aqueous solution is shown in Figure 2.036 which indicates the possibility of cathodic protection for this alloy around -1.5 volts. The influence of potential on crack velocity is shown to be linear in Figure 2.037. This relationship, however, would be expected to vary as a function of heat treatment and specimen orientation. For example, grain size can alter both the slope of this line and its intercept on the potential axis (22).

2.033 Stress corrosion cracking threshold stress intensity factor for failure in 3.5 percent NaCl solution (aqueous) under open circuit conditions (no applied potential), Figure 2.033.

2.034 Effect of aging temperature and stress intensity factor on stress corrosion crack velocity for cracked specimens immersed in 0.6M KCl aqueous solution with -500 mv applied potential, Figure 2.034.

2.035 Effect of aging time and stress intensity factor on stress corrosion crack velocity for cracked specimens immersed in 0.6M KCl aqueous solution with -500 mv applied potential, Figure 2.035.

2.036 Effect of applied electric potential on crack initiation stress intensity factor for cracked specimens immersed in 0.6M KCl aqueous solution, Figure 2.036.

2.037 Effect of applied electric potential on stress corrosion crack velocity for cracked specimens immersed in 0.6M KCl aqueous solution, Figure 2.037.

2.038 Hot salt stress corrosion characteristics of bar, Table 2.038.

2.039 Hot salt stress corrosion characteristics of plate, Table 2.039.

2.0310 Corrosion rates of Ti-11.5Mo-6Zr-4.5Sn and unalloyed titanium in hydrochloric and sulfuric acids, Table 2.0310.

2.04 Nuclear Properties

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 AMS specified mechanical properties for solution treated bars and wire and bars and wire for fastener application, Table 3.011.

	Ti
11.5	Mo
6	Zr
4.5	Sn

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3.012 AMS specified mechanical properties for solution treated and aged bars and wire, Table 3.012.

3.013 AMS specified mechanical properties for solution treated and aged bars and wire for fastener application, Table 3.013.

3.02 Mechanical Properties at Room Temperature

3.021 Tension.

3.0211 Typical stress-strain curves for aged sheet, Figure 3.0211.

3.0212 Variation in tensile properties for hot rolled billet, Table 3.0212.

3.0213 Variation in tensile properties for closed die forging, Table 3.0213.

3.0214 Effect of heat treated section size on tensile properties of unidirectionally forged square bars aged at 900F, Table 3.0214.

3.0215 Effect of heat treated section size on tensile properties of unidirectionally forged square bars aged at 950F, Table 3.0215.

3.0216 Effect of heat treated section size on tensile properties of unidirectionally forged square bars aged at 1000F, Table 3.0216.

3.0217 Effect of cross forging on tensile properties of 3 inch and 6 inch square forged bars aged at 950F, Table 3.0217

3.0218 Tensile properties of aged bars variously melted and solution treated, Figure 3.0218.

3.0219 Center and mid-radius tensile properties of 1 9/16 inch solution treated bar, Table 3.0219.

3.02110 Tensile property uniformity of 1 inch and 0.5 inch bar, Table 3.02110.

3.02111 Spread of tensile properties for 1/2 inch and 1 9/16 inch diameter bars solution treated at 1350F to 1450F and aged, Figure 3.02111.

3.02112 Effect of 100 hour exposure to elevated temperature with load on room temperature tensile properties of bar, Table 3.02112.

3.02113 Effect of 500 hour exposure to elevated temperature with load on room temperature tensile properties of bar, Table 3.02113.

3.02114 Effect of solution temperature on tensile properties of rod, Figure 3.02114.

3.02115 Spread of tensile properties for rod variously heat treated, Figure 3.02115.

3.02116 Effect of 100 hour exposure at 700F with load on room temperature tensile properties of rod, Table 3.02116.

3.02117 Effect of aging temperature on tensile properties of wire, Figure 3.02117.

3.02118 Tensile properties of seamless tubing, Table 3.02118.

3.02119 Effect of solution temperature on tensile properties of solution treated 0.5 inch plate, Figure 3.02119.

3.02120 Effect of solution temperature on tensile properties of solution treated and aged 0.5 inch plate, Figure 3.02120.

3.02121 Effect of aging temperature on tensile properties of 0.5 inch plate, Figure 3.02121.

3.02122 Effect of aging temperature on tensile properties of 1 inch plate, Figure 3.02122.

3.02123 Tensile properties of heavy plate, Table 3.02123.

3.02124 Tensile properties of double and triple vacuum-arc melted plate, Table 3.02124.

3.02125 Effect of quench rate from solution treatment temperature on tensile properties of plate, Table 3.02125.

3.02126 Effect of hot rolling temperature on tensile properties of plate, Figure 3.02126.

3.02127 Spread of tensile properties for plate variously hot rolled solution treated and aged, Figure 3.02127.

3.02128 Effect of 100 hour exposure to elevated temperature with load on room temperature tensile properties of plate, Table 3.02128.

3.02129 Effect of 500 hour exposure to elevated temperature with load on room temperature tensile properties of plate, Table 3.02129.

3.02130 Tensile properties of hot band, Table 3.02130.

3.02131 Effect of solution temperature on tensile properties of solution treated sheet, Figure 3.02131.

3.02132 Effect of solution temperature on tensile properties of aged sheet, Figure 3.02132.

3.02133 Effect of quench rate from solution treatment temperature on tensile properties of solution treated sheet, (see Figure 3.02136).

3.02134 Effect of aging temperature on tensile properties of hand sheet solution treated at 1350F, Figure 3.02134.

3.02135 Effect of aging temperature on tensile properties of hand sheet solution treated at 1450F, Figure 3.02135.

3.02136 Effect of aging temperature on tensile porperties of sheet solution treated at 1400 or 1450F, Figure 3.02136.

3.02137 Effect of aging time on tensile properties of sheet, Figure 3.02137.

3.02138 Effect of composition (variation in beta-phase-stabilizing element content) on tensile properties of sheet, Table 3.02138.

3.02139 Sheet tensile property variation for electron beam melted ingot, Figure 3.02139.

3.02140 Effect of cold reduction on tensile properties of sheet solution treated at 1350F and water quenched, Figure 3.02140.

3.02141 Effect of cold reduction on tensile properties of sheet solution treated at 1450F and air cooled, Figure 3.02141.

3.02142 Effect of cold reduction on aging response of sheet aged after cold rolling, Figure 3.02142.

3.02143 Effect of cold reduction on aging response of sheet resolution treated and aged after cold rolling, Figure 3.02143.

3.02144 Spread of tensile properties for sheet variously cold reduced, solution treated and aged, Figure 3.02144.

3.02145 Effect of exposure at 200F with load on room temperature tensile properties of sheet, Table 3.02145.

3.02146 Effect of 100 hour exposure to elevated temperature with load on room temperature tensile properties of sheet aged to medium strength level, Table 3.02146.

3.02147 Effect of 100 hour exposure to elevated temperature with load on room temperature tensile properties of sheet aged to high strength level, Table 3.02147.

3.02148 Effect of 500 hour exposure to elevated temperature with load on room temperature tensile properties of sheet aged to medium strength level, Table 3.02148.

3.02149 Effect of 500 hour exposure to elevated temperature with load on room temperature tensile properties of sheet aged to high strength level, Table 3.02149.

3.02150 Effect of 100 hour exposure to elevated temperature with load on room temperature tensile properties of sheet variously aged, Figure 3.02150.

3.02151 Effect of aging temperature on tensile properties of coil sheet, Figure 3.02151.

3.02152 Tensile properties of foil, Table 3.02152.

3.022 Compression.

3.0221 Typical compressive stress-strain curves for sheet, Figure 3.0221.

3.0222 Compressive yield strength of bar, Table 3.0222.

3.0223 Compressive yield strength of plate, Table 3.0223.

3.0224 Compressive yield strength of sheet, Table 3.0224.

3.023 Impact (see 3.033).

3.024 Bending.

3.025 Torsion and shear.

3.0251 Double shear strength of aged bars variously melted and solution treated, Figure 3.0251.

3.0252 Effect of solution temperature on shear strength of rod, Figure 3.0252.

3.0253 Spread of shear strength for rod aged at different temperatures, Figure 3.0253.

3.0254 Shear strength of sheet, Table 3.0254.

3.026 Bearing.

3.027 Stress concentration.

3.0271 Notch properties.

3.02711 Effect of composition (variation in beta-phase-stabilizing element content) on mild-notch tensile properties of sheet, Table 3.02711.

3.02712 Effect of yield strength level on strength of center fatigue crack sheet specimens, Figure 3.02712.

3.02713 Effect of cold reduction on strength of center fatigue-crack sheet specimens variously heat treated, Figure 3.02713.

3.0272 Fracture toughness.

3.02721 General. The aging response of this alloy is presented in Figure 3.02722 in terms of its yield strength and plane strain fracture toughness. According to a recent study by Feeney and Blackburn (15)(23), the trends observed

Ti
11.5 Mo
6 Zr
4.5 Sn

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may be interpreted in light of the alloy's transformation kinetics (see TTT diagram, Figure 2.0121).

The as-quenched β-phase structure contains ω-phase particles < 25 A° in diameter. Aging below 800 F to produce ω-phase particles ≥ 100 A° caused tension specimens to fail in a brittle manner without general yielding. These failures often originated at faint machine markings extensometer marks, and thread roots. Such brittle specimens were therefore tested in compression and are suitably identified in Figure 3.02722.

Only a small increase in yield strength is obtained on aging at 550 F, even after 500 hours, at which time the ω-phase particle size is 100 A°. The corresponding decrease in plane strain fracture toughness is marked (a near-linear decrease from 65.9 ksi$\sqrt{\text{in}}$ to 9.4 ksi$\sqrt{\text{in}}$). At 700 F, aging produces a rapid increase in yield strength. The maximum value of 220 ksi is associated with an average particle size of 900 A°. The plane strain fracture toughness is reduced to a limiting value of about 20 ksi $\sqrt{\text{in}}$ early in the aging cycle and is thus apparently independent of both particle size and yield strength when the ω-phase particle size exceeds 100 A°.

The effect of α-phase precipitation on yield strength and plane strain fracture toughness is typified by the 900 F aging curve. It is apparent that the best combination of strength and toughness is obtained by aging beyond 32 hours at 900 F, which results in the precipitation of a fine dispersion of α-phase. The low fracture toughness value obtained for specimens aged 0.5 hour at 900 F is reproducible and, according to the investigator(15), may be explained by the large mass of the fracture toughness specimen which is responsible for slow heating and slow cooling through the ω-phase transformation region during the aging cycle. Hence the high volume fraction of β-phase may be slightly embrittled by this treatment. The fracture toughness minimum at 8 hours aging is not unexpected as it is associated with maximum strengthening at this aging temperature.

3.02722 Effect of aging time on the plane strain fracture toughness of plate, Figure 3.02722.
3.02723 Plane strain fracture toughness of press forgings, Table 3.02723.
3.028 Combined properties.

3.03 Mechanical Properties at Various Temperatures
3.031 Tension.
3.0311 Typical stress-strain curves at various temperatures for sheet in longitudinal direction, Figure 3.0311.
3.0312 Typical stress-strain curves at various temperatures for sheet in transverse direction, Figure 3.0312.
3.0313 Effect of test temperature on tensile properties of bar, Figure 3.0313.
3.0314 Effect of test temperature on tensile properties of plate, Figure 3.0314.
3.0315 Effect of test temperature on tensile properties of sheet, Figure 3.0315.
3.032 Compression.
3.0321 Typical compressive stress-strain curves at various temperatures for sheet in longitudinal direction, Figure 3.0321.
3.0322 Typical compressive stress-strain curves at various temperatures for sheet in transverse direction, Figure 3.0322.
3.0323 Effect of test temperature on compressive yield strength of sheet, Figure 3.0323.
3.033 Impact.
3.0331 Charpy-V impact energy for bar at room temperature and -40 F, Table 3.0331.
3.0332 Charpy-V impact energy for bar at -40 F, Table 3.0332.
3.0333 Effect of aging temperature on -40 F impact energy of 0.5 inch plate, Figure 3.0333.
3.0334 Effect of aging temperature on -40 F impact energy of 1 inch plate, Figure 3.0334.
3.0335 Effect of hot rolling temperature and cooling rate from the solution treatment temperature on the room temperature and -40 F impact energy of 0.5 inch plate, Table 3.0335.
3.034 Bending.
3.035 Torsion and shear.
3.036 Bearing.
3.037 Stress concentration.
3.0371 Notch properties.
3.0372 Fracture toughness.
3.038 Combined properties.

3.04 Creep and Creep Rupture Properties
3.041 100 hour creep deformation for bar (see Table 3.02112).
3.042 500 hour creep deformation for bar (see Table 3.02113).
3.043 100 hour creep deformation for plate, Figure 3.043.
3.044 500 hour creep deformation for plate (see Table 3.02129).
3.045 Smooth stress rupture properties for plate at room temperature and 500 F, Table 3.045.
3.046 5 hour mild-notch stress rupture strength for plate, Table 3.046.
3.047 100 hour creep deformation for sheet, Figure 3.047.
3.048 500 hour creep deformation for sheet, Figure 3.048.
3.049 200 F creep deformation for sheet, Table 3.049.
3.0410 500 hour mild-notch rupture strength for sheet at room temperature, Table 3.0410.

3.05 Fatigue Properties
3.051 Axial load and rotating beam fatigue properties of bar, Figure 3.051.
3.052 Axial load smooth and mild-notch fatigue properties of bar, Figure 3.052.
3.053 Axial load smooth fatigue properties of plate, Figure 3.053.
3.054 Axial load smooth and mild-notch fatigue properties of sheet, Figure 3.054.

3.06 Elastic Properties
3.061 Poisson's ratio for sheet, Table 3.061.
3.0621 Effect of heat treated section size on elastic modulus of unidirectionally forged square bars aged at 900 F, (see Table 3.0214).
3.0622 Effect of test temperature on elastic modulus of bar, Figure 3.0622.
3.0623 Compressive elastic modulus of bar, Table 3.0623.
3.0624 Effect of aging temperature on elastic modulus of plate and sheet, Figure 3.0624.
3.0625 Compressive elastic modulus of plate, Table 3.0625.
3.0626 Effect of solution temperature on elastic modulus of solution treated sheet, Figure 3.0626.
3.0627 Effect of test temperature on elastic modulus of sheet, Figure 3.0627.
3.0628 Effect of test temperature on compressive elastic modulus of sheet, Figure 3.0628.
3.0629 Effect of aging temperature on elastic modulus of coil sheet, Figure 3.0629.
3.06210 Elastic modulus of foil, (see Table 3.02152).
3.0631 Typical compressive tangent modulus at various temperatures for sheet in longitudinal direction, Figure 3.0631.
3.0632 Typical compressive tangent modulus at various temperatures for sheet in transverse direction, Figure 3.0632.

4. FABRICATION

4.01 Formability.
4.011 Cold forming. The cold formability of this alloy is discussed in reference 20. The alloy is more readily cold formed than previously available high strength titanium alloys and is approximately equal in cold formability to half-hard Type 301 stainless steel and A-70 unalloyed titanium. This formability should permit cold forming of many sheet metal parts which would require hot forming alpha-beta grades. The alloy has also been successfully cold shear spun to high reductions.

The alloy exhibits high springback like all titanium alloys. Warm forming may be required when springback cannot be corrected by means of stretch forming or overbending. The alloy can be warm formed at 950-1000 F. Inexpensive tooling materials are suitable for forming at such

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4.5 Sn

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temperatures, in contrast to the high-alloy die materials required for hot forming alpha-beta grades at 1400F. Low temperature forming also minimizes contamination of the surface and subsequent metal removal by pickling. Formed sheet can be simply aged to very high strength levels.

The alloy has been successfully processed to tubing. Tensile properties of tubing are presented in Table 3.02118.

4.0111 Flattening and flaring performance of seamless tubing, Table 4.0111.

4.012 Forging. Forging can be started at temperatures up to 2000F, and minimum temperature is determined solely by equipment power limitations. Finish forging at relatively low temperature (e.g., 1600F) is generally recommended for fine grain size and maximum aged ductility, where equipment limitations permit (7).

4.013 Rollability. The good workability of this alloy, both hot and cold, recommends it for continuous strip processing. At 1700F, the alloy has flow stresses equivalent to Ti-6Al-4V and about 60 percent that for Ti-13V-11Cr-3Al (see Figure 4.0131). It can be processed at reasonable roll loads at temperatures as low as 1400F (see also Figure 4.0131). The roll energy requirement for this alloy is comparable to Type 304 stainless steel (see Figure 4.0132).

The effect of initial and final pass entry temperatures on the tensile properties of sheet is shown in Table 4.0133. The alloy producer recommends an initial pass entry temperature of 1850F (4). Higher temperatures offer no property advantage and would require more conditioning than the 1850F initial entry temperature due to heating contamination, but would provide a safety factor for the mill. Lower initial rolling temperature might cause mill coiling problems. Hot rolling of plate at 1500F appears to produce the best combination of strength and ductility for solution treated or solution treated and aged plate (see Figures 4.0134 and 4.0135).

Figure 4.0136 illustrates the cold rollability of this alloy from 0.195 inch, representing the heaviest practical hot-band gage, down to 0.002 inch foil. It is seen to be somewhat stiffer than commercially pure titanium, requiring about 10-20 percent additional rolling passes at normal roll loads to achieve gage. In terms of cold rollability without edge cracking, this alloy surpasses commercially pure titanium and many commercial alloys. Cold reductions exceeding 90 percent without edge cracking are possible (see Table 4.0137).

4.0131 Hot rollability of Ti-11.5Mo-6Zr-4.5Sn and several other alloys, Figure 4.0131.

4.0132 Energy for hot strip rolling, Figure 4.0132.

4.0133 Effect of hot rolling temperature on tensile properties of hot rolled sheet, Table 4.0133.

4.0134 Effect of hot rolling temperature on tensile properties of solution treated plate, Figure 4.0134.

4.0135 Effect of hot rolling temperature on tensile properties of solution treated and aged plate, Figure 4.0135.

4.0136 Cold rollability, Figure 4.0136.

4.0137 Several cold rolling factors related to reduction limits, Table 4.0137.

4.014 Fasteners. The cold formability of this alloy makes it particularly suitable for aircraft fastener applications. Solution treated rivets can be readily installed by gun driving without fear of cracking due to its low rate of work hardening. Solution treated rivets are suitable only for low strength applications and where service temperatures do not exceed 350F (see stability considerations in Section 1.092).

Where higher strength is required rivets may be readily driven in the overaged condition (1050-1100F). Such rivets can be driven by either squeezing or gun driving, are metallurgically stable up to 800F, and can statistically meet 95 ksi minimum shear strength.

The effect of bucking tool configuration has been recently studied (18). While no effect is observed on the cross tension or lap shear strength of rivet joints (see Table 4.0143 and Figure 4.0144), a significant difference in fatigue strength for joints with or without previous exposure to elevated temperature is shown in Table 4.0146 for flat versus cavity bucking tool configurations.

4.0141 Effect of solution temperature on cold headability of rod, Figure 4.0141.

4.0142 Cross tension and lap shear strength of rivet joints with and without exposure to elevated temperature with load, Table 4.0142.

4.0143 Effect of bucking tool configuration on cross tension strength of rivet joints with and without exposure to elevated temperature, Table 4.0143.

4.0144 Effect of bucking tool configuration and test temperature on lap shear strength of rivet joints with and without previous exposure to elevated temperature, Figure 4.0144.

4.0145 Fatigue strength of riveted lap shear joints, Figure 4.0145.

4.0146 Effect of bucking tool configuration on fatigue strength of riveted lap shear joints with and without previous exposure to elevated temperature, Table 4.0146.

4.02 Machining and Grinding

Contact Air Force Machinability Data Center, 3980 Rosslyn Drive, Cincinnati, Ohio 45209.

4.03 Welding

4.031 Fusion welding. Data shown in Table 4.0311 were obtained on GTA welded sheet prepared for welding by pickling in 2 percent hydrofluoric, 20 percent nitric acid. After pickling, the panels were rinsed in warm water and dried; the sheared panel edges were not dressed in any manner. Welding was manual, single pass, and without addition of filler. Current was 90 ampere at 11 volts. All joints were transverse to the rolling direction. Weld beads were ground flush with the parent metal.

The aged strength of weld joints was about 90 percent that of the aged parent sheet (compare Table 4.0311 with Figure 3.02134). Low-high aging cycles (e.g., 800F, 8 hr + 1050F, 8 hr) produce a fine alpha precipitate and increased aged strength compared with single aging (e.g. 1050F, 8 hr).

Electron beam welding appears to offer no aged strength advantage over GTA welding (compare Tables 4.0311 and 4.0312).

4.0311 Tensile properties of GTA fusion welded sheet, Table 4.0311.

4.0312 Tensile properties of electron-beam fusion welded sheet, Table 4.0312.

4.032 Spot welding. As in the preparation of fusion welds above spot weld specimens for which data are presented in Table 4.0321 were descaled and pickled in nitric-hydrofluoric acid immediately prior to joining. As is general practice for titanium, no inert gas shielding was required during spot welding. This results in only a very superficial oxide film around the weld because the fusion areas are pressed closely together and the weld cycle is short due to the relatively high resistivity of the metal.

Since spot welds develop only a limited fusion area, the spot weld strength may be expected to be influenced by the pre-weld solution temperature. Thus the 1350F pre-weld solution treatment produces higher lap shear strength for unaged, pre-weld aged or post-weld aged welds with one exception - welds post-weld aged at 1000F. With the exception of unaged welds, the cross tension strength of welds pre-weld solution treated at 1450F exceeds that for welds pre-weld solution treated at 1350F. Post-weld high-strength aging treatments at 950 and 1000F are generally unsatisfactory. Only after these aging treatments are weld bond failures observed at the original interface. Only marginal recovery of weld strength is observed in medium strength post-weld aging at 1050F.

4.0321 Cross tension and lap shear strengths of spot welded sheet, Table 4.0321.

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

4.04 Heat Treatment

High strength can be produced in this alloy by aging followed by air cooling. Little or no distortion occurs. Resolution treatment prior to aging is recommended for sheet parts where improved ductility and toughness is desired in heavily worked areas. This can be accomplished by heating to 1325-1350 F, holding 1-2 minutes, and water quenching or individually air cooling. Some distortion is likely, but to a lesser degree than in heat treatment of other titanium alloys.

4.05 Surface Treating

In common with other titanium alloys, this alloy is susceptible to the embrittling effect of a high-oxygen surface layer. Removal of scale and oxygen-rich surface after heat treatment is recommended. The oxide formed in aging at 900 F can be removed by pickling in 25 percent nitric-2 percent hydrofluoric acid at 140-150 F. Molten salt descaling prior to pickling is preferred after aging at higher temperatures or after solution treatment and aging. Acid pickling to reduce thickness by 0.0005 inch is adequate after aging, but 0.001-0.002 inch thickness reduction is recommended after solution treatment and aging. Vacuum or inert atmosphere heat treatment does not necessarily eliminate the need for surface removal.

Beta alloys absorb hydrogen quite rapidly, though they are affected less by hydrogen pickup than alpha or alpha-beta alloys. The nitric-hydrofluoric ratio in pickling baths should be maintained at 10-15 to 1 to minimize hydrogen absorption.

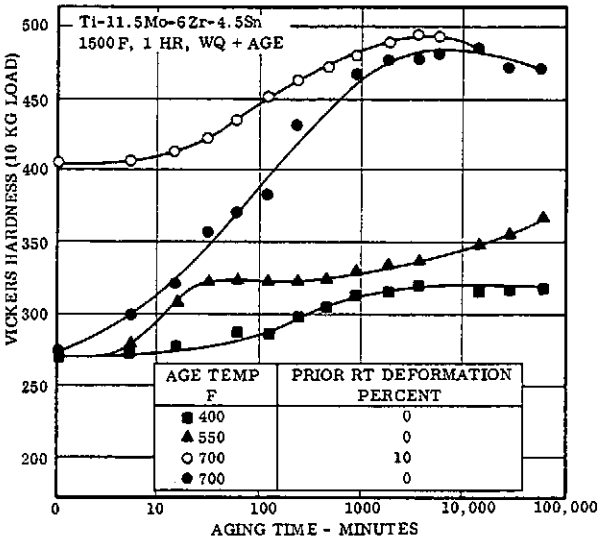


FIG. 1.064 EFFECT OF AGING TIME ON HARDNESS OF SPECIMENS AGED BELOW 800 F. (15)

Source	AMS (1)(2) Military (3)	
	Weight Percent	
	Minimum	Maximum
Molybdenum	10.00	13.00
Zirconium	4.50	7.50
Tin	3.75	5.25
Iron	-	0.35
Oxygen	-	0.18
Hydrogen	-	0.0200*
Carbon	-	0.10
Nitrogen	-	0.05
Other Elements (total)	-	0.40
Titanium	Balance	

* Military gives 0.015 max (to be determined on each lot of product as shipped).

TABLE 1.041 AMS AND MILITARY SPECIFIED COMPOSITIONS.

Source	AMS (2)	
Alloy	Ti-11.5Mo-6Zr-4.5Sn	
Form	Bars and Wire	
Condition	1300-1450 F, 15 min max, WQ	1300-1450 F, 15 min max, WQ + 910-940 F, 8 hr, AC
Hardness-R_C	30 max	34-45

TABLE 1.062 AMS SPECIFIED HARDNESS FOR BARS AND WIRE.

Source	AMS (1)	
Alloy	Ti-11.5Mo-6Zr-4.5Sn	
Form	Bars and Wire (Fastener Stock)	
Condition	1275-1350 F, 15 min, WQ	1275-1350 F, 15 min, WQ + 1050-1100 F, 2 hr minimum, AC
Hardness-R_C	30 max	30-38

TABLE 1.063 AMS SPECIFIED HARDNESS FOR BARS AND WIRE FOR FASTENER APPLICATION.

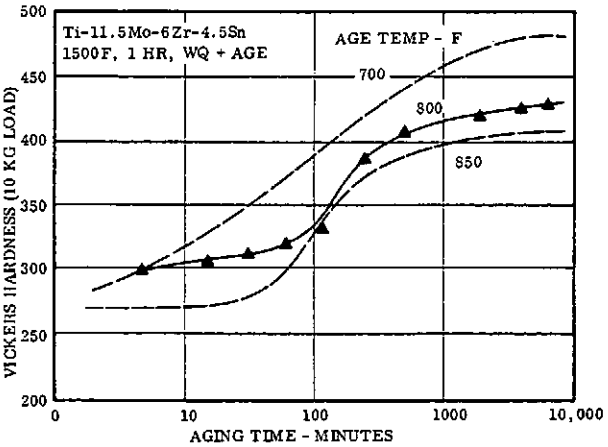


FIG. 1.065 EFFECT OF AGING TIME ON HARDNESS OF SPECIMENS AGED AT 800 F. (15)

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

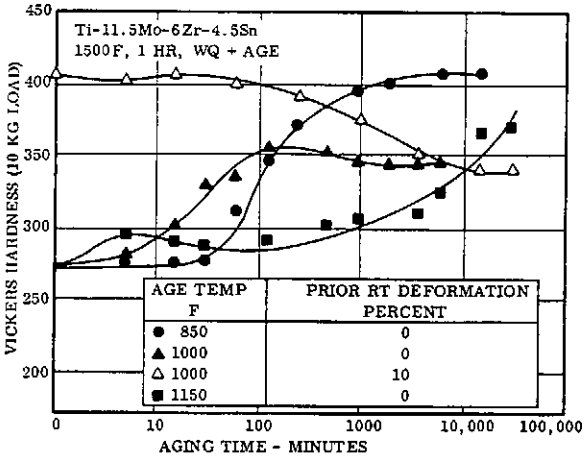


FIG. 1.066 EFFECT OF AGING TIME ON HARDNESS OF SPECIMENS AGED ABOVE 800F. (15)

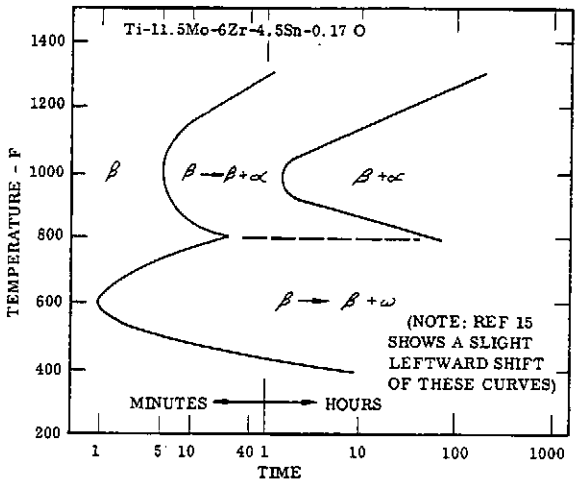


FIG. 2.0121 TIME-TEMPERATURE-TRANSFORMATION DIAGRAM, (10)

Source	(8)			
Alloy	Ti-11.5Mo-6Zr-4.5Sn			
Form	Cast-to-Size Tensile Specimens			
Heat / Condition	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
A(a) As Cast	121.9	107.7	18.5	61.1
	126.6	115.2	17.0	52.7
1350F, WQ + 750F, 8 hr	136.1	(d)	-	-
	151.8	(d)	-	-
1350F, WQ + 900F, 8 hr	191.7	184.1	2.5	4.4
	195.1	180.9	2.5	4.3
1350F, WQ + 1100F, 8 hr	142.9	135.8	8.0	28.9
	143.2	135.7	6.0	23.9
1350F, WQ + 750F, 8 hr + 800F, 8 hr	149.9	(d)	-	-
	103.3	(d)	-	-
A(b) As Cast	124.7	114.4	16.8	53.1
	117.1	101.3	19.8	59.8
	118.2	104.4	18.4	60.6
1400F, 1 hr, WQ + 950F, 8 hr	187.4	179.3	2.7	7.9
	193.5	183.7	3.1	7.9
	191.0	179.3	2.4	3.9
	190.0	179.8	2.6	5.4
B(c) 1350F, WQ + 920F, 8 hr	197.0	180.0	6	8
1350F, WQ + 950F, 8 hr	182.0	164.0	7	15

(a) Cast and tested by investigator No. 1.
(b) Cast and tested by investigator No. 2.
(c) Cast and tested by investigator No. 3.
(d) Specimen failed with less than 0.2 percent plastic deformation.

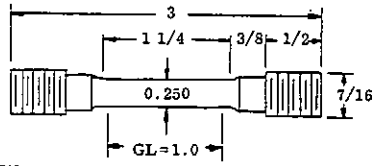


TABLE 1.083 TENSILE PROPERTIES OF CAST-TO-SIZE SPECIMENS.

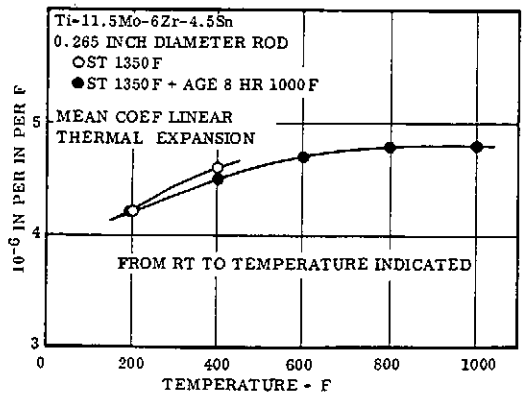


FIG. 2.014 THERMAL EXPANSION. (4)

Ti	
11.5	Mo
6	Zr
4.5	Sn

BETA III

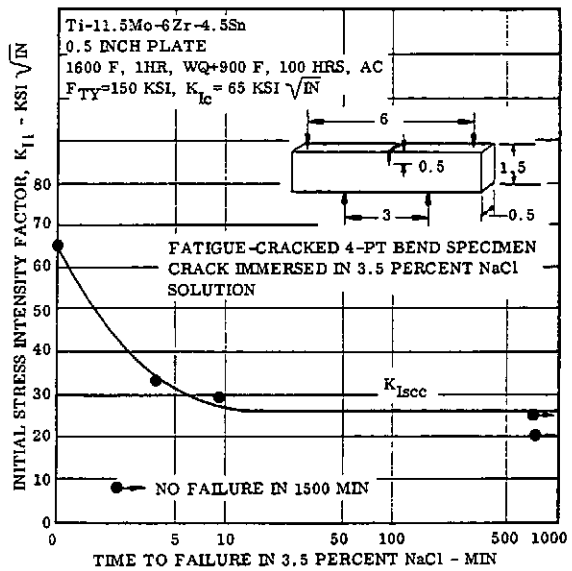


FIG. 2.033 STRESS CORROSION CRACKING THRESHOLD STRESS INTENSITY FACTOR FOR FAILURE IN 3.5 PERCENT NaCl SOLUTION (AQUEOUS) UNDER OPEN CIRCUIT CONDITIONS (NO APPLIED POTENTIAL). (15)(21)(23)

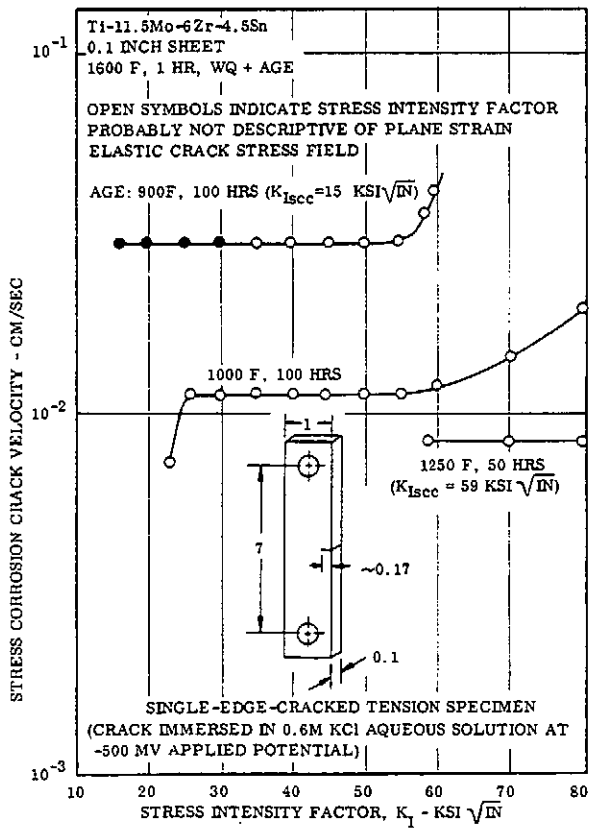


FIG. 2.034 EFFECT OF AGING TEMPERATURE AND STRESS INTENSITY FACTOR ON STRESS CORROSION CRACK VELOCITY FOR CRACKED SPECIMENS IMMERSED IN 0.6M KCl AQUEOUS SOLUTION WITH -500 MV APPLIED POTENTIAL. (15)(22)

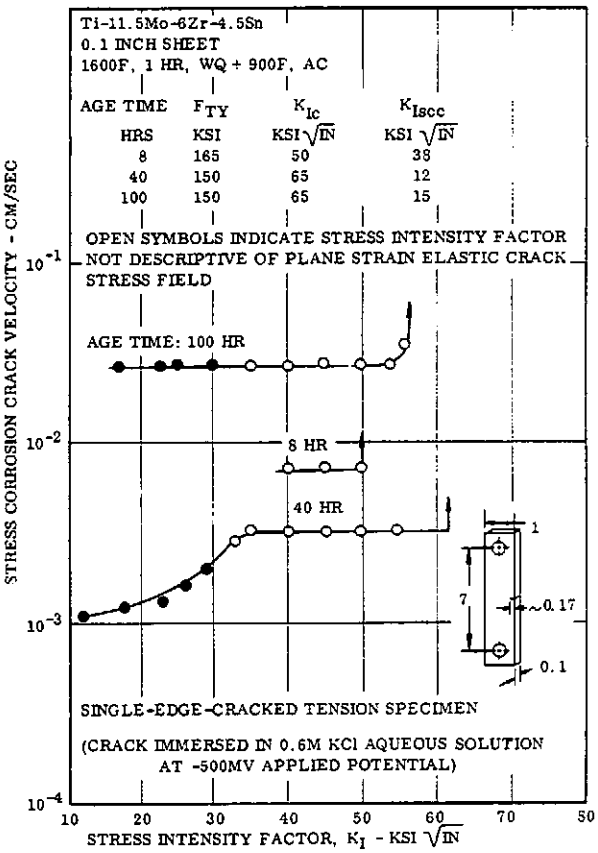


FIG 2.035 EFFECT OF AGING TIME AND STRESS INTENSITY FACTOR ON STRESS CORROSION CRACK VELOCITY FOR CRACKED SPECIMENS IMMERSED IN 0.6M KCl AQUEOUS SOLUTION WITH -500 MV APPLIED POTENTIAL. (15)(22)

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

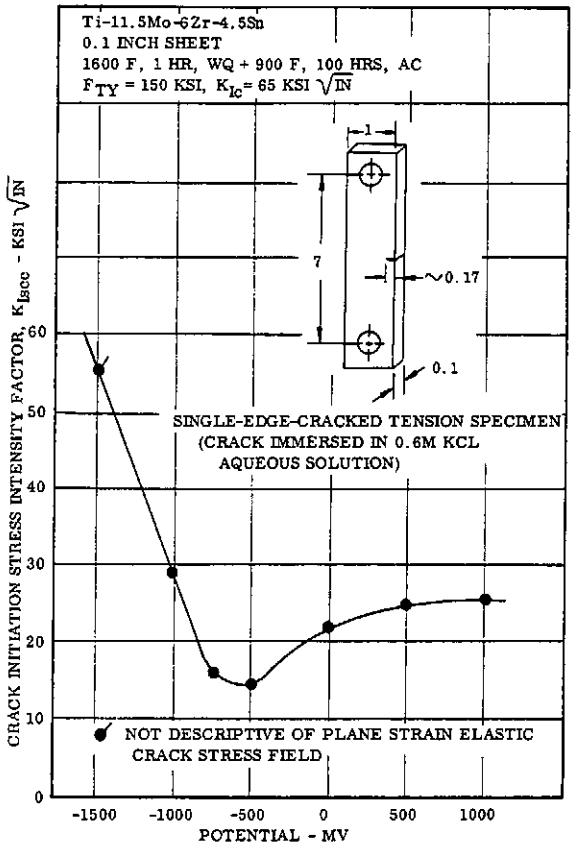


FIG. 2.036 EFFECT OF APPLIED ELECTRIC POTENTIAL ON CRACK INITIATION STRESS INTENSITY FACTOR FOR CRACKED SPECIMENS IMMERSED IN 0.6M KCL AQUEOUS SOLUTION. (15)(21)(22)

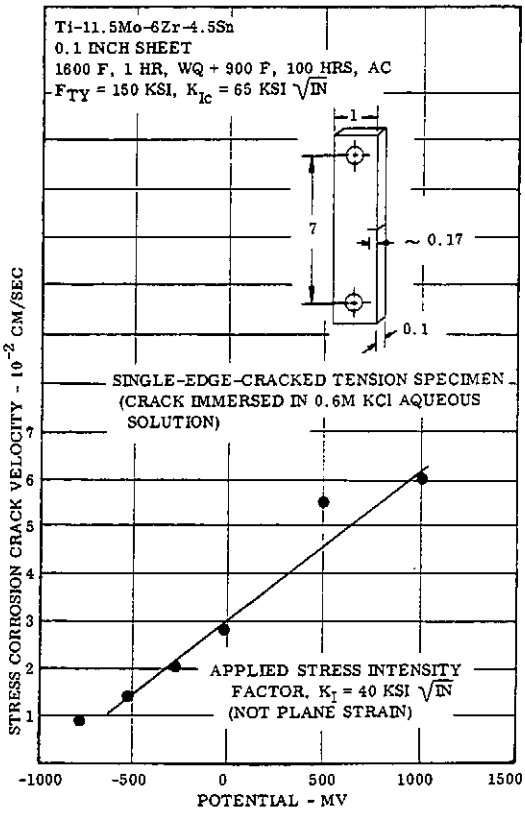


FIG. 2.037 EFFECT OF APPLIED ELECTRIC POTENTIAL ON STRESS CORROSION CRACK VELOCITY FOR CRACKED SPECIMENS IMMERSED IN 0.6M KCl AQUEOUS SOLUTION. (15)(22)

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

Source				(4)				
Alloy				Ti-11.5Mo-6Zr-4.5Sn				
Form				0.5 inch diameter bar				
Condition				1420F, WQ + 950F, 8 hr				
100 hour exposure				Subsequent RT tensile properties				
Temp F	Stress ksi	Permanent Deformation percent	Surface Coating	F_{tu} ksi	F_{ty} ksi	e(4D) percent	RA percent	Salt Attack at Break percent*
Unexposed			none	193.7	181.0	8.0	34.3	0
500	125	0.00	none	200.1	190.0	5.0	16.4	0
500	110	0.10	salt**	196.2	187.6	9.0	31.9	0
500	130	0.01	salt**	199.8	190.8	8.0	28.7	0
500	140	0.36	none	196.9	192.4	11.0	32.5	0
500	140	0.00	salt**	196.4	187.9	8.0	23.8	0
500	150	0.50	salt**	201.2	199.2	3.0	25.7	0
700	90	0.30	none	202.4	191.3	8.0	25.1	0
700	50	0.02	salt**	202.8	191.3	7.0	23.7	0
700	75	0.24	salt**	199.4	192.4	10.0	29.2	0
700	80	0.48	salt**	160.3	-	-	-	15
700	85	0.14	salt**	130.8	-	-	-	20
750	40	0.16	salt**	198.4	187.9	6.0	27.2	0

* Percent of cross section.
** Specimens coated with a slurry of powdered NaCl and water.

TABLE 2.038 HOT SALT STRESS CORROSION CHARACTERISTICS OF BAR.

Source			(4)				
Alloy			Ti-11Mo-5.5Zr-4.5Sn				
Form			0.063 inch sheet				
Condition			ST 1400F + 900F, 8 hr				
650F, 40 ksi Exposure			Subsequent RT Tensile Properties				
Time hr	Permanent Deformation percent	Surface Coating	F_{tu} ksi	F_{ty} ksi	e(2 in) percent	RA percent	Salt Attack at Break percent*
0	-	None	213.6	197.6	8.0	26.7	0
500	0.05	None	220.2	204.5	5.0	18.9	0
500	0.09	None	222.1	208.1	6.0	22.1	0
500	0.05	Salt	215.5	199.7	5.0	25.4	0
500	<0.01	Salt	223.9	207.6	4.5	9.0	1

* Percent of cross section.

TABLE 2.039 HOT SALT STRESS CORROSION CHARACTERISTICS OF PLATE.

Source	AMS(1)		AMS(2)	
Alloy	Ti-11.5Mo-6Zr-4.5Sn			
Form	Bars and Wire (Fastener Stock)		Bars and Wire	
Condition	1275-1350F, 15 min, WQ		1300-1450F, 15 min maximum, WQ	
Nominal Diameter or Distance Between Parallel Sides inches	F_{tu} - ksi minimum	F_{ty} - ksi minimum	e(2 in or 4D) percent minimum	RA percent* minimum
1.625	110	90	15	50
1.625 to 3.000	100	90	15	50

* Round specimens.
Longitudinal direction.

TABLE 3.011 AMS SPECIFIED MECHANICAL PROPERTIES FOR SOLUTION TREATED BARS AND WIRE AND BARS AND WIRE FOR FASTENER APPLICATION.

Source	(4)			
Corrosive Medium	Corrosion Rate - mils per year			
	RT		Boiling	
Acid	Weight percent	A70 (a) (500 hr test)	Beta III (b) (1000 hr test)	A70 (a) (48 hr test)	Beta III (b) (48 hr test)
HCl	2	0.034	0.062	297.0	4.28
	3	0.104	0.062	569.0	15.5
	5	7.45	0.078	1393	104.3
	10	26.55	0.164	3155	676.5
	15	-	-	5205	3093
	20	72.0	8.69	-	-
	30	316.5	17.55	-	-
H_2SO_4	1	-	-	456.5	1.80
	3	-	-	1182	15.05
	5	-	-	1830	38.89
	10	-	-	2833	135.1
	15	-	-	4055	241.0

(a) Unalloyed titanium grade A70, mill annealed sheet 0.087 inch thick.
(b) Ti-11.5Mo-6Zr-4.5Sn, ST 1400F, WQ, 0.040 inch thick.

TABLE 2.0310 CORROSION RATES OF Ti-11.5Mo-6Zr-4.5Sn AND UNALLOYED TITANIUM IN HYDROCHLORIC AND SULFURIC ACIDS.

Source	AMS(2)			
Alloy	Ti-11.5Mo-6Zr-4.5Sn			
Form	Bars and Wire			
Condition	1300-1450F, 15 min maximum, WQ + 910-940F, 8 hr, AC			
Nominal Diameter or Distance Between Parallel Sides inches	F_{tu} - ksi minimum	F_{ty} - ksi minimum	e(2 in or 4D) percent minimum	RA percent* minimum
≤1.625	180	175	8	22
>1.625 to 3.000	180	170	4	10

* Round specimens.
Longitudinal direction.

TABLE 3.012 AMS SPECIFIED MECHANICAL PROPERTIES FOR SOLUTION TREATED AND AGED BARS AND WIRE.

Ti	
11.5	Mo
6	Zr
4.5	Sn

BETA III

Source	AMS(1)			
Alloy	Ti-11.5Mo-6Zr-4.5Sn			
Form	Bars and Wire (Fastener Stock)			
Condition	1275-1350F, 15 min, WQ + 1050-1100F, 2 hr minimum, AC			
Nominal Diameter or Distance Between Parallel Sides inches	F_{tu} - ksi minimum	F_{ty} - ksi minimum	e(2 in or 4D) percent minimum	RA percent* minimum
≤1.625	135	130	12	40
* Round specimens.				

TABLE 3.013 AMS SPECIFIED MECHANICAL PROPERTIES FOR SOLUTION TREATED AND AGED BARS AND WIRE FOR FASTENER APPLICATION.

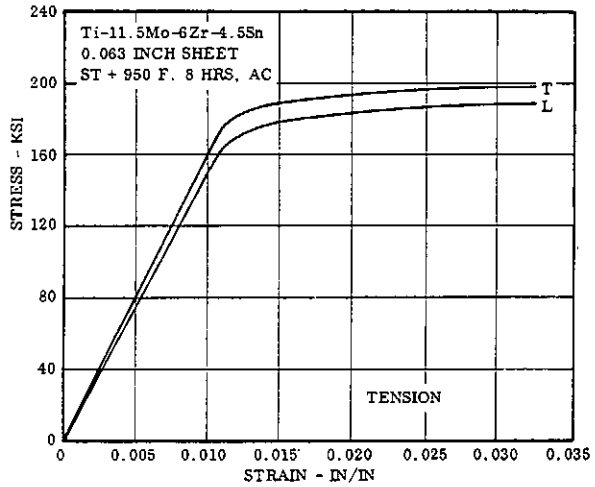


FIG. 3.0211 TYPICAL STRESS-STRAIN CURVES FOR AGED SHEET.

(19)

Source	(4)				
Alloy	Ti-11.6Mo-6.5Zr-4.2Sn-0.12O				
Form	3 1/4 inch square billet				
Condition	Hot rolled+1425F, 15 min, WQ+age, 8 hr*				
Age Temp F	Test Location	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
Unaged	Corner	116.0	104.2	21.0	71.4
	Center	108.1	93.0	20.0	61.6
900	Corner	183.9	176.3	6.0	25.6
	Center	186.4	173.6	6.0	13.0
1100	Corner	134.9	127.4	15.0	57.5
	Center	134.3	126.3	14.0	44.9
* Billet solution treated in full section; aging performed on individual test coupons.					

TABLE 3.0212 VARIATION IN TENSILE PROPERTIES FOR HOT ROLLED BILLET.

Source	(11)(17)			
Alloy	Ti-11.5Mo-6Zr-4.5Sn-0.10O			
Form	Closed Die Press Forging			
Condition	1325F, 1 hr, WQ + 950F, 8 hr, AC*			
Location	F_{tu} - ksi	F_{ty} - ksi	e - percent	RA - percent
1 - Panel transverse	188.0	176.4	5.0	17.4
2 - Panel longitudinal	193.6	185.2	5.0	12.2
3 - Rib longitudinal	192.4	184.0	4.5	10.0
4 - Center surface longitudinal	184.0	183.2	2.5	4.7
5 - Center mid-radius longitudinal	189.2	182.4	2.5	6.2
6 - Center longitudinal	190.8	182.0	4.0	10.8
7 - Center short transverse	183.6	174.0	3.0	10.0
8 - Center longitudinal transverse	180.0	170.0	5.0	13.7
9 - Center transverse end	184.8	173.6	5.5	15.2
10 - Center transverse end	184.5	174.0	4.5	16.5
11 - Center longitudinal end	184.0	173.2	4.0	10.8
* Heat treated in full section.				

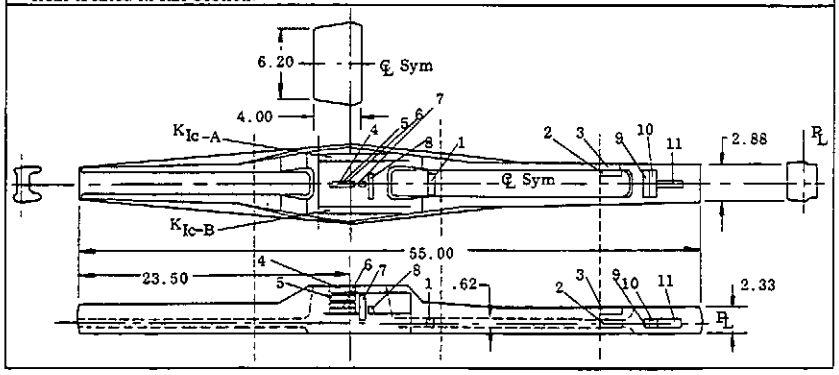


TABLE 3.0213 VARIATION IN TENSILE PROPERTIES FOR CLOSED DIE FORGING.

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

Source	(13)(14)						
Alloy	Ti-11Mo-5Zr-7Sn-0.07O						
Form	Forged Square Bars						
Condition	1400F, 1 hr, WQ + 900F, 8 hr, AC *						
Bar Size in	Test		F_{tu} ksi	F_{ty} ksi	e(4D) percent	RA percent	E 10^3 ksi
	Direction	Location					
1	Long	Center	191.1	179.8	9.0	29.6	14.2
	Long	Center	188.8	171.2	10.0	29.0	14.9
2	Long	Edge	182.2	175.1	7.0	24.0	14.0
	Long	Center	176.6	168.9	7.0	19.0	12.8
	Long	Edge	187.0	178.9	8.0	22.3	14.2
	Trans	Edge	206.3	200.8	4.0	12.5	-**
	Trans	Center	181.7	175.0	8.0	24.9	-**
	Trans	Edge	190.9	186.3	4.0	11.1	-**
3	Long	Edge	184.1	171.8	8.0	19.6	14.1
	Long	Center	177.4	170.4	9.0	25.3	12.8
	Long	Edge	185.5	178.1	9.0	15.7	13.8
	Trans	Edge	192.8	184.4	6.0	4.0	14.3
	Trans	Center	Broke Before Yield				
	Trans	Edge	191.3	184.9	3.0	3.9	13.9
4	Long	Edge	188.1	183.4	6.0	10.9	14.4
	Long	Mid-Radius	195.2	183.2	7.0	9.1	14.9
	Long	Center	185.7	173.5	6.0	12.8	13.5
	Trans	Edge	Broke Before Yield				
	Trans	Mid-Radius	198.4	191.0	2.0	6.0	14.6
	Trans	Center	192.4	185.6	3.0	4.8	13.2
6	Long	Edge	195.9	190.6	10.0	10.5	14.6
	Long	Mid-Radius	194.1	188.3	6.0	7.8	15.0
	Long	Center	195.2	185.8	6.0	7.8	14.9
	Long	Mid-Radius	196.5	191.5	5.0	11.6	14.7
	Long	Edge	194.5	188.9	8.0	12.3	14.1
	Trans	Edge	202.8	197.2	2.0	4.3	14.6
	Trans	Mid-Radius	201.7	200.0	3.0	3.9	14.5
	Trans	Center	Broke Before Yield				
	Trans	Mid-Radius	206.4	206.0	1.0	2.4	14.3
	Trans	Edge	201.1	200.0	3.0	2.4	14.6

Bars successivly reduced in size from common starting billet.
* Heat treated in full section size.
** Not determined.

TABLE 3.0214 EFFECT OF HEAT TREATED SECTION SIZE ON TENSILE PROPERTIES OF UNIDIRECTIONALLY FORGED SQUARE BARS AGED AT 900F.

Source	(13)(14)					
Alloy	Ti-11Mo-5Zr-7Sn-0.07O					
Form	Forged Square Bars					
Condition	1400F, 1 hr, WQ + 950F, 8 hr, AC*					
Bar Size in	Test		F_{tu} ksi	F_{ty} ksi	e(4D) percent	RA percent
	Direction	Location				
1	long	center	183.7	172.9	10.0	31.6
2	long	edge	182.9	174.1	8.0	21.1
	long	center	167.0	160.1	17.0	30.7
	long	edge	177.2	170.3	9.0	18.6
	trans	edge	191.4	188.6	6.0	12.5
	trans	center	173.1	-	5.0	12.5
3	long	edge	178.5	171.9	9.0	16.8
	long	center	162.7	154.7	12.0	32.7
	long	edge	178.3	167.7	8.0	14.7
	trans	edge	191.6	183.9	3.0	2.8
	trans	center	167.2	160.4	4.0	3.2
	trans	edge	179.3	174.9	5.0	7.8
4	long	edge	183.9	176.9	10.0	20.0
	long	mid-rad	181.6	172.8	10.0	16.8
	long	center	176.1	166.9	9.0	17.9
	trans	edge	185.0	179.9	3.0	3.6
	trans	mid-rad	185.6	179.0	3.0	4.7
	trans	center	186.8	180.0	3.0	5.1
6	long	edge	187.1	183.1	6.0	12.4
	long	mid-rad	182.2	176.0	7.0	8.6
	long	center	184.3	171.2	10.0	15.7
	long	mid-rad	182.7	176.1	7.0	14.6
	long	edge	182.2	178.5	9.0	12.4
	trans	edge	186.1	-	2.0	2.0
	trans	mid-rad	193.3	187.8	3.0	4.0
	trans	center	191.7	189.5	2.0	2.0
	trans	mid-rad	139.7	-	3.0	2.0
	trans	edge	184.4	183.0	2.0	2.4

Bars successively reduced in size from common starting billet.
* Heat treated in full section size.

TABLE 3.0215 EFFECT OF HEAT TREATED SECTION SIZE ON TENSILE PROPERTIES OF UNIDIRECTIONALLY FORGED SQUARE BARS AGED AT 950F.

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

Source	(13)(14)					
Alloy	Ti-11Mo-5Zr-7Sn-0.07O					
Form	Forged Square Bars					
Condition	1400F, 1 hr, WQ + 1000F, 8 hr, AC*					
Bar Size	Test		F_{tu}	F_{ty}	e(4D)	RA
in	Direction	Location	ksi	ksi	percent	percent
1	long	center	171.7	161.3	13.0	39.3
2	long	edge	171.0	164.1	10.0	11.6
	long	center	159.5	154.6	14.0	31.7
	long	edge	171.3	164.5	10.0	26.9
	trans	edge	172.9	167.8	8.0	15.7
	trans	center	164.1	161.1	10.0	29.9
3	long	edge	168.4	161.1	9.0	15.7
	long	center	155.0	152.8	18.0	51.9
	long	edge	170.6	163.3	8.0	13.8
	trans	edge	170.0	164.6	2.0	5.9
	trans	center	154.4	147.1	7.0	19.7
	trans	edge	176.9	171.8	3.0	2.8
4	long	edge	174.2	167.2	11.0	24.6
	long	mid-rad	171.5	164.4	11.0	14.4
	long	center	167.2	160.1	9.0	24.9
	trans	edge	174.4	169.9	4.0	9.4
	trans	mid-rad	178.9	171.9	4.0	3.0
	trans	center	166.2	159.0	5.0	6.3
6	long	edge	182.4	176.9	7.0	13.3
	long	mid-rad	177.2	169.1	8.0	10.9
	long	center	173.3	164.0	9.0	20.8
	long	mid-rad	178.8	171.2	7.0	10.1
	long	edge	179.0	174.2	8.0	11.2
	trans	edge	175.5	-	2.0	5.5
	trans	mid-rad	152.3	-	1.0	2.4
	trans	center	178.5	174.8	3.0	2.0
	trans	mid-rad	179.9	-	3.0	2.4
	trans	edge	172.7	-	4.0	2.0

Bars successively reduced in size from common starting billet.
* Heat treated in full section size.

TABLE 3.0216 EFFECT OF HEAT TREATED SECTION SIZE ON TENSILE PROPERTIES OF UNIDIRECTIONALLY FORGED SQUARE BARS AGED AT 1000F.

Source	(14)											
Alloy	Ti-11Mo-5Zr-7Sn											
Form	Forged Square Bars											
Condition	1400F, 1 hr, WQ + 950F, 8 hr, AC*											
Direction	Location	F_{tu} - ksi			F_{ty} - ksi			e(4D) - percent			RA - percent	
		(Six inch square forged bar)										
		(a)	(b)		(a)	(b)		(a)	(b)		(a)	(b)
Longitudinal	Edge	187.1	188.0		183.1	178.7		6.0	2.0		12.4	5.5
	Mid-Radius	182.2	183.0		176.0	173.9		7.0	5.0		8.6	9.4
	Center	184.3	172.1		171.2	160.0		10.0	5.5		15.7	13.5
	Mid-Radius	182.7	170.7		176.1	160.1		7.0	6.5		14.6	17.6
	Edge	182.2	172.4		178.5	160.0		9.0	7.0		12.4	16.8
Transverse	Edge	186.1	188.2		-	181.3		2.0	-		2.0	8.5
	Mid-Radius	193.3	176.9		187.8	171.3		3.0	2.0		4.0	5.4
	Center	191.7	176.9		189.5	169.4		2.0	3.0		2.0	10.5
	Mid-Radius	139.7	187.3		-	180.1		3.0	2.0		2.0	5.5
	Edge	184.4	182.2		183.0	175.1		2.0	2.0		2.4	6.3
		(Three inch square forged bar)										
		(c)	(d)	(e)	(c)	(d)	(e)	(c)	(d)	(e)	(c)	(d)	(e)
Longitudinal	Edge	178.5	180.4	166.1	171.9	173.0	162.2	9.0	-	3.0	16.8	5.9	7.1
	Center	162.7	170.8	166.2	154.7	164.1	158.4	12.0	7.0	7.0	32.7	20.3	26.8
	Edge	178.3	165.1	169.6	167.7	164.1	161.4	8.0	-	5.0	14.7	-	10.4
Transverse	Edge	191.6	189.0	171.0	183.9	182.5	163.7	3.0	-	-	2.8	4.0	5.5
	Center	167.2	179.8	168.3	160.4	173.7	161.9	4.0	8.5	5.0	3.2	14.2	21.1
	Edge	179.3	176.2	170.8	174.9	172.2	162.9	5.0	-	3.0	7.8	4.0	10.2

(a) 6 inch square bar unidirectionally forged 1650F.
(b) 6 inch square x 10 inch long bar press upset 1600F to 6 inch thick, cross forged to 6 inch square x length.
(c) 3 inch square bar unidirectionally forged 1650F.
(d) 3 inch square x 5 inch long bar press upset 1600F to 3 inch thick, cross forged to 3 inch square x length.
(e) 3 inch square x 5 inch long bar press upset 1400F to 3 inch thick, cross forged to 3 inch square x length.
* Heat treated in full section size.

TABLE 3.0217 EFFECT OF CROSS FORGING ON TENSILE PROPERTIES OF 3 INCH AND 6 INCH SQUARE FORGED BARS AGED AT 950F.

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

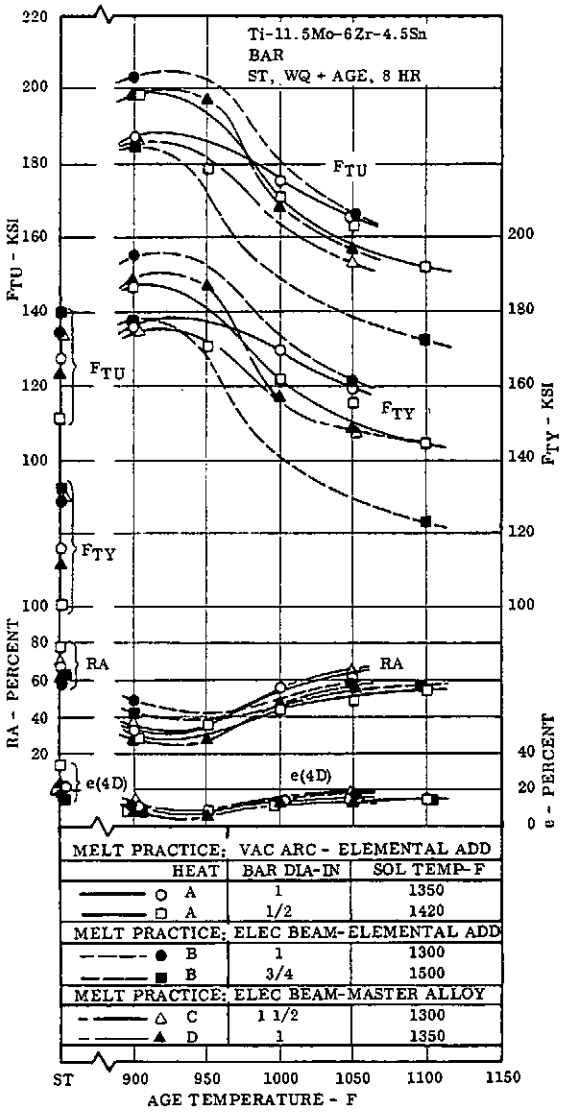


FIG. 3.0218 TENSILE PROPERTIES OF AGED BARS VARIOUSLY MELTED AND SOLUTION TREATED. (4)(7)

Source		(4)			
Alloy		Ti-11.5Mo-6Zr-4.5Sn			
Form		Bar			
Dia - in	Condition	F_{tu} ksi	F_{ty} ksi	e(4D) percent	RA percent
1.0	As hot rolled (a)	117.9	106.2	26.0	79.7
	1350 F, WQ (b)	123.0 - 133.1	108.2 - 125.3	22.0 - 23.0	59.9 - 69.7
	1350 F, WQ+900 F, 8 hr(b)	181.5 - 199.6	167.9 - 191.1	10.0 - 15.0	26.1 - 44.6
0.5	As hot rolled (a)	121.1	108.4	26.0	80.1
	1425 F, WQ (c)	107.0 - 116.5	92.8 - 108.2	32.0 - 38.0	76.2 - 80.3
	1425 F, WQ+900 F, 8 hr(c)	185.9 - 205.8	175.8 - 194.4	9.0 - 11.0	23.8 - 35.0

(a) 3 1/4 in square billet rolled at 1750 F to nominal bar size, solution treated, water quenched and centerless ground to final size.
(b) Range for four of sixteen 10-ft lengths randomly sampled.
(c) Range for eight of forty 10-ft lengths randomly sampled.

TABLE 3.02110 TENSILE PROPERTY UNIFORMITY OF 1 INCH AND 0.5 INCH BAR.

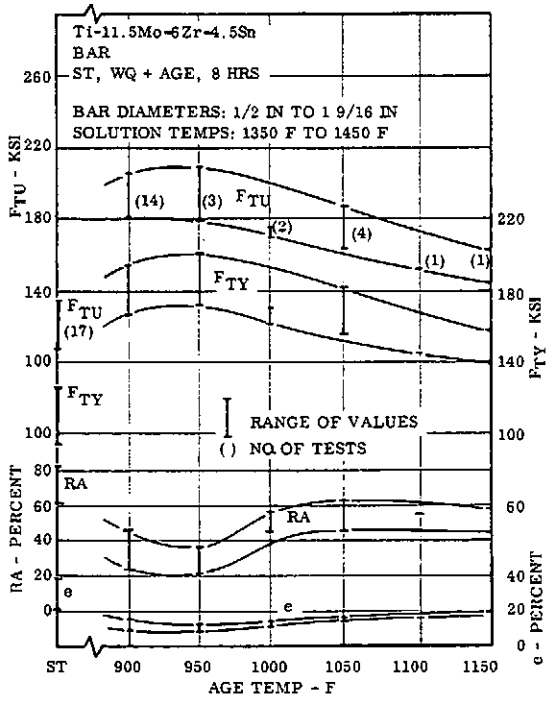


FIG. 3.02111 SPREAD OF TENSILE PROPERTIES FOR 1/2 INCH TO 1 9/16 INCH DIAMETER BARS SOLUTION TREATED AT 1350 F TO 1450 F AND AGED. (4)

Source	(4)			
Alloy	Ti-11.5Mo-6Zr-4.5Sn			
Form	1 9/16 inch diameter bar			
Condition	1450 F, 5 min, WQ			
Location	F_{tu}-ksi	F_{ty}-ksi	e(4D)-percent	RA-percent
Center	130.1	111.1	20.0	70.6
Mid-radius	132.3	110.2	20.0	66.1

TABLE 3.0219 CENTER AND MID-RADIUS TENSILE PROPERTIES OF 1 9/16 INCH SOLUTION TREATED BAR.

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

Source	(4)						
Alloy	Ti-11.5Mo-6Zr-4.5Sn						
Form	1/2 inch diameter bar						
Condition	1425 F, WQ + age, 8 hr						
	100-hr Creep Exposure			Subsequent RT Tensile Properties*			
Age Temp F	Temp F	Stress ksi	Permanent Deformation percent	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
		unexposed		199.6	187.6	9.6	27.2
	500	125	0.11	204.4	192.7	12.0	26.5
900	600	105	0.05**	-	-	-	-
	800	15	0.26	212.1	199.1	8.0	19.6
		unexposed		193.7	181.0	8.0	34.3
	RT	163	0.17**	-	-	-	-
	RT	172	0.11**	-	-	-	-
950	500	125	0.00	200.1	190.0	5.0	16.4
	500	140	0.36	196.9	192.4	11.0	32.5
	700	60	0.16	191.1	182.7	10.0	29.5
	700	90	0.30	202.4	191.3	8.0	25.1
		unexposed		171.0	163.9	11.0	40.6
	500	110	0.41	162.1	159.1	14.0	54.1
1050	600	90	0.18	172.8	165.3	12.0	41.3
	800	15	0.02	176.9	165.3	12.0	38.9

* Tests made after creep exposure without surface conditioning.
** Not tensile tested after creep exposure.

TABLE 3.02112 EFFECT OF 100 HOUR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF BAR.

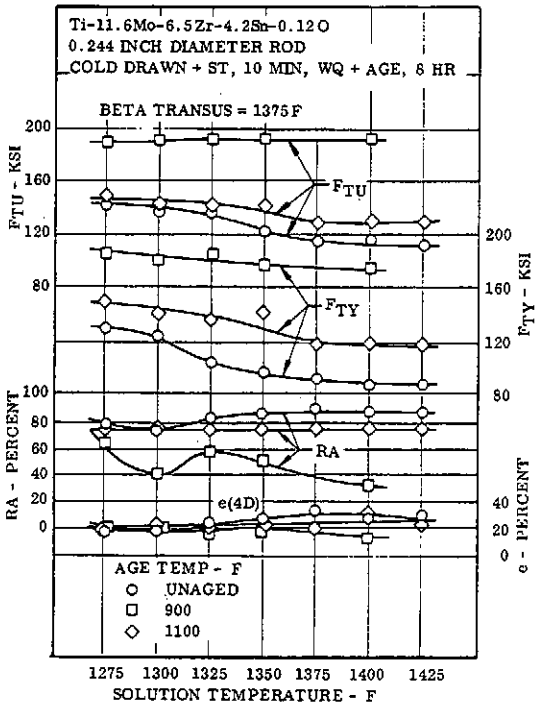


FIG. 3.02114 EFFECT OF SOLUTION TEMPERATURE ON TENSILE PROPERTIES OF ROD. (4)

Source	(4)						
Alloy	Ti-11.5Mo-6Zr-4.5Sn						
Form	1/2 inch diameter bar						
Condition	1425 F, WQ + age, 8 hr						
	500-hr Creep Exposure			Subsequent RT Tensile Properties*			
Age Temp F	Temp F	Stress ksi	Permanent Deformation percent	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
		unexposed		199.6	187.6	9.6	27.2
900	500	125	0.00	210.4	199.9	6.0	21.2
	700	80	0.61	216.2	208.7	7.0	16.7
		unexposed		171.0	163.9	11.0	40.6
1050	500	110	0.00	162.8	156.3	11.0	49.7
	700	60	0.07	171.5	161.0	13.0	43.5

* Tests made after creep exposure without surface conditioning.

TABLE 3.02113 EFFECT OF 500 HOUR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF BAR.

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

Source	(4)					
Alloy	Ti-11.5Mo-6Zr-4.5Sn					
Form	0.275 inch diameter rod					
Condition	Cold drawn + 1400F, WQ + 1100F, 8 hr					
100-hr Creep Exposure			Subsequent RT Tensile Properties*			
Temp F	Stress ksi	Permanent Deformation percent	F_{tu} ksi	F_{ty} ksi	e(4D) percent	RA percent
unexposed			147.3	138.9	20.0	71.4
			144.6	136.8	21.4	72.4
700	60	0.09	150.0	138.7	20.0	68.0
		0.07	155.6	141.9	20.0	69.3
* Tests made after creep exposure without surface conditioning.						

TABLE 3.02116 EFFECT OF 100 HOUR EXPOSURE AT 700 F WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF ROD.

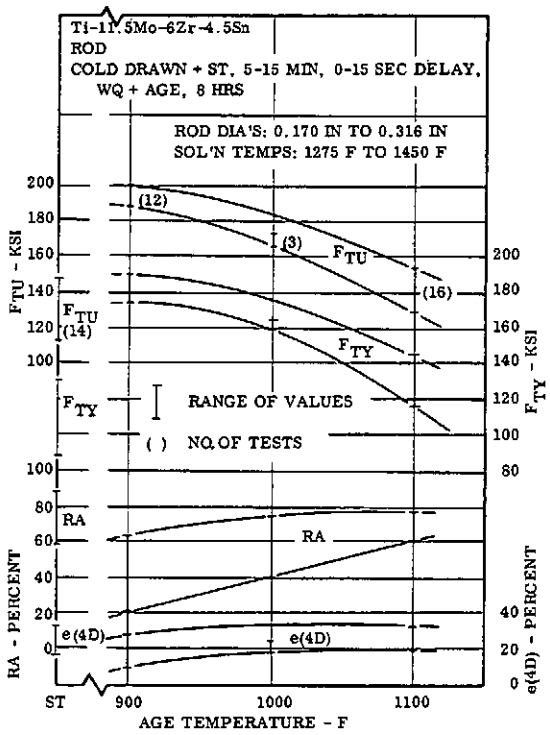


FIG. 3.02115 SPREAD OF TENSILE PROPERTIES FOR ROD VARIOUSLY HEAT TREATED. (4)

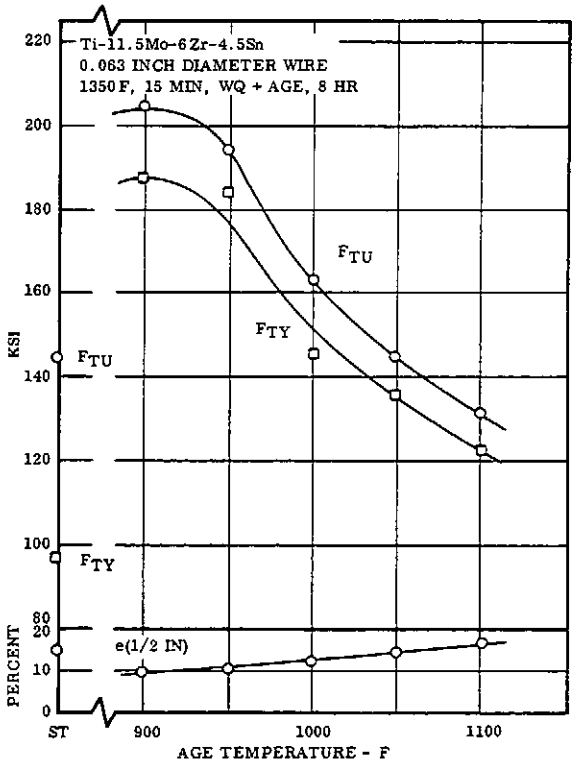


FIG. 3.02117 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF WIRE. (4)

Ti	
11.5	Mo
6	Zr
4.5	Sn

BETA III

Source		(4)				
Alloy		Ti-11.5Mo-6Zr-4.5Sn				
Form		Seamless Tubing				
Tube Size-in		Condition	F_{tu}(a) ksi	F_{ty} ksi	e(2 in) percent	RA percent
OD	Wall t					
1.5	0.173	As extruded (b)	116.0	99.7	16.0	75.6
			123.9	107.1	18.0	72.0
		As extruded + 950F, 8 hr	200.4(c)	184.3	8.0	18.4
			199.6(c)	183.4	8.0	22.6
1.26	0.120	Mill annealed (d)	143.8	134.1	13.2	42.0
		Mill annealed + pickled	143.4	135.6	13.0	47.5
		Mill annealed + 1350F, WQ	131.3	114.8	13.5	50.9
		Mill annealed + 1350F, WQ + 950F, 8 hr	185.4	176.3	7.5	26.7
		Mill annealed + 1350F, WQ + 1000F, 8 hr	173.7	164.8	9.2	36.5
0.884	0.050	Mill annealed (d)	154.7	141.0	8.5	16.6
		Mill annealed + pickled	151.0	138.2	8.5	24.7
		Mill annealed + 1350F, WQ	117.4	101.2	20.8	36.0
		Mill annealed + 1350F, WQ + 950F, 8 hr	180.4	169.0	6.0	12.3
		Mill annealed + 1350F, WQ + 1000F, 8 hr	169.8	159.8	7.2	15.6
0.5	0.024	As finish cold drawn (e)	162	120	7.0	-
		Cold drawn + 1450F, WQ	122	111	18.0	-
		Cold drawn+1350F, rapid AC+950F, 8 hr	189	183	5.5	-
		Cold drawn+1350F, rapid AC+1000F, 8 hr	184	173	7.5	-
		Cold drawn+1350F, rapid AC+1050F, 8 hr	168	150	9.5	-

(a) Specimens machined from longitudinal sections of tubing subtended by 3/4 inch cords. Specimen uniform section 0.5 inch wide: gage length 2 inches.
(b) 2.8 inch OD x 1.260 inch ID hollow billets canned in mild steel, heated to 1500F, extruded to tube hollow (reduction 7.2:1) and water quenched.
(c) Machined round specimen: uniform section 0.125 inch diameter, gage length 0.5 inch.
(d) Tube hollows cold reduced to finished tubing in a single pass with tube reducers, followed by vacuum anneal: 1350F, 1/2 hr, rapid cool + 1150F, 4 hr, furnace cool to 900F.
(e) 1.02 inch diameter bar gun drilled and cold drawn to finished tubing.

TABLE 3.02118 TENSILE PROPERTIES OF SEAMLESS TUBING.

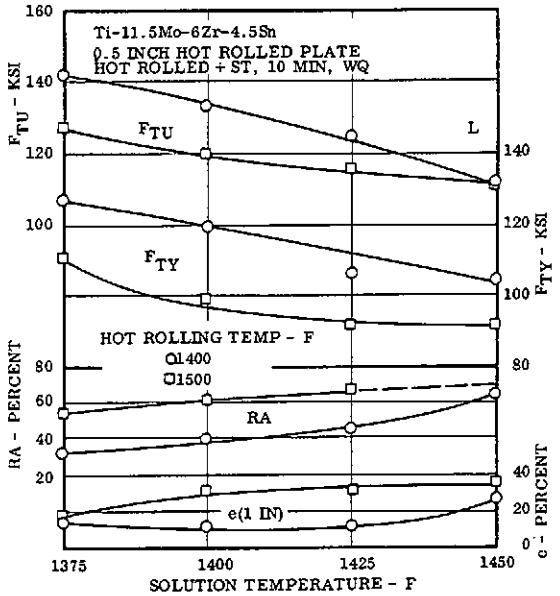


FIG. 3.02119 EFFECT OF SOLUTION TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION TREATED 0.5 INCH PLATE. (4)

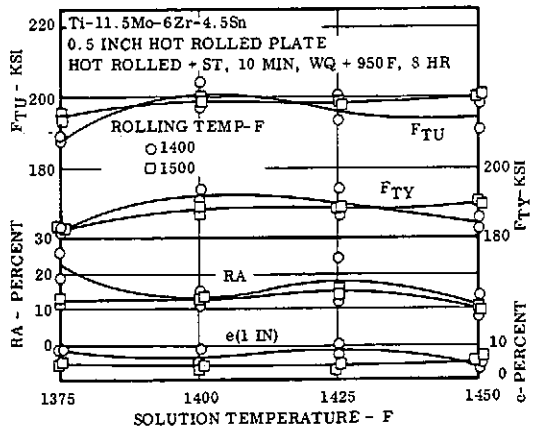


FIG. 3.02120 EFFECT OF SOLUTION TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION TREATED AND AGED 0.5 INCH PLATE. (4)

Ti	
11.5	Mo
6	Zr
4.5	Sn

BETA III

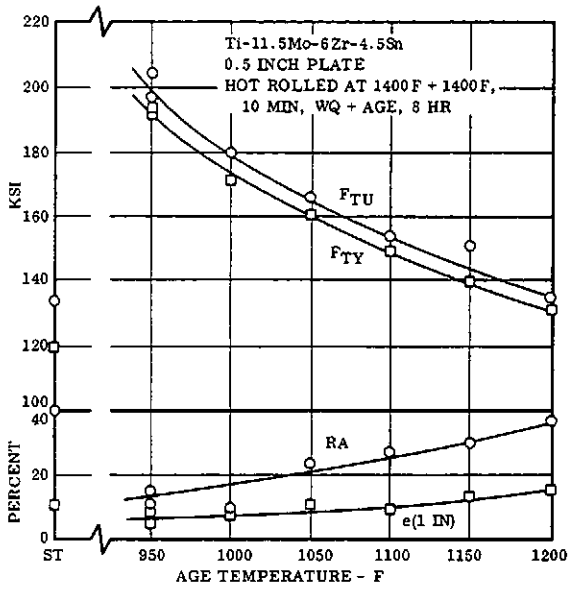


FIG. 3.02121 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF 0.5 INCH PLATE. (4)

Source	(7)					
Alloy	Ti-11.5Mo-6Zr-4.5Sn					
Form	Plate					
Condition	ST, WQ					
Plate Thickness in	Solution Temp F	Test Direction	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
2	1400	L	123.7	106.4	22.3	63.8
		T	119.8	100.7	25.0	65.9
2	1350	T	137.0	128.3	11.0	33.4
0.625	1400	L	132.3	118.8	18.8	50.1
		T	130.3	113.6	16.8	55.4
0.625	1350	L	135.7	125.6	15.3	46.7
		T	132.8	120.3	15.8	51.7
Beta transus ~1375 F.						

TABLE 3.02123 TENSILE PROPERTIES OF HEAVY PLATE.

Source	(4)				
Alloy	Ti-11.5Mo-6Zr-4.5Sn				
Form	0.5 inch plate				
Condition	Hot rolled at 1400 F+heat treat				
Heat Treatment	Test Dir	F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
Double Vacuum-Arc Melted					
1400 F, 10 min, AC	L	140.3	133.9	14.0	37.6
	T	137.9	128.8	8.5	29.2
1400 F, 10 min, WQ	L	127.8	114.3	18.0	51.9
	T	133.0	119.1	12.5	45.0
1400 F, 10 min, WQ+950 F, 8 hr	L	189.9	176.2	6.5	7.5
	T	196.2	187.7	2.5	12.5
1400 F, 10 min, WQ+1050 F, 8 hr	L	164.7	160.9	8.5	16.7
Triple Vacuum-Arc Melted					
1400 F, 10 min, AC	L	146.8	137.8	11.0	29.5
1400 F, 10 min, WQ	L	131.7	113.7	15.0	37.7
	T	132.6	114.9	15.0	41.5
1400 F, 10 min, WQ+950 F, 8 hr	L	193.4	179.4	5.5	9.0
	T	196.2	185.0	4.0	10.5
1400 F, 10 min, WQ+1050 F, 8 hr	L	169.6	157.4	6.7	8.6
	T	172.2	162.5	7.0	14.5

TABLE 3.02124 TENSILE PROPERTIES OF DOUBLE AND TRIPLE VACUUM-ARC MELTED PLATE.

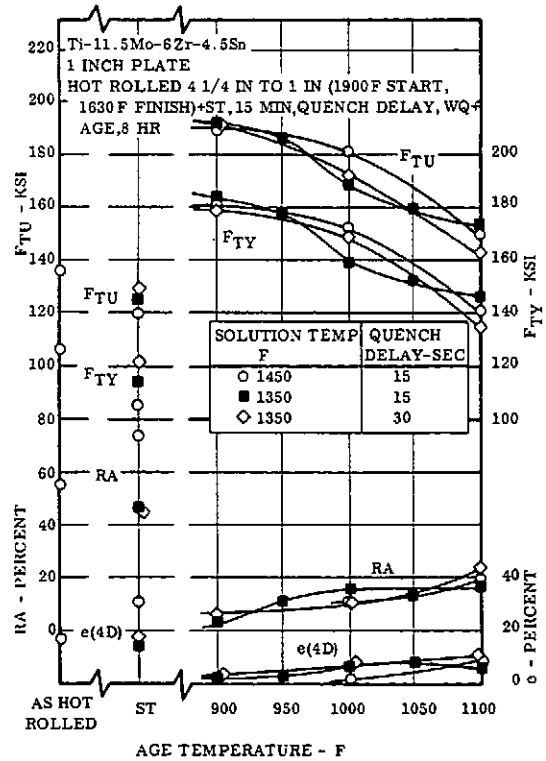


FIG. 3.02122 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF 1 INCH PLATE. (4)

Source	(4)					
Alloy	Ti-11.5Mo-6Zr-4.5Sn					
Form	0.5 inch plate					
Condition	Hot roll + ST, 10 min, Quench					
Hot Roll Temp-F	Solution Treatment		F_{tu} ksi	F_{ty} ksi	e(1 in) percent	RA percent
	Temp-F	Quench				
1800	1450	AC	124.7	111.4	11.1	20.9
	1450	WQ	114.1	96.0	27.5	25.4
1500	1450	AC	135.3	121.7	12.0	36.5
	1450	WQ	114.5	99.4	38.0	65.8
	1400	WQ	119.4	99.1	31.0	61.8
1400	1400	AC	143.5	135.9	12.5	33.6
	1400	WQ	129.8	113.9	16.5	44.9
Each value average two tests, longitudinal specimens.						

TABLE 3.02125 EFFECT OF QUENCH RATE FROM SOLUTION TREATMENT TEMPERATURE ON TENSILE PROPERTIES OF PLATE.

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

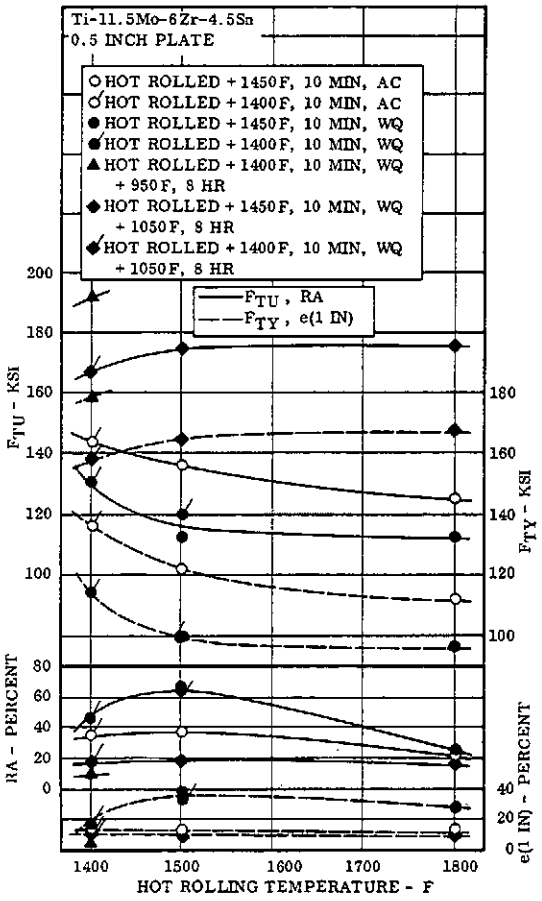


FIG. 3.02126 EFFECT OF HOT ROLLING TEMPERATURE ON TENSILE PROPERTIES OF PLATE. (4)

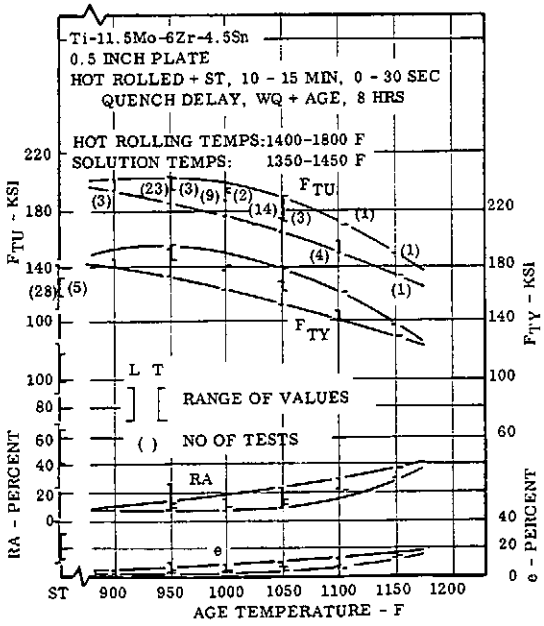


FIG. 3.02127 SPREAD OF TENSILE PROPERTIES FOR PLATE VARIOUSLY HOT ROLLED, SOLUTION TREATED AND AGED. (4)

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

Source	(4)						
Alloy	Ti-11.5Mo-6Zr-4.5Sn						
Form	0.5 inch plate						
	100 hr Creep Exposure			Subsequent RT Tensile Properties*			
Heat / Condition	Temp F	Stress ksi	Permanent Deformation percent	F_{tu} ksi	F_{ty} ksi	e(2 in) percent	RA percent
A: Hot rolled at 1400 F + 1400 F, 15 min, WQ + 950 F, 8 hr	unexposed			193.3	179.4	5.5	9.0
	500	120	0.11	195.9	185.6	- (a)	- (a)
	500	130	0.18	193.3	190.6	4.0	6.3
	600	100	0.04	196.8	185.7	5.0	8.6
	600	130	0.25	192.4	188.3	3.0	7.4
	700	50	0.04	193.4	180.4	- (a)	- (a)
	700	90	0.14	193.9	183.4	- (b)	- (b)
	800	14	0.07	195.4	182.8	4.0	8.4
	800	27	0.15	195.9	182.2	4.0	5.6
B: Hot rolled + 1350 F, 15 min, 15 sec delay, WQ + 950 F, 8 hr	unexposed			188.4	175.5	4.0	9.6
	500	120	0.08	187.4	176.2	5.0	7.8
	500	130	0.05	194.9	185.5	3.0	7.0
	600	120	0.13	194.4	183.9	3.0	6.3
	600	130	0.13	200.0	191.8	2.0	2.7
	700	65	0.13	197.9	184.3	3.0	4.0
	800	10	0.12	193.4	179.2	4.0	5.6
	800	20	0.17	195.4	182.5	3.0	7.8
B: Hot rolled + 1350 F, 15 min, 15 sec delay, WQ + 1000 F, 8 hr	unexposed			175.7	163.0	5.0	11.0
	500	110	0.04	178.4	166.7	4.0	7.0
	500	130	0.08	181.9	174.3	1.0	4.0
	600	100	0.10	182.9	170.7	5.0	7.8
	600	120	0.08	182.8	175.4	4.0	9.3
	700	65	0.11	182.3	168.5	4.0	8.7
	700	95	0.20	181.8	171.2	4.0	6.3
	800	10	0.12	184.4	168.9	3.0	7.8
	800	20	0.25	183.4	169.8	4.0	12.4

* Tests made after creep exposure without surface conditioning.
(a) Broke outside gage mark.
(b) Broke at gage mark.

TABLE 3.02128 EFFECT OF 100 HOUR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF PLATE.

Source	(4)						
Alloy	Ti-11.5Mo-6Zr-4.5Sn						
Form	0.5 inch plate						
	500 hr Creep Exposure			Subsequent RT Tensile Properties*			
Condition	Temp F	Stress ksi	Permanent Deformation percent	F_{tu} ksi	F_{ty} ksi	e(2 in) percent	RA percent
Hot rolled + 1350 F, 15 min, 15 sec delay, WQ + 950 F, 8 hr	unexposed			188.4	175.5	4.0	9.6
	500	105	0.05	184.9	174.0	4.0	6.3
	700	50	0.17	193.8	181.3	2.0	5.6
Hot rolled + 1350 F, 15 min, 15 sec delay, WQ + 1000 F, 8 hr	unexposed			175.7	163.0	5.0	11.0
	500	120	0.11	183.4	174.0	4.0	11.4
	700	55	0.17	183.9	170.4	5.0	10.0

* Tests made after creep exposure without surface conditioning.

TABLE 3.02129 EFFECT OF 500 HOUR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF PLATE.

Source	(4)					
Alloy	Ti-11.5Mo-6Zr-4.5Sn					
Form	0.140 inch hot band					
Condition	Location*	Dir	F_{tu} ksi	F_{ty} ksi	e(2 in) percent	RA percent
As hot rolled	Tail	L	137.8	122.4	4.5	57.6
	Tail	T	146.4	138.0	6.0	37.0
Box annealed 1200 F, 8 hr	Head	L	125.6	119.3	10.0	51.5
	Head	T	125.6	115.6	10.0	31.6
	Tail	L	123.6	115.4	15.0	58.7
	Tail	T	132.8	126.6	9.5	30.2
Box annealed 1200 F, 8 hr + ST 1350 F, 5 min, AC	Head	L	137.5	126.0	12.0	31.2
	Head	T	144.9	136.6	9.5	24.3
	Tail	T	143.8	135.7	9.0	46.3

* Test location in coil.

TABLE 3.02130 TENSILE PROPERTIES OF HOT BAND.

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

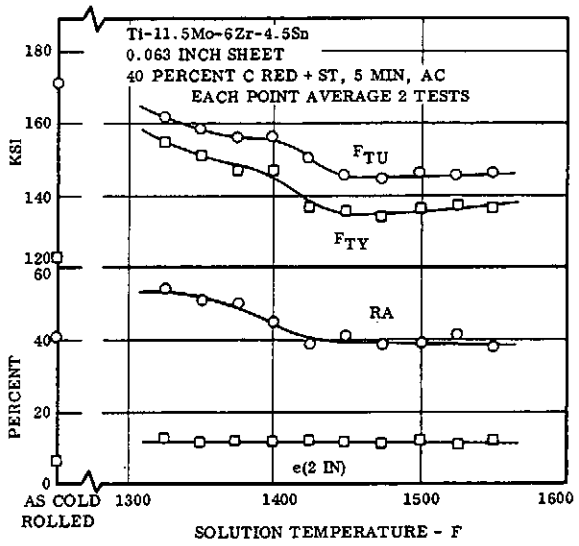


FIG. 3.02131 EFFECT OF SOLUTION TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION TREATED SHEET. (4)

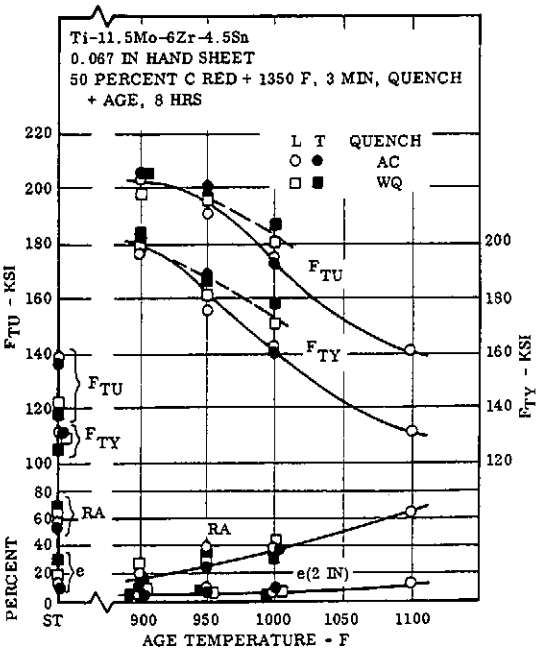


FIG. 3.02134 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF HAND SHEET SOLUTION TREATED AT 1350 F. (4)

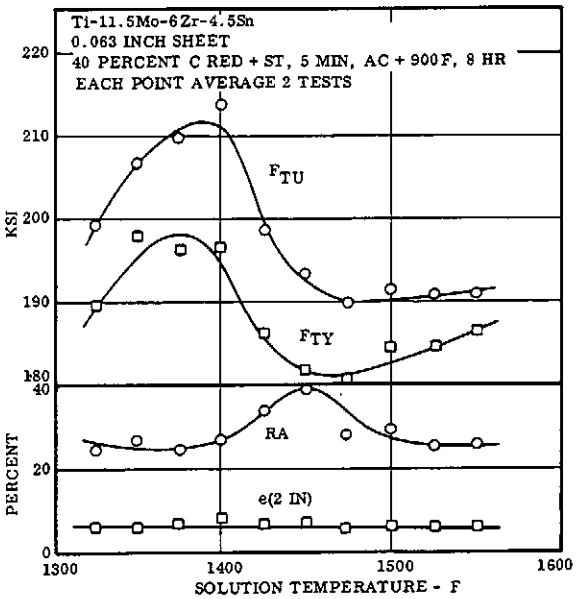


FIG. 3.02132 EFFECT OF SOLUTION TEMPERATURE ON TENSILE PROPERTIES OF AGED SHEET. (4)

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

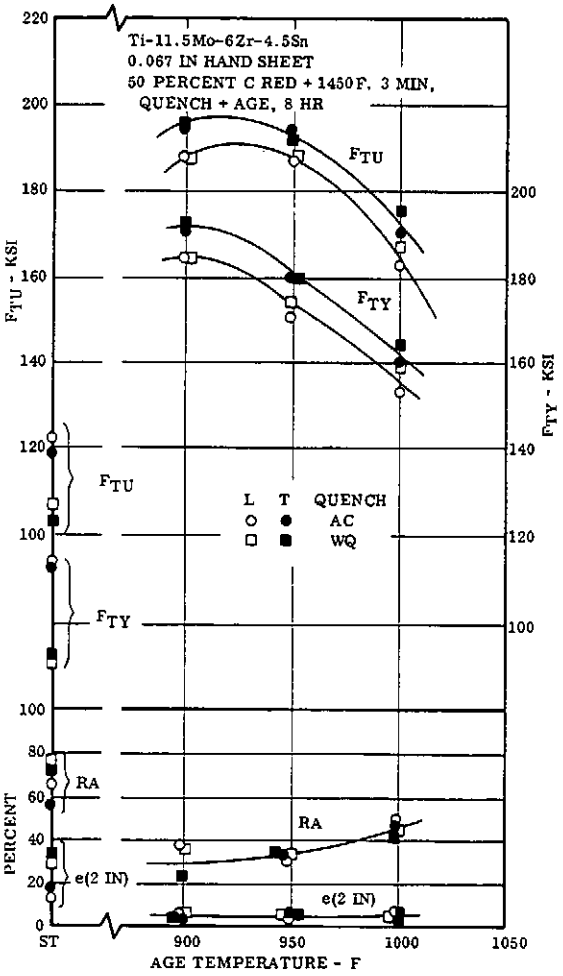


FIG. 3.02135 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF HAND SHEET SOLUTION TREATED AT 1450F. (4)

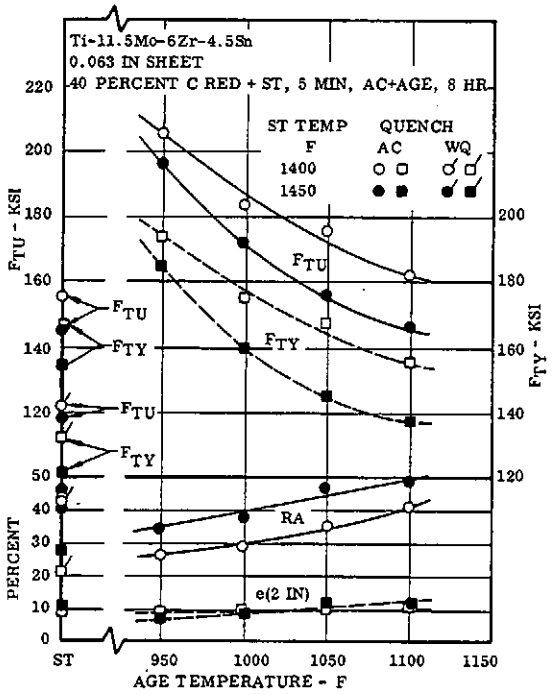


FIG. 3.02136 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF SHEET SOLUTION TREATED AT 1400 OR 1450F. (4)

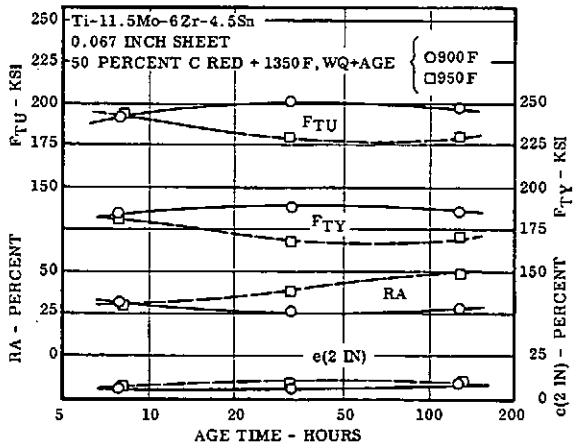


FIG. 3.02137 EFFECT OF AGING TIME ON TENSILE PROPERTIES OF SHEET. (4)

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

Source								(4)				
Alloy								See Compositions Below				
Form								0.063 inch sheet				
Condition								40 percent c red + 1400 F, 5 min, AC + age, 8 hr				
Composition - weight percent								Age Temp	F_{tu}	F_{ty}	e(2 in)	RA
Ti	Mo	Zr	Sn	Fe	C	O	N	F	ksi	ksi	percent	percent
Bal	10.8	5.8	4.4	0.08	0.06	0.15	0.010	As ST (1)	155.3	146.2	9.0	44.3
								950 (1)	205.2	193.7	8.0	26.0
								1050 (1)	175.2	167.3	9.8	35.2
Bal	12.2	6.7	4.1	0.03	0.04	0.14	0.013	As ST (2)	144.1	138.3	11.5	41.6
									145.2	139.9	12.5	37.9
								950 (2)	193.9	180.8	9.5	31.0
									195.2	185.5	8.5	30.0
								1050 (2)	167.2	158.7	8.0	34.8
									166.4	157.0	9.0	35.5

(1) Specimen orientation not given.
(2) longitudinal specimen direction.

TABLE 3.02138 EFFECT OF COMPOSITION (VARIATION IN BETA-PHASE-STABILIZING ELEMENT CONTENT) ON TENSILE PROPERTIES OF SHEET.

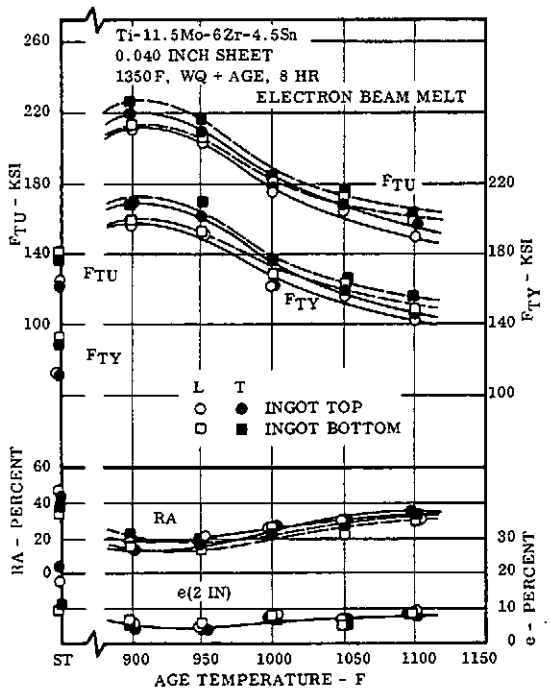


FIG. 3.02139 SHEET TENSILE PROPERTY VARIATION FOR ELECTRON BEAM MELTED INGOT. (7)

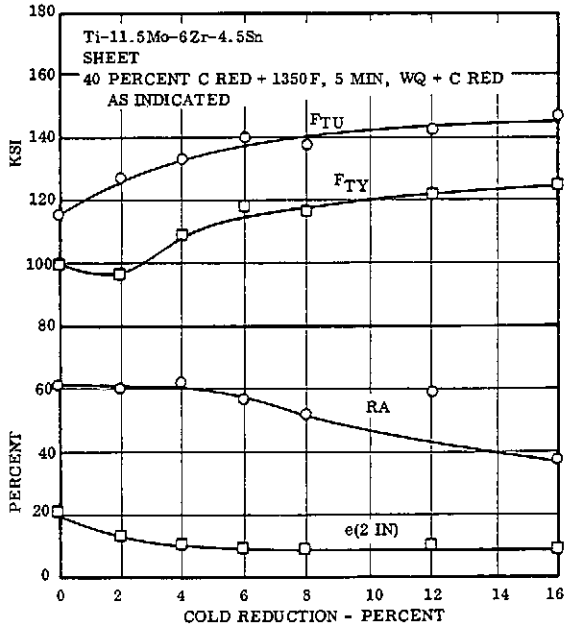


FIG. 3.02140 EFFECT OF COLD REDUCTION ON TENSILE PROPERTIES OF SHEET SOLUTION TREATED AT 1350 F AND WATER QUENCHED. (4)

Ti	
11.5	Mo
6	Zr
4.5	Sn

BETA III

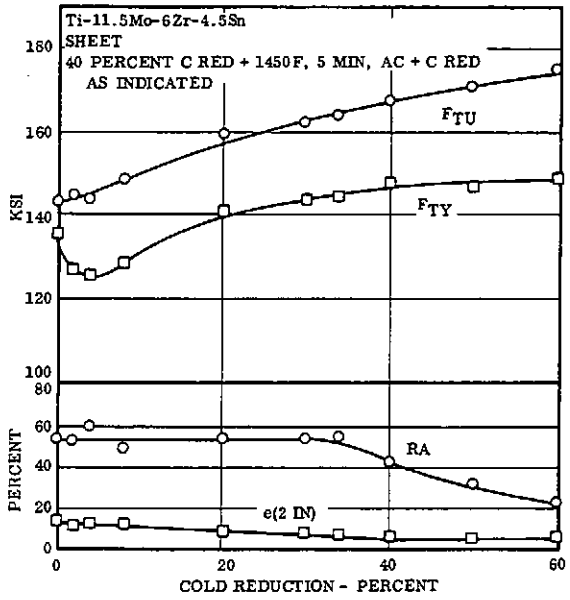


FIG. 3.02141 EFFECT OF COLD REDUCTION ON TENSILE PROPERTIES OF SHEET SOLUTION TREATED AT 1450F AND AIR COOLED. (4)

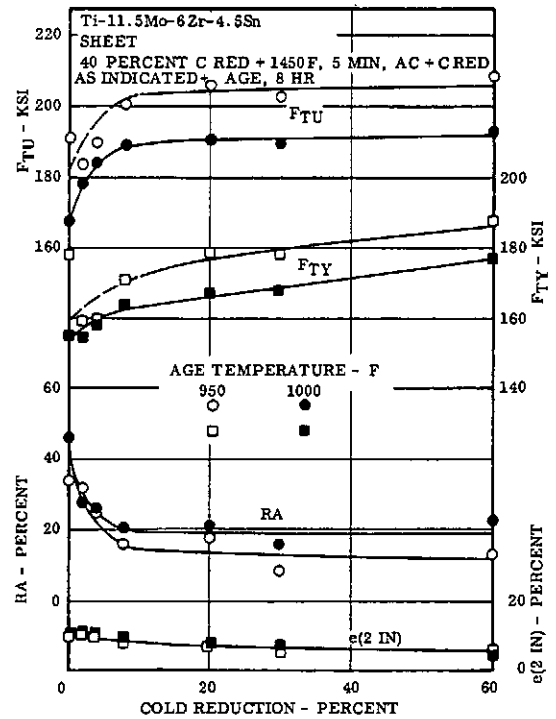


FIG. 3.02142 EFFECT OF COLD REDUCTION ON AGING RESPONSE OF SHEET AGED AFTER COLD ROLLING. (4)

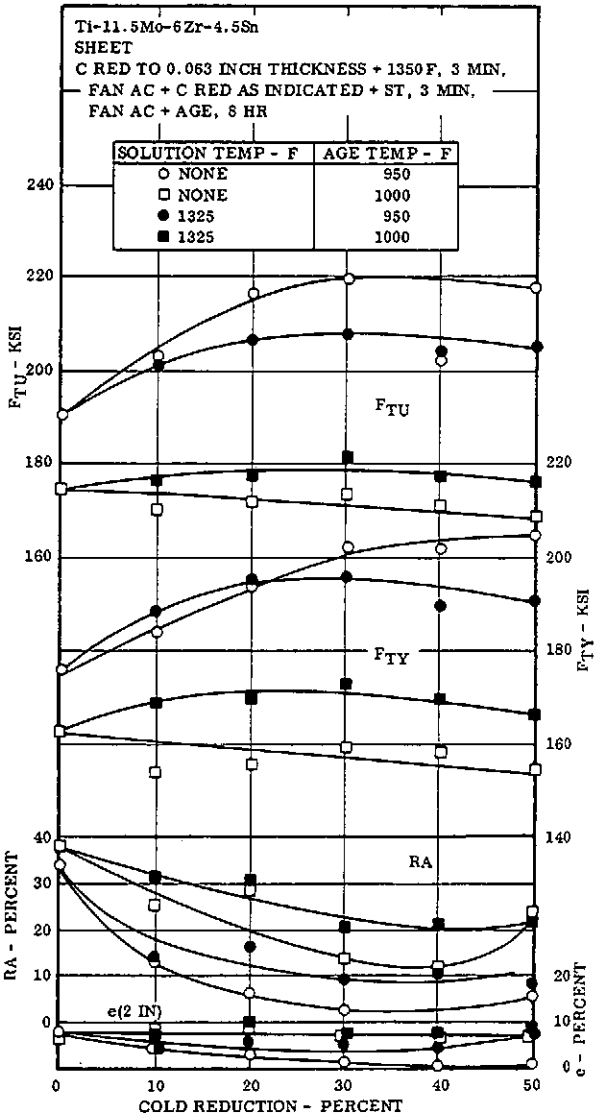


FIG. 3.02143 EFFECT OF COLD REDUCTION ON AGING RESPONSE OF SHEET RESOLUTION TREATED AND AGED AFTER COLD ROLLING. (4)

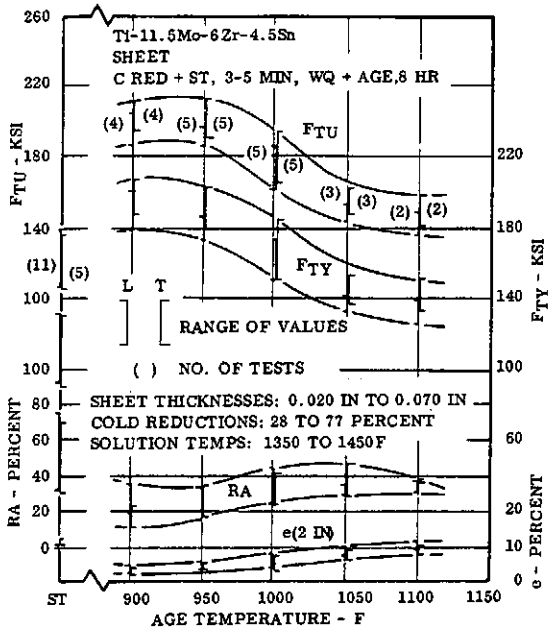


FIG. 3.02144 SPREAD OF TENSILE PROPERTIES FOR SHEET VARIOUSLY COLD REDUCED, SOLUTION TREATED AND AGED. (4)

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

Source	(4)						
Alloy	Ti-11.5Mo-6Zr-4.5Sn						
Form	0.063 inch sheet						
Condition	200F Creep Exposure			Subsequent RT Tensile Properties			
	Stress ksi	Time hr	Permanent Deformation percent	F_{tu} ksi	F_{ty} ksi	e(2 in) percent	RA percent
50 percent c red + 1350F, AC	unexposed			144.5	135.0	8.0	43.1
	unexposed			145.5	136.9	8.0	43.0
	109	762	0.08	144.0	138.4	7.5	42.7
	109	1000	0.03	147.5	143.2	8.0	37.4
50 percent c red + 1350F, AC + 1100F, 8 hr	unexposed			143.8	137.8	8.5	58.1
	unexposed			144.5	138.6	8.5	42.2
	111	1000	0.09	143.3	140.0	9.5	54.8
	111	1000	0.78	147.3	144.8	9.5	42.7
Test made after creep exposure without surface conditioning.							

TABLE 3.02145 EFFECT OF EXPOSURE AT 200F WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF SHEET.

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

Source	(4)								
Alloy	Ti-11.5Mo-6Zr-4.5Sn								
Form	Sheet								
			100 hr Creep Exposure			Subsequent RT Tensile Properties (a)			
Heat	Sheet Thickness in	Condition	Temp F	Stress ksi	Permanent Deformation percent	F_{tu} ksi	F_{ty} ksi	e(2 in) percent	RA percent
A	0.063	40 percent c red + 1400 F, 5 min, AC + 1050 F, 8 hr	unexposed (b)			175.2	167.3	9.7	35.2
			500	115	0.08	181.0	175.5	8.5	55.1
			500	130	0.16	182.1	178.6	8.5	56.2
			600	100	0.11	173.8	166.2	7.5	47.0
			600	115	0.19	179.9	176.0	9.0	52.6
			700	55	0.10	183.1	176.2	7.5	44.8
			700	75	0.15	181.2	175.2	7.5	35.5
			700	85	0.17	186.6	179.4	8.5	47.4
			800	13	0.10	184.7	177.3	9.0	42.4
			800	23	0.16	183.6	171.7	7.5	37.9
B	0.063	40 percent c red + 1400 F, 5 min, AC + 1050 F, 8 hr	unexposed			167.2	158.7	8.0	34.8
			unexposed			166.4	157.0	9.0	35.5
			500	115	0.18	174.9	171.3	5.5	40.2
			500	130	0.12	174.8	170.6	5.0	48.6
			600	100	0.11	172.5	165.0	5.5	45.0
			600	115	0.21	180.2	175.0	5.5	45.6
			700	55	0.12	179.9	(c)	4.3	45.4
			700	75	0.15	175.9	168.8	5.0	39.7
			800	13	0.04	178.6	169.0	5.5	40.2
			800	23	0.16	175.4	163.6	5.5	41.3
C	0.067	50 percent c red + 1350 F, AC + 1000 F, 8 hr	unexposed			178.0	164.5	4.5	34.9
			unexposed			170.6	159.7	7.5	39.4
			500	90	0.13	172.9	163.8	8.0	40.6
			500	110	0.15	172.9	168.3	4.0	35.2
			600	70	0.12	174.1	164.2	8.0	43.5
			600	90	0.19	173.0	164.1	9.0	50.9
			700	45	0.09	178.1	166.6	3.5	39.5
			800	12	0.00	176.5	163.7	8.5	35.5
			800	22	0.10	181.1	168.4	7.0	23.2
C	0.067	50 percent c red + 1450 F, AC + 1000 F, 8 hr	unexposed			162.1	156.5	5.5	50.9
			unexposed			163.1	150.3	8.0	47.6
			500	120	0.21	169.7	167.3	6.5	40.4
			700	75	0.11	176.6	167.2	4.0	36.8

(a) Tests made after creep exposure without surface conditioning.
(b) Unexposed values average two tests.
(c) Not determined.

TABLE 3.02146 EFFECT OF 100 HOUR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF SHEET AGED TO MEDIUM STRENGTH LEVEL.

Ti	
11.5	Mo
6	Zr
4.5	Sn

BETA III

Source	(4)
Alloy	Ti-11.5Mo-6Zr-4.5Sn
Form	Sheet

Heat	Sheet Thickness in	Condition	100 hr Creep Exposure			Subsequent RT Tensile Properties(a)			
			Temp F	Stress ksi	Permanent Deformation percent	F_{tu} ksi	F_{ty} ksi	e(2 in) percent	RA percent
A	0.063	40 percent c red + 1400F, 5 min, AC + 900F, 8 hr	unexposed(b)			213.6	197.6	8.0	26.7
			500	130	0.07	214.6	206.4	4.0	19.1
			500	140	0.14	219.3	212.3	7.0	22.9
			600	90	0.07	214.6	202.2	4.5	21.9
			600	115	0.14	219.2	210.2	6.5	26.0
			600	130	0.16	217.6	208.7	6.0	27.5
			700	60	0.11	219.8	206.0	5.0	21.9
			700	75	0.16	217.4	207.7	3.5	14.9
			700	90	0.22	222.2	209.1	5.0	(c)
B	0.063	40 percent c red + 1400F, 5 min, AC + 950F, 8 hr	unexposed			193.9	180.8	9.5	31.0
			unexposed			195.2	185.5	8.5	30.0
			500	130	0.07	199.2	191.8	5.5	42.8
			500	150	0.35	202.4	200.0	4.0	38.0
			600	90	0.05	201.0	190.8	5.0	27.8
			600	115	0.16	202.1	195.4	5.5	33.3
			700	35	0.05	202.3	186.2	5.0	22.5
			700	75	0.17	206.4	197.5	5.5	30.2
			800	10	0.04	205.2	192.4	7.0	25.3
			800	23	0.20	204.4	192.6	5.5	30.7
C	0.067	50 percent c red + 1350F, AC + 900F, 8 hr	unexposed			200.9	196.8	4.5	25.9
			unexposed			204.5	194.9	3.0	11.1
			500	110	0.06	200.9	191.5	3.5	17.0
			500	140	0.31	203.6	203.6	3.5	14.7
			600	90	0.05	200.4	192.7	3.5	18.9
			600	115	0.13	202.7	198.4	2.5	15.6
			700	60	0.05	214.7	203.2	2.5	16.0
			700	75	0.02	219.7	217.9	(c)	(c)
			800	10	0.11	205.8	193.8	4.5	10.2
			800	20	0.37	204.5	195.4	2.5	14.9
C	0.067	50 percent c red + 1350F, AC +950F, 8 hr	unexposed			188.9	172.8	7.0	30.9
			unexposed			191.4	177.8	7.5	35.6
			700	75	0.24	203.7	192.5	4.5	19.4
C	0.067	50 percent c red + 1350F, WQ + 900F, 8 hr	unexposed(b)			191.4	184.0	6.0	30.4
			700	70	0.33	216.3	213.9	5.0	7.2
C	0.067	50 percent c red + 1350F, WQ + 950F, 8 hr	unexposed(b)			192.5	179.9	7.0	31.1
			700	70	0.04	196.5	185.8	6.5	27.9
C	0.067	50 percent c red + 1450F, AC + 900F, 8 hr	unexposed			186.6	185.8	4.0	36.6
			unexposed			188.3	183.3	5.0	(c)
			500	120	0.27	199.3	197.3	3.0	9.0
C	0.067	50 percent c red + 1450F, AC + 950F, 8 hr	unexposed			184.6	169.8	5.5	33.5
			unexposed			188.2	172.5	4.0	25.2
			500	120	0.08	193.0	157.9	18.5	33.3
			700	75	0.24	199.5	189.2	4.0	24.6

(a) Tests made after creep exposure without surface conditioning.
(b) Unexposed values average two tests.
(c) Not determined.

TABLE 3.02147 EFFECT OF 100 HOUR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF SHEET AGED TO HIGH STRENGTH LEVEL.

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

Source		(4)							
Alloy		Ti-11.5Mo-6Zr-4.5Sn							
Form		Sheet							
			500 hr Creep Exposure			Subsequent RT Tensile Properties(a)			
Heat	Sheet Thickness in	Condition	Temp F	Stress ksi	Permanent Deformation percent	F_{tu} ksi	F_{ty} ksi	e(2 in) percent	RA percent
A	0.063	40 percent c red + 1400 F, 5 min, AC + 1050 F, 8 hr	unexposed(b)			175.2	167.3	9.7	35.2
			500	110	0.08	181.2	176.0	8.0	41.8
			500	125	0.19	187.2	183.9	4.0	46.7
			600	80	0.09	184.4	179.7	7.5	33.8
			600	100	0.16	183.6	177.0	9.0	49.2
			700	30	0.09	185.5	179.0	8.0	49.4
			700	50	0.15	190.4	179.6	6.5	46.7
			800	10	0.14	185.1	175.0	8.0	48.2
			800	15	0.21	183.7	177.3	6.5	32.0
B	0.067	50 percent c red + 1350 F, AC + 1000 F, 8 hr	unexposed			178.0	164.5	4.5	34.9
			unexposed			170.6	159.7	7.5	39.4
			500	110	0.27	159.3	155.3	9.0	35.4
			700	50	0.75	185.3	165.8	4.0	25.9

(a) Tests made after creep exposure without surface conditioning.
(b) Unexposed values average two tests.

TABLE 3.02148 EFFECT OF 500 HOUR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF SHEET AGED TO MEDIUM STRENGTH LEVEL.

Source		(4)							
Alloy		Ti-11.5Mo-6Zr-4.5Sn							
Form		Sheet							
			500 hr Creep Exposure			Subsequent RT Tensile Properties(a)			
Heat	Sheet Thickness in	Condition	Temp F	Stress ksi	Permanent Deformation percent	F_{tu} ksi	F_{ty} ksi	e(2 in) percent	RA percent
A	0.063	40 percent c red + 1400 F, 5 min, AC + 900 F, 8 hr	unexposed(b)			213.6	179.6	8.0	26.7
			500	110	0.08	219.1	204.8	6.5	23.7
			500	115	0.07	219.5	207.4	6.0	24.8
			500	125	0.10	217.3	208.9	4.5	20.2
			600	90	0.12	218.2	205.4	5.5	20.0
			600	100	0.11	220.3	189.8	5.0	19.8
			600	110	0.20	219.3	215.1	4.0	18.7
			700	30	0.06	221.0	216.5	5.5	11.6
			700	40	0.14	225.2	207.4	6.0	21.7
			700	50	0.16	214.2	200.0	6.0	18.3
			800	5	0.13	222.6	209.1	6.0	12.2
			800	7	0.13	222.2	209.2	6.0	19.6
			800	15	0.22	219.4	206.8	5.0	18.9
B	0.067	50 percent c red + 1350 F, AC + 900 F, 8 hr	unexposed			200.9	196.8	4.5	25.9
			unexposed			204.5	194.9	3.0	11.1
			500	120	0.18	199.1	188.5	6.0	20.8

(a) Tests made after creep exposure without surface conditioning.
(b) Unexposed values average two tests.

TABLE 3.02149 EFFECT OF 500 HOUR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF SHEET AGED TO HIGH STRENGTH LEVEL.

Ti	
11.5	Mo
6	Zr
4.5	Sn

BETA III

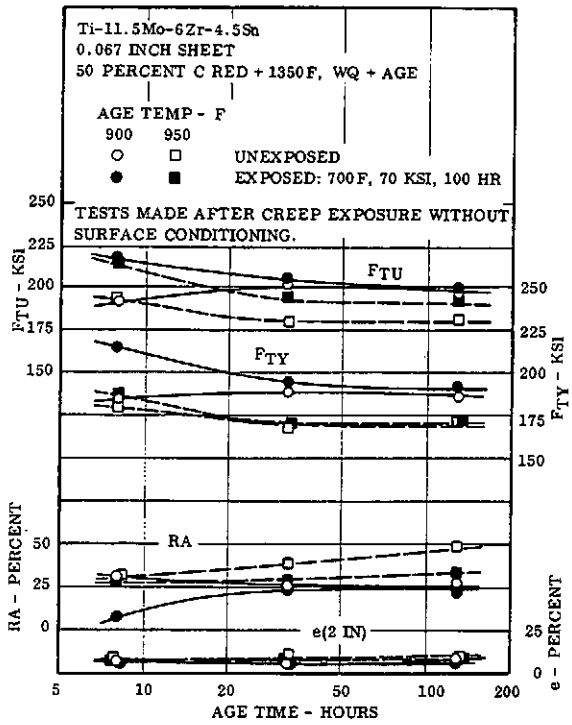


FIG. 3.02150 EFFECT OF 100 HR EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD ON ROOM TEMPERATURE TENSILE PROPERTIES OF SHEET VARIOUSLY AGED. (4)

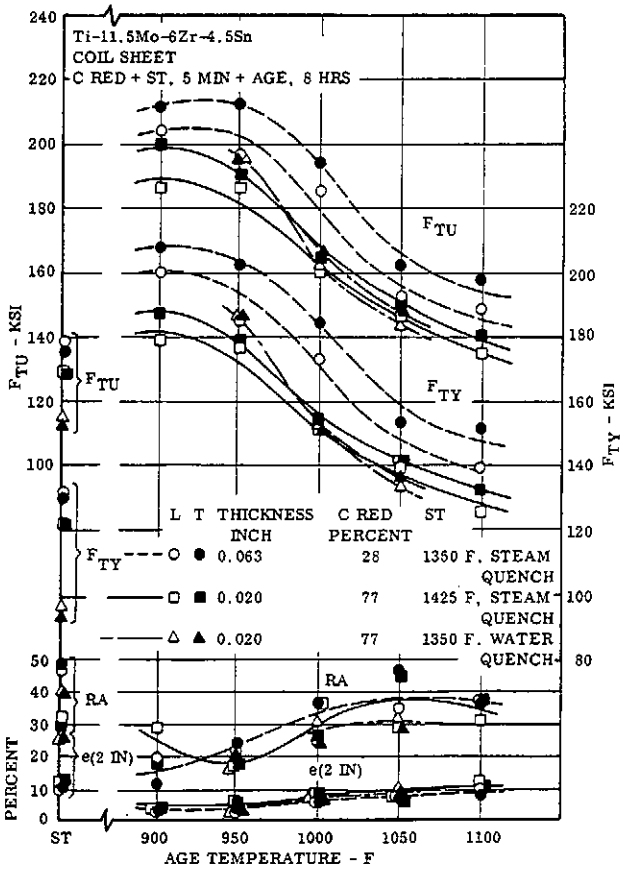


FIG. 3.02151 EFFECT OF AGING TEMPERATURE ON TENSILE PROPERTIES OF COIL SHEET. (4)

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

Source	(4)							
Alloy	Ti-11.5Mo-6Zr-4.5Sn							
Form	Foil							
Condition	1450F in Argon, AC + Age, 8 hr in Vacuum (2×10^{-5} mm Hg)							
				Tensile Properties (b)				
Foil Gage in	Age Temp F	Deskin(a)	Test Dir	F_{tu} ksi	F_{ty} ksi	e(2 in) percent	RA percent	E Static 1000 ksi
0.010(c)	unaged	No	L	143.7	134.2	10.8	28.6	11.5
		S	L	144.8	135.8	9.8	30.0	11.9
		No	T	143.7	139.8	7.5	27.5	11.2
		S	T	141.3	137.1	8.0	37.2	12.6
	950	No	L	201.2	191.5	3.2	10.0	15.6
		S	L	174.7	162.0	4.5	22.0	15.5
		A	L	173.0	164.0	5.5	22.8	16.1
	1000	No	L	158.0	156.0	4.5	24.0	15.8
		S	L	168.4	161.0	4.0	22.4	15.7
		A	L	157.0	149.7	5.5	25.5	16.8
0.005(c)	unaged	No	L	152.1	137.0	10.0	-	11.2
		S	L	151.5	141.0	8.0	-	12.8
		No	T	153.7	148.6	5.7	-	12.8
		S	T	151.7	139.5	9.2	-	12.6
	950	No	L	203.3	190.6	2.5	-	16.9
		S	L	185.0	177.6	3.3	-	15.1
		A	L	187.8	178.1	3.5	-	15.8
	1000	No	L	170.8	167.0	4.0	-	15.4
		S	L	170.6	163.3	3.0	-	16.2
		A	L	175.5	165.0	5.0	-	16.2
0.0035(d)	950	No	L	194.1	180.3	4.2	-	16.1
		S	L	162.6	153.6	4.0	-	14.5
		A	L	177.1	165.1	5.0	-	15.6
	1000	No	L	161.1	151.7	3.5	-	15.1
		S	L	166.9	161.2	8.0	-	16.1
		A	L	166.9	156.9	4.5	-	16.6
0.002(e)	unaged	No	L	141.6	133.2	8.5	-	10.2
		S	L	145.6	144.3	6.0	-	10.8
		No	T	145.0	138.4	6.2	-	11.5
		S	T	144.4	140.7	6.2	-	11.0
	950	No	L	227.3	213.3	2.0	-	18.4
		S	L	242.8	232.9	1.7	-	17.3
		A	L	178.5	168.0	1.0	-	15.0
	1000	No	L	170.0	168.0	(f)	-	17.4
		A	L	186.7	177.0	4.0	-	17.9

(a) Deskin acid pickle: S = 0.0005 in after ST, A = 0.0005 in after aging.
(b) Average of duplicate tests.
(c) Cold reduced from 0.020 in strip.
(d) Produced by cold reducing solution treated 0.010 in foil.
(e) Produced by cold reducing solution treated 0.005 in foil.
(f) Failed at gage mark.

TABLE 3.02152 TENSILE PROPERTIES OF FOIL.

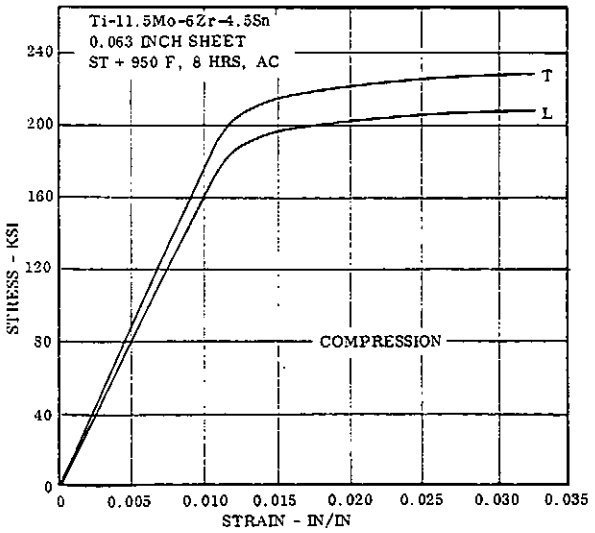


FIG. 3.0221 TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR SHEET. (19)

Source	(4)	
Alloy	Ti-11.5Mo-6Zr-4.5Sn	
Form	1/2 inch diameter bar	
Condition	1420F, WQ + age, 8 hr	
Age Temp-F	F_{ty} - ksi	F_{cy} - ksi*
As ST	99.9	119.2
		112.2
900	187.6	203.2
		194.3
1000	155.6	162.8

* Specimens 0.5 inch diameter x 1.250 inch height.

TABLE 3.0222 COMPRESSIVE YIELD STRENGTH OF BAR.

Source	(4)	
Alloy	Ti-11.5Mo-6Zr-4.5Sn	
Form	0.5 inch plate	
Condition	Hot rolled 1.1 in to 0.5 in + 1350F, 15 min, 15 sec delay, WQ + Age, 8 hr	
Age Temp F	F_{ty} - ksi	F_{cy}* - ksi
Unaged	105.6	123.6
		124.1
950	175.5	188.2
		184.2
1000	163.0	169.0
		170.5
* Compression specimens 0.5 inch diameter by 1.250 inch height.		

TABLE 3.0223 COMPRESSIVE YIELD STRENGTH OF PLATE.

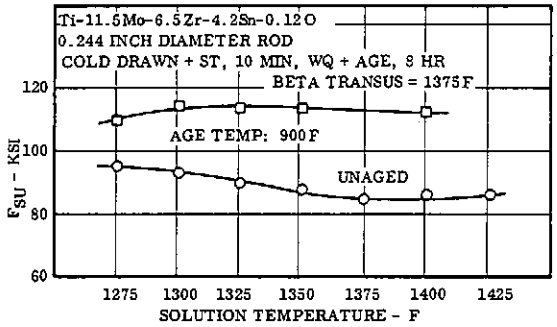


FIG. 3.0252 EFFECT OF SOLUTION TEMPERATURE ON SHEAR STRENGTH OF ROD. (4)

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

Source	(19)	
Alloy	Ti-11.5Mo-6Zr-4.5Sn	
Form	0.063 inch sheet	
Condition	ST + 950F, 8 hr, AC	
Test Direction	F_{ty} - ksi	F_{cy} - ksi
L	175	195
T	185	211

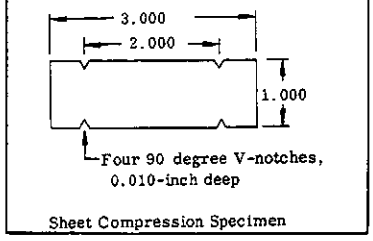


TABLE 3.0224 COMPRESSIVE YIELD STRENGTH OF SHEET.

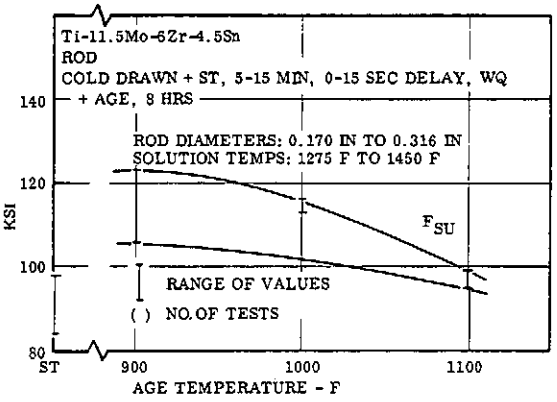


FIG. 3.0253 SPREAD OF SHEAR STRENGTH FOR ROD AGED AT DIFFERENT TEMPERATURES. (4)

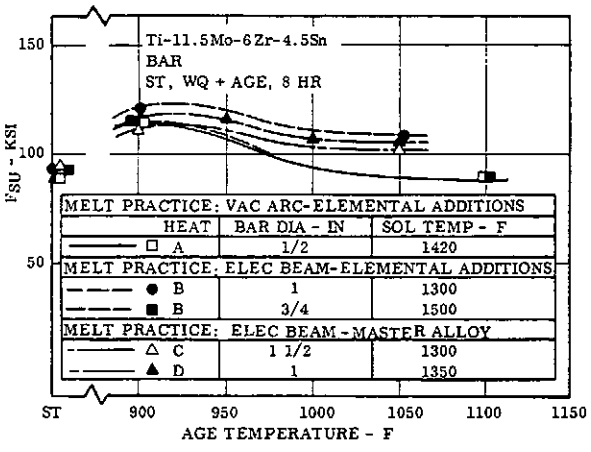


FIG. 3.0251 DOUBLE SHEAR STRENGTH OF AGED BARS VARIOUSLY MELTED AND SOLUTION TREATED. (7)

Source	(19)
Alloy	Ti-11.5Mo-6Zr-4.5Sn
Form	0.063 inch sheet
Condition	ST + 950F, 8 hr, AC
Test Direction	F_{su} - ksi
L	117
T	118

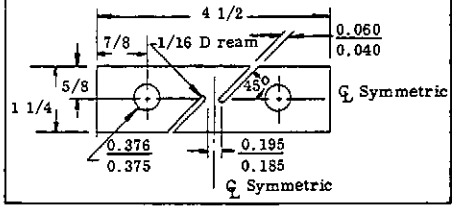
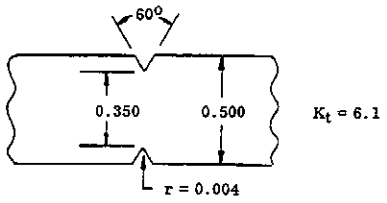


TABLE 3.0254 SHEAR STRENGTH OF SHEET.

Ti
11.5 Mo
6 Zr
4.5 Sn

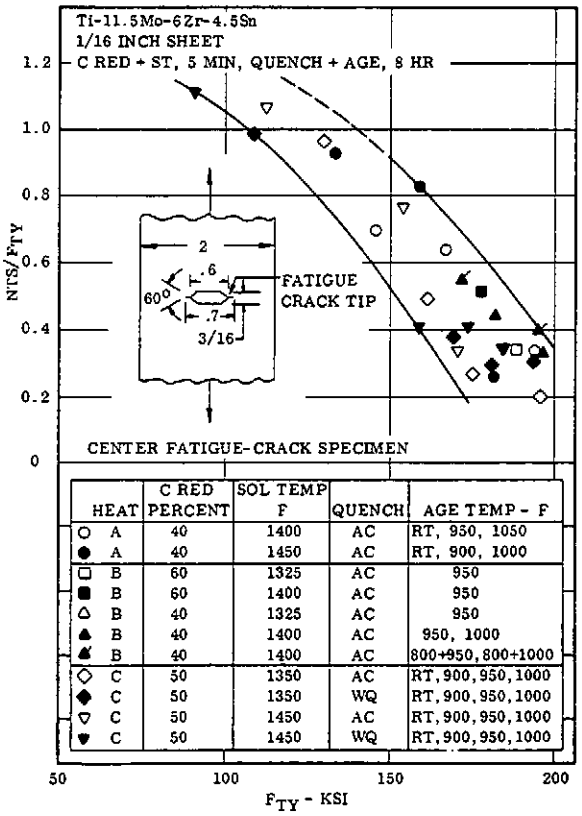
BETA III

Source								(4)		
Alloy								See Compositions Below		
Form								0.063 inch Sheet		
Condition								40 percent c red + 1400 F, 5 min, AC + age, 8 hr		
Composition - weight percent										
Ti	Mo	Zr	Sn	Fe	C	O	N	Age Temp - F	F_{ty} - ksi	NTS* - ksi
Bal	10.8	5.8	4.4	0.08	0.06	0.15	0.010	900	196.3	212.0 199.4
								1050	167.3	197.8 198.4
Bal	12.2	6.7	4.1	0.03	0.04	0.14	0.013	950	183.1	201.4 214.0
								1050	157.8	185.7 183.3



* No load crosshead speed 0.05 in/min

TABLE 3.02711 EFFECT OF COMPOSITION (VARIATION IN BETA-PHASE-STABILIZING ELEMENT CONTENT) ON MILD-NOTCH TENSILE PROPERTIES OF SHEET.



HEAT	C RED PERCENT	SOL TEMP F	QUENCH	AGE TEMP - F
○ A	40	1400	AC	RT, 950, 1050
● A	40	1450	AC	RT, 900, 1000
□ B	60	1325	AC	950
■ B	60	1400	AC	950
△ B	40	1325	AC	950
▲ B	40	1400	AC	950, 1000
◢ B	40	1400	AC	800+950, 800+1000
◇ C	50	1350	AC	RT, 900, 950, 1000
◆ C	50	1350	WQ	RT, 900, 950, 1000
▽ C	50	1450	AC	RT, 900, 950, 1000
▼ C	50	1450	WQ	RT, 900, 950, 1000

FIG. 3.02712 EFFECT OF YIELD STRENGTH LEVEL ON STRENGTH OF CENTER FATIGUE-CRACK SHEET SPECIMENS. (4)

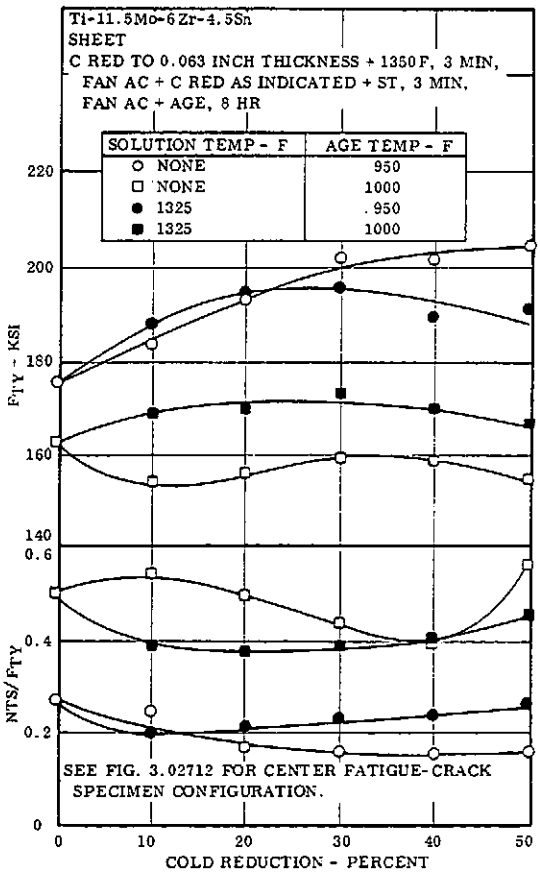


FIG. 3.02713 EFFECT OF COLD REDUCTION ON STRENGTH OF CENTER FATIGUE-CRACK SHEET SPECIMENS VARIOUSLY HEAT TREATED. (4)

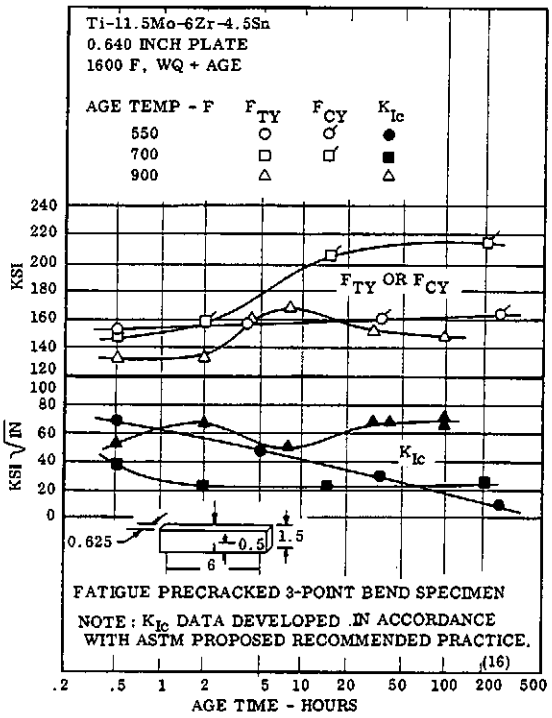
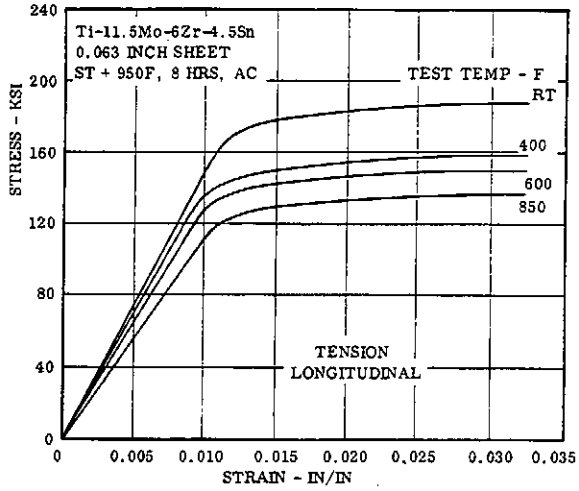


FIG. 3.02722 EFFECT OF AGING TIME ON THE PLANE STRAIN FRACTURE TOUGHNESS OF PLATE. (15)



Ti
11.5 Mo
6 Zr
4.5 Sn
BETA III

FIG. 3.0311 TYPICAL STRESS-STRAIN CURVES AT VARIOUS TEMPERATURES FOR SHEET IN LONGITUDINAL DIRECTION. (19)

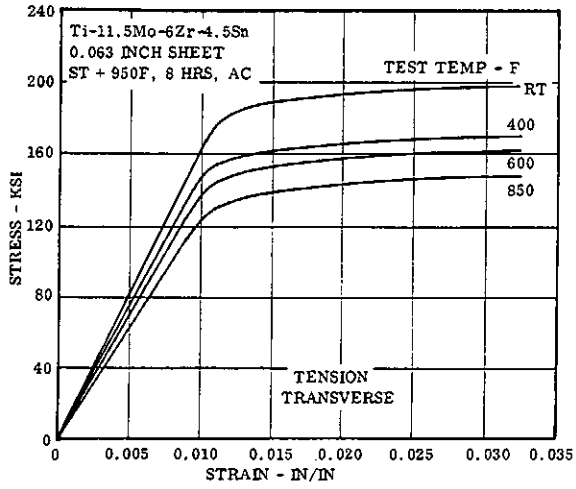
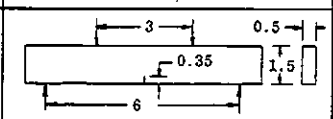
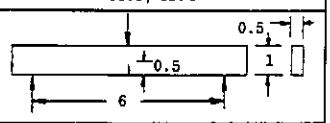


FIG. 3.0312 TYPICAL STRESS-STRAIN CURVES AT VARIOUS TEMPERATURES FOR SHEET IN TRANSVERSE DIRECTION. (19)

Source	(11)	(12)(14)
Alloy	Ti-11.5Mo-6Zr-4.5Sn	
Form	Closed Die Press Forging*	Press Forged 3 inch Square
Condition	1325F, 1 hr, WQ + 950F, 8 hr, AC**	1400F, 1 hr, WQ + 950F, 8 hr, AC**
F_{ty} - ksi	182	165
K_{Ic} - ksi√in	57.2, 59.6	58.9, 63.4
Fatigue-Cracked Bend Specimens		

* See Table 3.0213 for forging configuration and specimen locations (specimens K_{Ic} -A and K_{Ic} -B).
** Heat treated in full section.

TABLE 3.02723 PLANE STRAIN FRACTURE TOUGHNESS OF PRESS FORGINGS.

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

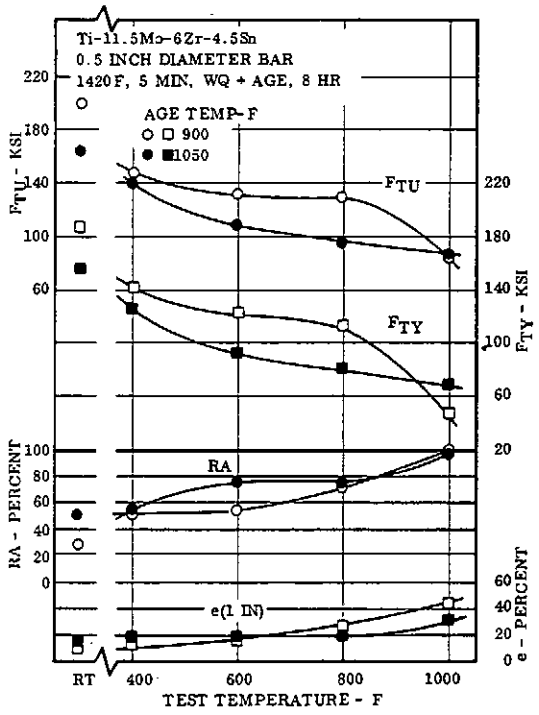


FIG. 3.0313 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF BAR. (4)

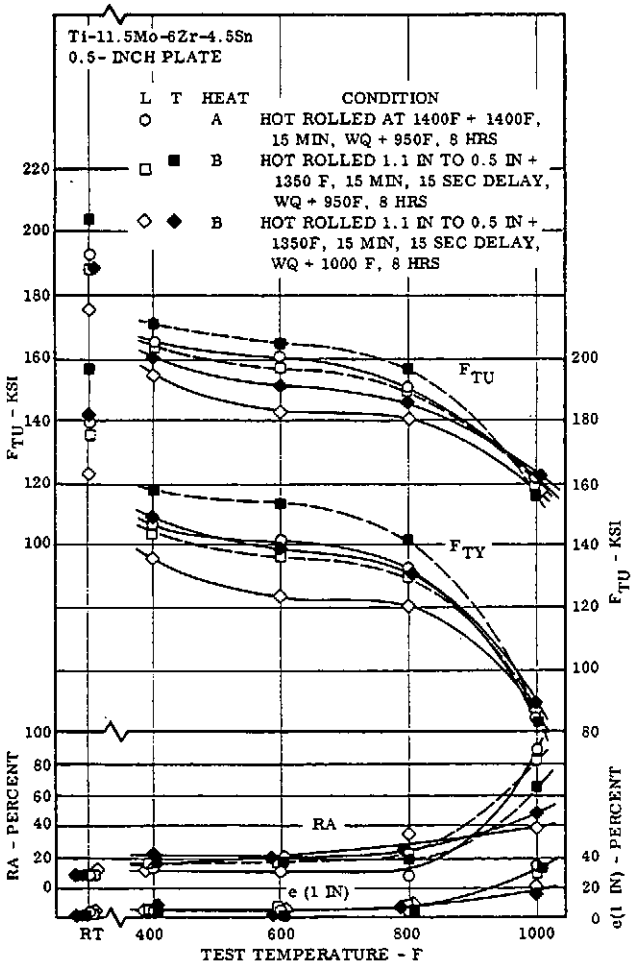


FIG. 3.0314 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF PLATE. (4)

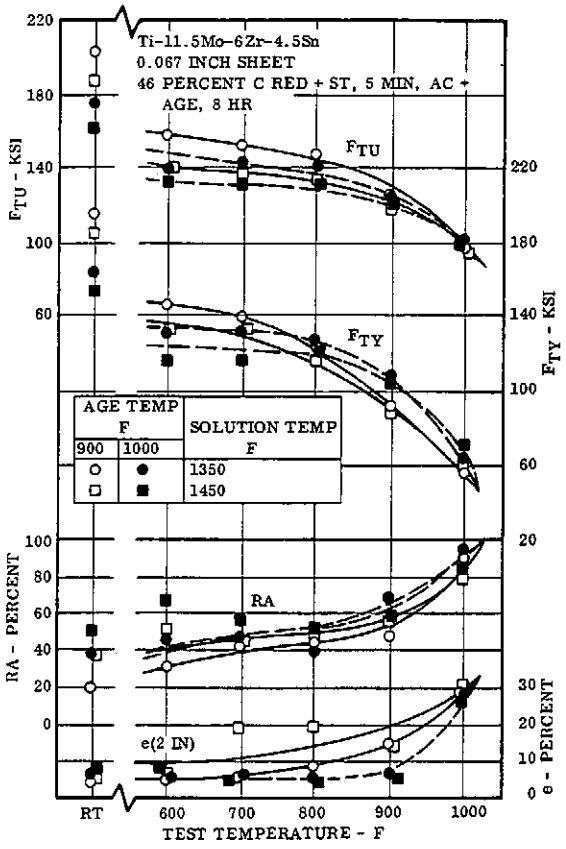


FIG. 3.0315 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SHEET. (4)

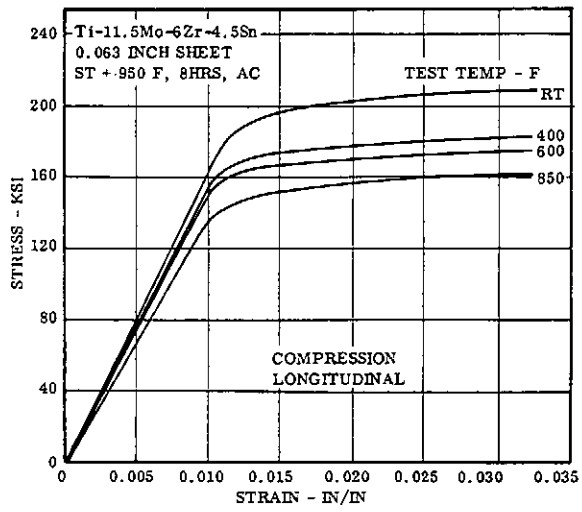


FIG. 3.0321 TYPICAL COMPRESSIVE STRESS-STRAIN CURVES AT VARIOUS TEMPERATURES FOR SHEET IN LONGITUDINAL DIRECTION. (19)

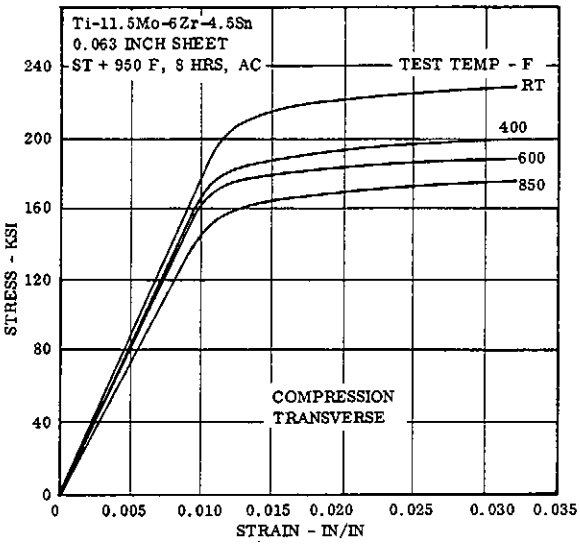


FIG. 3.0322 TYPICAL COMPRESSIVE STRESS-STRAIN CURVES AT VARIOUS TEMPERATURES FOR SHEET IN TRANSVERSE DIRECTION. (19)

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

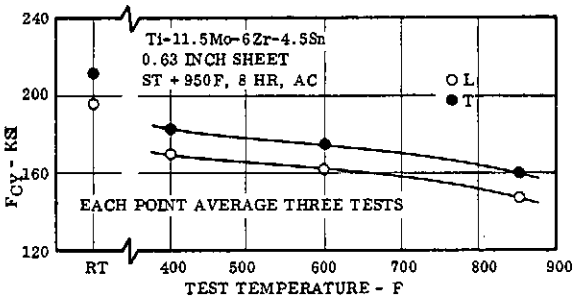


FIG. 3.0323 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF SHEET. (19)

Source	(4)		
Alloy	Ti-11.5Mo-6Zr-4.5Sn		
Form	1 9/16 inch dia bar		
Condition	Test Temp F	F_{ty} ksi	IE, Charpy-V ft-lb
1350 F, WQ + 900 F, 8 hr	RT	176.3	14.5
	-40		13.0
1350 F, WQ + 1050 F, 8 hr	RT	159.3	13.5
	-40		10.5
Mid-radius properties			

TABLE 3.0331 CHARPY-V IMPACT ENERGY FOR BAR AT ROOM TEMPERATURE AND -40 F.

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

Source		(4)		
Alloy		Ti-11.5Mo-6Zr-4.5Sn		
Form		Bar		
Heat	Dia inch	Condition	F_{ty} at RT ksi	IE, Charpy-V at -40 F ft-lb
A	1 9/16	1450 F, WQ	111.1*	25*
		1450 F, WQ + 950 F, 8 hr	184.8	6
		1450 F, WQ + 1050 F, 8 hr	158.0	10
B	1	1350 F, WQ + 900 F, 8 hr	176.3	13
		1350 F, WQ + 1050 F, 8 hr	159.3	10.5
* Center; all other values mid-radius.				

TABLE 3.0332 CHARPY-V IMPACT ENERGY FOR BAR AT -40 F.

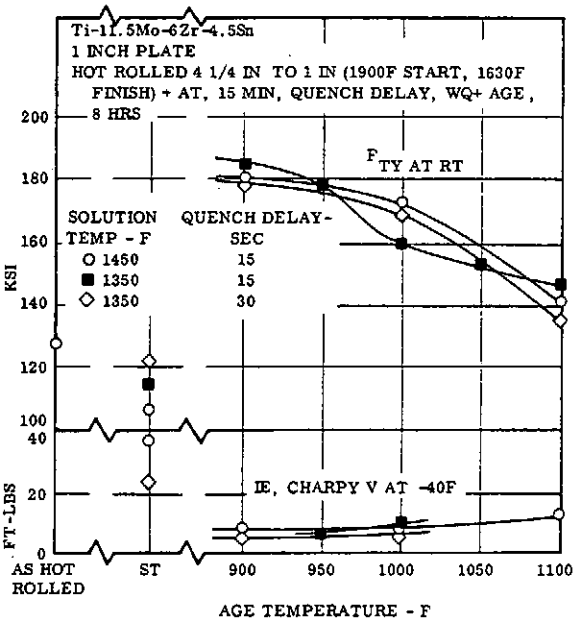


FIG. 3.0334 EFFECT OF AGING TEMPERATURE ON -40F IMPACT ENERGY OF 1 INCH PLATE. (4)

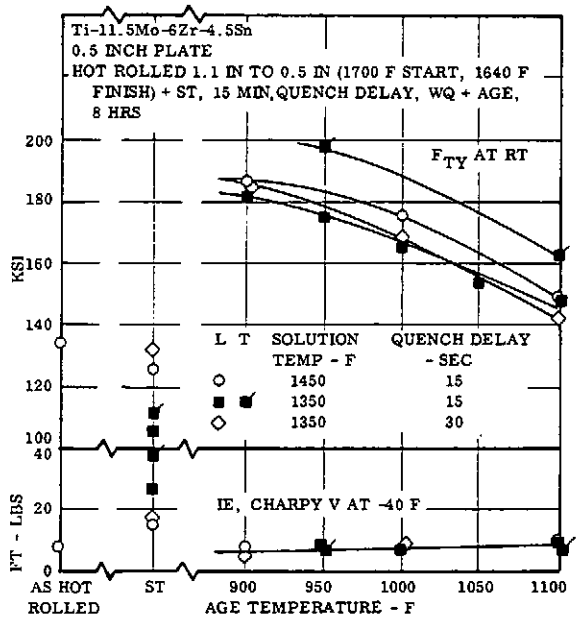


FIG. 3.0333 EFFECT OF AGING TEMPERATURE ON -40 F IMPACT ENERGY OF 0.5 INCH PLATE. (4)

Source	(4)			
Alloy	Ti-11.5Mo-6Zr-4.5Sn			
Form	0.5 inch plate			
Condition	Hot rolled + heat treated			
Hot Rolling Temp F	Heat Treatment	Test Temp F	F_{ty} ksi	IE, Charpy-V ft-lb
1800	1450 F, 10 min, AC	RT	111.4	5
		-40		5
	1450 F, 10 min, WQ	RT	96.0	7
		-40		6
1500	1450 F, 10 min, AC	RT	121.7	11
		-40		9
	1450 F, 10 min, WQ	RT	99.4	23
		-40		17
	1400 F, 10 min, WQ	RT	99.1	16
		-40		16
1400	1400 F, 10 min, AC	RT	135.9	12
		-40		10
	1400 F, 10 min, WQ	RT	113.9	27
		-40		20
1400	1400 F, 10 min, WQ + 950 F, 8 hr	RT	178.3	9
		-40		7
1800	1450 F, 10 min, WQ + 1050 F, 8 hr	RT	166.8	5
		-40		3
1500	1450 F, 10 min, WQ + 1050 F, 8 hr	RT	164.7	10
		-40		9
1400	1400 F, 10 min, WQ + 1050 F, 8 hr	RT	157.2	10
		-40		8
All values average duplicate tests.				

TABLE 3.0335 EFFECT OF HOT ROLLING TEMPERATURE AND COOLING RATE FROM THE SOLUTION TREATMENT TEMPERATURE ON THE ROOM TEMPERATURE AND -40 F IMPACT ENERGY OF 0.5 INCH PLATE.

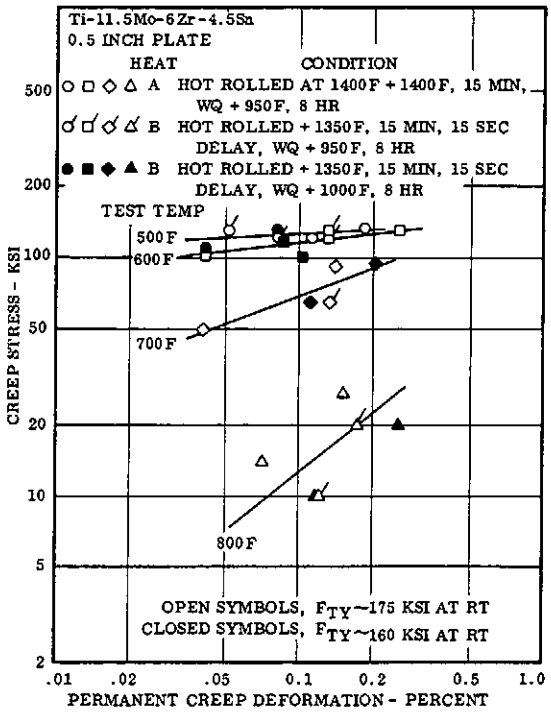


FIG. 3.043 100 HOUR CREEP DEFORMATION FOR PLATE. (4)

Source	(4)		
Alloy	Ti-11.5Mo-6Zr-4.5Sn		
Form	0.5 inch plate		
Condition	Hot rolled + 1350F, 15 min, 15 sec delay, WQ + Age, 8 hr		
Age Temp F	Test Temp F	F_{ty} ksi	5 hr mild notch stress rupture strength* - ksi
950	RT	175.5	190.0
	500	140.0	210.0
1000	RT	163.0	215.0
	500	129.4	204.4

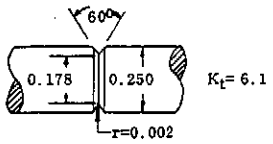


TABLE 3.046 5 HOUR MILD-NOTCH STRESS RUPTURE STRENGTH FOR PLATE.

Ti
11.5 Mo
6 Zr
4.5 Sn
BETA III

Source	(4)			
Alloy	Ti-11.5Mo-6Zr-4.5Sn			
Form	0.5 inch plate			
Condition	Hot rolled + 1350F, 15 min, 15 sec delay, WQ + age, 8 hr			
			Smooth Stress Rupture Properties	
Age Temp F	Test Temp F	F_{ty} ksi	Stress ksi	Time to Failure hours
950	RT	175.5	186	9.6
	RT		183	>1604
	500	140.0	160	>1250
1000	RT	163.0	168	4.1
	RT		165	>1416
	500	129.4	145	>1251

TABLE 3.045 SMOOTH STRESS RUPTURE PROPERTIES FOR PLATE AT ROOM TEMPERATURE AND 500F.

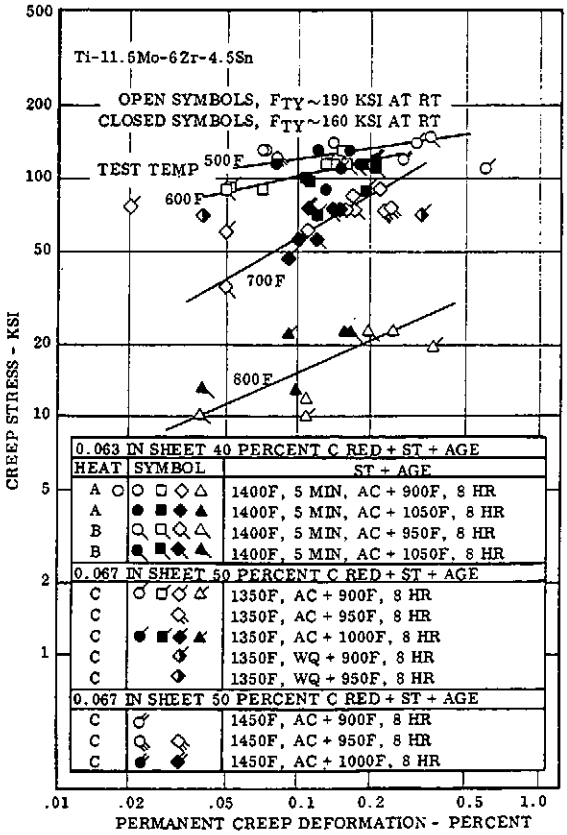


FIG. 3.047 100 HR CREEP DEFORMATION FOR SHEET. (4)

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

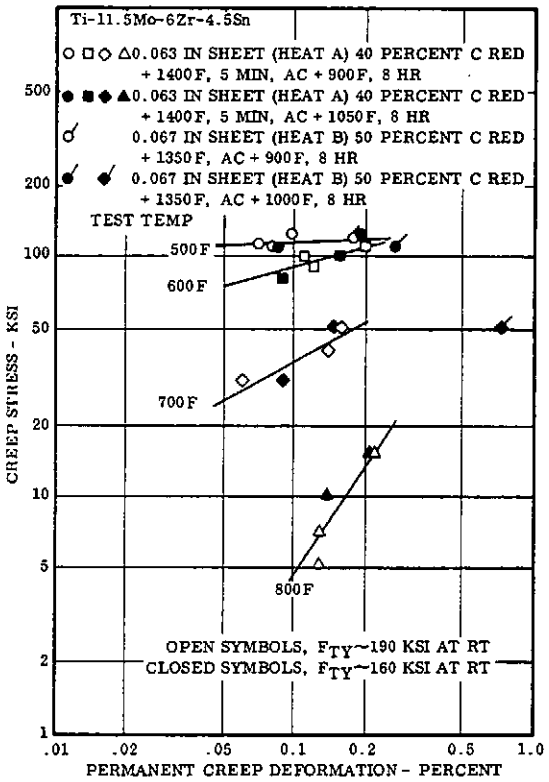


FIG. 3.048 500 HOUR CREEP DEFORMATION FOR SHEET.(4)

Source	(4)		
Alloy	Ti-11.5Mo-6Zr-4.5Sn		
Form	0.063 inch sheet		
Condition	200F Creep Exposure		Permanent Creep Deformation - percent
	Stress ksi	Time hours	
50 percent C Red+1350F, AC	109	762	0.08
	109	1000	0.03
50 percent C Red + 1350F, AC + 1100F, 8 hr	111	1000	0.09
	111	1000	0.78

TABLE 3.049 200F CREEP DEFORMATION FOR SHEET.

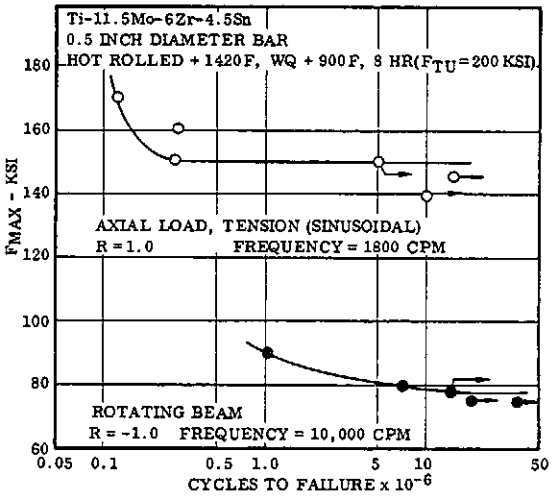


FIG. 3.051 AXIAL LOAD AND ROTATING BEAM FATIGUE PROPERTIES OF BAR. (4)

Source	(4)	
Alloy	Ti-11.5Mo-6Zr-4.5Sn	
Form	0.063 inch sheet	
Condition	40 percent C Red + 1400F, 5 min, AC + age, 8 hr	
Age Temp F	Fty ksi	500 hr, RT Mild Notch* Rupture Strength - ksi
900	196.3	190.0
1050	167.3	182.0
* See Table 3.02711 for specimen configuration.		

TABLE 3.0410 500 HOUR MILD-NOTCH RUPTURE STRENGTH FOR SHEET AT ROOM TEMPERATURE.

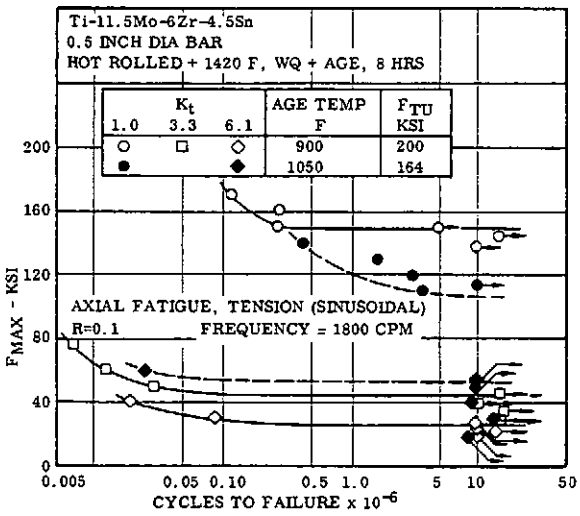


FIG. 3.052 AXIAL LOAD SMOOTH AND MILD NOTCH FATIGUE PROPERTIES OF BAR. (4)(7)

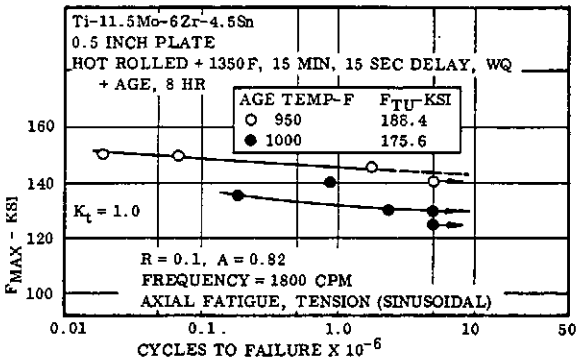


FIG. 3.053 AXIAL LOAD SMOOTH FATIGUE PROPERTIES OF PLATE. (4)

Ti
11.5 Mo
6 Zr
4.5 Sn
BETA III

Source	(7)
Alloy	Ti-11.5Mo-6Zr-4.5Sn
Form	0.063 inch sheet
Condition	Poisson's Ratio, μ
1450 F, WQ	0.382
1350 F, WQ	0.368, 0.359
1350 F, WQ + 900 F, 8 hr, AC	0.312, 0.313
1350 F, WQ + 1100 F, 8 hr, AC	0.335, 0.325
All specimens longitudinal.	

TABLE 3.061 POISSON'S RATIO FOR SHEET.

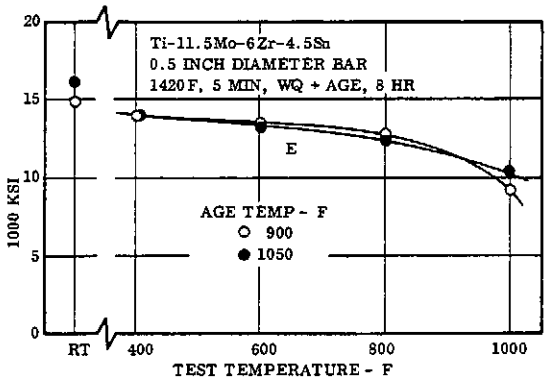


FIG. 3.0622 EFFECT OF TEST TEMPERATURE ON ELASTIC MODULUS OF BAR. (4)

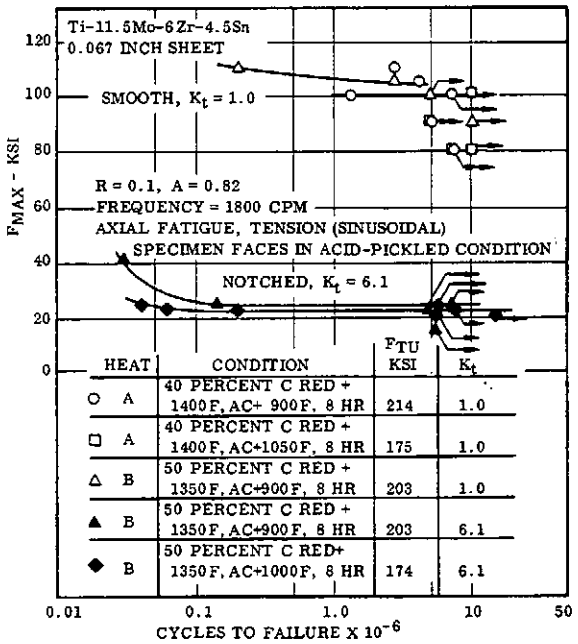


FIG. 3.054 AXIAL LOAD SMOOTH AND MILD-NOTCH FATIGUE PROPERTIES OF SHEET. (4)

Source	(4)	
Alloy	Ti-11.5Mo-6Zr-4.5Sn	
Form	0.5 inch plate	
Condition	Hot rolled 1.1 in to 0.5 in + 1350F, 15 min, 15 sec delay, WQ + age, 8 hr	
Age Temp - F	E - 10^3 ksi	E_c* - 10^3 ksi
Unaged	11.5	12.0
		11.8
950	15.8	16.7
		17.0
1000	15.9	15.8
		15.8
* Compression specimens 0.5 inch diameter by 1.250 inch height.		

TABLE 3.0625 COMPRESSIVE ELASTIC MODULUS OF PLATE.

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

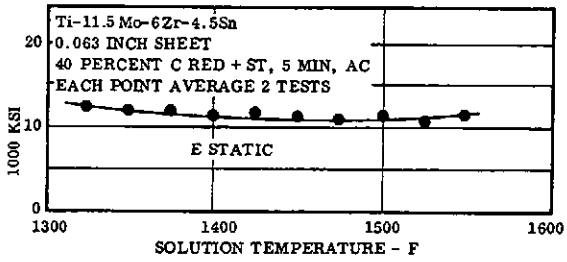


FIG. 3.0626 EFFECT OF SOLUTION TEMPERATURE ON ELASTIC MODULUS OF SOLUTION TREATED SHEET. (4)

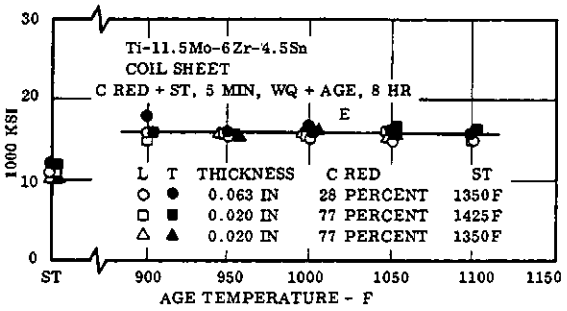


FIG. 3.0629 EFFECT OF AGING TEMPERATURE ON ELASTIC MODULUS OF COIL SHEET. (4)

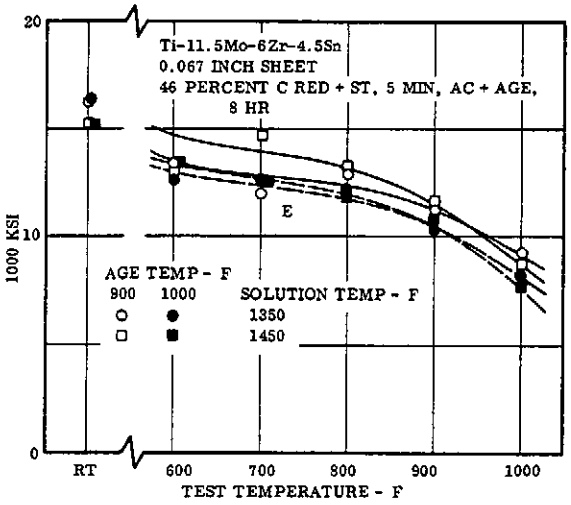


FIG. 3.0627 EFFECT OF TEST TEMPERATURE ON ELASTIC MODULUS OF SHEET. (4)

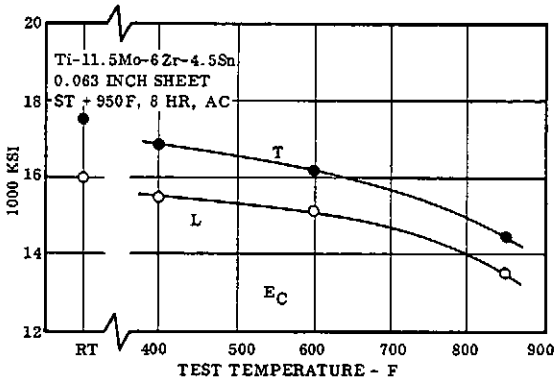


FIG. 3.0628 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE ELASTIC MODULUS OF SHEET. (19)

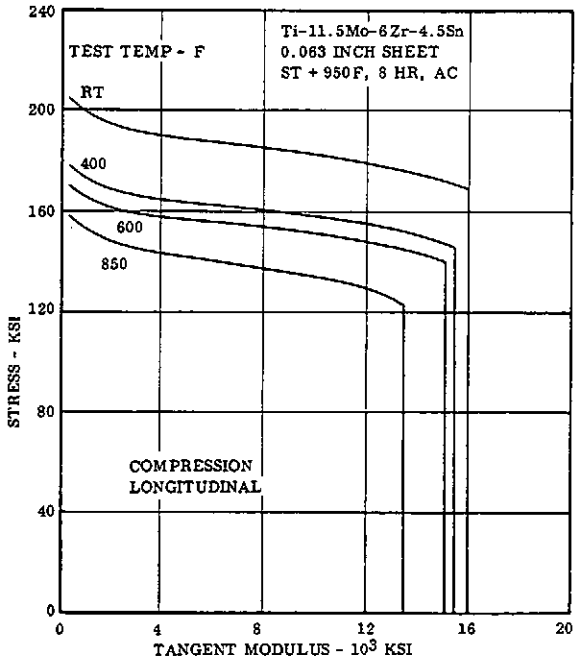


FIG. 3.0631 TYPICAL COMPRESSIVE TANGENT MODULUS AT VARIOUS TEMPERATURES FOR SHEET IN LONGITUDINAL DIRECTION. (19).

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

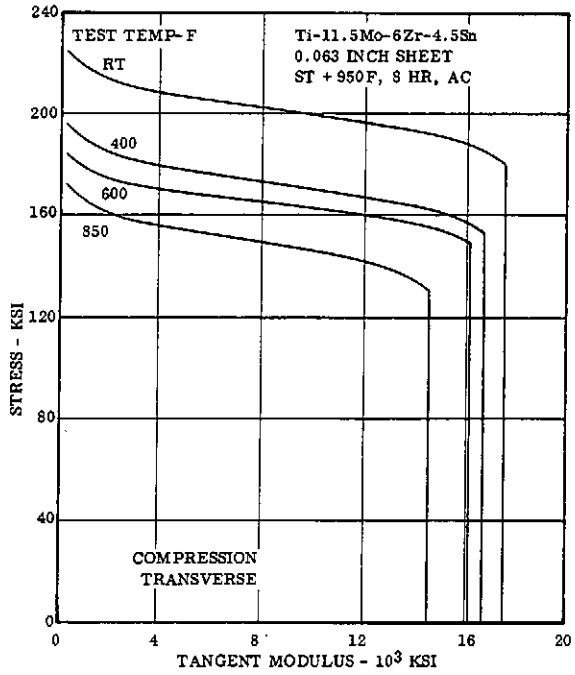


FIG. 3.0632 TYPICAL COMPRESSIVE TANGENT MODULUS AT VARIOUS TEMPERATURES FOR SHEET IN TRANSVERSE DIRECTION. (19)

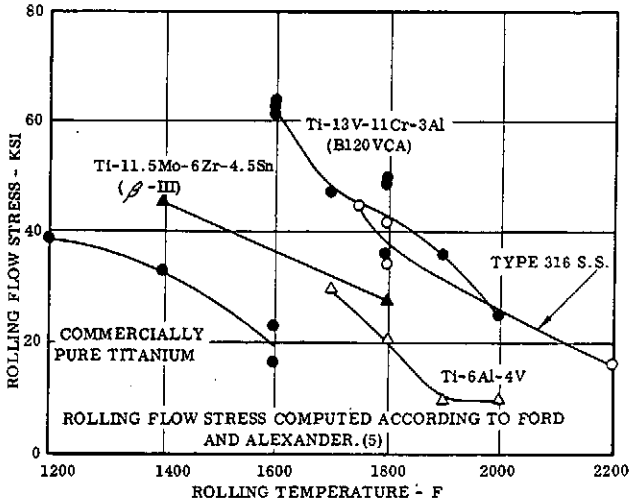


FIG. 4.0131 HOT ROLLABILITY OF Ti-11.5Mo-6Zr-4.5Sn AND SEVERAL OTHER ALLOYS. (4)

Source		(4)		
Alloy		Ti-11.5Mo-6Zr-4.5Sn		
Form		Seamless Tubing		
Tube Size in		Condition	Flattening Test (a)	Flaring Test (b)
OD	Wall t		OD_f/t	percent
1.5	0.173	As extruded (c)	3.7	-
1.26	0.120	Mill annealed (d)	9.0	13.5
		Mill annealed + pickled	8.1	12.0
		Mill annealed+1350F, WQ	7.0	32.3
0.884	0.050	Mill annealed (d)	11.8	16.3
		Mill annealed + pickled	12.2	15.7
		Mill annealed + 1350F, WQ	6.6	27.8

(a) Flattening performance - ratio: height (outside diameter) at failure/wall thickness.
(b) Flaring performance - percentage increase in outside diameter at the location of failure.
(c) 2.8 inch OD x 1.260 inch ID hollow billets canned in mild steel, heated to 1500F, extruded to tube hollow (reduction 7.2:1) and water quenched.
(d) Tube hollows cold reduced to finished tubing in a single pass with tube reducers, followed by vacuum anneal: 1350F, 1/2 hr, rapid cool + 1150F, 4 hr, furnace cool to 900F.

TABLE 4.0111 FLATTENING AND FLARING PERFORMANCE OF SEAMLESS TUBING.

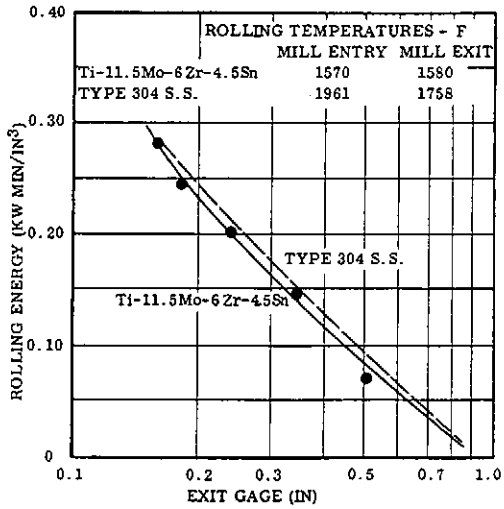


FIG. 4.0132 ENERGY FOR HOT STRIP ROLLING. (4)

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

Source	(4)				
Alloy	Ti-11.5Mo-6Zr-4.5Sn				
Form	0.195 inch hot rolled sheet				
Hot Rolling Temp - F (a) Start	Finish(b)	Heat Treatment	F_{tu} ksi	F_{ty} ksi	e(2 in) percent	RA percent
1925	1550	As-hot rolled, AC	133.3	121.9	10.0	29.7
1850	1475		145.5	134.6	7.0	38.2
1775	1400		152.4	143.4	6.0	27.1
1925	1550	1450F, 5 min, AC	125.6	111.6	11.0	42.1
1850	1475		131.8	118.7	12.0	50.0
1775	1400		131.6	121.0	10.0	46.0
1925	1550	1450F, 5 min, WQ	112.7	93.4	27.0	54.9
1850	1475		117.3	99.0	26.5	61.2
1775	1400		116.3	97.8	27.0	52.3
1925	1550	1450F, 5 min, WQ + 1000F, 8 hr	193.8	187.5	5.0	19.9
1850	1475		189.6	182.1	3.5	20.6
1775	1400		178.5	170.0	6.0	26.5

(a) Initial slab thickness: 2.5 inches. Reduction per pass: 22.5 percent.
(b) Temperature at final pass entry.
Results for 0.135 inch sheet essentially the same.

TABLE 4.0133 EFFECT OF HOT ROLLING TEMPERATURE ON TENSILE PROPERTIES OF HOT ROLLED SHEET.

Source	(4)	
Alloy	Ti-11.5Mo-6Zr-4.5Sn	
Form	1/2 inch dia bar	
Condition	1420F, WQ + age, 8 hr	
Age Temp - F	E_t - 1000 ksi	E_c - 1000 ksi*
Unaged	9.9	11.1
		11.7
900	14.8	16.2
		16.0
1050	15.7	15.4

* Specimens 0.5 inch dia x 1.250 inch height.

TABLE 3.0623 COMPRESSIVE ELASTIC MODULUS OF BAR.

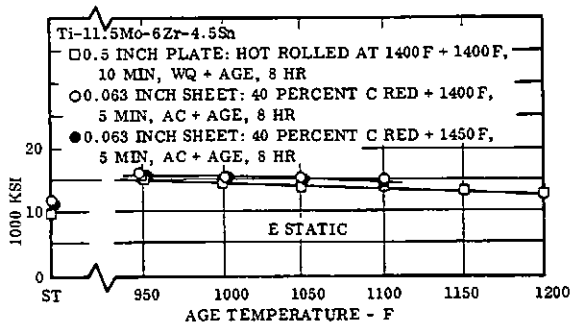


FIG. 3.0624 EFFECT OF AGING TEMPERATURE ON ELASTIC MODULUS OF PLATE AND SHEET. (4)

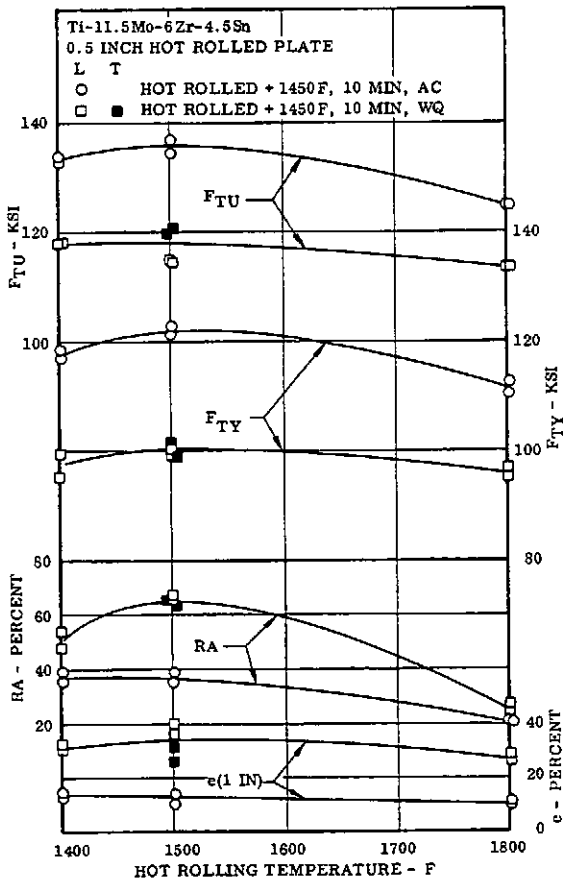


FIG. 4.0134 EFFECT OF HOT ROLLING TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION TREATED PLATE. (4)

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

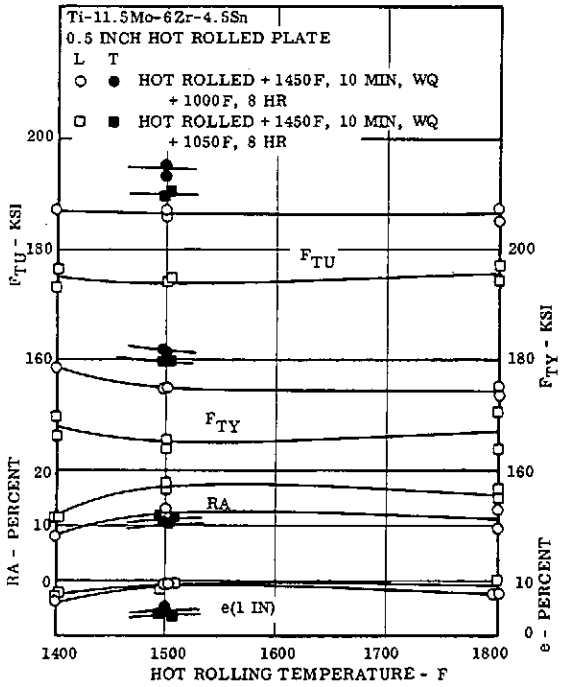


FIG. 4.0135 EFFECT OF HOT ROLLING TEMPERATURE ON TENSILE PROPERTIES OF SOLUTION TREATED AND AGED 0.5 INCH PLATE. (4)

Source	(4)		
Alloy	Deformation Banding Limit percent	Cold Work Without Edge Cracking percent	Ratio: Roll Diameter to Min Practical Thickness
Ti-11.5Mo-6Zr-4.5Sn	none	>90	250
Ti Commercially Pure	none	50	300
Ti-13V-11Cr-3Al	none	40	250
Ti-6Al-4V	20	20	250
Ti-8Al-1Mo-1V	<20	10	-

TABLE 4.0137 SEVERAL COLD ROLLING FACTORS RELATED TO REDUCTION LIMITS.

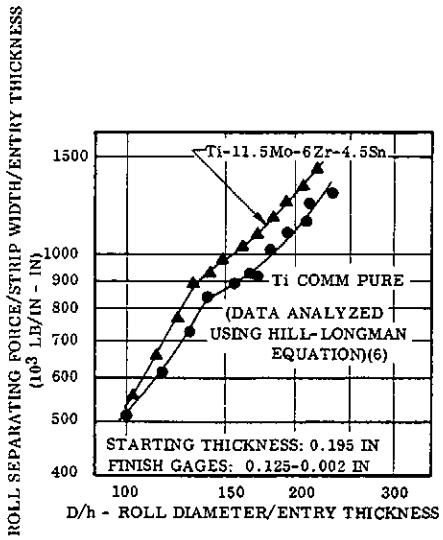


FIG. 4.0136 COLD ROLLABILITY. (4)

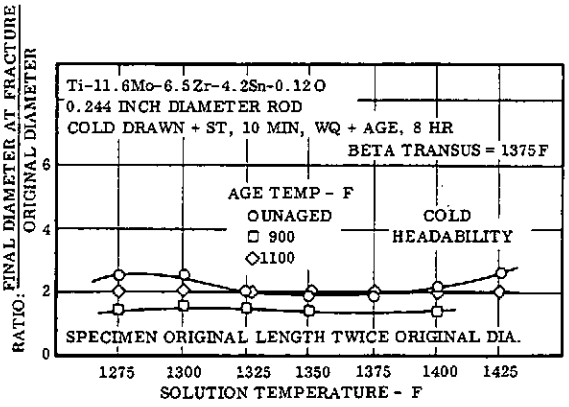


FIG. 4.0141 EFFECT OF SOLUTION TEMPERATURE ON COLD HEADABILITY OF ROD. (4)

Ti
11.5 Mo
6 Zr
4.5 Sn

BETA III

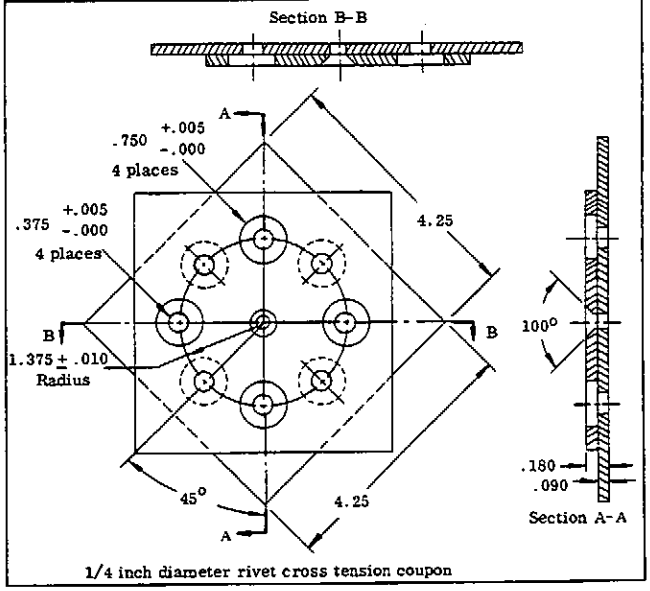
Source	(4)						
Alloy	Ti-11.5Mo-6Zr-4.5Sn						
Form	Rivet Joints (a)						
Type (b) of Test	Ratio (c): Rivet Tail Protrusion to Dia	Cold Head Ratio D_f/D_i	Rivet Joint Exposure Temp F	Stress ksi	Time hr	Ultimate Strength ksi	Type(d) of Failure
Lap Shear	1	1.45	-	-	-	107.0	S
	1	1.45	-	-	-	101.0	S
	1	1.45	500	50	100	110.0	S
	1	1.45	700	25	100	112.0	S
Cross Tension	1/2	1.30	-	-	-	73.0	H
	1/2	1.30	-	-	-	96.0	T
	1/2	1.30	500	-	100	73.0	H
	1/2	1.30	700	-	100	55.0	H
	1	1.45	-	-	-	62.2	H
	1	1.45	-	-	-	78.0	H
	1	1.45	500	-	100	73.5	H
	1	1.45	700	-	100	67.0	H

(a) Ti-6Al-4V sheet (0.067 inch thick) joined with a Ti-11.5Mo-6Zr-4Sn rivet 0.124 inch diameter.
(b) Specimen configurations same as those for spot weld tests shown in Table 4.0321.
(c) Ti-11.5Mo-6Zr-4.5Sn mill solution treated rod aged 1100F, 8 hr and machined to rivet. Rivet head countersunk with 82° included angle. Rivet head protrusion about 0.003 inch.
(d) Type of failure: S = shear, H = countersunk head, T = bucktail.

TABLE 4.0142 CROSS TENSION AND LAP SHEAR STRENGTH OF RIVET JOINTS WITH AND WITHOUT EXPOSURE TO ELEVATED TEMPERATURE WITH LOAD.

Source	(18)		
Alloy	Ti-11.5Mo-6Zr-4.5Sn		
Form	Rivet Joint (a)		
Condition	ST + head forged + 1275F, 10 min, WQ + 1050F, 8 hr, AC + press cold bucked (1.35 Bucktail Expansion)		
Bucking Tool Configuration (b)	Rivet Joint Expansion Temp - F	Time - hr	Cross Tension Strength ksi
Flat	Unexposed		65.9
Cavity	Unexposed		57.2
Flat	550	500	67.8
Cavity	550	500	66.9

(a) Ti-6Al-4V sheet (0.090 inch thick) joined with a Ti-11.5Mo-6Zr-4.5Sn rivet 0.250 inch diameter. See Figure 4.0144 for rivet configuration.
(b) See Figure 4.0144 for cavity bucking tool configuration.



1/4 inch diameter rivet cross tension coupon

TABLE 4.0143 EFFECT OF BUCKING TOOL CONFIGURATION ON CROSS TENSION STRENGTH OF RIVET JOINTS WITH AND WITHOUT EXPOSURE TO ELEVATED TEMPERATURE.

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

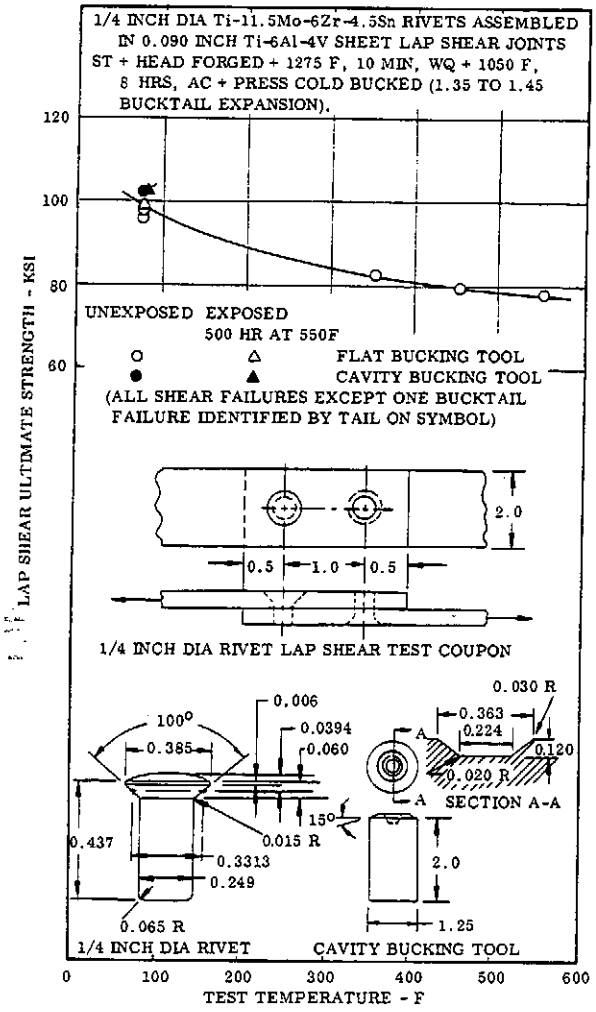


FIG. 4.0144 EFFECT OF BUCKING TOOL CONFIGURATION AND TEST TEMPERATURE ON LAP SHEAR STRENGTH OF RIVET JOINTS WITH AND WITHOUT PREVIOUS EXPOSURE TO ELEVATED TEMPERATURE. (18)

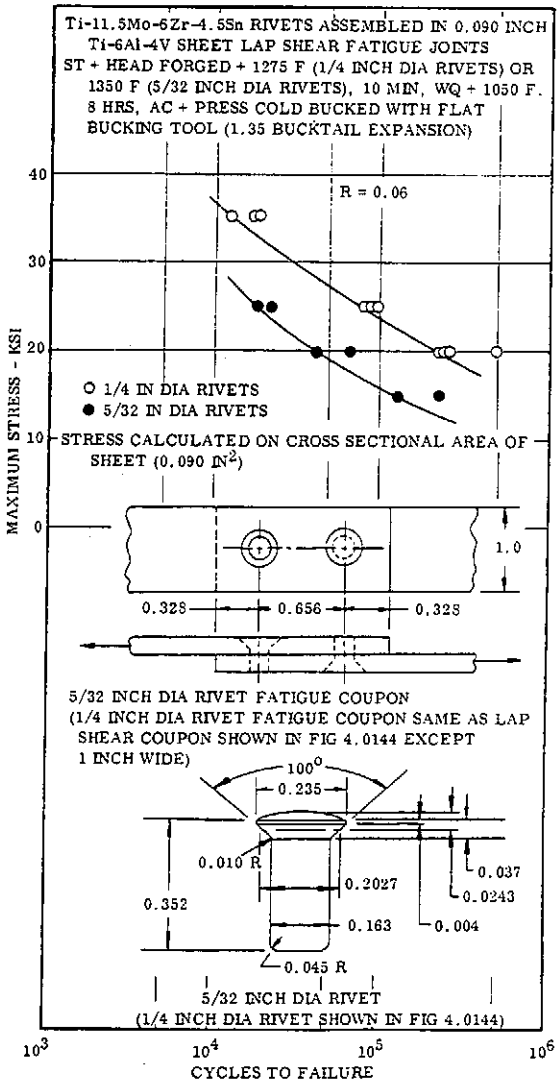


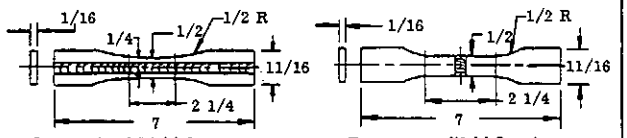
FIG. 4.0145 FATIGUE STRENGTH OF RIVETED LAP SHEAR JOINTS. (18)

	Ti
11.5	Mo
6	Zr
4.5	Sn

BETA III

Source	(4)(9)						
Alloy	Ti-11.5Mo-6Zr-4.5Sn						
Form	GTA fusion welded 0.067 inch sheet*.						
Condition	50 percent CRed + 1350 F, 5 min, AC + weld with or without 8 hr pre-weld or post-weld aging						
Test Dir	Pre-Weld Aging Temp - F	Post-Weld Aging Temp - F	F_{tu} ksi	F_{ty} ksi	e(2 in) percent	RA percent	Location of Break**
L	-	-	106.5	89.3	12.0	49.4	-
	950	-	112.1	99.6	20.0	48.0	-
	1100	-	113.3	100.4	17.0	56.1	-
T	-	-	109.2	95.3	2.5	20.6	W
	950	-	116.5	106.6	6.8	54.0	W
	1100	-	111.2	100.0	6.3	53.2	W
T	-	950	167.6	164.9	1.0	9.1	W
	-	950	190.0	160.1	4.0	24.7	P
	-	1000	150.2	144.0	3.0	26.9	W
	-	800 + 1000	157.4	151.3	2.0	15.9	W
	-	1050	139.3	131.1	3.0	25.4	W
	-	800 + 1050	155.4	147.7	3.0	21.9	HAZ
	-	1100	128.3	121.5	3.0	25.0	W
	-	800 + 1100	123.6	116.8	4.5	25.7	W

* GTA welded in argon-filled tank without filler metal additions.
** Location of break: W = weld fusion zone, P = parent metal, HAZ = heat affected zone.
Note: See Figure 3.02134 for parent sheet properties.



Longitudinal Weld Specimen Transverse Weld Specimen

TABLE 4.0311 TENSILE PROPERTIES OF GTA FUSION WELDED SHEET.

Source	(18)		
Alloy	Ti-11.5Mo-6Zr-4.5Sn		
Form	Rivet Joint(a)		
Condition	ST + head forged + 1275 F, 10 min, WQ + 1050 F, 8 hr, AC + press cold bucked (1.35 bucktail expansion)		
Bucking Tool Configuration (b)	Rivet Joint Exposure		Cycles to Failure at
	Temp - F	Time - hr	F_{max} = 35 ksi, R = .06
Flat	unexposed		19, 800
Flat	unexposed		14, 600
Flat	unexposed		19, 200
Flat	550	500	18, 500
Flat	550	500	22, 900
Flat	550	500	18, 700
Cavity	unexposed		155, 400
Cavity	unexposed		345, 800
Cavity	unexposed		309, 900
Cavity	550	500	251, 200

(a) Ti-6Al-4V sheet (0.090 inch thick) joined with Ti-11.5Mo-6Zr-4.5Sn rivets 0.250 inch diameter. See Figure 4.0144 for rivet configuration.
(b) See Figure 4.0144 for cavity bucking tool configuration.
(c) Rivet fatigue coupon same as lap shear coupon shown in Figure 4.0144 except 1 inch wide.
All failures through rivet holes in sheet material.

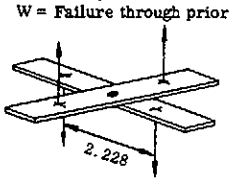
TABLE 4.0146 EFFECT OF BUCKING TOOL CONFIGURATION ON FATIGUE STRENGTH OF RIVETED LAP SHEAR JOINTS WITH AND WITHOUT PREVIOUS EXPOSURE TO ELEVATED TEMPERATURE.

Source	(25)			
Alloy	Ti-11.5Mo-6Zr-4.5Sn			
Form	Electron-beam fusion welded 0.02 inch sheet			
Condition	F_{tu} ksi	F_{ty} ksi	e(2 in) percent	Location of Break
Parent metal: ST + 950 F age	196	181	4.2	Parent metal
ST + weld + 950 F age	174	162	4.9	Parent metal
ST + 950 F age + weld	137	136	1.7	Weld fusion zone
ST + weld + ST + 950 F age	174	163	4.0	Two in parent metal Three in weld fusion zone

TABLE 4.0312 TENSILE PROPERTIES OF ELECTRON-BEAM FUSION WELDED SHEET.

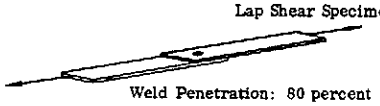
Source	(4)			
Alloy	Ti-11.5Mo-6Zr-4.5Sn			
Form	Spot Welded 0.067 inch Sheet			
Condition	46 percent C Red + ST, 5 min, AC + spot weld with or without 8 hr pre-weld or post-weld aging			
Pre-Weld Solution Temp F	Pre-Weld Aging Temp F	Post-Weld Aging Temp F	Cross Tension Maximum Load lb	Lap Shear Maximum Load lb
1350	-	-	3190 NP	5540 N
			2550NP	5360 NP
1450	-	-	2540 N	4750 PN
			2950 N	4825 N
1350	900	-	2260 P	6075 HP
			2470 P	6075 N
1450	900	-	2580 HP	5750 N
			2640 P	5700 N
1350	950	-	2270 P	6175 N
			2450 P	6100 HP
1450	950	-	2620 HP	6050 N
			2570 N	6050 N
1350	1000	-	2720 P	6125 HP
			2540 P	5925 HP
1450	1000	-	2720 NP	5700 N
			2605 HP	5700 N
1350	-	950	650 W	2800 WN
			675 N	2875 N
1450	-	950	730 WN	2650 WN
			700 WN	3050 N
1350	-	1000	810 W	3650 NP
			970 N	3475 N
1450	-	1000	830 W	3875 N
			960 N	3050 W
1350	-	1050	1100 N	4220 N
1450	-	1050	1145 N	4200 N

Sheet descaled before spot welding.
Post-weld aged specimens tested without removal of surface oxidation.
Spot weld failure code:
P = Failure through parent metal
HP = Failure through heat affected zone and parent metal
NP = Failure through weld nugget and parent metal
N = Pulled weld nugget
WN = Failure partially through pulled weld nugget and partially through prior spot weld interface.
W = Failure through prior spot weld interface



Cross Tension Specimen

Lap Shear Specimen



Weld Penetration: 80 percent
Weld Nugget Diameter: 0.300 inch

TABLE 4.0321 CROSS TENSION AND LAP SHEAR STRENGTHS OF SPOT WELDED SHEET.

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Ti	
11.5	Mo
6	Zr
4.5	Sn

BETA III

MARCH 1968
J.L. SHANNON AUTHOR

NONFERROUS ALLOYS

Ti
I Al
8 V
5 Fe

1. GENERAL

This is a heat treatable alpha-beta titanium alloy capable of developing strengths over 200 ksi ultimate. In the heat treated condition it developes shear strengths in excess of 115 ksi, higher than that of other presently available commercial titanium alloys, and is used in the aerospace industry primarily for fasteners. Unfortunately, no information is available on the fracture toughness of this alloy. However, based on experience with other high-strength titanium alloys and on the high sensitivity of this alloy to even mild stress concentrations, special attention should be given to crack propagation resistance when using this alloy in critical applications. In order to avoid segregation of beta-stabilizing elements, special precautions must be used when melting. Use of this alloy above 350 F is not recommended. Welding of this alloy is also not recommended.

1.01 Commercial Designation
Ti-1Al-8V-5Fe

1.02 Alternate Designation
RMI-1Al-8V-5Fe

1.03 Specifications
Standard Press Steel Company Specification
SPS-M-174

1.04 Composition
1.041 Producer's guaranteed composition and users specified composition, Table 1.041.

TABLE 1.041

Source	R.M.I. (1), S.P.S. (7)	
	Weight Percent	
	Min	Max
Aluminum	0.8	1.8
Vanadium	7.5	8.5
Iron	4.0	6.0
Carbon		0.05
Hydrogen		0.0125
Oxygen	0.25	0.50
Nitrogen		0.07
Titanium		Balance

1.05 Heat Treatment
1.051 Stress-relief anneal, 1000 to 1100F, 1-hour, air cool.
1.052 Anneal, 1250 F, 1 hour, furnace cool to 900 F, air cool.
1.0521 Producer notes that alternate production anneal of 1250 - 1350 F, 1 -2 Hours, air cool, may be used.
1.053 Solution treat, 1400F, 1-hour, water quench. Material's response to heat treatment is sometimes variable, requiring alternate solution treatment generally within the range 1350 to 1450F, to develop guaranteed properties.
1.054 Age, 900 - 1000 F, 2 hours, air cool.

1.06 Hardness

1.07 Forms and Conditions Available
1.071 Alloy is available in annealed condition as billet and bar.

1.08 Melting and Casting Practice
1.081 Melting. Multiple consumable electrode melting with at least one stage under vacuum.

1.09 Special Considerations
1.091 Alloy segregation. In common with other titanium alloys containing high percentages of the beta-stabilizing elements, special precautions must be used when melting this alloy to avoid segregation of these elements. Segregation of iron has been reported as a problem; however, the producer claims presently used melting methods minimize this problem. See Table 1.0911.

1.0911 Billet analysis survey of current heat where modified processing was employed, Table 1.0911.

TABLE 1.0911

Source	R.M.I. (1)								
Alloy	Ti-1Al-8V-5Fe								
Form	6 Inch Round Corner Square Billet								
	Weight Percent								
	Top (1)			Middle (1)			Bottom (1)		
	E(2)	MR(2)	C(2)	E	MR	C	E	MR	C
Al	1.7	1.7	1.8	1.8	1.7	1.7	1.7	1.8	1.8
V	8.2	8.3	8.2	8.2	8.2	8.3	8.1	8.2	8.2
Fe	4.8	4.9	5.7	4.8	4.9	5.4	4.8	4.9	4.6
O_2	0.373	0.384	0.377	0.408	0.437	0.428	0.427	0.394	0.384

(1) Billet location in ingot.
(2) E = Edge; MR = Mid-Radius; C = Center } Location in billet face

1.092 Toughness. The notch strength of this alloy is affected by both notch sharpness and strength level. Tests on small notched rounds, (Figure 3.02712) show a notch strength to yield strength ratio of unity for annealed material, (F_{ty} = 167 ksi) at K_t = 8 and for solution treated and aged material, (F_{ty} = 228 ksi) at K_t = 3. Care must be exercised in the use of this alloy in either heat treated condition for applications involving high stress levels and even moderate stress concentrations.
1.093 Stress corrosion. See section 2.031.
1.094 Stability. The only data available on the elevated temperature stability of this alloy are presented in Table 3.0216. They indicate only small changes in smooth properties for the exposure conditions investigated. One is to be cautioned, however, that a more discriminatory test using cracked specimens may not give the same result.

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties
2.011 Melting temperature.
2.012 Phase changes. Alloy transforms on cooling from beta to alpha + beta at 1525 F ± 25 F.
2.0121 Isothermal T-T-T Diagram, Figure 2.0121
2.013 Thermal conductivity.
2.014 Thermal expansion.
2.015 Specific heat.

2.02 Other Physical Properties
2.021 Density. 0.168 lb per cu in. 4.65 gr per cu cm.
2.022 Electrical resistivity.
2.023 Magnetic properties. Alloy is nonmagnetic.
2.024 Emissivity.
2.025 Damping capacity.

2.03 Chemical Properties
2.031 Corrosion resistance. Susceptibility to solid salt stress corrosion at elevated temperatures and delayed failure of cracked specimens at room temperature in aggressive aqueous environments have become critical problems in the application of titanium alloys to engineering structures. Unfortunately, no pertinent data of this sort are available to characterize the corrosion resistance of this alloy. The inadvertent stress corrosion crack developed in air during creep exposure for a single specimen in Table 3.0217 suggests that the corrosion susceptibility of this alloy in aggressive environments be studied before it is used in critical applications.

2.04 Nuclear Properties

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

Ti
I Al
8 V
5 Fe

3.011 Producer's guaranteed minimum properties at room temperature for heat treated bar, Table 3.011.

TABLE 3.011

Source		R.M.I. (1)
Alloy		Ti-1Al-8V-5Fe
Form		Up to 1 1/16 - in Diameter Bar
Condition		Heat Treated
Guaranteed RT Properties		
F_{tu}	min-ksi	210
F_{ty}	min-ksi	200
e	min-percent	6.0
RA	min-percent	12.0
F_{su}	min-ksi	115

3.012 Typical room temperature tensile properties of as-shipped, mill annealed bar of various sizes, Table 3.012.

TABLE 3.012

Source	R.M.I. (1)			
Alloy	Ti-1Al-8V-5Fe			
Form	Bar			
Condition	Mill Annealed			
	Typical RT Properties*			
Bar Diameter Inch	F_{tu} ksi	F_{ty} ksi	e(4D) percent	RA percent
3/8	175.2	169.1	13.0	37.6
1/2	175.7	168.7	14.0	49.0
3/4	168.3	162.3	18.0	37.1
1 1/16	178.0	166.0	17.0	43.0

* 1/4 - inch diameter specimens

3.02 Mechanical Properties at Room Temperature

3.021 Tension.

3.0211 Effect of annealing treatment on room temperature tensile properties of bar, Table 3.0211.

TABLE 3.0211

Source	R.M.I. (1)			
Alloy	Ti-1Al-8V-5Fe			
Form	3/8 - in Diameter Bar			
Condition	Annealed			
	Room Temperature Tensile Properties*			
Annealing Treatment	F_{tu} ksi	F_{ty} ksi	e(4D) percent	RA percent
1250 F, 1/2Hr, AC	183.0	178.7	15.0	47.5
1325 F, 1/2Hr, AC	175.3	169.5	16.0	47.7
1400 F, 1/2Hr, AC	170.9	166.8	13.5	43.0
1250 F, 1/2Hr, FC to 900F, AC	179.1	175.9	20.5	52.9

*1/4 - inch diameter specimens

3.0212 Effect of solution temperature on room temperature tensile properties of heat treated bar, Figure 3.0212.

3.0213 Effect of solution treat and aging temperature on room temperature tensile properties of bar, Figure 3.0213.

3.0214 Effect of quench rate from solution treat temperature on room temperature tensile properties of heat treated bar, Table 3.0214.

TABLE 3.0214

Source	R.M.I. (1)			
Alloy	Ti-1Al-8V-5Fe			
Form	9/16 - inch Diameter Bar			
Condition	Solution Treat + 1000F, 2 Hr, AC			
	Room Temperature Tensile Properties*			
Solution Treatment	F_{tu} ksi	F_{ty} ksi	e(4D) percent	RA percent
1375F, 1-Hr, WQ	206	194	15	39
1375F, 1-Hr, AC	205	194	16	41
1400F, 1-Hr, WQ	217	204	12	30
1400F, 1-Hr, AC	211	198	13	33

*1/4 - inch diameter specimens

3.0215 Effect of aging temperature and time on room temperature tensile properties of bar, Figure 3.0215.

3.0216 Effect of exposure to elevated temperature with load on room temperature tensile properties of annealed and heat treated bar, Table 3.0216.

TABLE 3.0216

Source			R.M.I. (1)				
Alloy			Ti-1Al-8V-5Fe				
Form			3/8 Inch Diameter Bar				
Creep Exposure				Subsequent RT Tensile Properties*			
Temp F	Stress ksi	Time Hr	Permanent deformation percent	F_{tu} ksi	F_{ty} ksi	e(4D) percent	RA percent
Annealed Bar							
—	None		—	178	171	18.3	44.8
800	20	10	0.155	177	172	23.5	52.3
800	50	10	0.83	177	174	23.5	52.5
800	20	313.3	1.29	177	171	7.5**	10.2**
800	30	310.5	2.79	177	170	23.0	54.0
600	110	310.5	0.78	177	167	22.5	51.1
Heat Treated Specimen							
—	None		—	208	198	12.0	37.5
800	45	212.5	—	211	202	15.0	36.9

* 1/4 - inch diameter specimens
** Stress corrosion crack

3.022 Compression.

3.023 Impact.

3.024 Bending.

3.025 Torsion and shear.

3.026 Bearing.

3.027 Stress concentration.

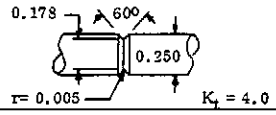
3.0271 Notch properties.

Ti
I Al
8 V
5 Fe

3.02711 Room temperature smooth and mild-notch tensile properties of annealed and heat treated bar, Table 3.02711.

TABLE 3.02711

Source	R.M.I. (1)				
Alloy	Ti-1Al-8V-5Fe				
Form	5/8 Inch Diameter Bar				
	Room Temperature Tensile Properties				
Heat Treatment	F_{tu} ksi	F_{ty} ksi	e(4D) percent	RA percent	NTS ksi
1250 F, 1-Hr, FC to 900 F, AC	181	170	18	50.5	244
1375 F, 1-Hr, WQ + 1000 F, 2-Hr, AC	203	197	15	39.7	250
1425 F, 1-Hr, WQ + 1000 F, 2-Hr, AC	212	200	10.5	27.9	254



3.02712 Effect of stress concentration factor on the notch strength of annealed and heat treated bar, Figure 3.02712.

3.028 Combined properties.

3.03 Mechanical Properties at Various Temperatures

3.031 Tension.

3.0311 Effect of test temperature on smooth tensile properties of annealed and heat treated bar, Figure 3.0311.

3.032 Compression.

3.033 Impact.

3.034 Bending.

3.035 Torsion and shear.

3.036 Bearing.

3.037 Stress concentration.

3.038 Combined properties.

3.04 Creep and Creep Rupture Properties

3.041 Creep deformation in 300-hours for annealed bar at 600F and 800F, Figure 3.041.

3.042 Minimum creep rate curves at 600F and 800F for annealed bar, Figure 3.042.

3.043 Effect of stress concentration factor on room temperature notch stress rupture strength for annealed and heat treated bar, Figure 3.043.

3.05 Fatigue Properties

3.051 Room temperature axial load fatigue properties of 3/8 - 24 bolts, Figure 3.051.

3.06 Elastic Properties

3.061 Modulus of elasticity at room temperature and 600 F for annealed and heat treated conditions, Table 3.061.

TABLE 3.061

Source	(8)	
Alloy	Ti-1Al-8V-5Fe	
Temp-F	Anneal	ST + Age
RT	16.5	16.5
600 F	14.7	14.5

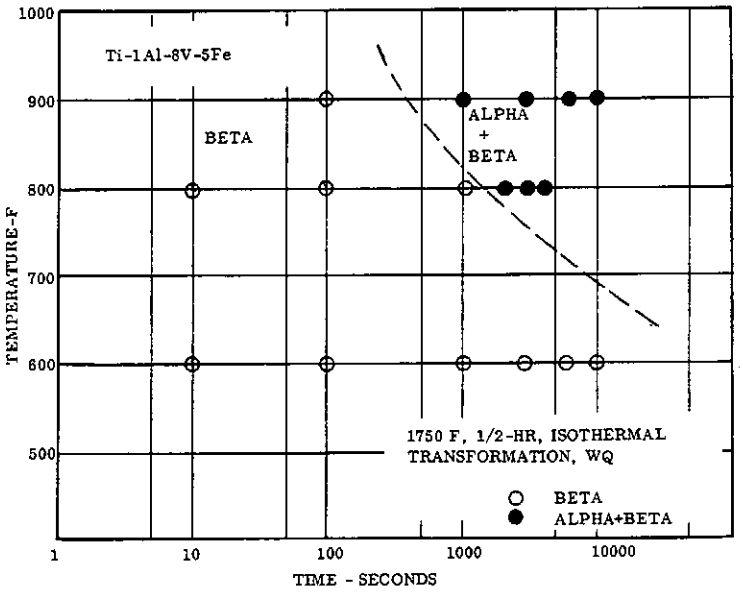


FIG. 2.0121 ISOTHERMAL T-T-T DIAGRAM (5,p.5)

4. FABRICATION

4.01 Formability

4.011 This alloy has a low beta transus, 1525 F ± 25 F. and to obtain optimum tensile ductility the material should receive final reductions of 50 percent or more below 1500 F .

	Ti
1	Al
8	V
5	Fe

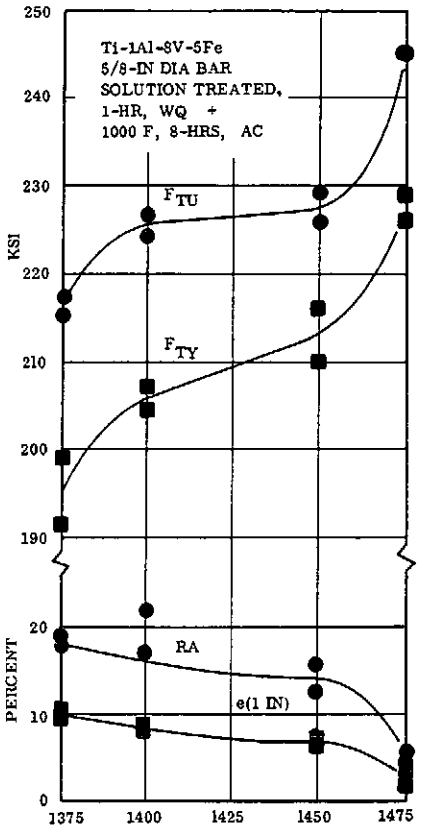


FIG. 3.0212 EFFECT OF SOLUTION TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF HEAT TREATED BAR (3,p.7)

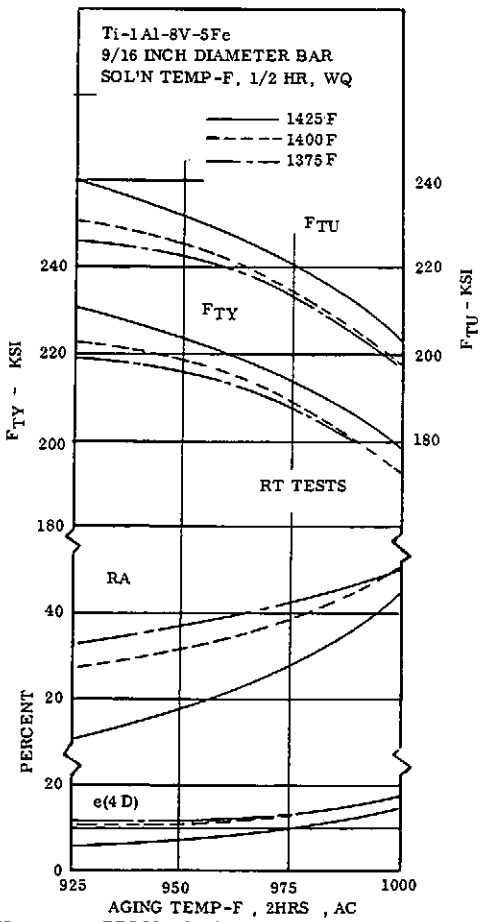


FIG. 3.0213 EFFECT OF SOLUTION TREAT AND AGING TEMPERATURES ON ROOM TEMPERATURE TENSILE PROPERTIES OF BAR (1)

	Ti
I	Al
8	V
5	Fe

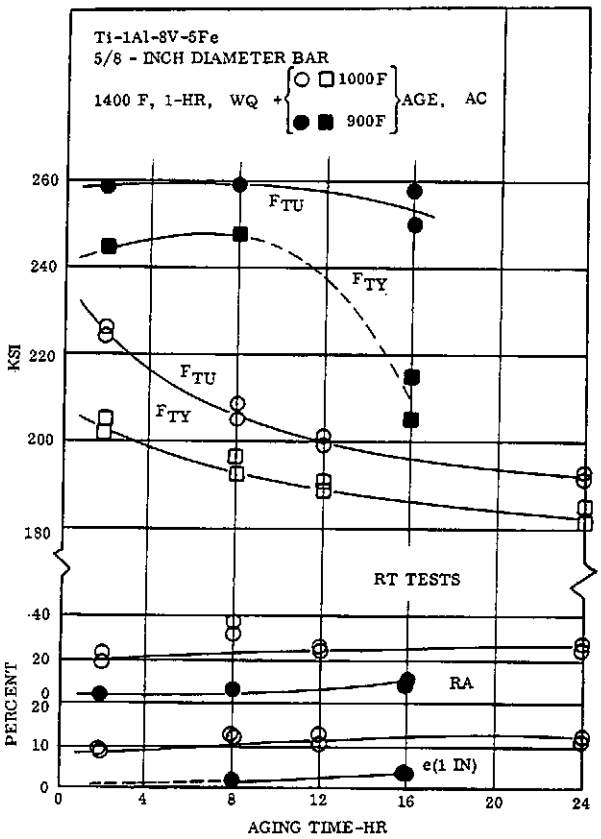


FIG. 3.0215 EFFECT OF AGING TEMPERATURE AND TIME ON ROOM TEMPERATURE TENSILE PROPERTIES OF BAR

(3,p.6)

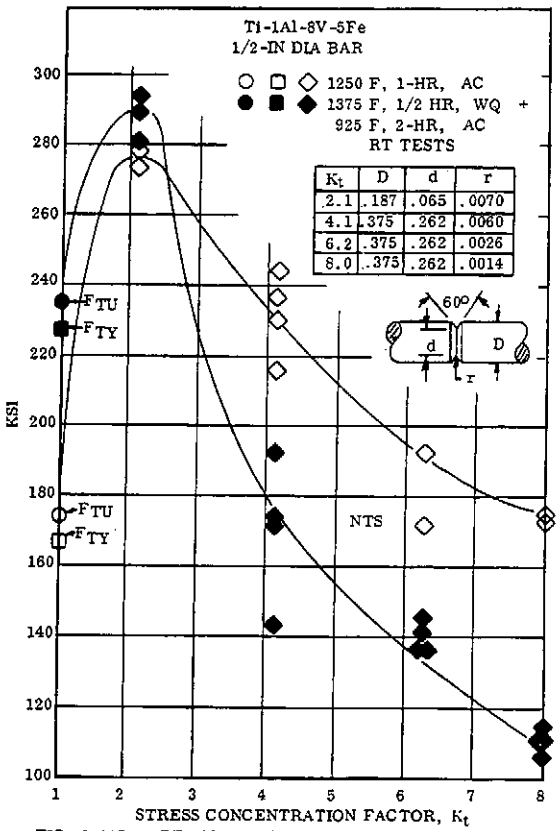


FIG. 3.02712 EFFECT OF STRESS CONCENTRATION FACTOR ON THE NOTCH STRENGTH OF ANNEALED AND HEAT TREATED BAR

(2,pp. 5-7)

	Ti
1	Al
8	V
5	Fe

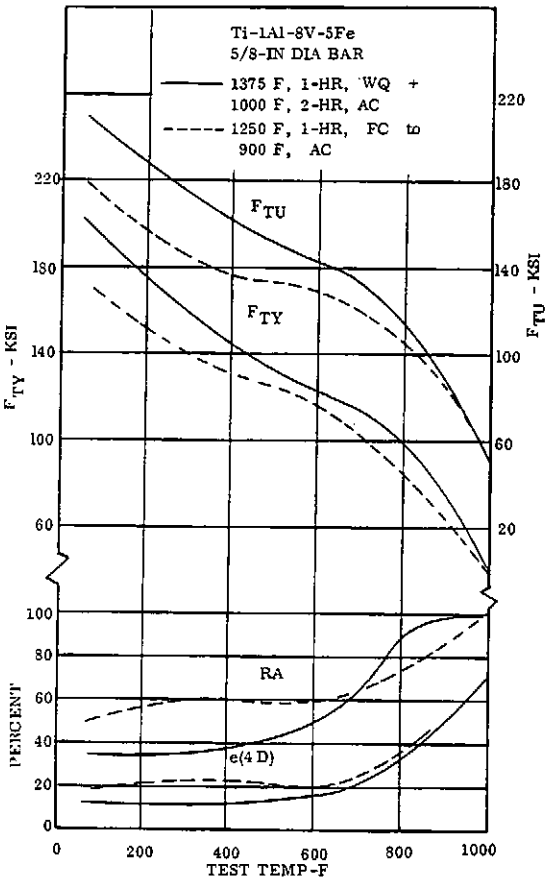


FIG. 3.0311 EFFECT OF TEST TEMPERATURE ON SMOOTH TENSILE PROPERTIES OF ANNEALED AND HEAT TREATED BAR
(1)

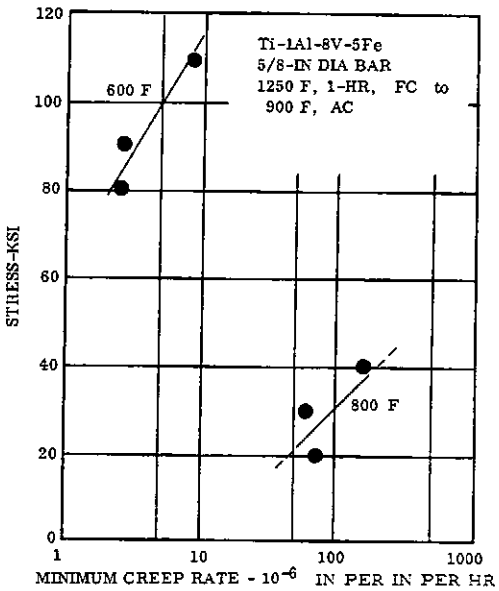


FIG. 3.042 MINIMUM CREEP RATE CURVES AT 600 F AND 800 F FOR ANNEALED BAR
(4,p.6)

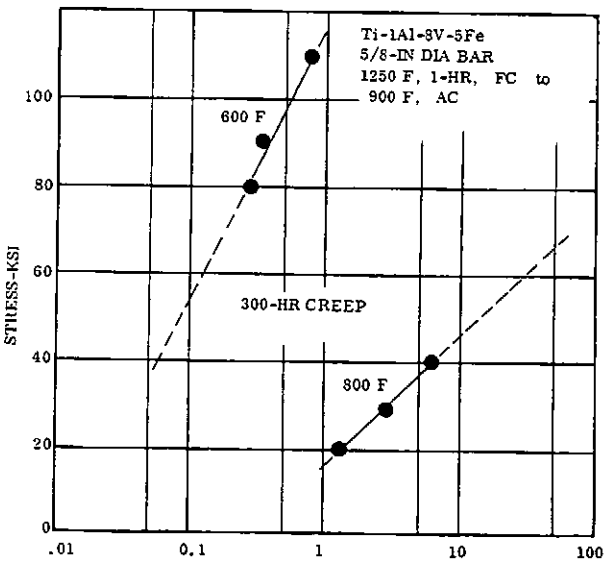


FIG. 3.041 CREEP DEFORMATION IN 300-HOURS FOR ANNEALED BAR AT 600 F AND 800 F
(4,p.6)

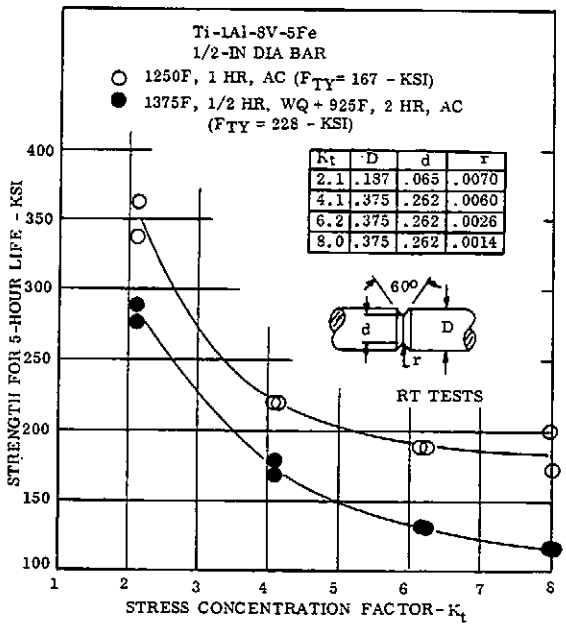


FIG. 3.043 EFFECT OF STRESS CONCENTRATION FACTOR ON ROOM TEMPERATURE NOTCH STRESS RUPTURE STRENGTH FOR ANNEALED AND HEAT TREATED BAR
(2,p.8)

	Ti
1	Al
8	V
5	Fe

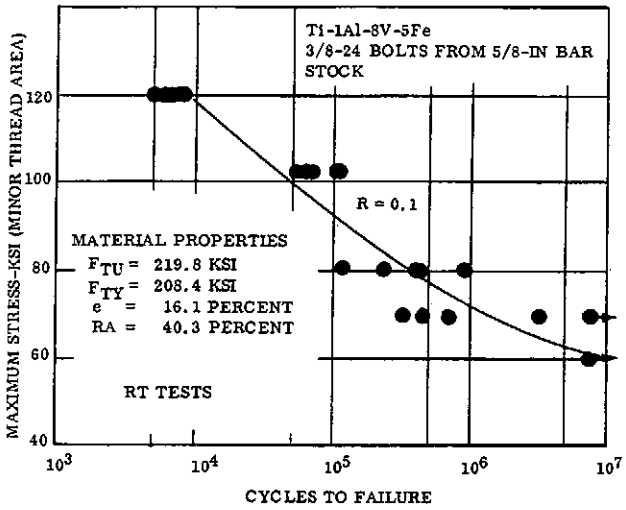


FIG. 3.051 ROOM TEMPERATURE AXIAL LOAD FATIGUE PROPERTIES OF 3/8-24 BOLTS
(1)

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2. L. J. Bartlo, "The Effect of Stress Concentration on Notch Tensile and Static Notch Properties of Ti-1Al-8V-5Fe," Reactive Metals, Inc., Research Report No. 1000R459, M.O. 75003, December 30, 1964.
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9. J. L. Shannon, Jr. and W. F. Brown Jr., " A Review of Factors Influencing the Crack Tolerance of Titanium Alloys," Applications Related Phenomena in Titanium Alloys, ASTM STP 432, American Society for Testing and Materials, 1967

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Ti
3 Al
2.5 V

Ti-3Al-2.5V

1 GENERAL

Ti-3Al-2.5V is a near alpha, alpha-beta alloy, sometimes referred to as "half 6-4". It offers 20 to 50 percent higher tensile strength than the strongest commercially pure grade of titanium at both room and elevated temperatures. It is much more amenable to cold working than Ti-6Al-4V, and is as weldable as the commercially pure grades. It is used principally as tubing in aircraft and jet engine hydraulic systems, and as foil in aircraft honeycomb panels. Nonaerospace applications include golf club shafts, tennis rackets, bicycle frames, and expensive ball point pen casings.

1.01 Commercial Designation

3Al-2.5V Titanium alloy.

1.02 Alternate Designations

Ti-3Al-2.5V.
RMI 3Al-2.5V.
OMC Ti-3Al-2.5V.
Crucible 3Al-2.5V.
Allvac 3-2.5.
MMA-3138.
ASTM B337, Grade 9.
ASTM B338, Grade 9.
AMS 4943.
AMS 4944.
T-A3V2.5 (France).
T-A3V (France).
UTA3V (France).
IMP-7 (USSR).
R-56320 (Unified Numbering System, UNS).
ERTi-3Al-2.5V (Bare Welding Rods and Electrodes).
ERTi-3Al-2.5V-1 (Bare Welding Rods and Electrodes).

1.03 Specifications

Table 1.03.

1.04 Composition

1.041 AMS specified composition for tubing, Table 1.041.

1.042 Users' specified composition for tubing and pipe, Table 1.042.

1.043 Users' specified composition for ingot and for aircraft quality bars (rolled or forged) and reforging stock, Table 1.043.

1.044 Users' specified composition for sheet, strip, and foil, Table 1.044.

1.045 AWS specified composition for welding rods and electrodes, Table 1.045.

1.05 Heat Treatment

1.051 General. This alloy is commonly used in the annealed or cold worked plus stress relieved conditions. Annealing is done below the beta transus. Varying the cold working and stress relieving schedules will produce a range of wrought microstructures with an associated range of properties. Due to the relatively low beta stabilizing alloy content, only a small increase in strength level is possible in thin sections by solution treating and aging. For example, 0.070-inch sheet solution treated 15 minutes at 1675 F, water quenched, and aged 8 hours at 950 F produces strengths only 20-25 ksi greater than the annealed values, and not much different from those achieved by cold working and stress relieving. There is a considerable variation in specified heat treatments for this alloy, as shown in Table 1.052.

1.052 Specified heat treatments, Table 1.052.

1.053 Stress relief. Specified stress relief treatments range from 600 to 1200 F for ½ to 3 hours, followed by air cooling. However, heating the alloy above 1000 F reduces the hardness and strength substantially (Figures 1.061, 3.0213 and 3.0215), with but a small improvement in flaring and flattening ease (Figures 4.011 and 4.012).

1.054 Anneal. Specified annealing schedules range from 1100 to 1450 F for 1 to 3 hours, followed by air cooling, or slower. It appears from Figures 1.061, 3.0213, 3.0215, 4.011 and 4.012 that a 2-hour anneal at 1300 F is required to develop the full annealed condition. The results in Tables 3.0311 and 3.0331 show no advantage to annealing above 1475 F, and annealing in the beta region reduces the Charpy-V impact energy in the range 200 F to -80 F by more than a factor of two.

1.055 Solution treat and age. 1600-1700 F, 1/4-1/3 hour, WQ + 900-950 F, 2-8 hours, AC.

1.056 Effect of annealing (or stress relieving) temperature on hardness of full hard (50 percent cold worked) tubing, see Figure 1.061.

1.057 Effect of annealing (or stress relieving) temperature on room temperature tensile properties of full hard (50 percent cold worked) tubing, see Figure 3.0213.

1.058 Effect of annealing (or stress relieving) temperature on room temperature yield and burst strengths of internally pressurized full hard (50 percent cold worked) tubing, see Figure 3.0215.

1.059 Effect of annealing (or stress relieving) temperature on room temperature flaring of full hard (50 percent cold worked) tubing, see Figure 4.011.

1.0510 Effect of annealing (or stress relieving) temperature on room temperature flattening of full hard (50 percent cold worked) tubing, see Figure 4.012.

1.0511 Effect of annealing cycle on room temperature tensile properties of hot rolled sheet, see Table 3.0211.

1.0512 Effect of annealing temperature and cooling rate from the annealing temperature on room temperature and 200 F tensile properties of extruded plate, see Table 3.0311.

1.0513 Effect of annealing temperature and cooling rate from the annealing temperature on Charpy-V impact energy of extruded plate at test temperatures ranging from -80 F to +200 F, see Table 3.0331.

1.06 Hardness

The hardness of this alloy in the wrought condition will be directional because of differential working and crystallographic texturing.

Ti
3 Al
2.5 V

Ti-3Al-2.5V

1.061 Effect of annealing (or stress relieving) temperature on hardness of full hard (50 percent cold worked) tubing, Figure 1.061.

1.062 Effect of 10-second, annealing temperature on Knoop hardness of cold worked and annealed (partially recrystallized) tubing, simulating hardness profile of EB weld, see Figure 4.03132.

1.063 Effect of 30-second annealing temperature on Knoop hardness of cold worked and annealed (partially recrystallized) tubing, simulating hardness profile of GTA weld, see Figure 4.03133.

1.064 Knoop hardness traverse of GTA and Electron Beam (EB) welds in 55 percent cold worked and partially recrystallized tubing, see Figure 4.03134.

1.065 Effect of homogenizing heat treat temperature and cooling rate from that temperature on microhardness of small samples taken from forged billet, see Figure 4.015.

1.07 Forms and Conditions Available
Ingot, sheet, strip, foil, tubing, seamless tubing, seamless hydraulic tubing, seamless tubing and welded tubing for heat exchangers and condensers, seamless and welded pipe, powder metallurgy alloy (USSR), bars (France), forgings (France), plate (France), (16).

1.08 Melting and Casting Practice. In common with other titanium alloys, this alloy is multiple melted under vacuum in order to minimize impurity levels.

1.09 Special Considerations

1.091 Rotary flexure fatigue life of pressurized tubing is influenced by its crystallographic texture, residual stresses produced in straightening operations, and surface roughness, as indicated by the results in Figures 3.054 and 3.055 and Table 3.056.

1.092 Flattening (ovalization) of tubing during bending operations reduces the impulse fatigue life due to the superposition of three additive stresses: residual stresses due to ovalization, membrane stresses after pressurization, and bending stresses in the ovalized tube wall, see Figure 3.057.

1.093 Overpressurization of tubing can decrease ovalization, increasing the impulse fatigue life; see Figure 3.058. However, improper support assemblies may cause end fitting displacement with attendant installation stresses on the final system outweighing the beneficial effect of overpressurization.

1.094 Tubing reliability is adversely affected by cracking in service due to internal and surface irregularities. Production defects may be inclusions, separations in the tubing wall, or fissures at the inner and outer surfaces. Service damage usually takes the form of chafes or dents. The strength reducing effect of tubing defects is not well documented, and therefore specifications for allowable defect severity do not exist. Some attempts have been recently made to examine the effect of tubing defects on performance (see Figures 3.059 and 3.0510). Successful burst test performance does not ensure successful hydraulic impulse or flexure fatigue performance.

2 PHYSICAL PROPERTIES AND ENVIRONMENTAL EFFECTS

2.01 Thermal Properties

2.011 Melting range. Approximately 3100 F.

2.012 Phase changes. The following description of the transformation kinetics of this alloy has been excerpted from reference (6):

The $\alpha+\beta$ alloy Ti-3Al-2.5V consists of a single β-phase structure above 1715 F. In isothermal treatments above M_S (1454 ± 9 F), the alloy transforms partially to α-phase, resulting in an $\alpha+\beta$ equilibrium structure. On cooling to an isothermal temperature below the M_S point, first some α-phase is formed above M_S and then the remaining (predominate) portion of the β-phase is transformed into a supersaturated hexagonal martensite, α''-phase. Below M_S and above M_f (1364 ± 9 F), there remains a residual β-phase β_r, which is probably transformed isothermally to α-phase. Transformation of this β_r-phase into α-phase is assumed to take place very rapidly and the resulting structure for isothermal reaction is $\alpha+\alpha''$. The α''-phase decomposes *discontinuously* into a two-phase $\alpha+\beta$-structure below 1382 F, and an $\alpha+\beta_m$-structure below 1382 F (β_m-phase is a metastable β-phase enriched in β-stabilizing elements). It is assumed this discontinuous decomposition of α'' is a diffusion mechanism resembling the mechanism of a eutectoid reaction observed earlier in Ti-6Al-4V alloy [7].

Hexagonal martensite formed by quenching to RT is tempered in the range 1112-1382 F by precipitation of β-phase in the α''-matrix. The composition of the matrix continuously approaches the equilibrium α composition. The mechansim of this *continuous* decomposition of α'' appears to be the same as that observed for hexagonal martensite in Ti-6Al-4V quenched to RT. [8]

The process of decomposition of β-phase during *continuous cooling* is dependent on the cooling rate. At a cooling rate of 142,200 F/hr (WQ), the structure contains primary α-phase in a matrix of α''-martensite. After cooling at 97,200 F/hr (OQ), a thick film of grain-boundary α (G.B.-α) appears in the martensitic matrix. Cooling at rates ranging from 32,400 F/hr down to 1,260 F/hr produces a structure which consists of grain boundary α and Widmanstätten α-plates with β_m-phase between them. At cooling rates between 540 F/hr and 90 F/hr, a structure is obtained which contains a needle-like precipitate, β_1, in the β_m-phase. This β_1-phase has been observed previously in Ti-6Al-4V [9]. For the cooling rate 90 F/hr, the first α-phase is nucleated at 1715 F in grain boundaries. The grain boundary film

grows at a rather moderate growth rate. At about 1652 F, Widmanstätten α-plates grow from grain boundaries and from nuclei within grains, and the growth rate increases markedly. The major portion of the transformation is terminated at about 1382 F. This temperature corresponds well with the alteration from β to β_m and appears independent of cooling rate. On cooling below 932 F, β_1-precipitate occurs in the structure as small needles.

2.0121 Ti-3Al-2.5V isothermal transformation (TTT) diagram, Figure 2.0121.

2.0122 Ti-3Al-2.5V continuous cooling transformation (CCT) diagram, Figure 2.0122.

2.013 Thermal conductivity, Figure 2.013.

2.014 Thermal expansion. From RT to 600 F, 4.4 x 10^{-6} (46), 5.5 x 10^{-6} (13) in./in./F.

2.015 Specific heat.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density, 0.162 lb per cu inch, 4.484 gr per cu cm.

2.022 Electrical properties.

2.0221 Electrical resistivity, Figure 2.0221.

2.023 Magnetic properties.

2.024 Emittance.

2.025 Damping Capacity.

2.03 Chemical Environments

2.031 Corrosion. Titanium and its alloys are as a class, credited with superior resistance to corrosive attack by a broad range of aggressive agents. Ti-3Al-2.5V is no exception, being corrosion resistant in many environments including hydraulic fluid and fuel (28). In 3.5 percent NaCl solution at ambient temperatures, Ti-3Al-2.5V foil is more electropositive than Ti-6Al-4V sheet (see Figure 2.0311), and the foil would therefore be more corrosion resistant than Ti-6Al-4V (28).

2.0311 Effect of temperature on electrode potential for Ti-3Al-2.5V foil and Ti-6Al-4V sheet in 3.5 percent NaCl solution, Figure 2.0311.

2.0312 General Corrosion. The general corrosion of titanium and its alloys is discussed at some length in reference (31). The following is excerpted from that reference.

The superior corrosion resistance of titanium and its alloys is owed to a thin, tenacious oxide film that develops rapidly in air or other oxygen-bearing environments. The most protective films are developed when the environment contains water, even in trace amounts. Exposure to strongly oxidizing environments in the absence of moisture produces a non-protective film. Sometimes the oxidation is rapid, and can be pyrophoric. Dry chlorine and dry fuming nitric acid are examples.

Environments that destroy the oxide film can rapidly corrode titanium and its alloys. Some of these are hydrofluoric, hydrochloric, sulfuric, phosphoric, oxalic, and formic acids. Attack by these may, however, be reduced in many instances by the addition of acid salts, oxidizing acids, and certain other inhibitors. Dry chlorine also attacks titanium, but it is quite resistant to wet chlorine (1 percent moisture) and other oxidizing gases, such as SO_2 and CO_2.

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Titanium has excellent corrosion resistance to all concentrations of nitric acid (except anhydrous) up to 350 F; above 20 percent concentration at 375 F, on the other hand, corrosion rates are substantial. Anhydrous fuming HNO_3 can be pyrophoric. Titanium resists chromic acid quite well, and is resistant to aqua regia. For mixtures of sulfuric and nitric acids, corrosion rates increase with increasing H_2SO_4 concentration.

Titanium has good resistance to dilute solutions of alkali. Hot, strong, caustic solutions will attack unalloyed titanium and titanium alloys. On the other hand, titanium does not appear susceptible to caustic embrittlement as are carbon steels and stainless steels.

Titanium is more resistant than stainless steel to corrosion and pitting in most neutral chloride solutions. The main exceptions are boiling solutions of aluminum chloride, stannic chloride, cupric chloride, zinc chloride, magnesium chloride and calcium chloride, which all cause pitting of titanium alloys. Additionally, above about 200 F titanium may crevice corrode in seawater or in bromine. In contrast, titanium is not attacked by the highly corrosive ferric chloride and sodium hypochlorite solutions which are corrosive to stainless steel.

Titanium is remarkably resistant to pitting, stress corrosion, galvanic corrosion, crevice corrosion (below about 200 F), erosion-corrosion, and corrosion fatigue in marine environments.

Pure hydrocarbons are not considered corrosive to titanium, and titanium exhibits good corrosion behavior in most chlorinated and fluorinated hydrocarbons. However, such materials may hydrolize in the presence of water, forming HF or HCl, which in turn may attack titanium. In addition, at elevated temperatures, these hydrocarbons may decompose, liberating hydrogen which may be absorbed by the titanium, causing loss of ductility, or chlorides may be released that may initiate elevated-temperature stress corrosion cracking.

Titanium is not recommended for use in gaseous or liquid oxygen since a violent reaction can occur. Fresh titanium surfaces exposed to gaseous oxygen, even at -250 F and at pressures of about 50 to 100 psi, can burn. The oxide is soluble in the molten metal, so that the oxide formed is not protective. Titanium is impact sensitive in liquid oxygen. Pyrophoric reactions can also occur under

Ti
3 Al
2.5 V

Ti-3Al-2.5V

impact in chlorine trifluoride, liquid fluorine and nitrogen tetroxide. Only in liquid and gaseous oxygen is the reaction sustained, once initiated.

2.032 Stress Corrosion Cracking. There are no available stress corrosion cracking (SCC) data specific to this alloy. This is somewhat surprising since, while titanium and its alloys have a good record of freedom from stress corrosion cracking in service, it is not perfect. This good record is likely due to the restricted usage of titanium and its alloys, coupled with either fortuitous usage in service environments where stress corrosion cracking is not a problem, or the judicious selection of alloys and their design parameters.

Some of the known environments in which titanium and its alloys have shown cracking susceptibility have been summarized by Brown (27) and are catagorized in the following several sections. While this list is understandably incomplete and not necessarily applicable to Ti-3Al-2.5V alloy, it provides the reader with a guideline concerning the various service environments that should be considered suspect in the application of this alloy.

2.0321 Liquid Environments.

2.03211 Water (seawater, tap water, distilled water, and neutral natural aqueous solutions, but apparently not atmospheric water). All of these cause stress corrosion cracking in precracked specimens in many titanium alloys. It is essential, therefore, to explore the possibility of adverse reaction to these environments through fracture mechanics type tests in these environments prior to service application.

2.03212 Methanol. This liquid has been found to cause SCC in more than one titanium alloy, including the most important commercial alloys. This may occur at all levels of methanol purity, and sometimes in the absence of stress. Occasionally, a pre-existing crack is not required for cracking. Prudence requires that Ti-3Al-2.5V alloy not be exposed to methanol. In this regard, it should be noted that methanol is a constituent of many industrial substances, such as marking fluids, de-icers, and paint removers. Stressed titanium components of this alloy should therefore not be allowed contact with methanol without direct experimental evidence of compatibility using precracked specimens. Additionally, it should be noted that ethanol and ethylene glycol have also been observed to crack titanium alloys.

2.03213 Hot Salt. Though rarely observed, hot sodium chloride can cause SCC when the temperature exceeds 575 F, but only if water vapor and apparently oxygen are present. In one instance, the sodium chloride present was traced to fingerprints. As a practical measure, it is essential during heat treating to eliminate chloride and to provide white-glove handling of parts, perhaps supplemental to the use of a furnace atmosphere which is dry and non-oxidizing, such as dry argon. In applications where both chloride contamination and elevated service temperature are anticipated, a suitable barrier should be considered.

2.03214 Organic Fluids. Besides methanol, the following organic compounds are known to cause SCC in one or more titanium alloys: carbon tetrachloride, chlorinated diphenyl (at 600 F), ethanol, monomethyl hydrazine, trichlorofluoromethane, trichlorotrifluoroethane, and trichloroethane. None of these apparently cause danger equivalent to methanol, but should be avoided. Likewise, cleaning fluids such as hydrochloric acid, trichlorethylene, carbon tetrachloride, chlorinated cutting oils, freons, methyl alcohol and all chlorides should be avoided.

2.03215 Nitrogen Tetroxide. Failure of the Ti-6Al-4V alloy in tankage applications has occurred in N_2O_4 containing oxygen and chlorides as impurities. With the oxygen replaced by greater than 0.06 percent NO, failures are prevented. Current specifications for propellant-grade N_2O_4 require the NO content to be between 0.04 and 0.8 percent (28).

2.03216 Red Fuming Nitric Acid. This liquid can cause SCC and pyrophoric reaction with titanium if free from water as an inhibitive additive. Sulfuric acid is also known to cause cracking in titanium alloys.

2.03217 Halide Solutions. Chloride, bromide and iodide solutions all have caused cracking in the same manner as seawater.

2.03218 Gases. Chlorine gases at temperatures exceeding 550 F can crack certain titanium alloys. Hydrogen chloride has caused cracking of Ti-8Al-1Mo-1V. Hydrogen can cause slow growth of pre-existing cracks in stress titanium alloys. Water vapor may not be a problem, based on results with Ti-8Al-1Mo-1V, which is very sensitive to aqueous SCC.

2.0322 Solid and Liquid Metals. Liquid metal embrittlement has been observed to cause rapid cracking from mercury, gallium and molten cadmium. Above 650 F, silver in contact with some commercial titanium alloys can cause cracking, even though far below the melting point of silver. There has been similar experince with cadium at temperatures as low as 100 F.

2.0323 Sustained Load Cracking in Inert Environments. Sustained load cracking (SLC) in inert environments (including air) can occur in certain applications of titanium. It is exacerbated by hydrogen in solution in the metal, and thereby accounts in part for the stringent limits on hydrogen in chemical allowables. It is particularly important in titanium weldments which are more susceptible to pickup of hydrogen and may contain residual stresses if not stress relieved. For such, vacuum annealing is important.

2.033 Crevice Corrosion. Crevice corrosion of titanium and its alloys occurs in chloride-salt solutions above 200 F, and with increasing

frequency from 300 to 400 F. Acid and neutral solutions cause the greatest susceptibility, whereas no attack has been observed at pH of 9 or more. Crevice attack occurs with about the same frequency among unalloyed titanium and the common titanium alloys.

2.034 Corrosion Fatigue. Aggressive environments will accelerate fatigue crack growth rates. This effect is predominately at high crack stress intensity factor ranges. (32)

2.04 Nuclear Environments

3 MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 AMS specified tensile properties for tubing, Table 3.011.

3.012 Users' specified tensile properties for bars (rolled or forged) and reforging stock, Table 3.012.

3.013 Users' specified tensile properties for sheet, strip and foil, Table 3.013.

3.014 Users' specified tensile properties for tubing and pipe, Table 3.014.

3.015 AMS specified flarability for tubing, Table 3.015.

3.016 Users' specified tubing flarability requirements, Table 3.016.

3.017 AMS specified bendability for tubing, Table 3.017.

3.018 Users' specified bendability requirements for tubing and pipe, Table 3.018.

3.019 Users' specified bendability requirements for sheet, strip and foil, Table 3.019.

3.0110 AMS specified flattenability for tubing, Table 3.0110.

3.0111 Users' specified flattenability requirements for tubing and pipe, Table 3.0111.

3.0112 ASM specified pressuribility for tubing, Table 3.0112.

3.0113 Users' specified pressurability requirements for tubing and pipe, Table 3.0113.

3.02 Mechanical Properties at Room Temperature

3.021 Tension, see also 3.031.

3.0211 Effect of anneal cycle on room temperature tensile properties of hot rolled sheet, Table 3.0211.

3.0212 Effect of 1000 F age on room temperature tensile properties of strip, Figure 3.0212.

3.0213 Effect of annealing (or stress relieving) temperature on room temperature tensile properties of full hard (50 percent cold worked) tubing, Figure 3.0213.

3.0214 Room temperature tensile properties of tubing in hardness conditions ranging from full hard to fully annealed, Figure 3.0214.

3.0215 Effect of annealing (or stress relieving) temperature on room temperature yield and burst strengths of internally pressurized full hard (50 percent cold worked) tubing, Figure 3.0215.

3.0216 Effect of 112-hour exposure at 450 F on subsequent room temperature tensile properties of cold worked, stress relieved tubing, Table 3.0216.

3.0217 Effect of exposure to elevated temperature on subsequent room temperature tensile properties of annealed and cold worked, stress relieved tubing, Table 3.0217.

3.0218 Room temperature tensile properties of cold worked and annealed (partially recrystallized) tubing and of as-welded strips cut from portions of that tubing, see Table 4.03121.

3.022 Compression.

3.023 Impact, see 3.033.

3.024 Bending.

3.025 Torsion and Shear.

3.026 Bearing.

3.027 Stress concentration.

3.0271 Notch properties, see 3.0371.

3.0272 Fracture toughness.

3.028 Combined properties.

3.03 Mechanical Properties at Various Temperatures

3.031 Tension.

3.0311 Effect of annealing temperature and cooling rate from the annealing temperature on room temperature and 200 F tensile properties of extruded plate, Table 3.0311.

3.0312 Room temperature and 450 F tensile properties of cold worked, stress relieved tubing, Table 3.0312.

3.0313 450 F tensile properties of tubing in hardness conditions ranging from full hard to fully annealed, Figure 3.0313.

3.0314 600 F tensile properties of tubing in hardness conditions ranging from full hard to fully annealed, Figure 3.0314.

3.0315 Effect of test temperature on tensile properties of tubing in hardness conditions ranging from hard to fully annealed, Figure 3.0315.

3.0316 Tensile properties of tubing from room temperature to -453 F, Figure 3.0316.

3.0317 Tensile properties at 248 F of cold worked and annealed tubes and as-welded strips from GTA welded portions of those tubes, see Table 4.03122.

3.032 Compression.

3.033 Impact.

3.0331 Effect of annealing temperature and cooling rate from the annealing temperature on Charpy-V impact energy of extruded plate at best temperatures ranging from -80 to +200 F, Table 3.0331.

3.034 Bending.

3.035 Torsion and shear.

3.036 Bearing.

3.037 Stress concentration.

3.0371 Notch properties.

3.03711 Effect of cryogenic temperature on smooth and mild notch tensile properties of annealed sheet, Figure 3.03711.

3.03712 Smooth and mild notch tensile properties of parent metal and welded flattened tubing from room temperature to -423 F, Figure 3.03712.

3.0372 Fracture toughness.

3.038 Combined properties.

3.04 Creep and Creep Rupture Properties

Ti
3 Al
2.5 V
Ti-3Al-2.5V

Ti
3 Al
2.5 V

Ti-3Al-2.5V

3.05 Fatigue Properties

3.051 Room temperature smooth and mild notch bending fatigue strength of vacuum annealed sheet, Figure 3.051.

3.052 Room temperature high cycle fatigue of annealed tubing produced by two tubing producers from stock furnished by three metal producers, Figure 3.052.

3.053 Room temperature rotary flexure fatigue strength of cold worked, stress relieved tubing, Figure 3.053.

3.054 Rotary flexure fatigue strength of 1.0-inch OD x 0.080-inch wall, cold worked plus stress relieved, 4,150-psi system return-line tubing, Figure 3.054.

3.055 Rotary flexure fatigue strength of 3/8-inch OD x 0.020-inch wall, cold worked plus stress relieved, 4,150-psi system return-line tubing, Figure 3.055.

3.056 Influence of straightening procedure, heat treatment, and surface conditioning on rotary flexure fatigue life of tubing, Table 3.056.

3.057 Effect of tube ovality on hydraulic impulse fatigue life of 90°-bent, 3,000-psi system tubing, Figure 3.057.

3.058 Effect of overpressurization on impulse fatigue life of defective 3,000 psi system tubing containing two 90° bends (Z-shape), Figure 3.058.

3.059 Effect of chafe depth (simulated service damage) on hydraulic impulse fatigue life of 3,000-psi system tubing, Figure 3.059.

3.0510 Effect of defect size (simulated service damage) on hydraulic impulse fatigue life of 3,000-psi system tubing, Figure 3.0510.

3.06 Elastic Properties

3.061 Poisson's ratio.

3.062 Modulus of elasticity, see Table 3.0312.

3.063 Modulus of rigidity.

3.064 Tangent modulus.

3.065 Secant modulus.

4 FABRICATION

4.01 Forming, see also 1.091 and 1.092.

4.011 Effect of annealing (or stress relieving) temperature on room temperature flaring of full hard (50 percent cold worked) tubing, Figure 4.011.

4.012 Effect of annealing (or stress relieving) temperature on room temperature flattening of full hard (50 percent cold worked) tubing, Figure 4.012.

4.013 Billet homogenization. Dimensional and microstructural uniformity of tubing produced from this alloy will reflect the uniformity of the tube hollow from which it is fabricated. The tube hollow uniformity will be controlled by that of the starting billet. It is thought (41) that homogenization of the billet may be accomplished by suitable heat treatment. Homogenization would have the additional benefit of reducing billet hardness, allowing for high reduction ratios and simultaneous decrease in mandrel and die wear. Results of hardness, metallographic, and phase composition studies (41) on ½-inch x 5/8-inch x 1-inch samples taken from a 6-inch-diameter forged billet are presented in Figures 4.014 and 4.015.

The as-forged material shows the largest amount of beta. The investigators (41) claim that this is probably due to an orientation effect or possibly a strain-induced or strain-stabilized phenomenon when the material was worked in the high alpha + beta region and slow cooled. At 1292 F there is a large difference in beta intensity between the water-quenched and the slower cooled samples probably due to the difference in time at a temperature sufficiently high to allow the beta to deplete in aluminum and transform to alpha. At 1499 F and higher the beta is sufficiently enriched in vanadium to form martensite (α') on rapid cooling and is obscured in the alpha peak of the x-ray diffraction chart.

The hardness values and the amount of beta phase present indicate there is probably a linear relationship between the quenched hardness and the amount of α' (martensite) present.

4.014 Effect of homogenization heat treat temperature and cooling rate from that temperature on β intensity (content) determined on small samples taken from forged billet, Figure 4.014.

4.015 Effect of homogenizing heat treat temperature and cooling rate from that temperature on microhardness of small samples taken from forged billet, Figure 4.015.

4.016 Crystallographic texture. The microstructure of this alloy is predominately hexagonal close packed (hcp) α-phase. Cold working produces a crystallographic texture due to rotation of the basal poles into preferred orientations. Basal pole orientation in cold reduced tubing is controlled by the relative amounts of wall thinning and diameter reduction. This reduction ratio is expressed:

$$RR = [(t_o - t)/t_o]/[(D_o - D)/D_o],$$

where t_o and t are the initial and final wall thicknesses, respectively, and D_o and D the initial and final diameters. Deformation schedules which are predominately diameter reduction (sinking) rotate the basal poles toward a circumferential alignment, while predominately wall ironing schedules ($RR \to \infty$) produce a near radial orientation similar to that produced in sheet (42). RR values of unity produce a random 45° orientation. Values increasingly greater than unity produce increasing radial (sheet) texture, and values below unity produced increasingly circumferential textures. It is reported (42) that recrystallization annealing below the β-transus has little effect on the basal pole orientation developed during cold working. Since annealing is rarely done above the β-transus, textures developed during cold reduction are cumulative through successive anneals. Deformation

schedules must therefore be planned with the desired texture of the finished product in mind. These textures will affect the relative amounts of wall thinning and diameter contraction during bending operations, the yield and burst strengths under internal pressurization, the fatigue resistance in pressure-flexure tests, and the directionality of crack propagation resistance.

Rees (42) has studied the effect of cold reduction schedule on the resulting texture of annealed tubing. Both mandrel (rod) drawing and tube reducing (rolling) were examined. The results are shown in Figure 4.017. Interpretation of the ordinate is as follows: texture values of unity indicate a 45° orientation of the basal pole in the transverse plane; greater than unity shows resistance to wall thinning related to a radial pole orientation; less than unity denotes excessive wall thinning associated with circumferential basal poles.

There were four mandrel drawn tube productions. For each, two draws were required for each of the 50 percent deductions. After the first two draws, the tubing was annealed. The total cold work from start to finish was about 78 percent. At finish size, all drawn tubes were given an additional sink pass of 13 percent cold work.

The two tube-reduced tubings were each produced in a single pass. The tube reduced at RR = 2.1 was 65 percent cold worked, the other 55 percent. All drawn and tube-reduced tubes were annealed at 1300 F for 2 hours in a 10^5 Torr vacuum.

From the results in Figure 4.017, it is seen that drawing increases the texture, but the final texture appears rather insensitive to the reduction ratio (RR) for each reduction, and is controlled more by the starting and finish sizes. Rees (42) suggests, however, that this conclusion be subject to further study. The 13 percent sinking pass after drawing appears to cancel the accumulative texture produced by drawing.

Tube reducing produces a substantial texture and is very responsive to the reduction ratio. At RR = 5.8, a single 55 percent pass produced a texture approaching that of rolled sheet.

4.017 Effect of cold reduction schedule on crystallographic texture of cold worked, annealed tubing, Figure 4.017.

4.02 Machining and Grinding. Refer to Machinability Data Center, Metcut Research Associates, 390 Rosslyn Drive, Cincinnati, OH 45209.

4.03 Joining

4.031 Welding.

4.0311 General. Customarily tubes have been joined with brazed couplings. In recent years, however, increasingly stringent requirements for ductility and strength have resulted in an increase in the use of welding as a joining method.

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Ti-3Al-2.5V is as weldable as unalloyed titanium. Like unalloyed titanium, it has extremely good flow, which makes it possible to obtain completely smooth, flush welds without undercuts. Because of the need to protect the metal during welding from absorption of nitrogen and oxygen from the ambient atmosphere, gas tungsten-arc (GTA) and electron beam (EB) are the most suitable welding methods for this alloy. It has been observed by Andersson and Lundqvist (24) that GTA welds may contain pores if the metal is preparatorily cleaned with acetone, but not when cleaned by pickling with 35 percent HNO_3 + 5 percent HF + 60 percent H_2O solution. Either preparatory cleaning is apparently suitable for EB welding.

4.0312 Uniaxial tension. The room temperature uniaxial tension properties of unwelded and welded tubing are presented in Table 4.03121. The tubes were cold worked, partially recrystallized during annealing, and then welded using either GTA or EB methods. The transformation zone (see nonmenclature in Figure 4.03134) constitutes the weakest part of the GTA as-welded joint fot the tube condition tested when loaded in uniaxial tension. In contrast, EB welded joints and their heat affected zones are stronger than the base metal in those tests.

The uniaxial tension properties at slightly elevated temperature (248 F) of unwelded and GTA welded tubing are compiled in Table 4.03122 for three base metal conditions. All specimens failed in the transformation zone. However, the difference between base metal and weld properties lessens with increasing base-metal annealing temperature.

4.03121 Room temperature tensile properties of cold worked and annealed (partially recrystallized) tubing and of as-welded strips cut from portions of that tubing, Table 4.03121.

4.03122 Tensile properties at 248 F of cold worked and annealed tubes and as-welded strips from GTA welded portions of those tubes, Table 4.03122.

4.0313 Crystallographic texture and biaxial tension. During plastic deformation of Ti-3Al-2.5V alloy, the basal poles of the hexagonal α-phase crystal lattice tend to align themselves parallel to the direction of maximum compressive strain. This texture results in mechanical anisotropy, with greater hardness in the direction of the basal poles compared to that in the direction perpendicular to the basal poles and distortion of the corresponding yield locus.

Mechanical anisotropy of the base metal and of the transformation and low temperature heat affected zones of welded tubing has been studied by Andersson and Lundqvist (24). Hardness measurements were made in six

Ti
3 Al
2.5 V

Ti-3Al-2.5V

separate indenter orientations on the parent metal of cold worked and partially recrystallized tubing. The hardness values were plotted in a deviator stress diagram for six separate stress ratios according to the technique of Wheeler and Ireland (25). The resulting elliptical yield locus appears in Figure 4.03131. The character of the anistropy is described by the orientation of the major axis, which is 113 degrees, and the degree of anisotropy is represented by the eccentricity of the yield locus, which is 0.64 for the tube tested. It should be recalled that the yield locus of isotropic material is circular according to the von Mises criterion.

Andersson and Lundqvist attempted to simulate the anisotropy of the transformation and low temperature heat affected zones of GTA and EB tube welds by heating lengths of unwelded tubing in salt baths for 10 and 30 seconds at temperatures ranging from 1292 to 2372 F, followed by air cooling. The resulting structures indicated 10 seconds duration at the annealing temperature simulates EB welding and 30 seconds duration, GTA welding. The hardness results are shown in Figures 4.03132 and 4.03133. Hardness in the c, e and f directions decreases and hardness in the d direction increases with increased annealing temperature, indicating a decrease in mechanical anisotropy with increasing annealing temperature. Annealing in the β range (i.e., above 1706 F for this tubing) for 30 seconds makes the hardness for all orientations equal, which indicates the material becomes isotropic as a result of the phase transformations, $\alpha+\beta\rightarrow\beta$ upon heating and $\beta\rightarrow\alpha+\beta$ upon cooling. A 10-second anneal is too short for all the α-phase to transform within the temperature range 1706 to about 1922 F, so that mechanical anisotropy remains after cooling. It may be concluded from these results that the transformation zone becomes mechanically isotropic in GTA welding and nearly isotropic in EB welding. Further, the mechanical anisotropy of the low temperature heat affected zone can be expected to be less than that of the base metal. These expectations were realized in the hardness survey of GTA and EB tube welds shown in the simulations in Figures 4.03132 and 4.03133.

The transformation zone and base metal yield loci are compared for the same cold worked, partially recrystallized, and welded tubing in Figure 4.03134. These indicate that tension loaded (uniaxial, z direction) weld specimens plastically deform first in the transformation zone of GTA welded specimens and in the base metal of EB welded specimens. Failure would be expected to take place where plastic deformation begins, as confirmed by the test results in Table 4.03121.

The yield loci determined by Knoop hardness measurements can be used to predict yielding of welded Ti-3Al-2.5V tubes under different stress ratios. Of particular interest is the anticipated behavior of welded tubing under internal pressure with the stress ratio $\Sigma_\theta:\Sigma_z$ = 2:1. The interpretation of Figure 4.03135 is that plastic deformation will begin and failure ensue in the transformation zone for both GTA and EB welded tubes under internal pressure with a 2:1 stress ratio.

4.04 Surface Treating

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Ti
3 Al
2.5 V

Ti-3Al-2.5V

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Form	Condition	Specification
Tubing, Seamless, Hydraulic	Annealed	Aerospace Material Specification, AMS 4943A (7-15-77)
Tubing, Seamless, Hydraulic	Cold Worked, Stress Relieved	Aerospace Material Specification, AMS 4944B (1-15-79)
Ingot	As-Cast, Multiple CVM	TRE Corporation, ASTECH Division, TRE 2340A (7-31-79)
Foil	Annealed	TRE Corporation, ASTECH Division, TRE 2311D (4-26-77)
Tubing, Seamless, Hydraulic	Cold Worked, Stress Relieved	Lockheed-Georgia Company STM08-303C (7-7-72)
Bars (rolled or forged) and Reforging Stock, Aircraft Quality	Annealed	MILITARY SPECIFICATION MIL-T-9047G (12-15-78)
Tubing, Seamless	Cold Drawn, Annealed	General Electric Company, B50TF35-S7 (6-24-76)
Sheet, Strip and Foil	Annealed	General Electric Company, B50TF117-S3 (6-26-77)
Pipe, Seamless and Welded	Annealed and Cold Worked, Stress Relieved	American Society for Testing and Materials/American National Standards Institute Specification, ANSI/ASTM B 337 - 78
Tubes for Condensers and Heat Exchangers, seamless and welded	Cold Worked, Stress Relieved	American Society for Testing and Materials/American National Standards Institute Specification ANSI/ASTM G 338 - 78
Tubing, Seamless	Cold Drawn or Cold Reduced, Annealed	United Technologies Corporation, Pratt & Whitney Aircraft Group Specification, PWA 1260H (8-4-75)
Tubing, Seamless, Aircraft Hydraulic	Cold Worked, Stress Relieved	McDonnell Aircraft Company, McDonnell Douglas Corporation, MCAIR Material Specification MMS-1205D (16 June 1975)
Tubing, Seamless, Aircraft Hydraulic	Cold Worked, Stress Relieved	Wolverine Division, UOP, Inc. Proposed Material Specification (May, 1976) - Published in Reference (37)
Welding Rods and Electrodes	Bare	American Welding Society Specification AWS A5.16-70

TABLE 1.03. SPECIFICATIONS

Source	AMS 4943A and AMS 4944B	
Form	Tubing, Seamless, Hydraulic	
Condition	Annealed*	Cold Worked, Stress Relieved**
	Weight Percent	
	Min	Max
Aluminum	2.50	3.50
Vanadium	2.00	3.00
Iron	--	0.30
Oxygen	--	0.12
Carbon	--	0.05
Nitrogen	--	0.020 (200 ppm)
Hydrogen	--	0.015 (150 ppm)
Yttrium	--	0.005 (50 ppm)
Residual Elements, each***	--	0.10
Residual Elements, total***	--	0.40
Titanium	Balance	

* 1100-1450 F, ¼ - 1 hour, AC (or slower)
** 700 F min, ½ hour min
***Determination not required for routine acceptance.

TABLE 1.041 AMS SPECIFIED COMPOSITION FOR TUBING (2,3)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Source	Lockheed-Georgia (10)		General Electric (14)		ANSI/ASTM (18)		Pratt & Whitney (35)		McDonnell Aircraft (36)		ANSI/ASTM (17)	
Form	Tubing, Seamless, Hydraulic		Tubing, Seamless		Tubes for Condensers and Heat Exchangers, Seamless and Welded		Tubing, Seamless		Tubing, Seamless Aircraft Hydraulic		Pipe, Seamless and Welded	
Condition	Cold Worked, Stress Relieved		Cold Drawn, Annealed		Cold Worked, Stress Relieved		Cold Drawn or Cold Reduced, Annealed		Cold Worked, Stress Relieved		Annealed and Cold Worked, Stress Relieved	
	Weight Percent		Weight Percent		Weight Percent		Weight Percent		Weight Percent		Weight Percent	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Aluminum	2.5	3.5	2.50	3.50	2.5	3.5	2.5	3.5	2.5	3.5	2.5	3.5
Vanadium	2.0	3.0	2.00	3.00	2.0	3.0	2.0	3.0	2.0	3.0	2.0	3.0
Iron	--	0.30	--	0.30	--	0.25	--	0.30	--	0.30	--	0.25
Oxygen	--	0.12	--	0.12	--	0.12	--	0.125	--	0.12	--	0.12
Carbon	--	0.05	--	0.05	--	0.05	--	0.05	--	0.05	--	0.05
Nitrogen	--	0.02	--	0.050	--	0.02	--	0.020	--	0.02	--	0.02
Hydrogen	--	0.015(a)	--	0.0150	--	0.013	--	0.0150	--	0.015	--	0.013
Yttrium	--	--	--	0.0050	--	--	--	0.0050	--	--	--	--
Boron	--	--	--	0.001(b)	--	--	--	0.003	--	--	--	--
Tungsten	--	--	--	0.02	--	--	--	--	--	--	--	--
Silicon	--	--	--	--	--	--	--	0.10	--	--	--	--
Copper	--	--	--	--	--	--	--	0.10	--	--	--	--
Residual Elements, Each	--	--	--	--	--	0.01(c)	--	0.10	--	--	--	0.1(c)
Residual Elements, Total	--	--	--	--	--	0.04(c)	--	0.40	--	0.40(c)	--	0.4(c)
Titanium	Balance		Balance		Balance		Balance		Balance			

(a) Shall be determined after all processing is complete.
(b) Determination not required for routine acceptance.
(c) Need not be reported.

TABLE 1.042. USERS' SPECIFIED COMPOSITION FOR TUBING AND PIPE

Source	ASTECH (4)		Military (11)	
Form	Ingot		Bars (Rolled or Forged) and Re-forging Stock, Aircraft Quality	
Condition	As-Cast		Annealed	
	Weight Percent		Weight Percent	
	Min	Max	Min	Max
Aluminum	2.5	3.5	2.50	3.50
Vanadium	2.0	3.0	2.00	3.00
Iron	--	0.10	--	0.30
Oxygen	--	0.10	--	0.12
Carbon	--	0.05	--	0.05
Nitrogen	--	0.02	--	0.02
Hydrogen	--	0.010	--	0.015(a)
Yttrium	--	0.005	--	--
Boron	--	0.05	--	--
Tungsten	--	--	--	--
Silicon	--	--	--	--
Residual Elements, Each	--	0.10	--	0.10
Residual Elements, Total	--	0.40	--	0.40(b)
Titanium	Balance		Balance	

(a) Determined on each lot of the product as shipped.
(b) Need not be determined. Material shall meet this requirement when analyzed.

TABLE 1.043. USERS' SPECIFIED COMPOSITION FOR INGOT AND FOR AIRCRAFT QUALITY BARS (ROLLED OR FORGED) AND REFORGING STOCK

Source	ASTECH (5)		General Electric (15)	
Form	Foil		Sheet, Strip and Foil	
Condition	Annealed		Annealed	
	Weight Percent		Weight Percent	
	Min	Max	Min	Max
Aluminum	2.50	3.50	2.50	3.50
Vanadium	2.00	3.00	2.00	3.00
Iron	--	0.25	--	0.30
Oxygen	--	0.070	--	0.12
Carbon	--	0.070	--	0.05
Nitrogen	--	0.040	--	0.015
Hydrogen	--	0.015	--	0.015
Yttrium	--	--	--	0.0050
Boron	--	--	--	--
Tungsten	--	--	--	--
Silicon	--	--	--	0.30
Residual Elements, Each	--	--	--	0.10(a)
Residual Elements, Total	--	0.40(a)	--	0.40(a)
Titanium	Balance		Balance	

(a) Determination not required for routine acceptance.

TABLE 1.044. USERS' SPECIFIED COMPOSITION FOR SHEET, STRIP AND FOIL

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Source	AWS (20)			
Form	Welding Rods and Electrodes			
Condition	Bare			
AWS Classification	ERTi-3Al-2.5V		ERTi-3Al-2.5V-1*	
	Weight Percent**			
	Min	Max	Min	Max
Aluminum	2.5	3.5	2.5	3.5
Vanadium	2.0	3.0	2.0	3.0
Iron	--	0.25	--	0.25
Oxygen	--	0.12	--	0.10
Carbon	--	0.05	--	0.04
Nitrogen	--	0.020	--	0.012
Hydrogen	--	0.008	--	0.005
Titanium	Balance		Balance	

* This classification of filler material restricts the allowable interstitial content to a low level in order that the high toughness required for cryogenic applications and other special uses can be obtained in the deposited weld metal.

** Analysis for interstitial content shall be made after the welding rod or electrode has been reduced to its final diameter.

TABLE 1.045. AWS SPECIFIED COMPOSITION FOR WELDING RODS AND ELECTRODES

Form	Source	Stress Relief	Anneal
Bars and Reforging Stock	MIL-T-9047G (11)	700-1200 F, ½-3 hours	1300-1400 F, 1-3 hours, AC (or Slower)
Foil	ASTECH		≤1700 F
Tubing	TRE-2311D (5)		
	AMS 4944B (13)	700 F Min, ½-hour Min	
	Lockheed-Georgia STM08-303C (10)	600 F Min, ½-hour Min	
	McDonnell MMS-1205D (36)	600 F min, ½-hour Min; Except Rotary Straightened Tubing, 700 F Min, 2 hours Min	
	Wolverine (38)	600 F Min	
	AMS 4943A (2)		1100-1450 F, ¼-1 hour, AC (or Slower)
	Pratt & Whitney PWA-1260H (35)		1300 ± 25 F, 1-hour Min
	Zirtech (29)	600-1000 F	1000-1350 F
	RMI (13)	700-1200 F, ½-2 hours, AC	1200-1400 F, 1-2 hours, AC
All	MIL-HDBK-697A (31)	700-1200 F, ½-3 hours	1200-1400 F, 1-3 hours, AC
Flat-Rolled Products, and Bars and Forgings	MIL-HDBK-697A	Solution Treat and Age: 1600-1700 F, ¼-⅓ hour, WQ + 900-950 F, 2-8 hours, AC	

TABLE 1.052. SPECIFIED HEAT TREATMENTS

Source	AMS (2)	AMS (3)	
Form	Tubing, Seamless, Hydraulic		
Condition	Annealed*	Cold Worked, Stress Relieved**	
Nominal Wall Thickness	All	≤0.016 inch	>0.016 inch
F_{tu}, ksi, minimum	90	125	125
F_{ty}, ksi, minimum	75	105	105
e (2-inches), percent, minimum	15	8	10

* 1100 - 1450 F, ¼-1 hour, AC (or slower)

** 700 F min, ½-hour min

TABLE 3.011. AMS SPECIFIED TENSILE PROPERTIES FOR TUBING

Source	Military (11)
Form	Bars (Rolled or Forged) and Reforging Stock
Condition	Annealed*
Thickness, Diameter, or Distance Between Flats**, inches	≤1.00
F_{tu}, ksi, minimum	90
F_{ty}, ksi, minimum	75
e (4D), percent, minimum	15
RA, percent, minimum	30

*1300-1400 F, 1-3 hours, AC (or slower)
** Apply to products with a cross-sectional area of 16 square inches or less. Properties apply in any grain direction.

TABLE 3.012. USERS' SPECIFIED TENSILE PROPERTIES FOR BARS (ROLLED OR FORGED) AND REFORGING STOCK (11)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Source	General Electric (15)	ASTECH (5)	
Form	Sheet, Strip and Foil	Foil	
Condition	Annealed(a)	Annealed(b)	
Foil Thickness, inch	--	≤0.006	
Foil Width, inch	--	<0.500	≥0.500
F_{tu}, ksi, minimum	90	85	90
F_{ty}, ksi, minimum	75	70	75
e (2-inches), percent, minimum	20	16	20

(a) Anneal treatment unspecified.
(b) Anneal temperature not to exceed 1700 F.

TABLE 3.013. USERS' SPECIFIED TENSILE PROPERTIES FOR SHEET, STRIP AND FOIL

Source	Lockheed-Georgia (10)		General Electric (14)	ANSI/ASTM (17)		ANSI/ASTM (18)	Pratt & Whitney (35)	McDonnell Aircraft (36)			Wolverine (38)
Form	Tubing, Seamless, Hydraulic		Tubing, Seamless	Pipe, Seamless and Welded		Tubes for Condensers and Heat Exchangers, Seamless and Welded	Tubing, Seamless	Tubing, Seamless, Aircraft Hydraulic			Tubing, Seamless, Aircraft Hydraulic
Condition	Cold Worked, Stress Relieved(a)		Cold Drawn, Annealed(b)	Annealed(c)	Cold Worked, Stress Relieved(d)	Cold Worked, Stress Relieved(e)	Cold Drawn or Cold Reduced Annealed(f)	Cold Worked, Stress Relieved(g)			Cold Worked, Stress Relieved(h)
Tube OD, in.	1/4 and 3/8	>3/8	All	All		All	All	CWSR 70	CWSR 95	CSWR 105	All
F_{tu}, ksi	120, min	125, min	115, max	90, min	125, min	125, min	85 - 115	85 - 110	100 - 125	125 - 150	125 - 150
F_{ty}, ksi	90, min	95, min	75 - 90	70, min	105, min	105, min	65, min	70, min	95, min	105, min	105, min
e (2-inches), percent	10, min	10, min	15, min	15, min	10, min	10, min	20, min	15, min	13, min	10, min	10, min

(a) 600 F minimum, ½ hour minimum.
(b) Anneal treatment unspecified.
(c) Anneal treatment unspecified.
(d) Stress relief treatment unspecified.
(e) Stress relief treatment unspecified.
(f) 1300 ± 25 F, 1-hour, minimum.
(g) Stress relieved to minimum specified yield strength: 600 F minimum, ½-hour minimum, except rotary straightened tubing shall be stress relieved 700 F minimum, 2-hour minimum.
(h) Stress relief based on strength level of cold worked tube, but temperature shall not be less than 600 F.

TABLE 3.014. USERS' SPECIFIED TENSILE PROPERTIES FOR TUBING AND PIPE

Source	AMS (2)(3)
Form	Tubing, Seamless, Hydraulic
Annealed* (2)	Flarability Tubing shall withstand flaring at room temperature, without formation of cracks or other visible defects, by being forced axially with steady pressure over a hardened and polished tapered steel pin having a 74 degree included angle to produce a flare having a permanent expanded OD not less than 1.30 times the original nominal OD.
Cold Worked, Stress Relieved** (3)	Tubing shall withstand flaring at room temperature, without formation of cracks or other visible defects, by being forced axially with steady pressure over a hardened and polished tapered steel pin having a 74 degree included angle to produce a flare having a permanent expanded OD not less than 1.20 times the original nominal OD.

* 1100-1450 F, ¼ - 1 hour, AC (or slower).
** 700 F minimum, ½ hour minimum.

TABLE 3.015. AMS SPECIFIED FLARABILITY FOR TUBING

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Source	Specification	Form	Condition[a]	Size	Minimum OD Expansion on Flaring
Lockheed-Georgia (10)	STM08-303C	Tubing, Seamless, Hydraulic	Cold Worked, Stress Relieved	OD ≥0.125 inch	1.2[b]
General Electric (14)	B50TF35-S7	Tubing, Seamless	Cold Drawn, Annealed	All	1.30[c]
Pratt & Whitney (35)	PWA 1260H	Tubing, Seamless	Cold Drawn or Cold Reduced, Annealed	All	1.25[c]
ANSI/ASTM (18)	B338-78	Tubes for Condensers and Heat Exchangers, Seamless and Welded	Cold Worked, Stress Relieved	OD ≤3½ inches Wall ≤0.134 inch	1.20[d]

(a) See Table 1.052 for specified heat treatments and Table 3.014 for specified tensile properties.
(b) Expansion when forced axially with steady pressure at room temperature over hardened and polished tapered steel pin having a 74 degree included angle without rupture.
(c) Expansion when forced axially with steady pressure at room temperature over hardened and polished tapered steel pin having a 74 degree included angle without formation of cracks or other visible defects.
(d) Flared with a tool having a 60 degree included angle without showing visible cracking or rupture.

TABLE 3.016. USERS' SPECIFIED TUBING FLARABILITY REQUIREMENTS

Source	AMS (2)(3)
Form	Tubing, Seamless, Hydraulic
	Bendability
Annealed* (2)	Tubing shall show no cracks, tears, breaks, or other flaws when bent 180 degrees around a suitable bend die having a centerline radius equal to 3 times the nominal OD of the tubing. A solid rod or ball-type retractable mandrel inserted to the tangent of the bend shall be used to support the inside of the tube during bending.
Cold Worked, Stress Relieved** (3)	Tubing shall not develop cracks, tears, breaks, or other flaws when bent 180 degrees around a suitable bend die having a centerline radius equal to 3 times the nominal OD of the tubing. A solid rod or ball-type retractable mandrel inserted to the tangent of the bend, or an appropriate tube filler, shall be used to support the inside of the tube during bending to restrict flattening to a value that does not exceed 3 percent of the nominal OD of the tube.

* 1100 - 1450 F, ¼ - 1 hour, AC (or slower)
** 700 F minimum, ½ hour minimum

TABLE 3.017. AMS SPECIFIED BENDABILITY FOR TUBING

Source	Specification	Form	Condition[a]	Size	Bend Mandrel Diameter - multiple of tube OD
Lockheed-Georgia (10)	STM08-303C	Tubing, Seamless, Hydraulic	Cold Worked, Stress Relieved	All	5.0[b]
ANSI/ASTM (17)	B337-78	Pipe, Seamless and Welded	Annealed and Cold Worked, Stress Relieved	OD ≤2 inches	12.0[c]
Pratt & Whitney (35)	PWA 1260H	Tubing, Seamless	Cold Drawn or Cold Reduced, Annealed	All	6.0[d]
McDonnell Aircraft (36)	MMS-1205D	Tubing, Seamless, Aircraft Hydraulic	Cold Worked, Stress Relieved	All	5.0[e]

(a) See Table 1.052, for specified heat treatments and Table 3.014 for specified tensile properties.
(b) 180° cold bend without developing cracks, tears, breaks or other flaws.
(c) 90° cold bend without developing cracks.
(d) 180° bend without showing cracks, tears, wrinkles, waves or other defects. Mandrel or tube filler to be used to restrict flattening in the bend to value not exceeding 3 percent of the OD of the tube.
(e) 180° bend without wrinkles, waves, or other defects detrimental to high pressure hydraulic application. Mandrel or tube filler to be used to restrict flattening in the bend to 3 percent of OD of tube or less. The bend requirement is equivalent to a centerline bend radius of 3 times the OD of the tubing.

TABLE 3.018. USERS' SPECIFIED BENDABILITY REQUIREMENTS FOR TUBING AND PIPE

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Source	Specification	Form	Condition	Size	Bend Mandrel Diameter-Multiple of Thickness
General Electric (15)	B50TF117-S3	Sheet, Strip and Foil	Annealed	<0.010 inch 0.010 to 0.187 inch	2.5* 3.0*

* 180° room temperature bend in a V-block fixture without cracking.

TABLE 3.019. USER'S SPECIFIED BENDABILITY REQUIREMENTS FOR SHEET, STRIP AND FOIL

Source	AMS (2)(3)
Form	Tubing, Seamless, Hydraulic
Annealed* (2)	Flattenability Tubing shall show no cracks, tears, breaks, opened die marks, or opened polishing marks when a half-section of a tube is flattened between parallel plates until the distance between plates is essentially equal to the wall thickness of the tube. Alternatively, the half-tube sample may be placed between mandrels and pressed together to produce a flat surface approximately 3/8-inch wide on the tubing ID. The mandrel or mandrels shall be positioned so that the width of the flattened area will be parallel to the length of the half-section of tubing. The flattened sample shall be examined under a binocular microscope at 20-35X magnification, using fluorescent lighting.
Cold Worked, Stress Relieved** (3)	The inside and outside surfaces of tubing shall show no cracks, tears, breaks, opened die marks, or opened polishing marks when a full section of the tube is flattened between parallel plates under a gradual load applied perpendicularly to the longitudinal axis until the distance between the plates is not greater than shown in the table below. After examination of the outside surfaces, the sample shall be split longitudinally and the inside surfaces examined. Outside Diameter to Wall Thickness Ratio OD/t — Distance Between Plates Where t = Wall Thickness 10 or less — 8t 11 to 16 incl — 12t 17 to 30 incl — 15t 31 to 50 incl — 17t As an alternate flattening test, the half-tube sample may be placed between mandrels and pressed together to produce a flat surface approximately 3/8-inch wide on the tubing ID. The mandrel or mandrels shall be positioned so that the width of the flattened area will be parallel to the length of the half-section of tubing.

* 1100 - 1450 F, ¼ - 1 hour, AC (or slower)
** 700 F minimum, ½-hour minimum

TABLE 3.0110. AMS SPECIFIED FLATTENABILITY FOR TUBING

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Source	Specification	Form	Condition[a]	Size	Maximum Distance Between Flattening Plates – Multiple of Wall Thickness, t
Lockheed-Georgia (10)	STM08-303C	Tubing, Seamless, Hydraulic	Cold Worked, Stress Relieved	0.85 x OD ≤ t ≤1.15 x OD	12[b]
ANSI/ASTM (17)	B337-78	Pipe, Seamless, and Welded	Annealed and Cold Worked, Stress Relieved	All[d]	15[c][d]
ANSI/ASTM (18)	B338-78	Tubes for Condensers and Heat Exchangers, Seamless and Welded	Cold Worked, Stress Relieved	All	15[e]
		Tubes for Condensers and Heat Exchangers, Welded	Cold Worked, Stress Relieved	All	1[f]
Pratt & Whitney (35)	PWA126OH	Tubing, Seamless	Cold Drawn or Cold Reduced, Annealed	All	1[g]
McDonnell Aircraft (36)	MMS-1205D	Tubing, Seamless, Aircraft Hydraulic	Cold Worked Stress Relieved	OD/t ≤ 10	8[h]
				11 ≤ OD/t ≤ 16	12[h]
				17 ≤ OD/t ≤ 30	15[h]
				31 ≤ OD/t ≤ 50	17[h]

(a) See Table 1.052 for specified heat treatments and Table 3.014 for specified tensile properties.
(b) Flattening shall produce no evidence of cracks, tears or other flaws.
(c) Flattening shall produce no cracks. For welded pipe, weld is to be placed in the position of maximum deformation.
(d) For large diameter, thin-walled pipe where outside diameter-to-wall thickness exceeds 30, the maximum distance between flattening plates is negotiated.
(e) Flattening shall produce no cracks. For welded tube, weld is to be placed in the position of maximum deformation.
(f) Welded tube shall be subjected to a reverse flattening test. Tube is slit longitudinally 90 degrees either side of the weld, opened and flattened with the weld at the point of maximum bend. No cracking is permitted.
(g) Longitudinal half-section of tube is reverse flattened between parallel plates until the thickness of the specimen is approximately equal to the wall thickness, without development of cracks, tears, breaks, opened die or opened polishing marks.
(h) Flattened specimens shall be free from cracks, tears, breaks or opened die or polishing marks.

TABLE 3.0111. USERS' SPECIFIED FLATTENABILITY REQUIREMENTS FOR TUBING AND PIPE

Source	AMS (2)(3)
Form	Tubing, Seamless, Hydraulic
	Pressuribility
Annealed* (2)	Tubing shall show no bulges, leaks, pin holes, cracks, or other defects when subject to an internal hydrostatic pressure (P)*** sufficient to cause a tensile stress (S) of 75 ksi in the tubing wall, except that a diametric permanent set of 0.002-inch per inch of diameter is acceptable.
Cold Worked, Stress Relieved** (3)	Tubing shall show no bulges, leaks, pin holes, cracks, or other defects when subject to an internal hydrostatic pressure (P)*** sufficent to cause a tensile stress (S) of 105 ksi in the tubing wall, except that a diametric permanent set of 0.002-inch per inch of diameter is acceptable.

* 1300 - 1450 F, ¼ - 1 hour, AC (or slower)
** 700 F minimum, ¼-hour minimum
*** The hydrostatic pressure (P) shall be determined from the equation:

$$P = S\,\frac{D^2 - d^2}{D^2 + d^2}$$

where P = Internal hydrostatic test pressure in ksi
S = Tensile stress in ksi (specified)
D = Nominal OD
d = Nominal ID

TABLE 3.0112. AMS SPECIFIED PRESSURIBILITY FOR TUBING

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Source	Specification	Form	Condition[a]	Size	Specified Tube Wall Tensile (or Allowable Fiber) Stress, S, Produced By Hydrostatic Test Pressurization, ksi
Lockheed-Georgia (10)	STM08-303C	Tubing, Seamless, Hydraulic	Cold Worked, Stress Relieved	OD = 1/4 & 3/8 inch	90(b)(c)
				OD > 3/8 inch	95(b)(c)
General Electric (14)	B50TF35-S7	Tubing, Seamless	Cold Drawn, Annealed	All	60(d)
ANSI/ASTM (18)	B337-78	Pipe, Seamless and Welded	Annealed	All	45(d)(e)
ANSI/ASTM (18)	B338-78	Tubes for Condensers and Heat Exchangers, Seamless and Welded	Cold Worked, Stress Relieved	All	52.5(d)(e)(f)
Pratt & Whitney (35)	PWA 126OH	Tubing, Seamless	Cold Drawn or Cold Reduced, Annealed	All	65(g)(h)
McDonnell Aircraft	MMS-1205D	Tubing, Seamless, Aircraft Hydraulic	Cold Worked, Stress Relieved to:		
			F_{ty}, min = 70 ksi		70 (g)(i)(j)
			F_{ty}, min = 95 ksi	All	95 (g)(i)(j)
			F_{ty}, min = 105 ksi		105 (g)(i)(j)

(a) See Table 1.052 for specified heat treatments and Table 3.014 for specified tensile properties.

(b) $S = P(D^2 + d^2)/(D^2 - d^2)$, where S = Tube wall tensile stress in ksi produced by internal hydrostatic test pressurization.
P = Internal hydrostatic test pressure in ksi.
D = Tube nominal outside diameter in the same measurement units as d.
d = Tube inside diameter in the same measurement units as D.

(c) Shall produce no evidence of leakage, bulging, or other defects, except that a diametric permanent set of 0.002 inch per inch of diameter is acceptable.

(d) When pressurized at room temperature, shall show no bulges, leaks or other defects.

(e) S = PD/2t, where S = Tube allowable fiber stress in ksi produced by internal hydrostatic test pressurization.
P = Internal hydrostatic test pressure in ksi.
D = Tube nominal outside diameter in the same measurement unit as t.
t = Tube wall thickness in the same measurement unit as D.
Maximum hydrostatic test pressure not to exceed 2.500 ksi for OD ≤ 3 inches, or 2.800 ksi for OD > 3 inches. For OD ≤ 14 inches, P shall be equal to 1.5 times specified working pressure, provided S does not exceed values given here. When P = 1.5 times specified working pressure exceed 2.800 ksi, P shall be negotiable.

(f) Tube so hydrostatically tested shall withstand internal air pressure of 100 psi minimum for 5 seconds without evidence of leakage. Easy visual detection of leakage shall be provided, such as by immersion in water or by pressure differential method.

(g) $S = P(D^2 + d^2)/(D^2 - d^2)$, where P = Internal hydrostatic pressure in ksi.
D = Maximum permissible tube OD (nominal OD plus tolerance) in same measurement units as d.
d = Maximum permissible ID (computed as D minus twice the minimum permissible wall thickness) in same measurement units as D.

(h) When pressurized at room temperature, shall show no bulges, leaks, pinholes, cracks or other defects, except that a diametric permanent set of 0.002 inch per inch of diameter is acceptable.

(i) Shall be pressurized twice, maintaining pressure for 2 minutes minimum, to pressure P computed according to (g) above, or 15,000 psi, whichever is less, without producing evidence of leakage, bulging, or other defects, except that a diametric permanent set of 0.002 inch per inch is acceptable.

(j) After internal hydrostatic pressurization according to (i) above, tube shall be pressurized for 30 seconds minimum to pressure P, or 15,000 psi, whichever is less, where pressure P is computed according to (g) above with values of S as follows:

F_{ty}, Min = 70 ksi	S = 85 ksi
F_{ty}, Min = 95 ksi	S = 100 ksi
F_{ty}, Min = 105 ksi	S = 125 ksi

Pressurization shall produce no leakage or rupture of the tube.

TABLE 3.0113. USERS' SPECIFIED PRESSURIBILITY REQUIREMENTS FOR TUBING AND PIPE

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Source	(12)			
Form	0.045-inch Sheet			
Anneal Cycle	Test Direction	F_{tu}, ksi	F_{ty}, ksi	e, percent
1400 F, ½ hour, AC	L	109.7	107.1	14
	T	107.6	94.4	16
1400 F, ½ hour, AC + 1350 F, 2 hours, AC	L	105.1	101.3	18
	T	104.2	84.7	16
1400 F, ½ hour, AC + 1450 F, 2 hours, AC	L	103.7	99.6	17
	T	104.1	84.6	18

Each value average two tests minimum.

TABLE 3.0211. EFFECT OF ANNEAL CYCLE ON ROOM TEMPERATURE PROPERTIES OF HOT ROLLED SHEET (12)

Source	(43)		
Form	Tubing, Seamless, Hydraulic		
Condition	Cold Worked, Stress Relieved 700 F minimum, ½-hour minimum.		
Exposure Condition	F_{tu}, ksi	F_{ty}, ksi	e, percent
Unexposed	139.0	116.9	16.0
450 F, 112 hours	138.5	116.8	15.0

TABLE 3.0216. EFFECT OF 112-HOUR EXPOSURE AT 450 F ON SUBSEQUENT ROOM TEMPERATURE TENSILE PROPERTIES OF COLD-WORKED, STRESS-RELIEVED TUBING (43)

Source	(13)			
Form	Tubing: 1-inch OD x 0.048-inch Wall			
Condition	Exposure Temp/Time	F_{tu}, ksi	F_{ty}, ksi	e (2-inches), percent
Annealed 1400 F, 2 hours	Unexposed	92.0	79.5	35
	200 F/ 500 hr	92.0	77.5	35
	200 F/1000 hr	93.6	80.9	34
	600 F/ 500 hr	94.0	79.7	30
	600 F/1000 hr	93.9	78.8	33
Cold Worked, Stress Relieved 800 F, 2 hours	Unexposed	132.0	109.0	20
	200 F/ 500 hr	130.0	109.0	18
	200 F/1000 hr	133.0	111.9	20
	600 F/ 500 hr	130.9	108.9	20
	600 F/1000 hr	130.5	107.2	20

TABLE 3.0217. EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON SUBSEQUENT ROOM TEMPERATURE TENSILE PROPERTIES OF ANNEALED AND COLD WORKED, STRESS RELIEVED TUBING (13)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Source	(22)					
Form	1-inch Extruded Plate					
Condition	Test Temp, F	Test Direction	F_{tu}, ksi	F_{ty}, ksi	e (2-inches), percent	RA, percent
As-Extruded	RT	L	107	104	19	60
		T	98	82	20	47
	200	L	100	96	20	65
		T	89	71	22	45
Beta Anneal 1765 F, 30 min, AC	RT	L	86	74	14	24
		T	94	82	21	35
	200	L	80	64	13	23
		T	86	69	23	34
High Temperature Alpha + Beta Anneal 1680 F, 30 min, AC	RT	L	105	100	20	57
		T	95	79	21	47
	200	L	98	81	22	60
		T	88	67	25	43
High Temperature Alpha + Beta Anneal 1680 F, 30 min, WQ	RT	L	114	107	20	61
		T	103	83	22	51
	200	L	108	101	21	56
		T	97	77	24	47
Low Temperature Alpha + Beta Anneal 1475 F, 30 min, AC	RT	L	106	104	20	60
		T	96	81	20	41
	200	L	98	93	22	64
		T	89	75	23	44

Notes: 1. Properties for as-extruded and beta annealed material are based on the average of multiple tests.
2. Hardness range: R_A 60-62.

TABLE 3.0311. EFFECT OF ANNEALING TEMPERATURE AND COOLING RATE FROM THE ANNEALING TEMPERATURE ON ROOM TEMPERATURE AND 200 F TENSILE PROPERTIES OF EXTRUDED PLATE (22)

Source	(43)				
Form	Tubing, Seamless, Hydraulic				
Condition	Cold Worked, Stress Relieved ½-hours				
Tube Size OD x Wall, inches	Stress Relief Temperature, F	Test Temperature, F	F_{tu}, ksi	F_{ty}, ksi	E (modulus), 10^3 ksi
1.0 x 0.080	600	RT	126.4	104.6	14.5
3/8 x 0.020	600	RT	125.3	110.5	14.0
3/8 x 0.020*	600	RT	123.3	107.2	14.8
1.0 x 0.080	700	RT	125.4	106.1	14.9
1.0 x 0.033	700	RT	126.3	111.2	14.9
3/8 x 0.030	700	RT	131.8	116.0	14.0
3/8 x 0.020	700	RT	124.2	109.4	13.2
5/8 x 0.050	700	450	100.2	85.1	11.4
3/8 x 0.020	700	450	97.9	83.2	12.5

* Texture controlled.

TABLE 3.0312. ROOM TEMPERATURE AND 450 F TENSILE PROPERTIES OF COLD WORKED, STRESS RELIEVED TUBING (43)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Source	(22)				
Form	1-inch, Extruded Plate				
Condition	As-Extruded	Beta Anneal 1756 F, 30 min, AC	High Temperature Alpha + Beta Anneal 1680 F, 30 min, AC	High Temperature Alpha + Beta Anneal 1680 F, 30 min, WQ	Low Temperature Alpha + Beta Anneal 1475 F, 30 min, AC
Test Temp, F	Impact Energy Charpy-V, ft-lb				
200	--	36	87	91	86
RT	79	34	64	68	75
32	74	32	60	60	64
-80	--	28	51	45	51

See Table 3.0311 for corresponding tensile properties.

TABLE 3.0331. EFFECT OF ANNEALING TEMPERATURE AND COOLING RATE FROM THE ANNEALING TEMPERATURE ON CHARPY-V IMPACT ENERGY OF EXTRUDED PLATE AT TEST TEMPERATURES RANGING FROM -80 F TO +200 F (22)

Source	(44)				
Form	Tubing, Seamless, Hydraulic*				
Size OD x Wall, inch	Condition	Straightening Procedure	Tube Surface Conditioning	Maximum Longitudinal Stress**, ksi	Cycles to Failure
1 x 0.051	Cold Worked, Stress Relieved (F_{tu} = 133.7 ksi)	Cold-Stretch Straightened	(1)	25.4	182 x 10^3
			(2)	25.4	145 x 10^3
			(3)	24.6	92 x 10^3
		Rotary Straightened	(1)	24.6	141 x 10^3
			(2)	24.9	127 x 10^3
			(3)	25.7	93 x 10^3
1 x 0.066	Annealed (F_{tu} = 99.5 ksi)	Cold-Stretch Straightened	(1)	35.2	233 x 10^3
			(2)	34.8	115 x 10^3
			(3)	36.3	220 x 10^3
		Rotary Straightened	(1)	32.5	249 x 10^3
			(2)	34.8	304 x 10^3
			(3)	33.1	251 x 10^3

*Tube Reduced.
**Tubing pressurized to 3,000 psi during flexure.
(1) OD lightly polished; ID and OD chem milled.
(2) OD lightly polished; ID grit blasted; ID and OD chem milled.
(3) OD lightly polished; ID and OD chem milled; OD glass bead peened.

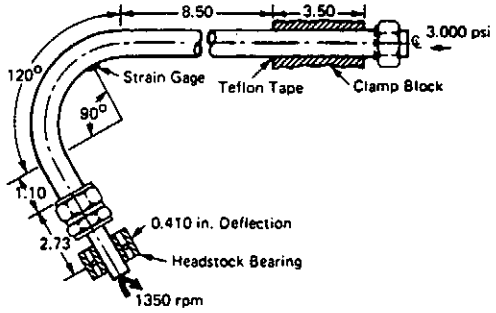


DIAGRAM OF ROTARY FLEXURE TEST SET-UP

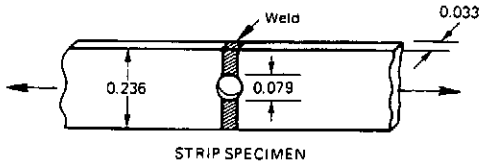
TABLE 3.056. INFLUENCE OF STRAIGHTENING PROCEDURE, HEAT TREATMENT, AND SURFACE CONDITIONING ON ROTARY FLEXURE FATIGUE LIFE OF TUBING (44)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

Source	(24)						
Form	Tubing, 0.5-inch OD x 0.033-inch Wall						
Condition	55 percent Cold Worked, 1-hour Anneal (partially Recrystallized) at 1112 F						
Weld Process	Specimen Type	No. of Tests	Test Location	F_{tu},(b) ksi	F_{ty}, (a)(b) ksi	e (0.50-inch), (b) percent	Failure Location
---	Tube(c)	7	Base Metal	109.6 ± 1.3	89.5 ± 1.6	17.2 ± 0.5	---
GTA	Strip(d)	19	Weld Joint	105.3 ± 2.0	89.9 ± 2.2	12.6 ± 0.9	Transformation Zone
EB	Strip(d)	23	Weld Metal	114.9 ± 4.50	---	40.0 ± 7.0 (e)	---
EB	Strip(d)	4	Weld Joint	110.4 ± 1.2	92.2 ± 2.3	14.0 ± 2.8	Base Metal

(a) 0.2 percent offset.
(b) Average values and standard deviation.
(c) Full section, unwelded tube.
(d) Strips taken from the as-welded tubes
(e) Elongation in 0.079-inch dia hole.

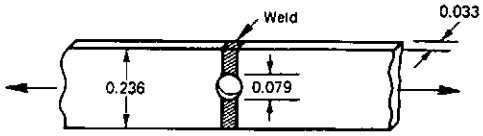


STRIP SPECIMEN

TABLE 4.03121. ROOM TEMPERATURE TENSILE PROPERTIES OF COLD WORKED AND ANNEALED (PARTIALLY RECRYSTALLIZED) TUBING AND AS-WELDED STRIPS CUT FROM PORTIONS OF THAT TUBING (24)

Source	(24)						
Form	Tubing, 0.5-inch OD x 0.033-inch Wall						
Condition	55 percent Cold Worked + 1-hour Anneal + GTA Welded						
Base Metal Annealing Temperature, F	Test Location(a)	F_{tu}, ksi	F_{ty}, (b) ksi	e (0.59-inch), percent	e (1.97-inch), percent	e of 0.079-inch Dia Hole, percent	Failure Location
1067(c)	Base Metal	100.8	80.5	---	14.4	---	---
1067(c)	Weld Joint	89.3	76.0	11.3	4.3	---	Transformation Zone
1067(c)	Weld Metal	96.7	---	---	---	54.0	---
1112(d)	Base Metal	96.5	77.5	---	16.1	---	---
1112(d)	Weld Joint	89.9	74.7	12.4	5.3	---	Transformation Zone
1112(d)	Weld Metal	96.9	---	---	---	50.0	---
1157(d)	Base Metal	89.9	73.1	---	16.9	---	---
1157(d)	Weld Joint	86.7	71.1	16.7	8.9	---	Transformation Zone
1157(d)	Weld Metal	94.6	---	---	---	53.0	---

(a) Triplicate specimens from each location: full section tubes for base metal tests: strips (as-welded) from welded tubes for weld joint and weld metal tests.
(b) 0.2 percent offset.
(c) Stress relieved.
(d) Partially recrystallized.



STRIP SPECIMEN

TABLE 4.03122. TENSILE PROPERTIES AT 248 F OF COLD WORKED AND ANNEALED TUBES AND AS-WELDED STRIPS FROM GTA WELDED PORTIONS OF THOSE TUBES (24)

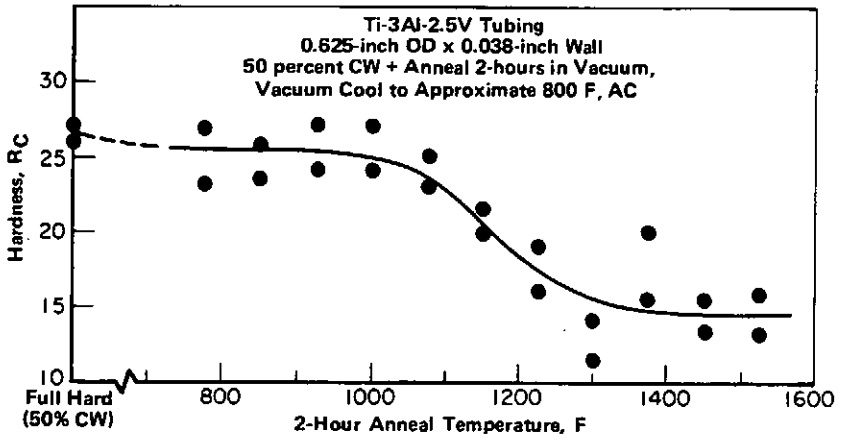


FIGURE 1.061. EFFECT OF ANNEALING (OR STRESS RELIEVING) TEMPERATURE ON HARDNESS OF FULL HARD (50 PERCENT COLD WORKED) TUBING (17)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

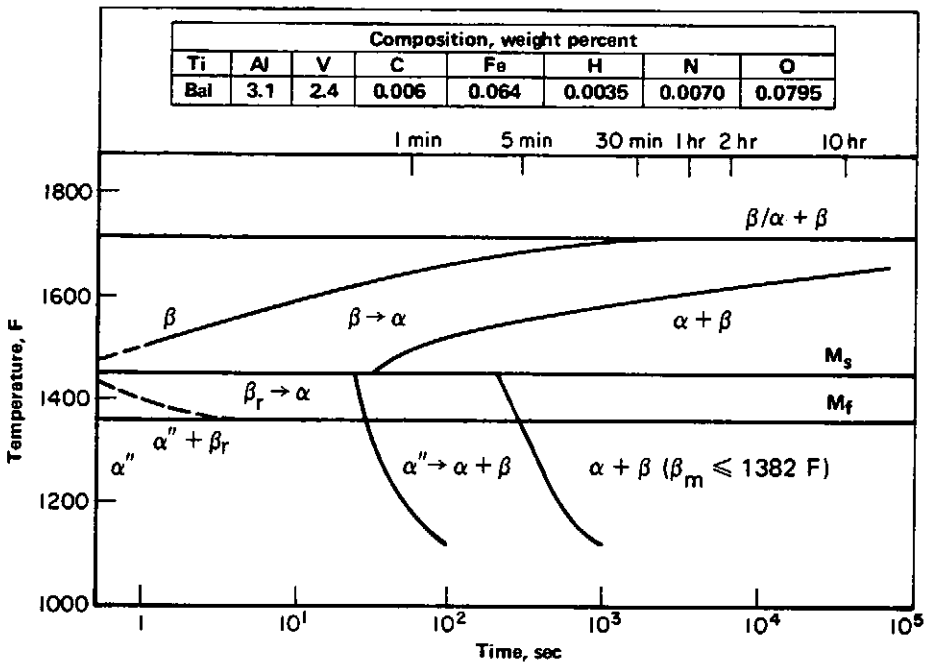


FIGURE 2.0121. Ti-3Al-2.5V ISOTHERMAL TRANSFORMATION (TTT) DIAGRAM (6)

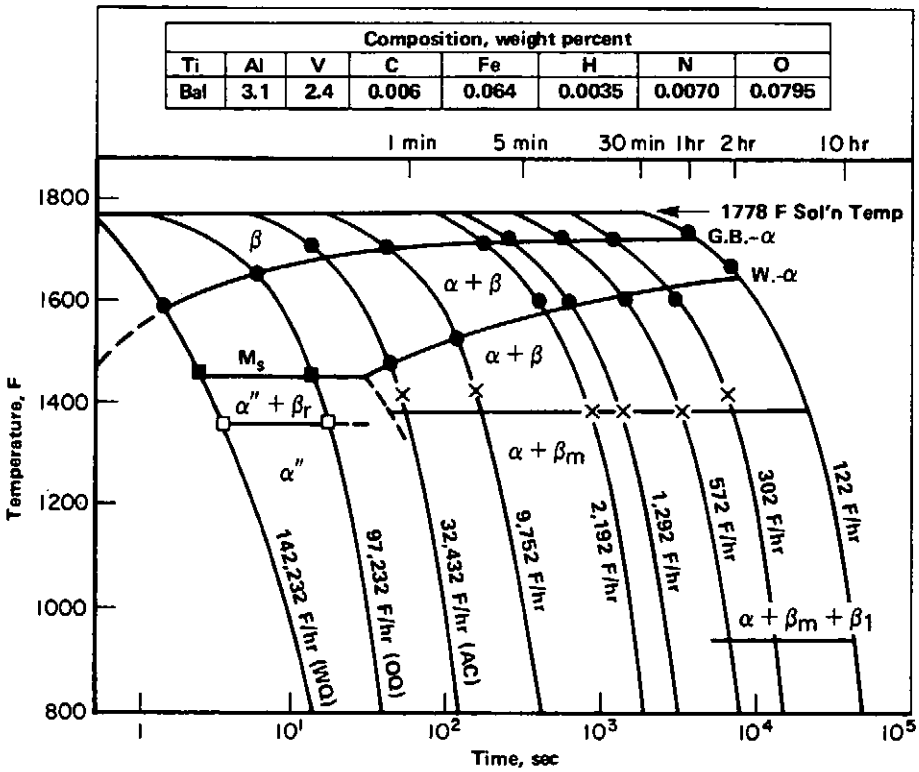


FIGURE 2.0122. Ti-3Al-2.5V CONTINUOUS COOLING TRANSFORMATION (CCT) DIAGRAM (6)

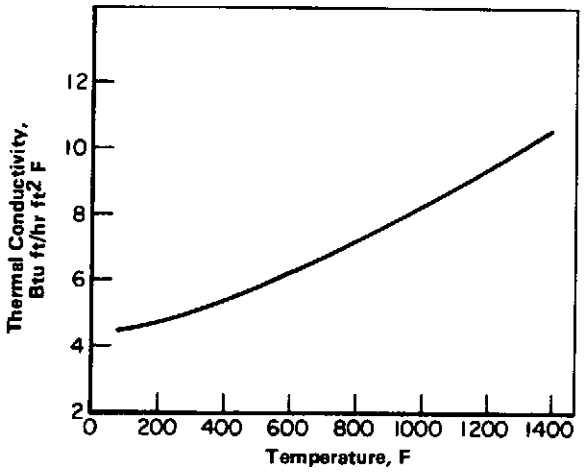
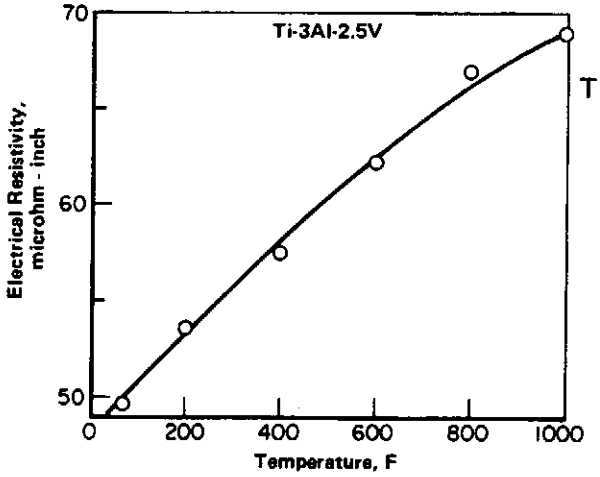


FIGURE 2.013. THERMAL CONDUCTIVITY (29)



Ti
3 Al
2.5 V
Ti-3Al-2.5V

FIGURE 2.0221. ELECTRICAL RESISTIVITY (29)

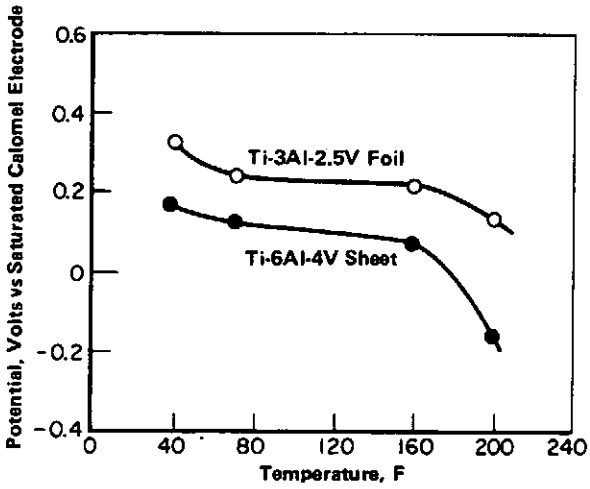


FIGURE 2.0311. EFFECT OF TEMPERATURE ON ELECTRODE POTENTIAL FOR Ti-3Al-2.5V FOIL AND Ti-6Al-4V SHEET IN 3.5 PERCENT NaCl SOLUTION (26)

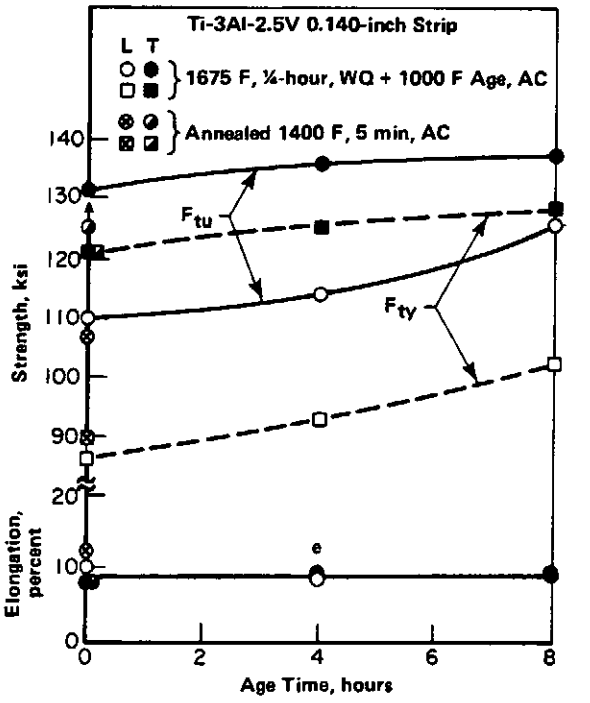


FIGURE 3.0212. EFFECT OF 1000 F AGE ON ROOM TEMPERATURE TENSILE PROPERTIES OF STRIP (12)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

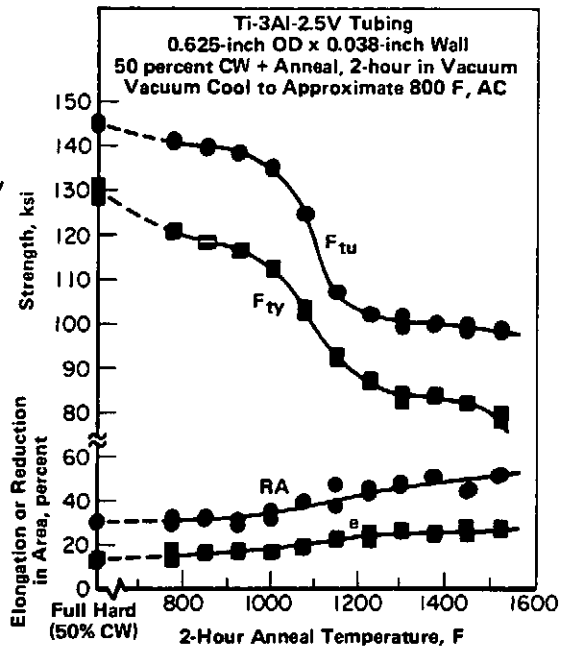


FIGURE 3.0213. EFFECT OF ANNEALING (OR STRESS RELIEVING) TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF FULL HARD (50 PERCENT COLD WORKED) TUBING (19)

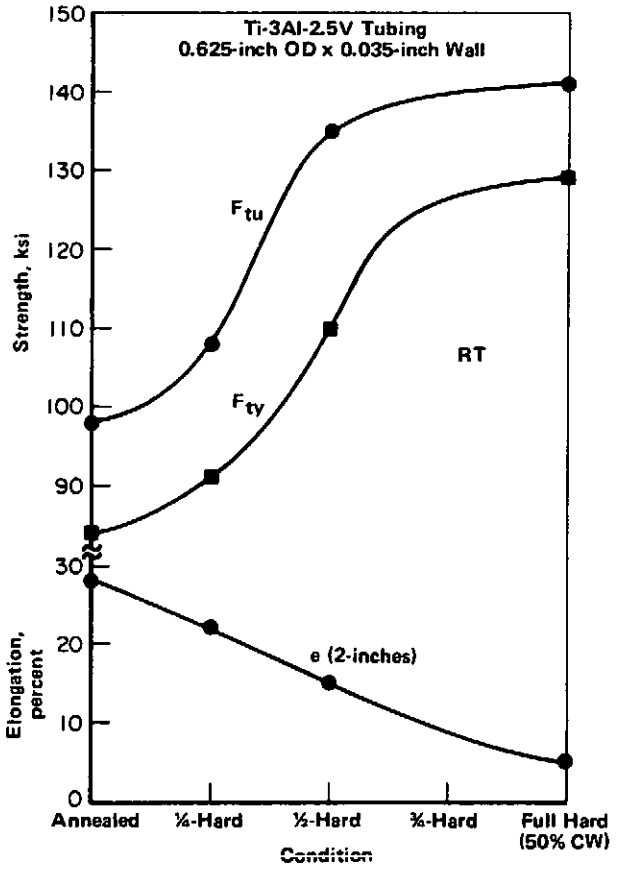


FIGURE 3.0214. ROOM TEMPERATURE TENSILE PROPERTIES OF TUBING IN HARDNESS CONDITIONS RANGING FROM FULL HARD TO FULLY ANNEALED (12)

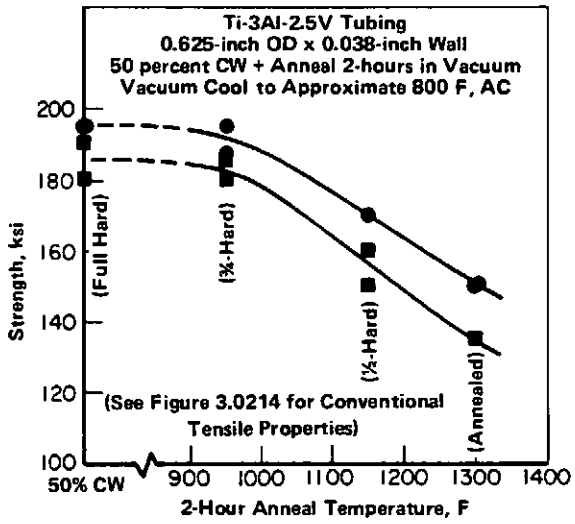


FIGURE 3.0215. EFFECT OF ANNEALING (OR STRESS RELIEVING) TEMPERATURE ON ROOM TEMPERATURE YIELD AND BURST STRENGTHS OF INTERNALLY PRESSURIZED FULL HARD (50 PERCENT COLD WORKED) TUBING (19)

Ti
3 Al
2.5 V
Ti-3Al-2.5V

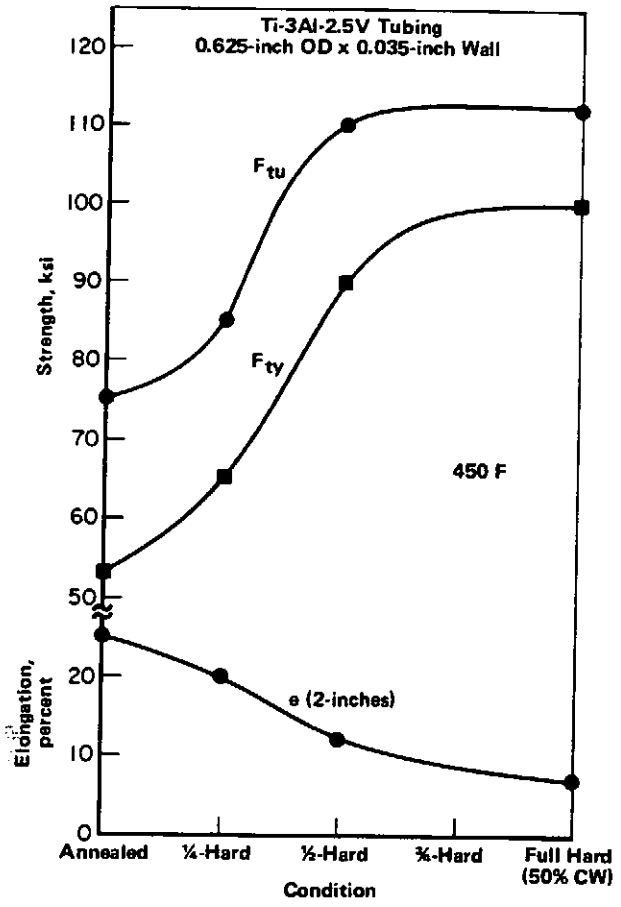


FIGURE 3.0313. 450 F TENSILE PROPERTIES OF TUBING IN HARDNESS CONDITIONS RANGING FROM FULL HARD TO FULLY ANNEALED (12)

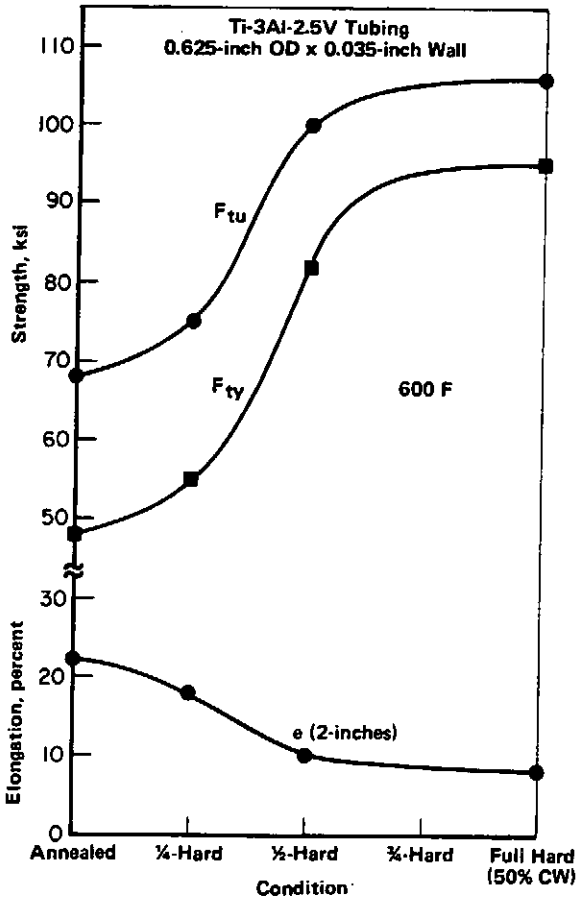


FIGURE 3.0314. 600 F TENSILE PROPERTIES OF TUBING IN HARDNESS CONDITIONS RANGING FROM FULL HARD TO FULLY ANNEALED (12)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

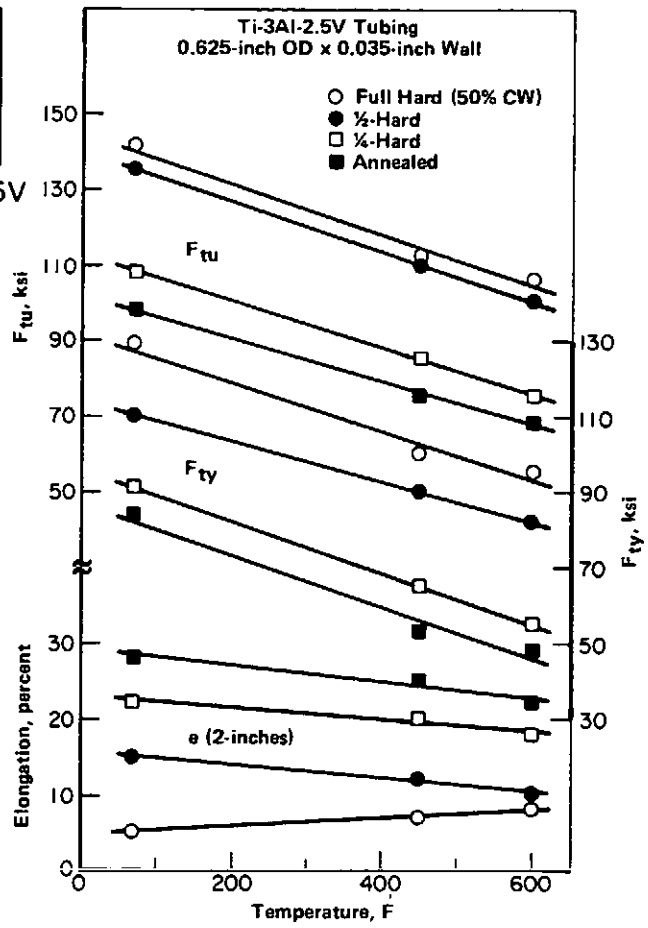


FIGURE 3.0315. EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF TUBING IN HARDNESS CONDITIONS RANGING FROM FULL HARD TO FULLY ANNEALED (12)

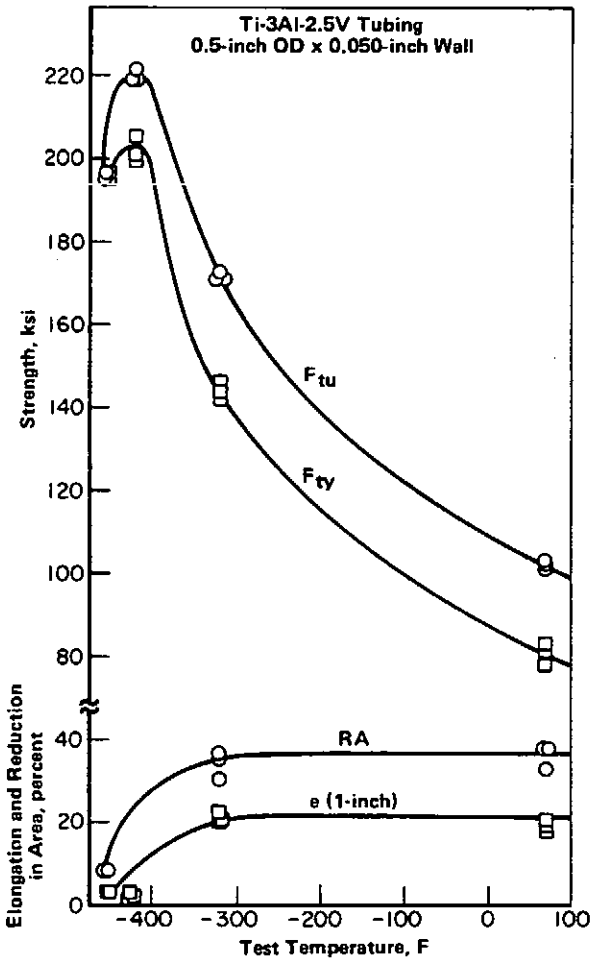


FIGURE 3.0316. TENSILE PROPERTIES OF TUBING FROM ROOM TEMPERATURE TO -453 F (45)

Ti
3 Al
2.5 V
Ti-3Al-2.5V

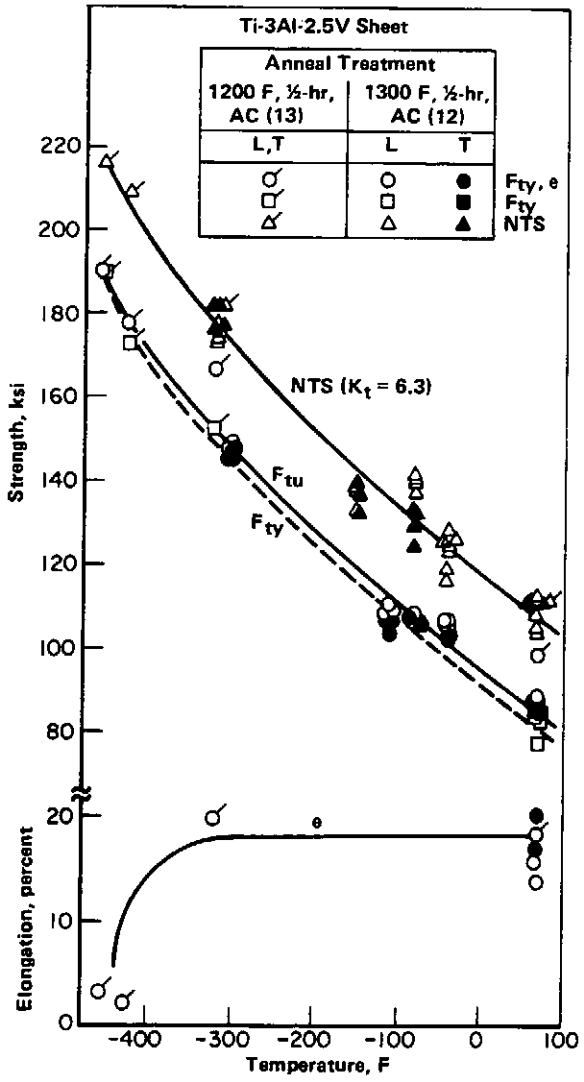


FIGURE 3.03711. EFFECT OF CRYOGENIC TEMPERATURE ON SMOOTH AND MILD NOTCH TENSILE PROPERTIES OF ANNEALED SHEET (12) (13)

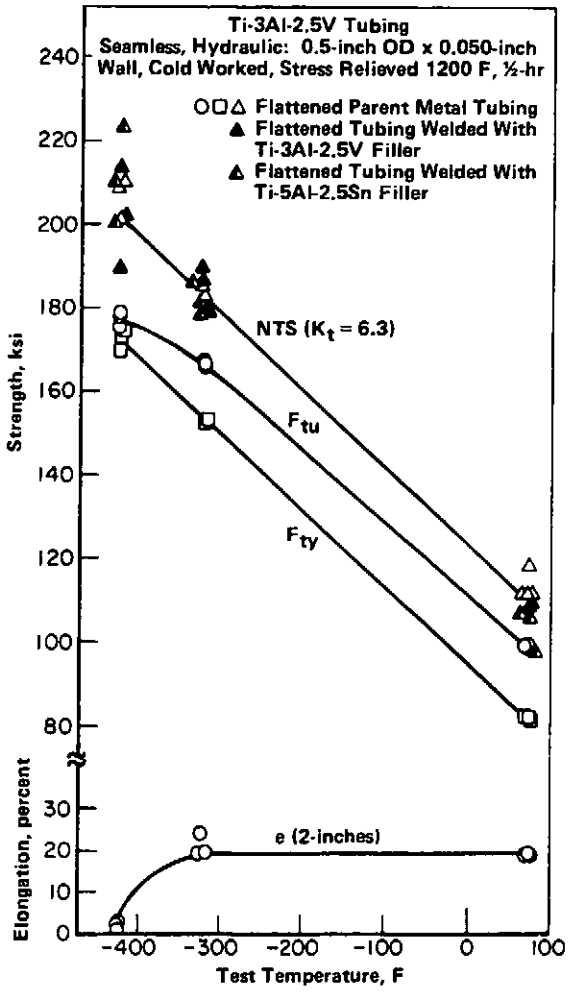


FIGURE 3.03712. SMOOTH AND MILD NOTCH TENSILE PROPERTIES OF PARENT METAL AND WELDED FLATTENED TUBING FROM ROOM TEMPERATURE TO -423 F (45)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

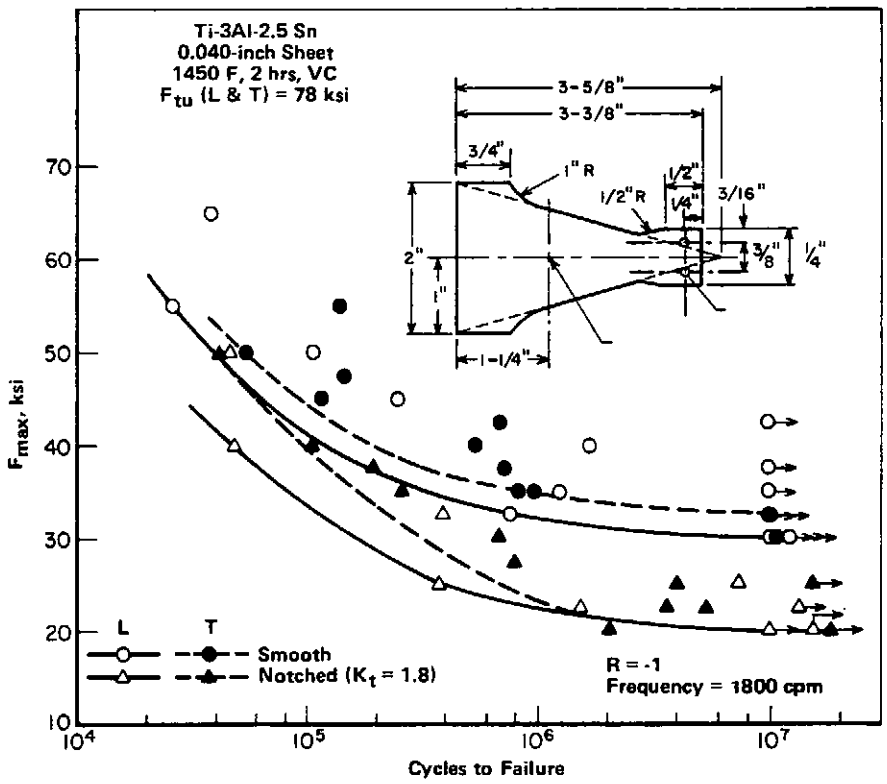


FIGURE 3.051. ROOM TEMPERATURE SMOOTH AND MILD NOTCH BENDING FATIGUE STRENGTH OF VARIOUS ANNEALED SHEET (1)

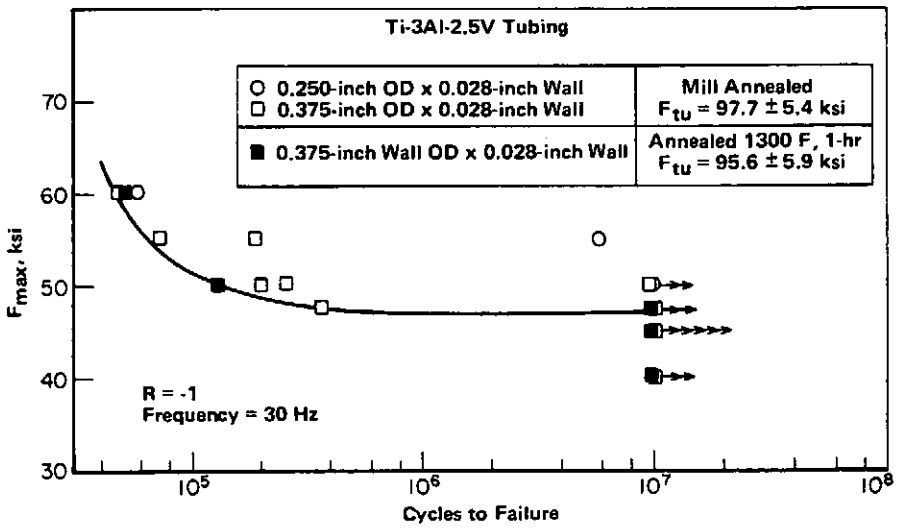


FIGURE 3.052. ROOM TEMPERATURE HIGH CYCLE FATIGUE STRENGTH OF ANNEALED TUBING PRODUCED BY TWO TUBING PRODUCERS FROM STOCK FURNISHED BY THREE METAL PRODUCERS (34)

Ti
3 Al
2.5 V
Ti-3Al-2.5V

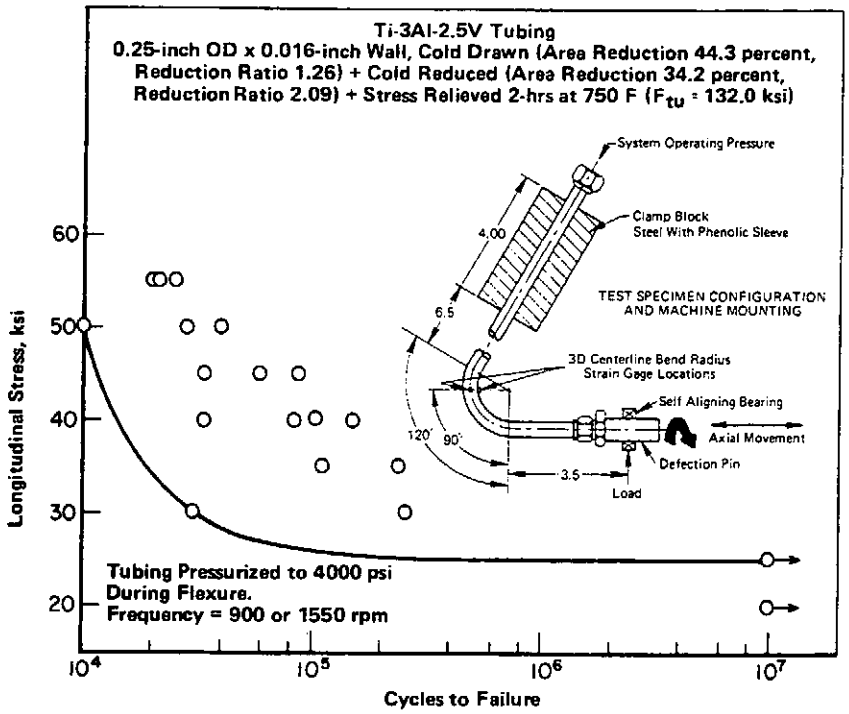


FIGURE 3.053. ROOM TEMPERATURE ROTARY FLEXURE FATIGUE STRENGTH OF COLD WORKED, STRESS RELIEVED TUBING (37)

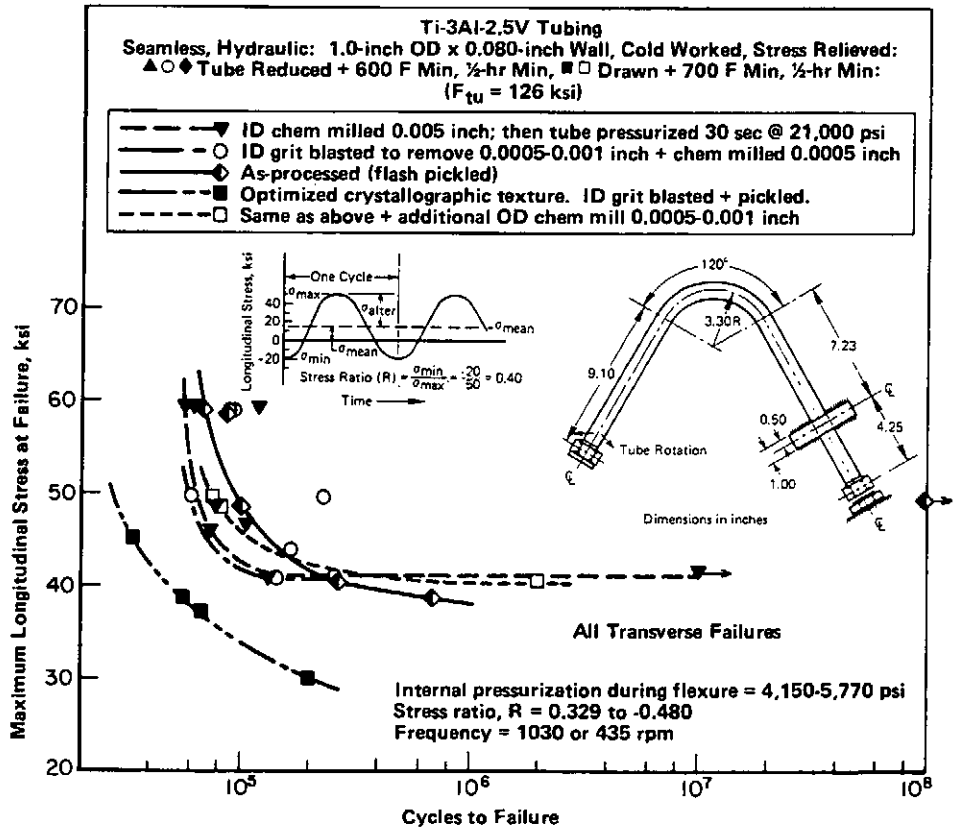


FIGURE 3.054. ROTARY FLEXURE FATIGUE STRENGTH OF 1.0-INCH OD X 0.080-INCH WALL, COLD WORKED PLUS STRESS RELIEVED, 4,150-PSI SYSTEM PRESSURE-LINE TUBING (43)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

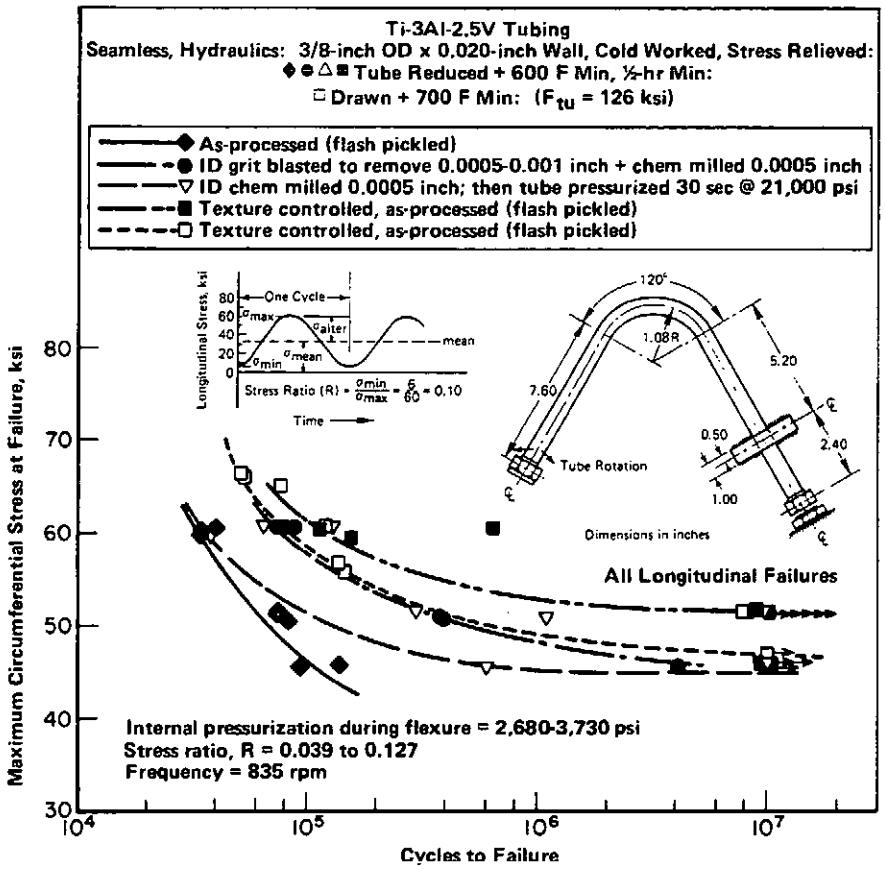


FIGURE 3.055. ROTARY FLEXURE FATIGUE STRENGTH OF 3/8-INCH OD X 0.020-INCH WALL, COLD WORKED PLUS STRESS RELIEVED, 4,150-PSI SYSTEM RETURN-LINE TUBING (41)

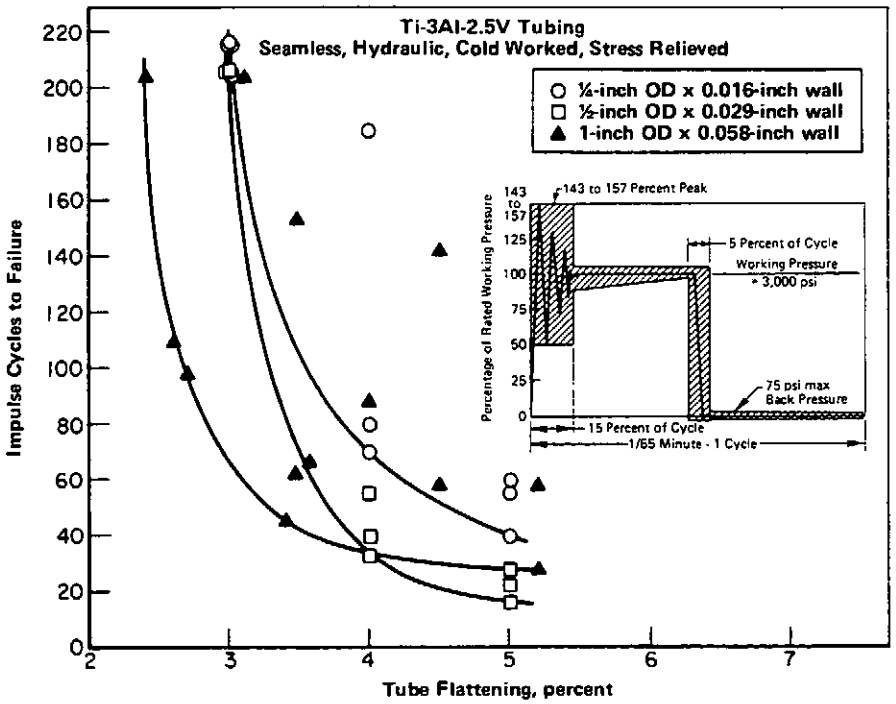


FIGURE 3.057. EFFECT OF TUBE OVALITY ON HYDRAULIC IMPULSE FATIGUE LIFE OF 90°-BENT, 3,000-PSI SYSTEM TUBING (40)

Ti
3 Al
2.5 V
Ti-3Al-2.5V

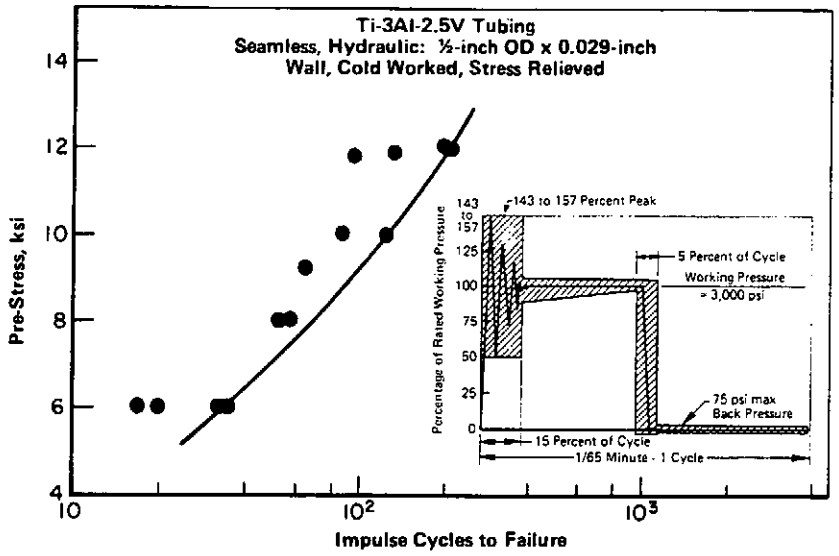


FIGURE 3.058. EFFECT OF OVERPRESSURIZATION ON IMPULSE FATIGUE LIFE OF DEFECTIVE, 3,000-PSI SYSTEM TUBING CONTAINING TWO 90° BENDS (Z-SHAPE) (40)

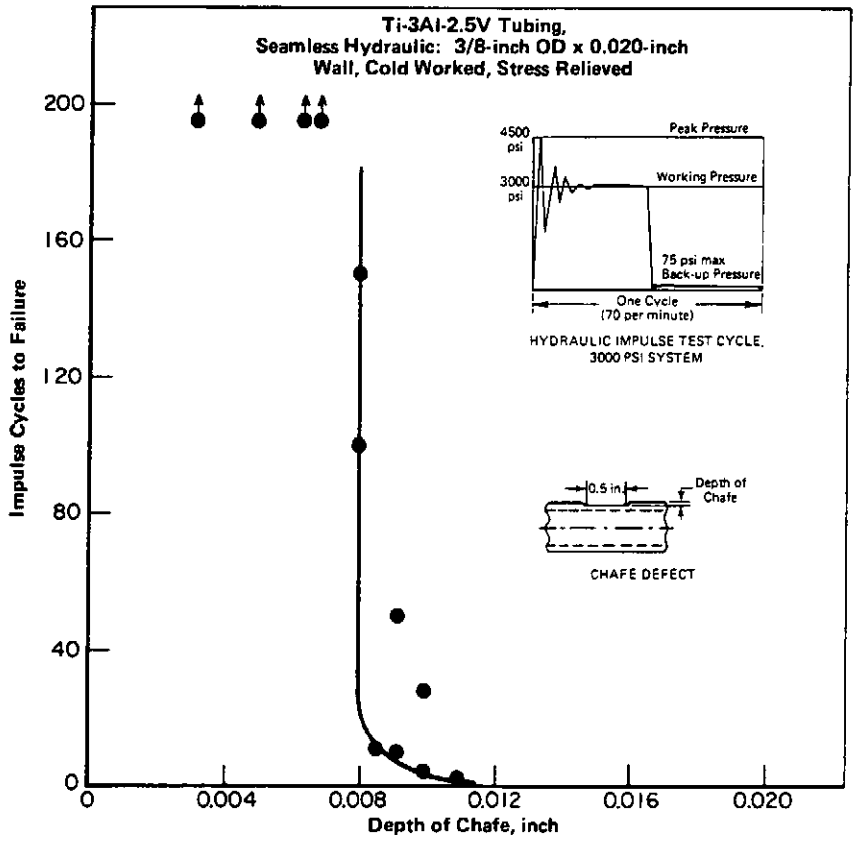


FIGURE 3.059. EFFECT OF CHAFE DEPTH (SIMULATED SERVICE DAMAGE) ON HYDRAULIC IMPULSE FATIGUE LIFE OF 3,000-PSI SYSTEM TUBING (39)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

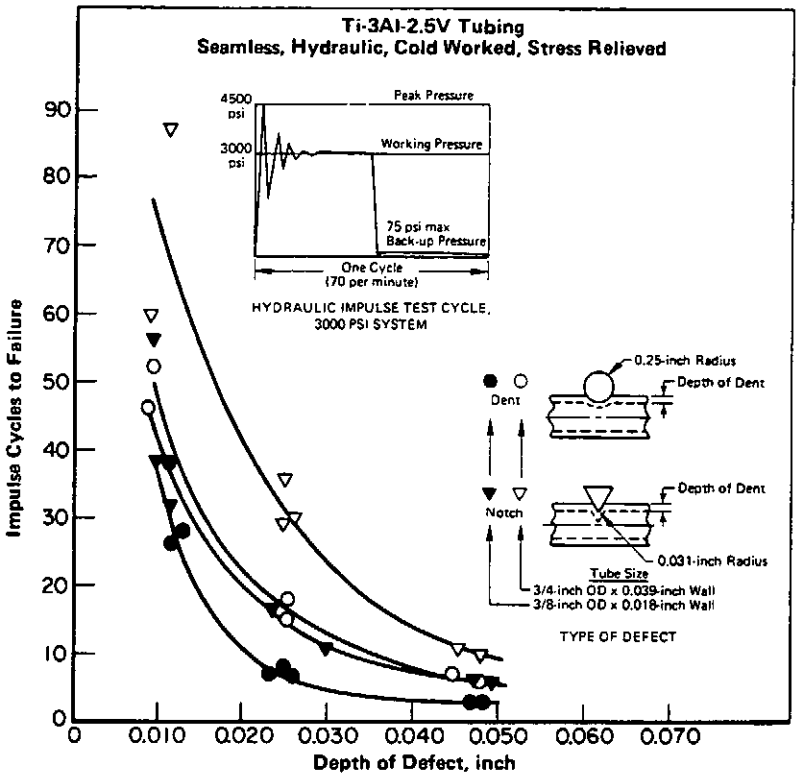


FIGURE 3.0510. EFFECT OF DEFECT SIZE (SIMULATED SERVICE DAMAGE) ON HYDRAULIC IMPULSE FATIGUE LIFE OF 3,000 PSI SYSTEM TUBING (39)

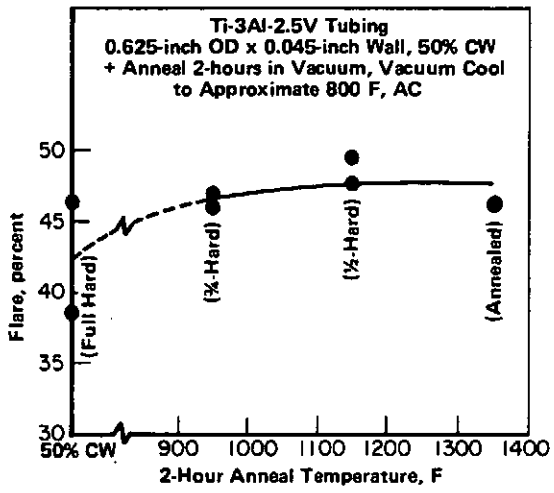


FIGURE 4.011. EFFECT OF ANNEALING (OR STRESS RELIEVING) TEMPERATURE ON ROOM TEMPERATURE FLARING OF FULL HARD (50 PERCENT COLD WORKED) TUBING (19)

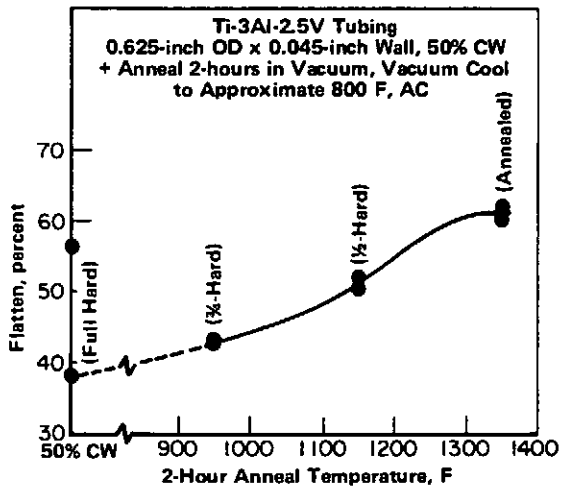


FIGURE 4.012. EFFECT OF ANNEALING (OR STRESS RELIEVING) TEMPERATURE ON ROOM TEMPERATURE FLATTENING OF FULL HARD (50 PERCENT COLD WORKED) TUBING (19)

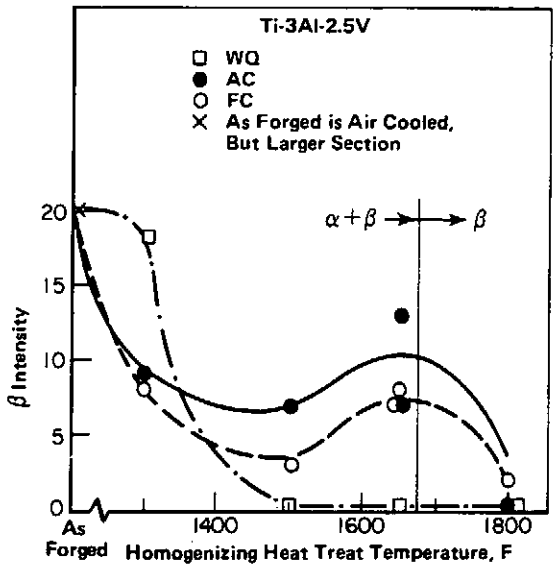


FIGURE 4.014. EFFECT OF HOMOGENIZING HEAT TREAT TEMPERATURE ON β INTENSITY (CONTENT) DETERMINED ON SMALL SAMPLES TAKEN FROM FORGED BILLET (41)

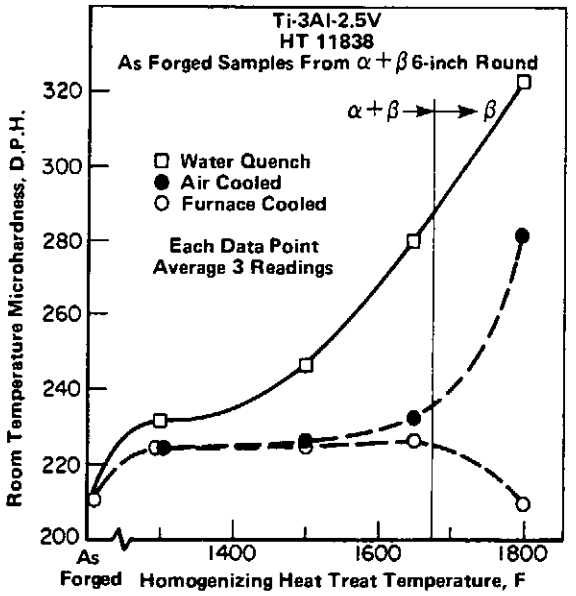


FIGURE 4.015. EFFECT OF HOMOGENIZING HEAT TREAT TEMPERATURE AND COOLING RATE FROM THAT TEMPERATURE ON MICROHARDNESS OF SMALL SAMPLES TAKEN FROM FORGED BILLET (41)

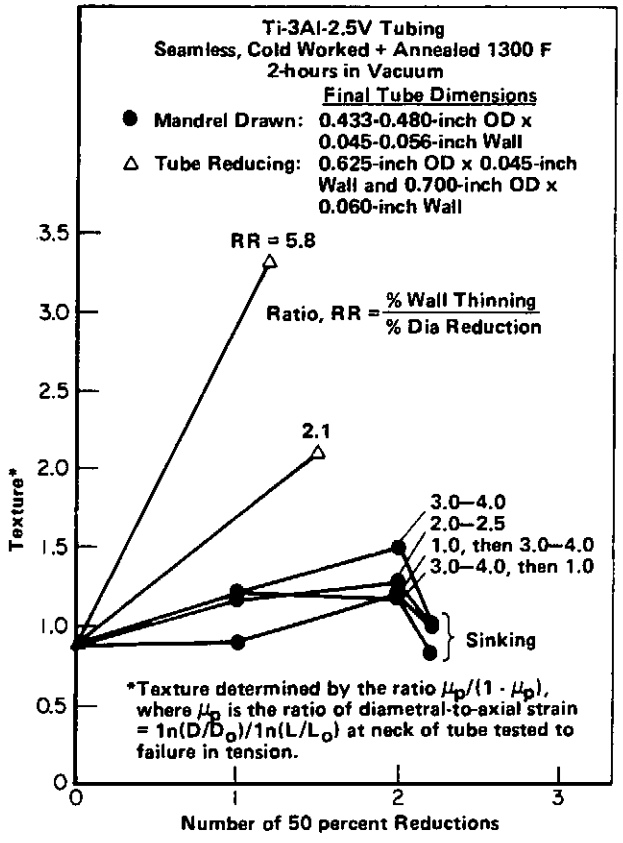


FIGURE 4.017. EFFECT OF COLD REDUCTION SCHEDULE ON CRYSTALLOGRAPHIC TEXTURE OF COLD WORKED, ANNEALED TUBING (42)

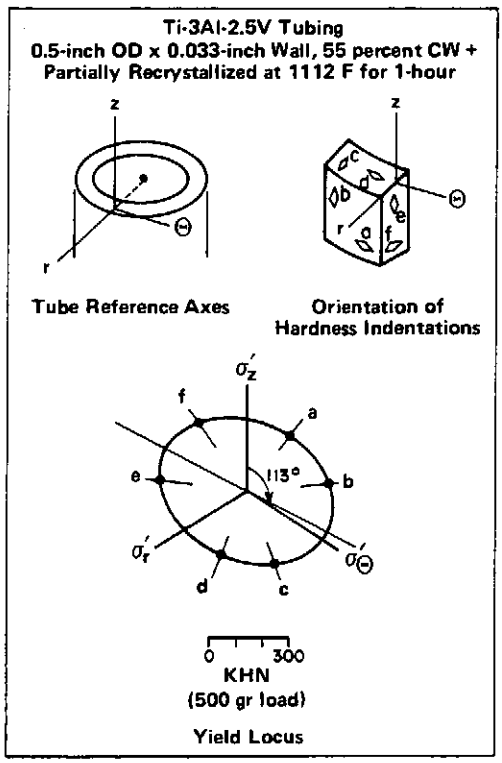


FIGURE 4.03131. MECHANICAL ANISOTROPY OF COLD WORKED AND PARTIALLY RECRYSTALLIZED TUBING AS ILLUSTRATED BY DISTORTION OF THE YIELD LOCUS DETERMINED FROM HARDNESS MEASUREMENTS ACCORDING TO THE TECHNIQUE OF WHEELER AND IRELAND (24)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

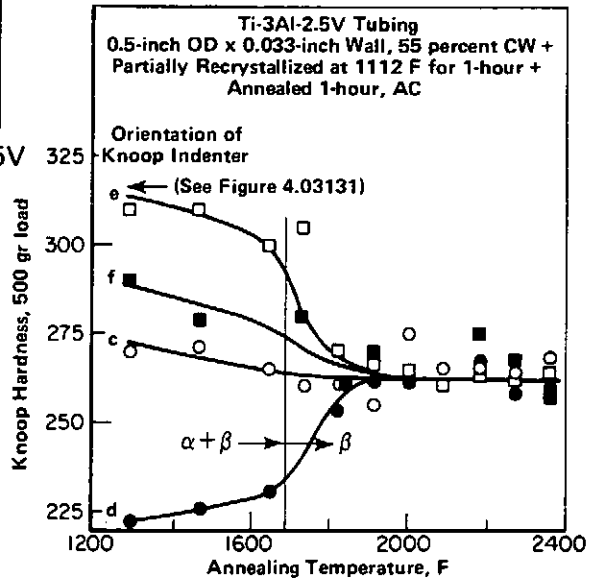


FIGURE 4.03132. EFFECT OF 10-SECOND ANNEALING TEMPERATURE ON KNOOP HARDNESS OF COLD WORKED AND ANNEALED (PARTIALLY RECRYSTALLIZED) TUBING, SIMULATING HARDNESS PROFILE OF EB WELD (24)

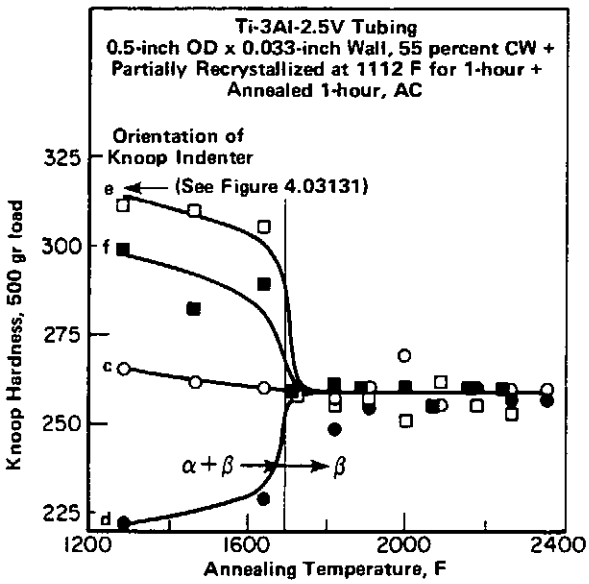


FIGURE 4.03133. EFFECT OF 30-SECOND ANNEALING TEMPERATURE ON KNOOP HARDNESS OF COLD WORKED AND ANNEALED (PARTIALLY RECRYSTALLIZED) TUBING, SIMULATING HARDNESS PROFILE OF GTA WELD (24)

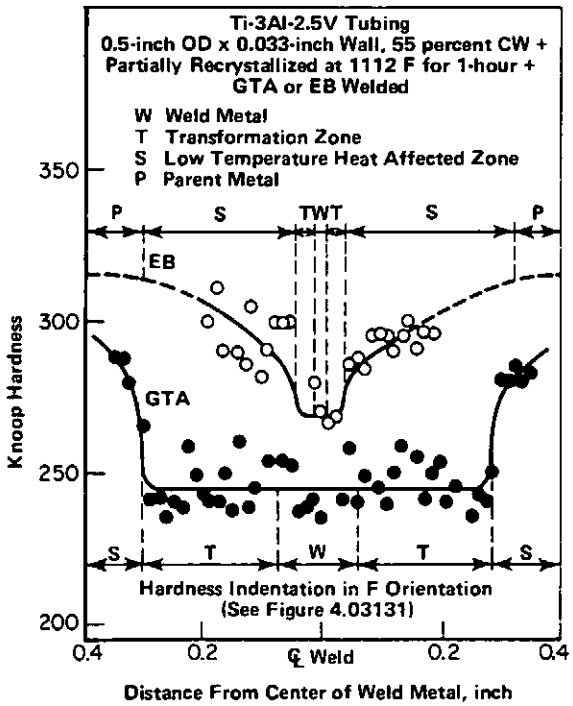


FIGURE 4.03134. KNOOP HARDNESS TRAVERSE OF GTA AND EB WELDS IN 55 PERCENT COLD WORKED AND PARTIALLY RECRYSTALLIZED TUBING (24)

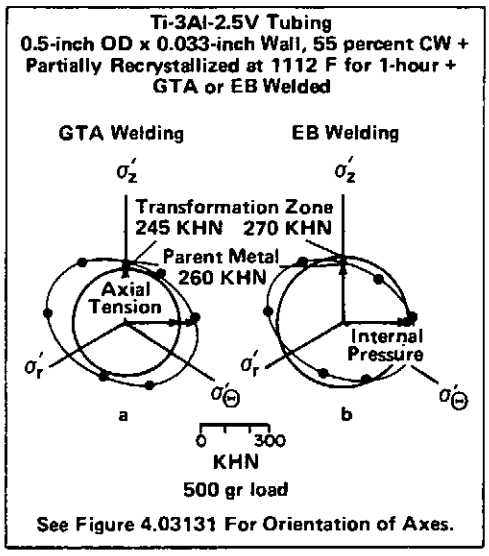


FIGURE 4.03135. YIELD LOCI OF BASE METAL AND TRANSFORMATION ZONE OF COLD WORKED AND PARTIALLY RECRYSTALLIZED TUBING AFTER GTA AND WELDING (24)

Ti
5 Al
2.5 Sn

Ti-5Al-2.5Sn

1. GENERAL

This is a medium strength all alpha titanium alloy used only in the annealed condition, having very high fracture toughness at room and elevated temperatures. In common with other titanium alloys the tensile strength increases rapidly with decreasing temperature. At liquid hydrogen temperature yield strength to density ratios from 1,200,000 to 1,500,000 are obtained, depending on the interstitial element content. The yield strength and tensile strength increase and the fracture toughness decreases with increased content of the interstitial elements. The extra low interstitial grade (ELI) is particularly well suited to service at cryogenic temperatures and in sheet form has an excellent combination of toughness and strength at -423F. Information concerning the toughness of heavy sections at cryogenic temperatures is not available as yet. This alloy is readily fusion welded using the TIG or MIG process. The toughness and strength of properly made fusion welds is equal to that of the parent metal. The stress corrosion resistance of this alloy at elevated temperatures in the presence of solid salt is lower than that of other commonly used titanium alloys. A severe explosion hazard may exist if the alloy is used in contact with liquid oxygen or in contact with gaseous oxygen at pressures above about 50 psi, (see 1.09).

1.01 Commercial Designation

5Al-2.5Sn Titanium alloy.

1.02 Alternate Designations

A110-AT, HA-5137, MST-5Al-2.5Sn, RS-110C, 5Al-2.5Sn ELI.

1.021 Producers of the alloy:

Crucible Steel
Harvey Aluminum
Reactive Metals
Republic Steel
Titanium Metals Corp. of America

1.03 Specifications

1.031 AMS Specifications, Table 1.031.

TABLE 1.031

AMS	Form	Military
4910A	Sheet, strip, plate	T9046 Class 3
4926	Bar	T9047 Class 2
4953	Weld wire	
4966	Forgings and forging stock	T9047 Class 2

1.04 Composition

1.041 Composition for standard grade, Table 1.041.

TABLE 1.041

Source	AMS (1)(2)(4)		AMS (5)		(15)	
Form	Sheet, strip, plate bar, forging and forging stock		Weld wire		Sheet, strip, plate, bar, billet, wire	
	Percent		Percent		Percent	
	Min	Max	Min	Max	Min	Max
Aluminum	4.0	6.0	4.0	6.0	4.0	6.0
Carbon	-	0.15	-	0.10	-	0.08
Hydrogen	0.003	0.020	-	0.015	-	(b)
Iron	-	0.50	-	0.50	-	0.50
Manganese	-	0.30	-	0.20	-	-
Nitrogen	-	0.07	-	0.07	-	0.05
Oxygen	-	0.20 (a)	-	0.0175(a)	-	-
Tin	2.0	3.0	2.0	3.0	2.0	3.0
Other elements	-	0.40	-	-	-	-
Titanium	Balance		Balance		Balance	

a) If determined (AMS 4926 and 4923)

b) Sheet, 0.0175 max; Bar, 0.0125 max; Billet, 0.0100 max.

1.042 Composition for ELI grade, Table 1.042.

TABLE 1.042

Source	(14)		(15)	
Form	Sheet		Sheet, strip, bar, billet and wire	
	Percent		Percent	
	Min	Max	Min	Max
Aluminum	5.0	5.8	4.7	5.6
Carbon	-	0.05	-	0.08
Chromium	-	0.10	-	-
Hydrogen	-	0.015	-	0.0175*
Iron	-	0.25	-	0.15
Manganese	-	0.10	-	-
Molybdenum	-	0.10	-	-
Nitrogen	-	0.04	-	0.05
Oxygen	-	0.12	-	0.12
Tin	2.2	2.8	2.0	3.0
Vanadium	-	0.10	-	-
Other elements	-	0.30	-	-
Titanium	Balance		Balance	

* 0.0125 on bar and billet

1.05 Heat Treatment

1.051 Anneal. 1325F to 1550F, 10 minutes to 4 hours, furnace cool or air cool. AMS 4910A and 4966 give 1475 to 1500F, 1 hour, air cool. Temperatures above 1400F appear to give somewhat improved tensile and impact properties (see Fig. 3.0331). Rapid cooling appears to increase fracture toughness as compared with slow cooling, (see Fig. 3.03722).

1.052 Stress relief 1000 to 1200F, 15 minutes to 1 hour, air cool.

1.06 Hardness

Annealed hardness approximately 36 RC.
As cast approximately 321 BHN.

1.07 Forms and Conditions Available

1.071 Alloy is available in the full commercial range of sizes for sheet, strip, plate, bar, forgings, wire and extrusions.

1.072 All wrought products are available in the annealed condition.

1.073 Castings are also available on a commercial basis.

1.08 Melting and Casting Practice

Consumable electrode double vacuum melt.

1.09 Special Considerations

1.091 Directionality. Depending on the rolling and annealing conditions, α Ti-Al alloys tend to develop a preferred orientation with the basal plane parallel to the sheet surface. This texture inhibits strain in the thickness direction when tensile stresses occur parallel to the sheet plane, (33). Since twinning is also able to produce deformation, factors which suppress this process such as a small grain size, also tend to inhibit thickness strain. The result of thickness strain inhibition is to raise the yield strength in a biaxial stress field beyond that for an isotropic material. This yield strength elevation can be calculated according to Hill, (31) as follows:

$$\frac{\sigma_1}{F_{TY}} = \left[1 + \frac{\sigma_2^2}{\sigma_1^2} - \frac{\sigma_2}{\sigma_1}\left(\frac{2R}{1+R}\right)\right]^{-1/2}$$

where σ_1 and σ_2 are the principal stresses and R is the ratio of natural strain in the width to that in the thickness direction in a tensile test:

$$R = \ln \frac{W_o}{W} \Big/ \ln \frac{t_o}{t}$$

Ti
5 Al
2.5 Sn

Ti-5Al-2.5Sn

where W and t are the instantaneous width and thickness and W_o and t_o are the corresponding initial values. An R value of one corresponds to istropic behavior, values as high as 3.0 are sometimes encountered in normally processed 5Al-2.5Sn sheet, (see Fig. 1.0911). By special rolling and annealing treatments values somewhat higher than four can be produced and give rise to considerable biaxial strengthening, (see Fig. 1.0912). Special compositions are under development which have higher R value than can be obtained with 5Al-2.5Sn, (32). It should be noted that the influence of texturing on properties other than the tensile strength have not been investigated at the time this chapter was prepared. In particular, the crack propagation resistance of texture strengthened sheet should be studied before applying it to critical applications.

1.0911 Directionality of tensile strength and plastic strain for three heats of annealed sheet, Fig. 1.0911.

1.0912 Effect of rolling temperature and annealing treatment on the uniaxial yield strength and the theoretical biaxial yield strength in a 2:1 stress field, Fig. 1.0912.

1.092 Interstitial embrittlement, (see 6Al-4V). Extra low interstitial grade(ELI)should be employed for cryogenic service. Reduction of the interstitial element content below that in present commercially produced ELI will give further improvements in toughness, (see Fig. 3.03714).

1.093 Embrittlement by β stabilizers. The toughness is reduced by β stabilizing elements. Iron is a common impurity and should be excluded as far as possible for alloy to be used at cryogenic temperatures, Fig. 1.0931.

1.0931 Effect of iron content on -423F tensile and mild notch properties of ELI sheet, Fig. 1.0931.

1.094 Reactivity. Under certain conditions titanium and its alloys exhibit extreme reactivity when exposed to oxygen environments. When in contact with liquid oxygen burning can occur in impact loading and violent explosive reactions have been observed when the metal is subjected to high velocity puncture or to shock waves from explosive charges. When in contact with gaseous oxygen at pressures as low as 50 psi and temperatures as low as -250F, fresh fracture surfaces will burn and the reaction may propagate, (30). Surface treatment has little or no effect in reducing the reactivity under the above conditions, (30).

1.095 Stress corrosion. This alloy is more susceptible to elevated temperature solid salt corrosion than other commonly used titanium alloys, (see 2.032).

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range, 2800-3000F.

2.012 Phase changes. β transus on cooling is 1900 to 2000F, transus on heating 1700 to 1775F.

2.0121 Time-temperature-transformation diagrams

2.013 Thermal conductivity, Fig. 2.013.

2.014 Thermal expansion, Fig. 2.014.

2.015 Specific heat, Fig. 2.015.

2.016 Thermal diffusivity

2.02 Other Physical Properties

2.021 Density. 0.161 lb per cu in. 4.46 gr per cu cm.

2.022 Electrical resistivity, Fig. 2.022.

2.023 Magnetic properties. Alloy is nonmagnetic. Permeability at 20 oersteds, 1.00005.

2.024 Emissivity. See Ti-6Al-4V.

2.025 Damping capacity

2.03 Chemical Properties

See also Ti Commercially Pure and Ti-6Al-4V

2.031 Corrosion by gases. Appears to require a protective coating when used with gaseous flourine, (16).

2.032 Corrosion by solid salt.(see also Ti-6Al-4V). This alloy is more susceptible to solid salt corrosion at elevated temperatures than 6Al-4V or 8Al-1Mo-1V. Insufficient data is available to define the stress and temperature limits for stress corrosion for times above about 100 hours. Exposure to solid synthetic sea salt in heavy coatings will produce stress corrosion in 100 hours at 600F if the stress is above about 30 ksi (see Fig. 2.0321).

2.0321 Effect of stress and temperature on 100 hour salt stress corrosion of sheet, Fig. 2.0321.

2.04 Nuclear Properties

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 AMS specified properties, Table 3.011.

TABLE 3.011

Source	(1)(2)(4) (c)	(3)
Alloy	Ti-5Al-2.5Sn	
Form	Sheet, strip, plate, bar, forgings and forging stock	Weld wire
Condition	1475 to 1525F, 1 hr, AC	-
F_{tu}, -min-ksi	115	115 to 150
F_{ty}, -min-ksi	110	-
e(4D) -min-percent(a)	10	-
RA, -min-percent(b)	25	-
Hardness, RC-max	36	-

a) e(2 in) for sheet $\leq$ 0.025 inch thick.
b) Not specified for sheet
c) For AMS 4926 and 4966. A tensile specimen with 60° V notch removing 50% of cross sectional area having 0.005 in tip radius shall have 5 hours, minimum rupture life at room temperature when loaded to 170 ksi.

3.012 Producer's specified mechanical properties, Table 3.012.

TABLE 3.012

Source	(15)	
Alloy	Ti-5Al-2.5Sn	
Form	Sheet, strip, plate, bar, billet	
Condition	Ann	
Grade	Standard	ELI
F_{tu}, -min-ksi	120	100
F_{ty}, -min-ksi	115	90
e(2 in) -min-percent(a)	10	10 (b)
RA, -min-percent	25	

(a) >0.025 in thick
(b) $\leq$ 0.020 in thick, 8 percent; determined by configuration of bar and forgings.

3.02 Mechanical Properties at Room Temperature

3.021 Tension

3.0211 Stress-strain diagrams, (see 3.0311).

3.0212 Effect of exposure in various mediums to elevated temperatures on tensile properties of sheet, Fig. 3.0212.

3.0213 Effect of stretching and stress relief on tensile and compressive yield strength of sheet, Fig. 3.0213.

3.022 Compression

3.0221 Stress-strain diagrams

3.023 Impact

3.024 Bending

3.025 Torsion and shear

3.026 Bearing

3.027 Stress concentration

3.0271 Notch properties

3.0272 Fracture toughness

3.028 Combined properties

3.03 Mechanical Properties at Various Temperatures

3.031 Tension

3.0311 Stress-strain diagrams

3.03111 Stress-strain curves for sheet, bar and forgings at room and elevated temperatures, Fig. 3.03111.

3.03112 Stress-strain curves for sheet at very high temperatures with various strain rates and holding times, Fig. 3.03112.

3.03113 Stress-strain curves for sheet at low temperatures, Fig. 3.03113.

3.0312 Effect of elevated test temperatures on the tensile properties of sheet, Fig. 3.0312.

	Ti
5	Al
2.5	Sn

Ti-5Al-2.5Sn

3.0313 Effect of low test temperatures and interstitial element and Fe-content on tensile properties of sheet, Fig. 3.0313.
3.0314 Effect of low and elevated test temperature on tensile properties of bar, Fig. 3.0314.
3.0315 Effect of test temperature, strain rate and holding time on tensile properties of sheet, Fig. 3.0315.
3.0316 Effect of test temperature on the tensile properties of castings, Fig. 3.0316.
3.032 Compression
3.0321 Stress-strain curves in compression for sheet, bar and forgings at room and elevated temperatures, Fig. 3.0321.
3.0322 Effect of test temperature on compressive yield strength of sheet, Fig. 3.0322.
3.033 Impact
3.0331 Effect of annealing temperature on the low temperature impact properties of ELI plate, Fig. 3.0331.
3.034 Bending
3.035 Torsion and shear
3.0351 Effect of test temperature on shear strength of bar, Fig. 3.0351.
3.036 Bearing
3.0361 Effect of test temperature on bearing properties of sheet, Fig. 3.0361.
3.037 Stress concentration
3.0371 Notch properties
3.03711 Effect of low test temperature, interstitial elements, and iron content on mild notch properties of sheet, Fig. 3.03711.
3.03712 Effect of test temperature on mild notch strength of sheet, Fig. 3.03712.
3.03713 Effect of test temperature on mild notch strength of bar, Fig. 3.03713.
3.03714 Effect of sheet thickness, interstitial element and iron content on sharp notch properties at -423F, Fig. 3.03714.
3.03715 Influence of cold rolling on -423F sharp notch strength of ELI sheet, Fig. 3.03715.
3.03716 Effect of stretching on the -423F sharp notch strength of ELI sheet, Fig. 3.03716.
3.0372 Fracture toughness
3.03721 General. The fracture toughness of this alloy is very high at room temperature and above. At cryogenic temperatures the toughness is highly dependent on the interstitial element content and the content of stabilizing elements. If the content of these elements is low (ELI grade) the alloy is very well suited to service at liquid hydrogen temperatures in sheet gages. Cooling rapidly from the annealing temperature appears to increase the toughness of sheet and this treatment should be used for critical applications. Fracture toughness values for plate are not yet available.
3.03722 Fracture toughness at -423F as function of thickness for ELI sheet cooled slowly and rapidly from annealing temperature, Fig. 3.03722.
3.038 Combined properties

3.04 Creep and Creep Rupture Properties
3.041 Creep deformation curves for sheet at 800F and 1000F, Fig. 3.041.
3.042 Creep deformation curves for sheet at 1100F, Fig. 3.042.
3.043 Isochronous stress-strain curves at 800F for annealed sheet, Fig. 3.043.
3.044 Isochronous stress-strain curves at 1000F for annealed sheet, Fig. 3.044.

3.05 Fatigue Properties
3.051 Rotating bending fatigue strength for smooth and notched sheet, Table 3.051.

TABLE 3.051

Source		(5, p. 6)					
Form		Sheet					
Condition		Ann					
Temp - F	Method	Stress Ratio A	Stress Ratio R	Stress Concentration	Fatigue Strength-ksi at cycles 10^5	10^6	10^7
RT	Rot beam	∞	-1	Smooth K = 1	77	64	62
				Notched K = 2.4	56	45	43
				K = 3.2	40	30	27

3.052 Stress range diagram at 10^7 cycles for smooth and notched specimens of sheet, Fig. 3.052.

3.06 Elastic Properties
3.061 Poisson s ratio
3.062 Modulus of elasticity
3.0621 Static modulus of elasticity at low and elevated temperatures, Fig. 3.0621.
3.0622 Dynamic modulus of elasticity at low and elevated temperatures, Fig. 3.0622.
3.063 Modulus of rigidity

4. FABRICATION

4.01 Formability
See Titanium Commercially Pure
4.011 General. Formability of Ti-5Al-2.5Sn is inferior to that of Commercially Pure Titanium and Ti-8Mn. Short heating times are necessary when forming above 1000F.
4.012 Forging. Starting temperature. 1925F maximum, finishing temperature, 1650F minimum. To obtain optimum properties, reductions equivalent to 25 to 40 percent should be performed below the beta to alpha + beta transformation temperature in the final forging operation. Subsequent reheating, such as required for sizing operations, should not exceed a temperature of about 200F below the beta to alpha + beta transformation temperature.

4.02 Machining and Grinding
See Titanium Commercially Pure

4.03 Welding
4.031 General. This alloy is readily weldable by the same processes used for Commercially Pure Titanium. Fusion welds using the TIG or MIG process are preferred for high toughness at cryogenic temperatures. The fracture toughness at -425F of TIG fusion welds made in sheet is as high as the fracture toughness of parent metal provided that contamination is avoided, (24). Brazing is not recommended at this time due to brittleness associated with the formation of intermetallic compounds.
4.032 Effect of test temperature on impact strength of plate MIG welded with various fillers, Fig. 4.032.

4.04 Heat Treatment

4.05 Surface Treatment
See Titanium Commercially Pure

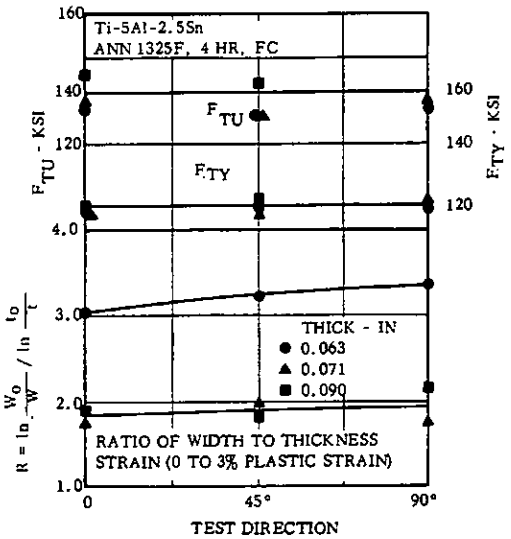


FIG. 1.0911 DIRECTIONALITY OF TENSILE STRENGTH AND PLASTIC STRAIN FOR THREE HEATS OF ANNEALED SHEET (29, p. 12)

Ti
5 Al
2.5 Sn

Ti-5Al-2.5Sn

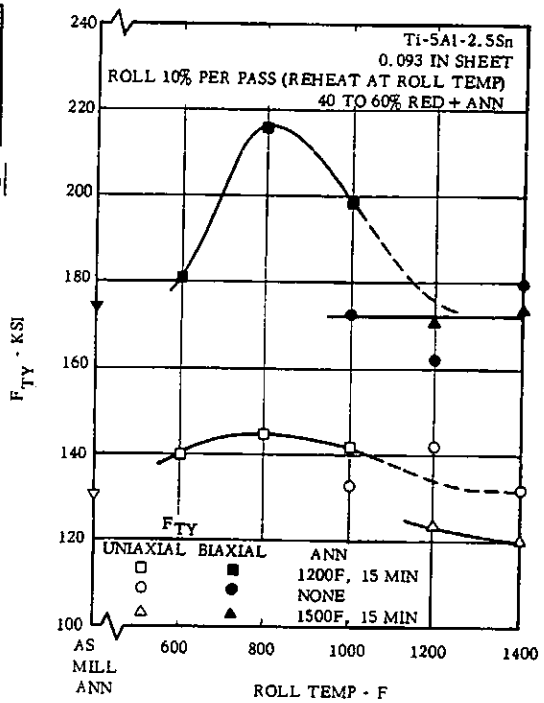


FIG. 1.0912 EFFECT OF ROLLING TEMPERATURE AND ANNEALING TREATMENT ON THE UNAXIAL YIELD STRENGTH AND THE THEORETICAL BIAXIAL YIELD STRENGTH IN A 2:1 STRESS FIELD (28, p. 5)

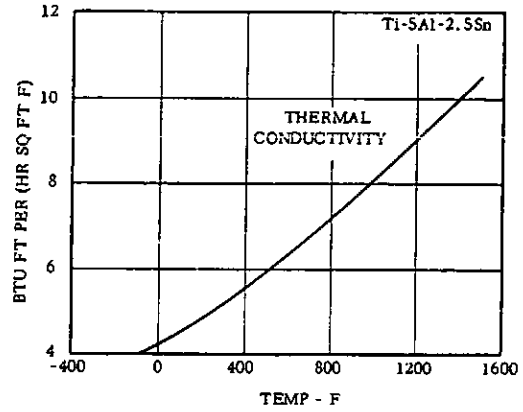


FIG. 2.013 THERMAL CONDUCTIVITY (5, p. 3)

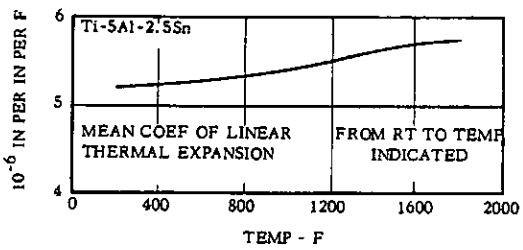


FIG. 2.014 THERMAL EXPANSION (5, p. 2)

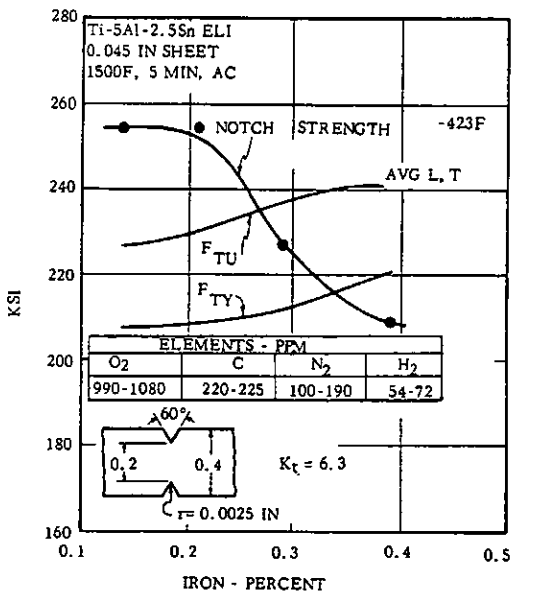


FIG. 1.0931 EFFECT OF IRON CONTENT ON -423F TENSILE AND MILD NOTCH PROPERTIES OF ELI SHEET (27)

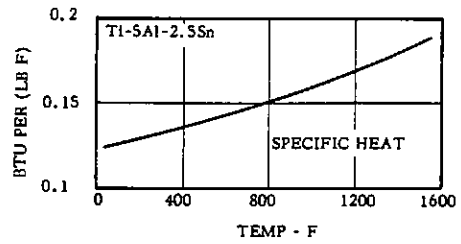


FIG. 2.015 SPECIFIC HEAT (5, p. 3)

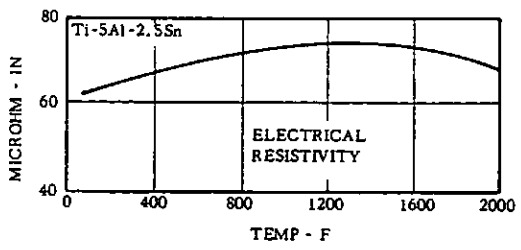


FIG. 2.022 ELECTRICAL RESISTIVITY (5, p. 2)

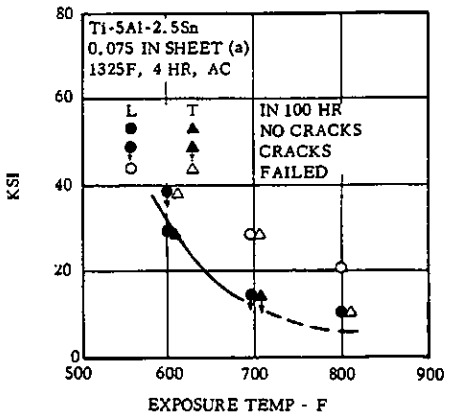
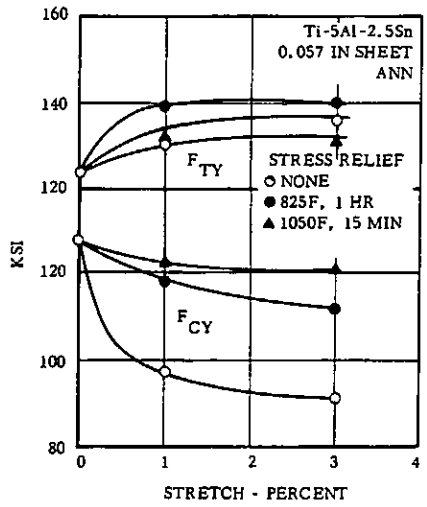


FIG. 2.0321 EFFECT OF STRESS AND TEMPERATURE ON 100 HOURS SALT STRESS CORROSION OF SHEET (17)

(a) 1/4 in wide smooth specimen coated 1/16 inch thick with ASTM sea salt.



Ti
5 Al
2.5 Sn
Ti-5Al-2.5Sn

FIG. 3.0213 EFFECT OF STRETCHING AND STRESS RELIEF ON TENSILE AND COMPRESSIVE YIELD STRENGTH OF SHEET (13)

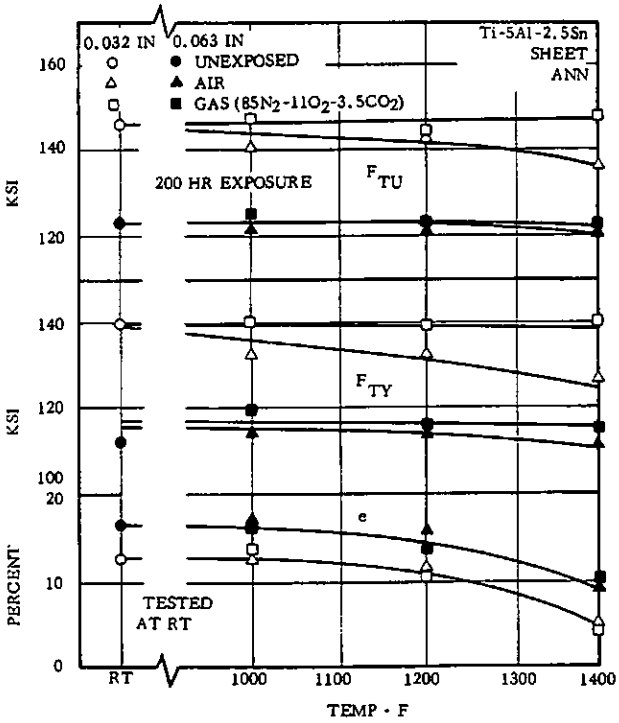


FIG. 3.0212 EFFECT OF EXPOSURE IN VARIOUS MEDIUMS TO ELEVATED TEMPERATURES ON TENSILE PROPERTIES OF SHEET (12)

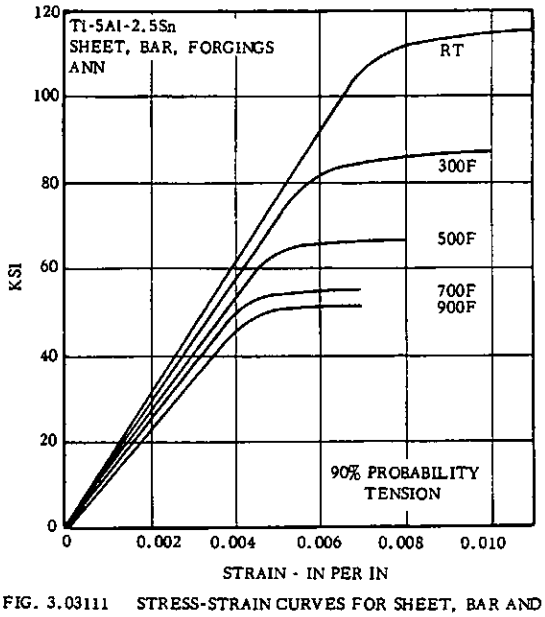


FIG. 3.03111 STRESS-STRAIN CURVES FOR SHEET, BAR AND FORGINGS AT ROOM AND ELEVATED TEMPERATURES (10, p. 31)

	Ti
5	Al
2.5	Sn

Ti-5Al-2.5Sn

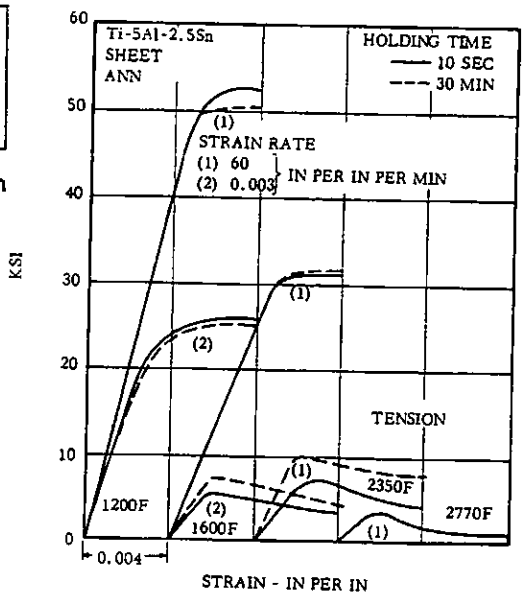


FIG. 3.03112 STRESS-STRAIN CURVES FOR SHEET AT VERY HIGH TEMPERATURES WITH VARIOUS STRAIN RATES AND HOLDING TIMES (9, p. 54)

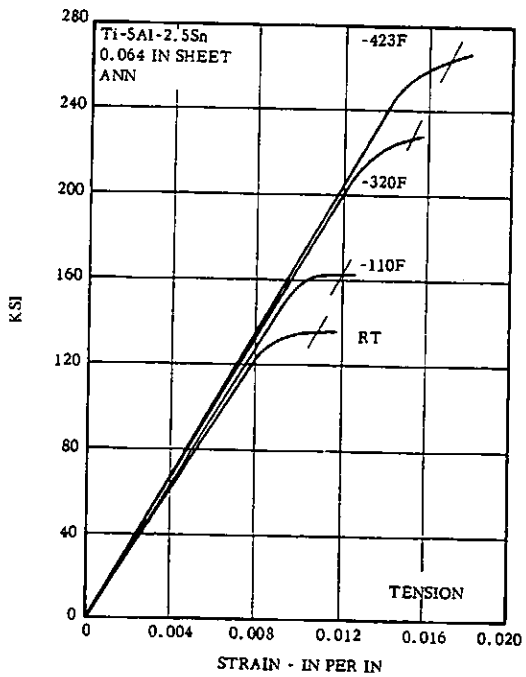


FIG. 3.03113 STRESS-STRAIN CURVES FOR SHEET AT LOW TEMPERATURES (8, p. 43)

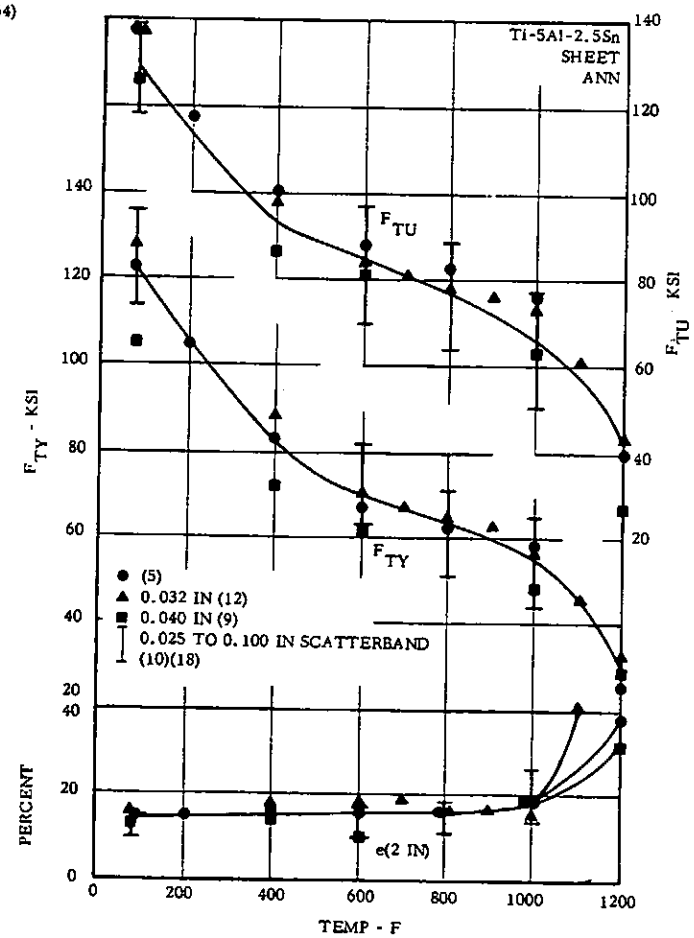


FIG. 3.0312 EFFECT OF ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF SHEET (5, p. 5)(9)(10, p. 15, 16)(12)(18, p. 5)

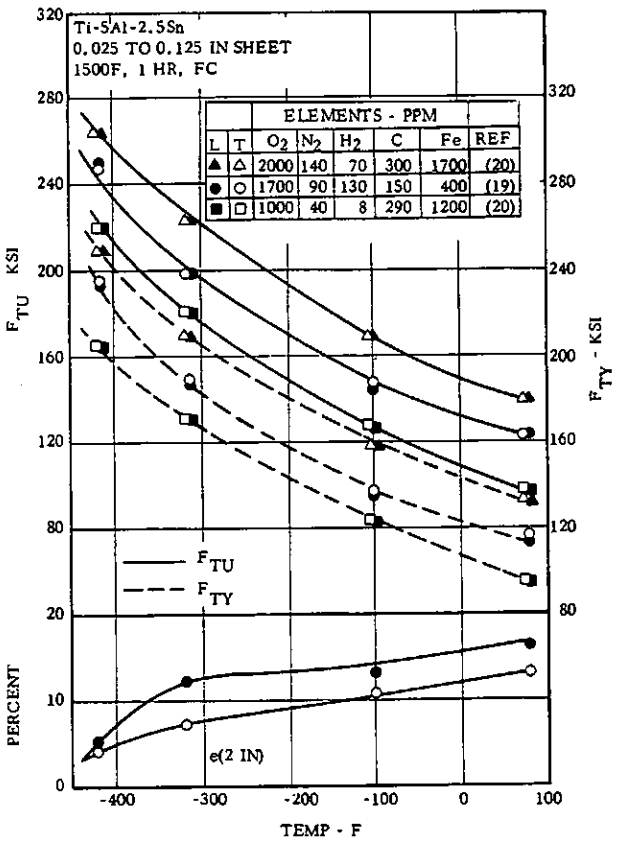


FIG. 3.0313 EFFECT OF LOW TEST TEMPERATURES AND INTERSTITIAL ELEMENT AND Fe-CONTENT ON TENSILE PROPERTIES OF SHEET (19, p. 204)(20)

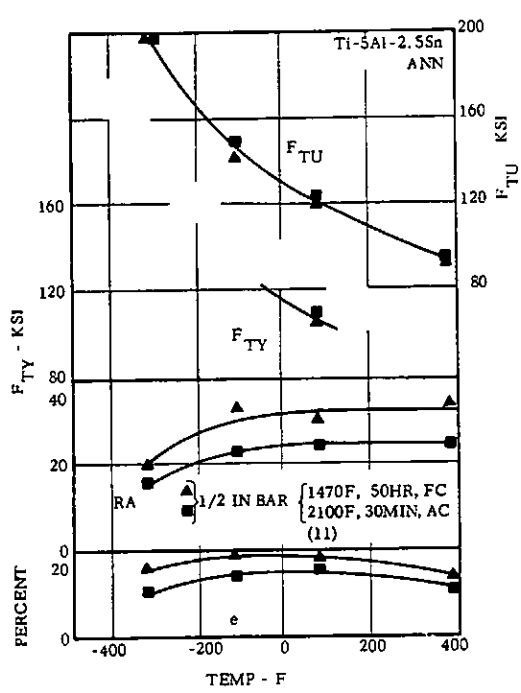


FIG. 3.0314 EFFECT OF LOW AND ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF BAR (11, p. 13, Tbl. 4)

Ti
5 Al
2.5 Sn
Ti-5Al-2.5Sn

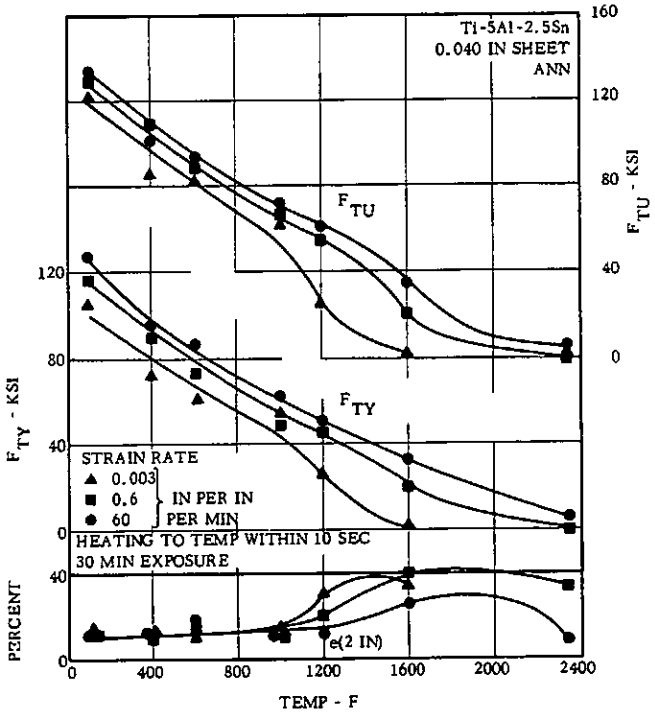


FIG. 3.0315 EFFECT OF TEST TEMPERATURE, STRAIN RATE AND HOLDING TIME ON TENSILE PROPERTIES OF SHEET (9, Tbl. VI)

	Ti
5	Al
2.5	Sn

Ti-5Al-2.5Sn

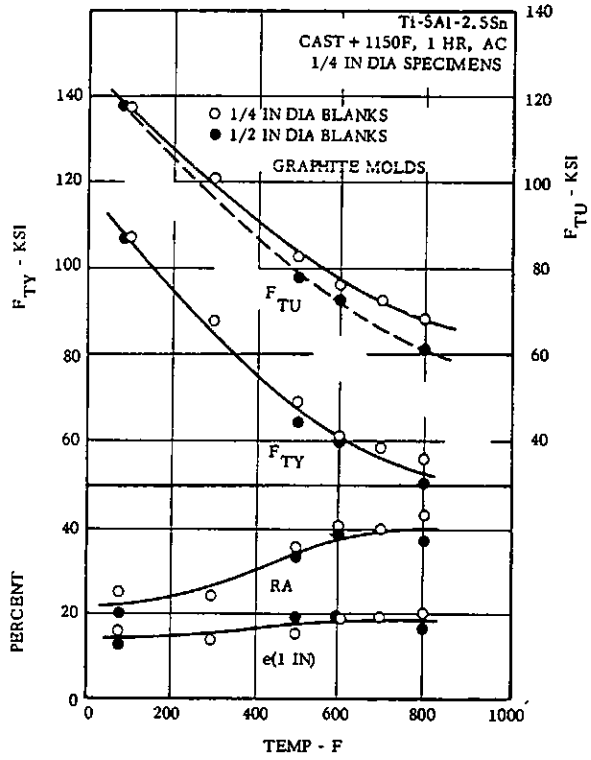


FIG. 3.0316 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF CASTINGS (21, p. A 4.2)

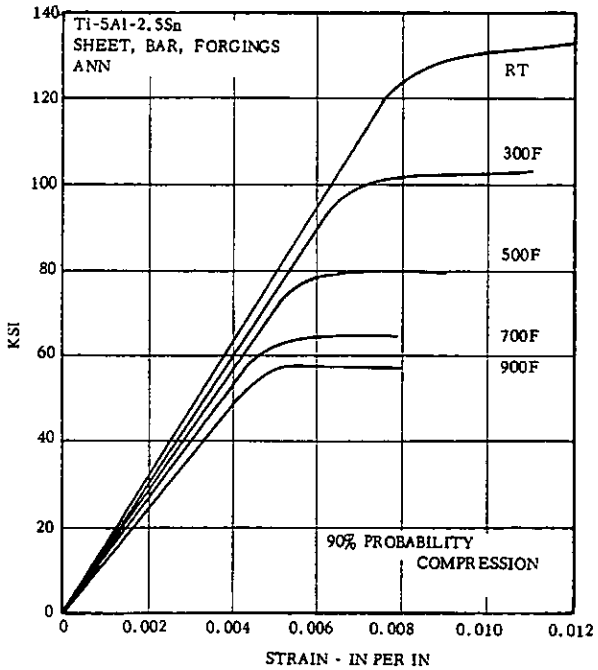


FIG. 3.0321 STRESS-STRAIN CURVES IN COMPRESSION FOR SHEET, BAR AND FORGINGS AT ROOM AND ELEVATED TEMPERATURES (10, p. 32)

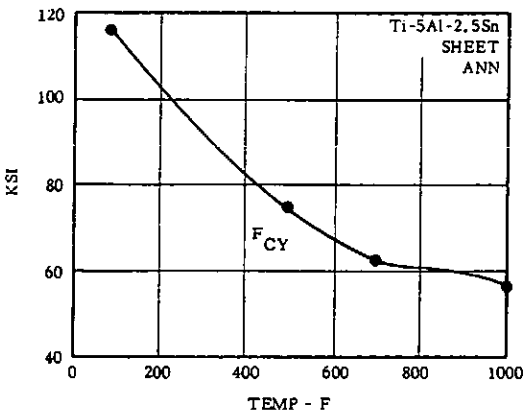


FIG. 3.0322 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF SHEET (6, p. 89)

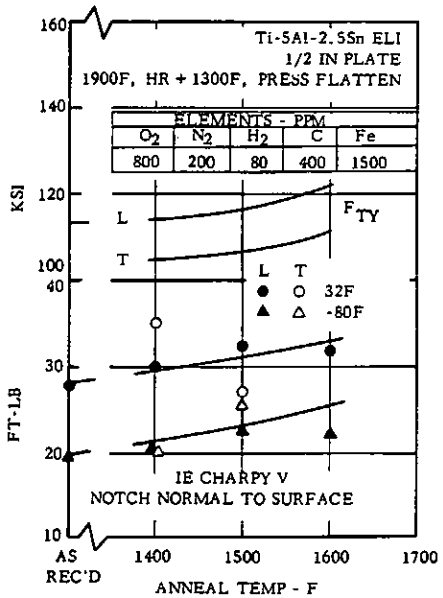


FIG. 3.0331 EFFECT OF ANNEALING TEMPERATURE ON THE LOW TEMPERATURE IMPACT PROPERTIES OF ELI PLATE (22)

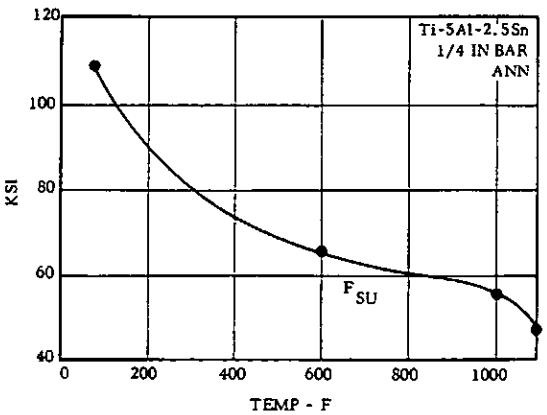


FIG. 3.0351 EFFECT OF TEST TEMPERATURE ON SHEAR STRENGTH OF BAR (10, p. 37)

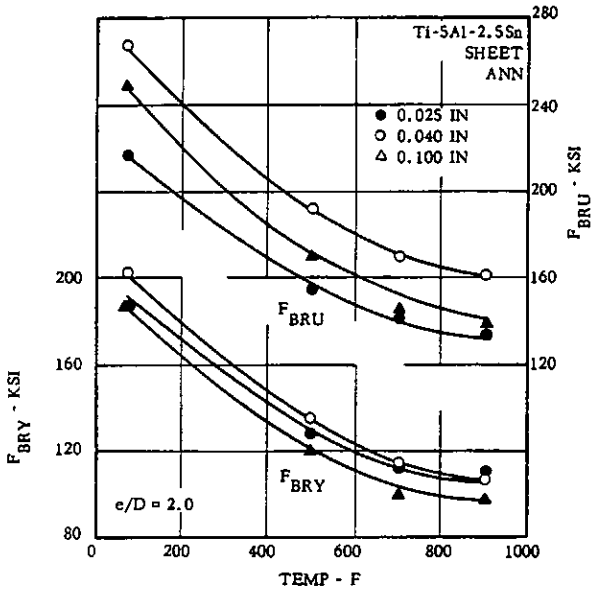
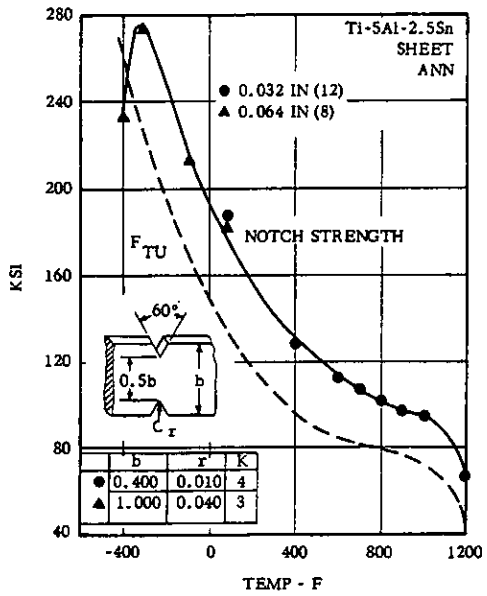


FIG. 3.0361 EFFECT OF TEST TEMPERATURE ON BEARING PROPERTIES OF SHEET (7, p. D-4)



Ti
5 Al
2.5 Sn
Ti-5Al-2.5Sn

FIG. 3.03712 EFFECT OF TEST TEMPERATURE ON MILD NOTCH STRENGTH OF SHEET (8, p. 37)(12)

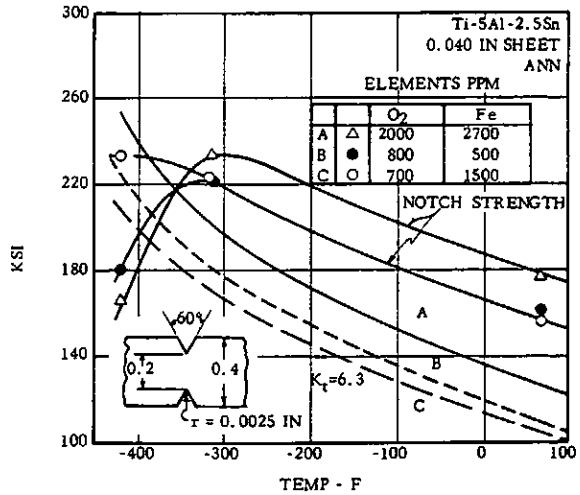


FIG. 3.03711 EFFECT OF LOW TEST TEMPERATURES, INTERSTITIAL ELEMENT AND IRON CONTENT ON MILD NOTCH PROPERTIES OF SHEET (23)

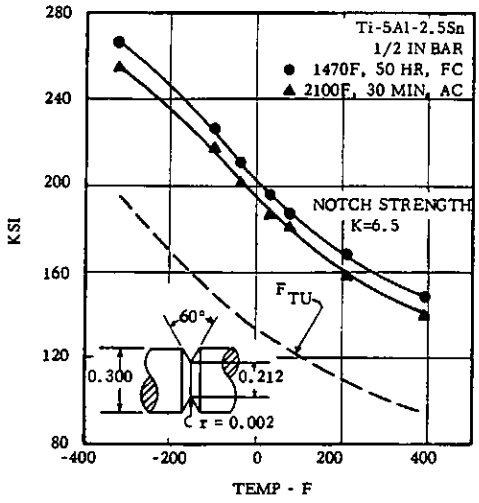


FIG. 3.03713 EFFECT OF TEST TEMPERATURE ON MILD NOTCH STRENGTH OF BAR (11)

Ti	
5	Al
2.5	Sn

Ti-5Al-2.5Sn

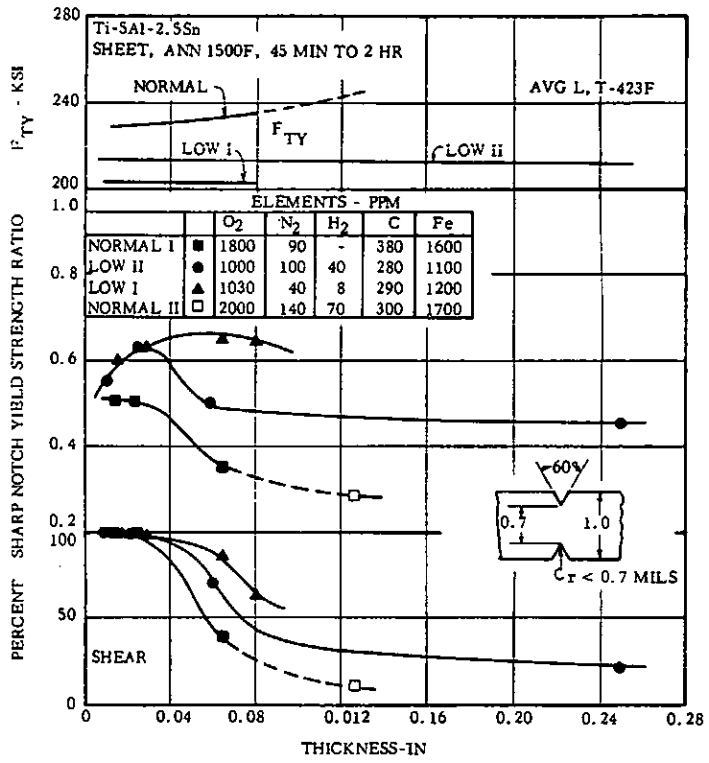


FIG. 3.03714 EFFECT OF SHEET THICKNESS, INTERSTITIAL ELEMENT AND IRON CONTENT ON SHARP NOTCH PROPERTIES AT -423F (24)

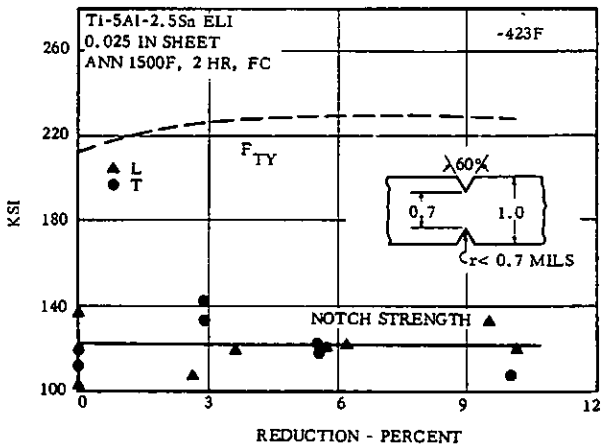


FIG. 3.03715 INFLUENCE OF COLD ROLLING ON -423F SHARP NOTCH STRENGTH OF ELI SHEET (24)

	Ti
5	Al
2.5	Sn

Ti-5Al-2.5Sn

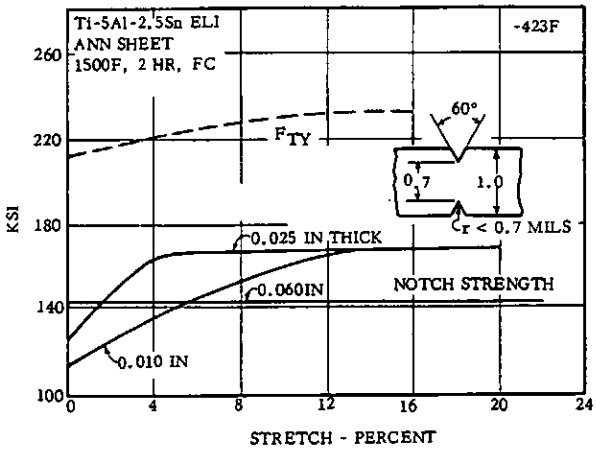


FIG. 3.03716 EFFECT OF STRETCHING ON -423F SHARP NOTCH STRENGTH OF ELI SHEET (24)

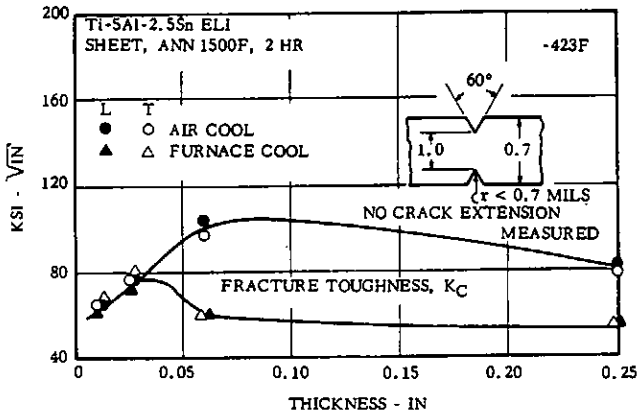


FIG. 3.03722 FRACTURE TOUGHNESS AT -423F AS FUNCTION OF THICKNESS FOR ELI SHEET COOLED SLOWLY AND RAPIDLY FROM ANNEALING TEMPERATURE (24)

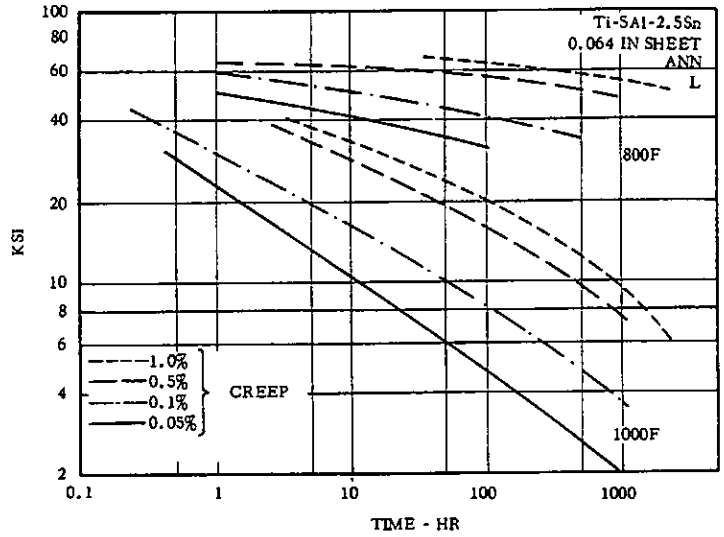


FIG. 3.041 CREEP DEFORMATION CURVES FOR SHEET AT 800 AND 1000F (18, p. 23)

	Ti
5	Al
2.5	Sn

Ti-5Al-2.5Sn

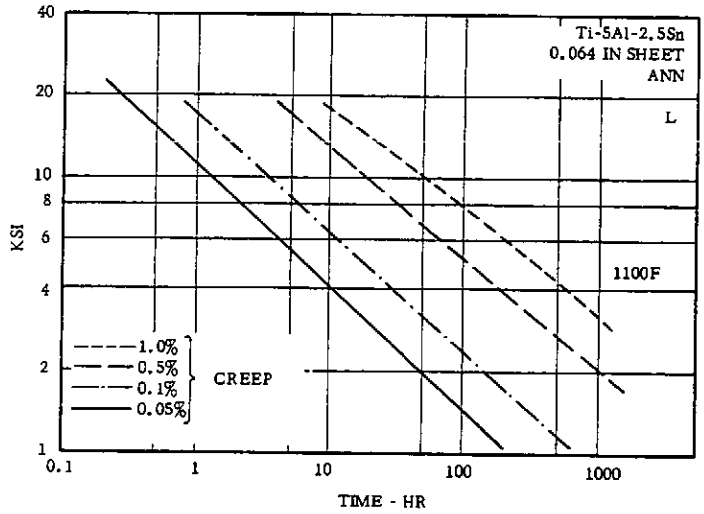


FIG. 3.042 CREEP DEFORMATION CURVES FOR SHEET AT 1100F (18, p. 23)

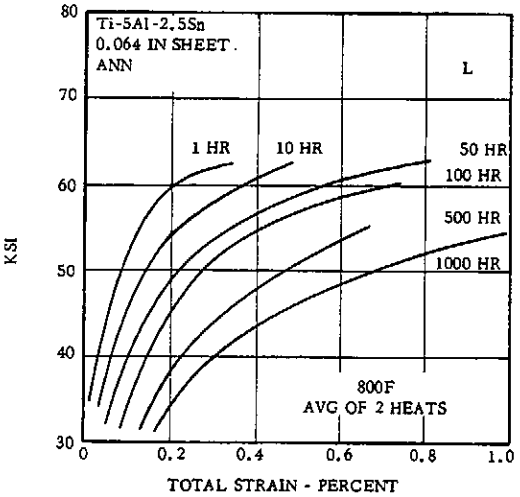


FIG. 3.043 ISOCHRONOUS STRESS-STRAIN CURVES AT 800F FOR ANNEALED SHEET (18, p. 17)

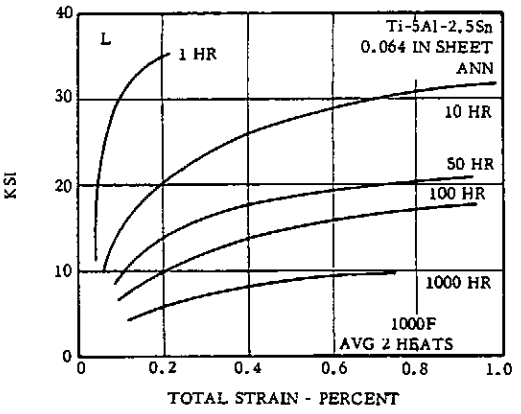


FIG. 3.044 ISOCHRONOUS STRESS-STRAIN CURVES AT 1000F FOR ANNEALED SHEET (18, p. 17)

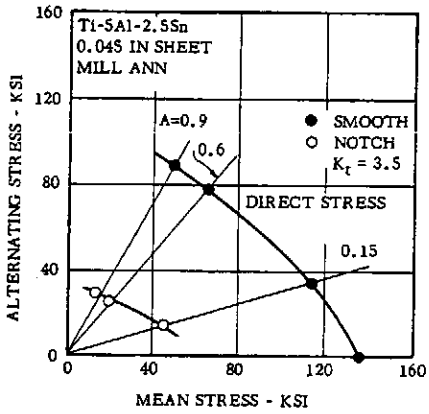


FIG. 3.052 STRESS RANGE DIAGRAM AT 10^7 CYCLES FOR SMOOTH AND NOTCHED SPECIMENS OF SHEET (25)

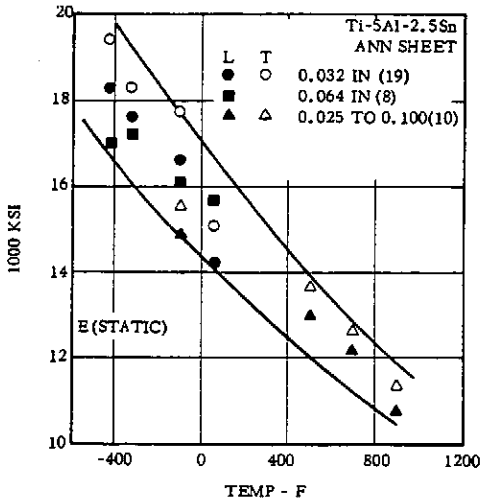


FIG. 3.0621 STATIC MODULUS OF ELASTICITY AT LOW AND ELEVATED TEMPERATURES (8)(10)(19)

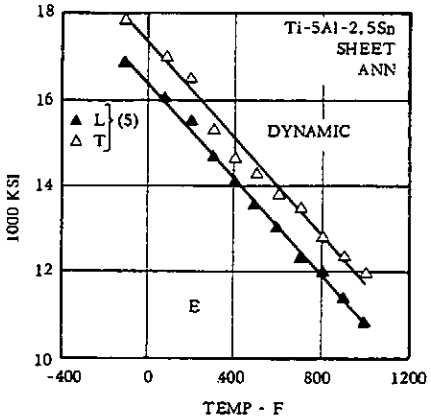


FIG. 3.0622 DYNAMIC MODULUS OF ELASTICITY AT LOW AND ELEVATED TEMPERATURES (5, p. 2)

REVISED: MARCH 1963

NONFERROUS ALLOYS

Ti
8 Mn

1. GENERAL

Ti-8Mn is an alpha beta type titanium alloy that has good elevated temperature strength and stability up to 600 F. The alloy is heat treatable, but it is used in the annealed condition only. It is available primarily in form of sheet and plate. The alloy possesses good formability, but its weldability is limited.

1.01 Commercial Designation. 8Mn Titanium Alloy.

1.02 Alternate Designations. Ti-8Mn, MST-8Mn, C-110M, RS-110A.

1.03 Specifications. Table 1.03.

TABLE 1.03

AMS	Form	Military
4908A	Sheet, strip, plate	MIL-T-009046 (ASG) Cl-1

1.04 Composition. Table 1.04.

TABLE 1.04

Source	AMS (1)	
	Percent	
	Min	Max
Manganese	6.50	9.00
Carbon	-	0.20
Oxygen	-	0.20*
Nitrogen	-	0.07
Hydrogen	-	0.015
Other elements, total	-	0.60**
Titanium	Balance	

* If determined
** Need not be reported

1.05 Heat Treatment
1.051 Anneal. 1300 F, 1 hr, cool 300 F per hr maximum to 1050 F maximum.
1.052 Stress relief. Below 700 F or at 1000 F. Stress relief at 700 to 850 F may result in notch sensitivity.
1.053 Heat treat. 1250 to 1400 F, 1/2 to 2 hr, water quench or air cool +900 to 950 F, 1 to 8 hr. This treatment can increase tensile strength by as much as 75 ksi.

1.06 Hardenability. Although this alloy is heat treatable, heat treatment is not recommended because of poor reproducibility of mechanical properties.

1.07 Forms and Conditions Available
1.071 Alloy is available in the full commercial range of sizes for sheet, strip and plate.
1.072 Other wrought products can be produced, but are not generally used.

1.08 Melting and Casting Practice. Consumable electrode double vacuum melt.

1.09 Special Considerations. See Ti, Commercially Pure.

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties
2.011 Melting range. 2730 to 2970F.
2.012 Phase changes. This alloy transforms on cooling from beta to alpha + beta at 1425 to 1525 F.
2.013 Thermal conductivity, Fig. 2.013.
2.014 Thermal expansion, Fig. 2.014.
2.015 Specific heat, Fig. 2.015.
2.02 Other Physical Properties
2.021 Density. 0.170 to 0.171 lb per cu in. 4.70 to 4.73 gr per cu cm.
2.022 Electrical resistivity, Fig. 2.022.
2.023 Magnetic properties. Alloy is nonmagnetic. Permeability at 20 oersteds, 1.00005.

2.03 Chemical Properties. See Ti, Commercially Pure. Only different or complementary information listed below.
2.031 Hydrogen embrittlement
2.0311 Effect of hydrogen content on tensile properties of sheet, Fig. 2.0311.
2.0312 Effect of hydrogen content on creep rupture curves for notched sheet, Fig. 2.0312.
2.0313 Effect of test temperature on tensile properties of sheet with various hydrogen contents, Fig. 2.0313.

2.04 Nuclear Properties

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties
3.011 AMS specified mechanical properties, Table 3.011.

TABLE 3.011

Source	AMS (1)
Alloy	Ti-8Mn
Form	Sheet, strip, plate
Condition	Ann
F_{tu}, min - ksi	120
F_{ty}, min - ksi	110
max - ksi	140
e, min - percent	10

3.02 Mechanical Properties at Room Temperature. See 3.03 also.
3.021 Hardness. Annealed sheet, 33 to 36 RC.
3.022 Effect of stretching on tensile and compressive yield strengths of annealed sheet (Bauschinger effect), Fig. 3.022.

3.03 Mechanical Properties at Various Temperatures
3.031 Short time tension properties
3.0311 Stress strain curves for annealed sheet, Fig. 3.0311.
3.0312 Effect of test temperature on tensile properties of annealed sheet, Fig. 3.0312.
3.0313 Effect of low test temperature on tensile properties of annealed sheet, Fig. 3.0313.
3.032 Short time properties other than tension
3.0321 Stress strain curves in compression for annealed sheet, Fig. 3.0321.
3.0322 Effect of test temperature on compressive yield strength of annealed sheet, Fig. 3.0322.
3.0323 Effect of test temperature on bearing properties of annealed sheet, Fig. 3.0323.
3.0324 Effect of test temperature on shear strength of annealed sheet, Fig. 3.0324.
3.033 Static stress concentration effects. Effect of test temperature on notch strength of annealed sheet, Fig. 3.033.

3.04 Creep and Creep Rupture Properties
3.041 Creep and creep rupture curves at 600 to 800 F for annealed sheet, Fig. 3.041.
3.042 Short time total strain curves at 800 to 1200 F for annealed sheet, Fig. 3.042.

3.05 Fatigue Properties
3.051 Room temperature fatigue strength of annealed sheet, Table 3.051.

TABLE 3.051

Source	(2)						
Form	Sheet						
Condition	Ann						
Temp F	Method	Stress Ratio		Stress Concentration	Fatigue Strength-ksi at Cycles		
		A	R		10^5	10^6	10^7
RT	Direct Stress	0.6	0.25	Smooth K = 1	85	85	85

Ti
8 Mn

3.06 Elastic Properties

3.061 Modulus of elasticity at room and elevated temperatures, Fig. 3.061.

3.052 Modulus of elasticity at room and low temperatures, Fig. 3.062.

3.053 Tangent modulus curves in compression at room and elevated temperatures, Fig. 3.053.

4. FABRICATION. See Ti, Commercially Pure. Only different or complementary information is given below.

4.01 Forming and Casting

4.011 General. 500 to 600 F is the optimum range for formability, and forming in this range reduces spring back, notch sensitivity and power required. Forming at 1000 to 1200F is also common, but a post forming anneal is required.

4.012 Forging. Starting temperature, 1700 F maximum, finishing temperature, 1450 F minimum. To obtain optimum properties, reductions equivalent to 25 to 40 percent should be performed in the alpha +beta range in the final forging operation. Subsequent reheating, such as required for sizing operations, should not exceed a temperature of about 200 F below the beta to alpha +beta transformation temperature.

4.03 Welding. Ti-8Mn is not recommended for any kind of fusion welding. Spot welding has been employed, although shear tests generally indicate poor weld characteristics.

4.04 Heating and Heat Treating. See Ti-6Al-4V.

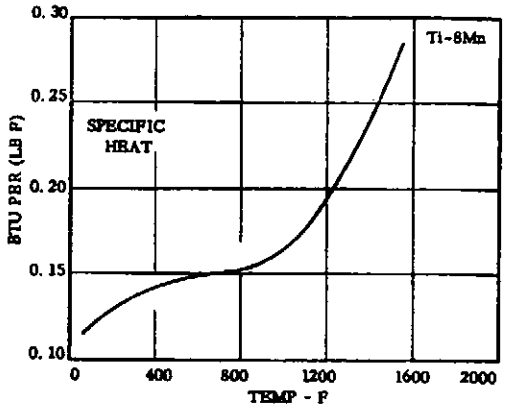


FIG. 2.015 SPECIFIC HEAT

(6, p. III-1-13)

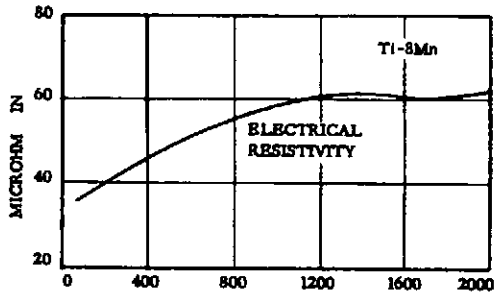


FIG. 2.022 ELECTRICAL RESISTIVITY

(3, p. W-3)

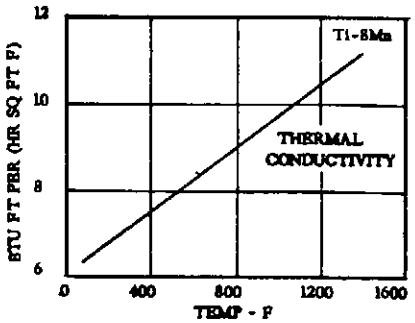


FIG. 2.013 THERMAL CONDUCTIVITY

(3, p. W-2)

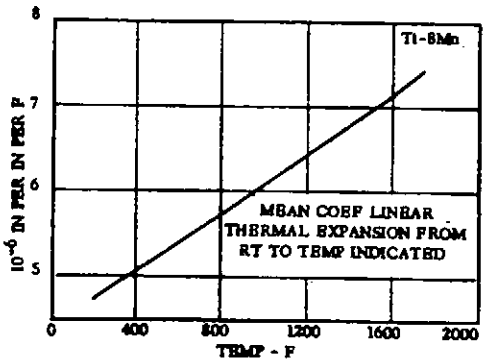


FIG. 2.014 THERMAL EXPANSION

(3, p. W-2)

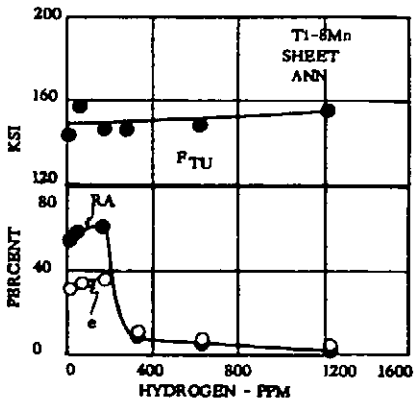


FIG. 2.031 EFFECT OF HYDROGEN CONTENT ON TENSILE PROPERTIES OF SHEET

(4)

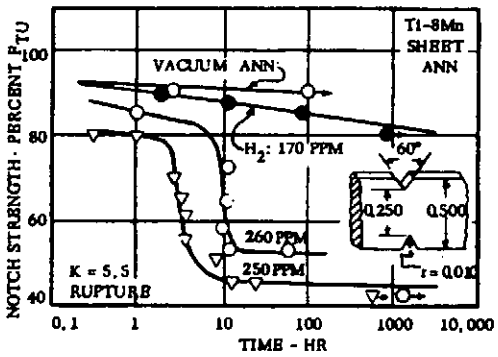
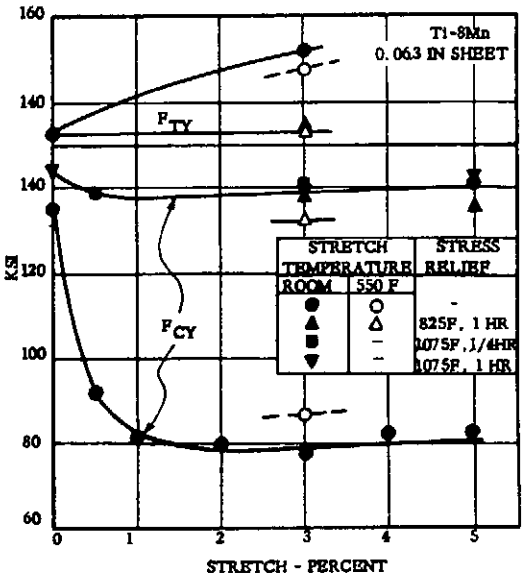


FIG. 2.0312 EFFECT OF HYDROGEN CONTENT ON CREEP RUPTURE CURVES FOR NOTCHED SHEET (4)



Ti
8 Mn

FIG. 3.022 EFFECT OF STRETCHING ON TENSILE AND COMPRESSIVE YIELD STRENGTHS OF ANNEALED SHEET (BAUSCHINGER EFFECT) (12)

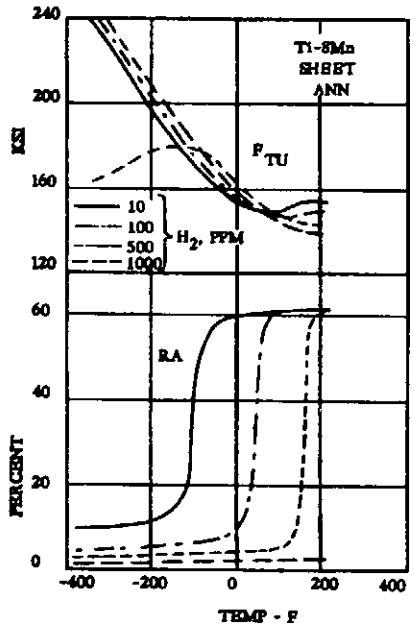


FIG. 2.0313 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SHEET WITH VARIOUS HYDROGEN CONTENTS (5)

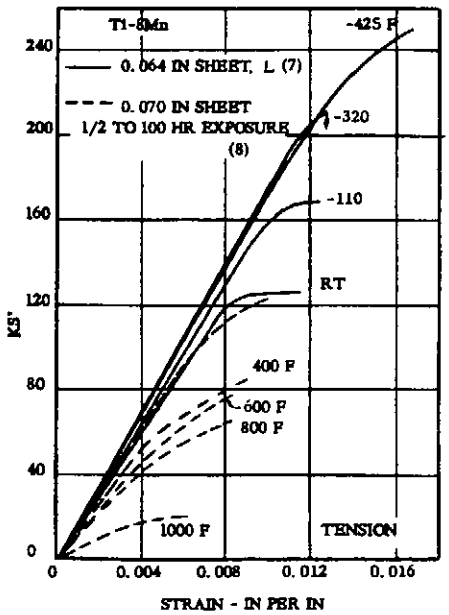


FIG. 3.0311 STRESS STRAIN CURVES FOR ANNEALED SHEET (7, p. 43)(8)

Ti
8 Mn

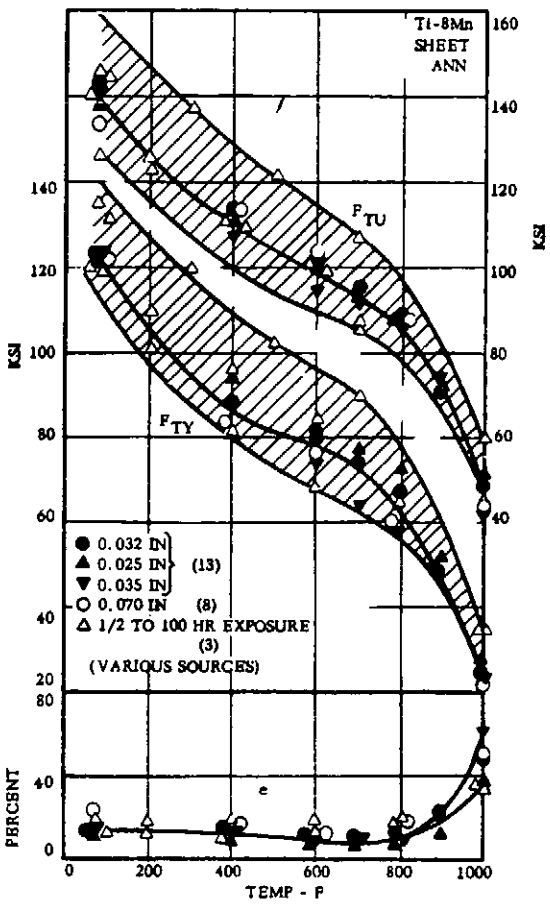


FIG. 3.0312 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED SHEET

(3)(8)(13)

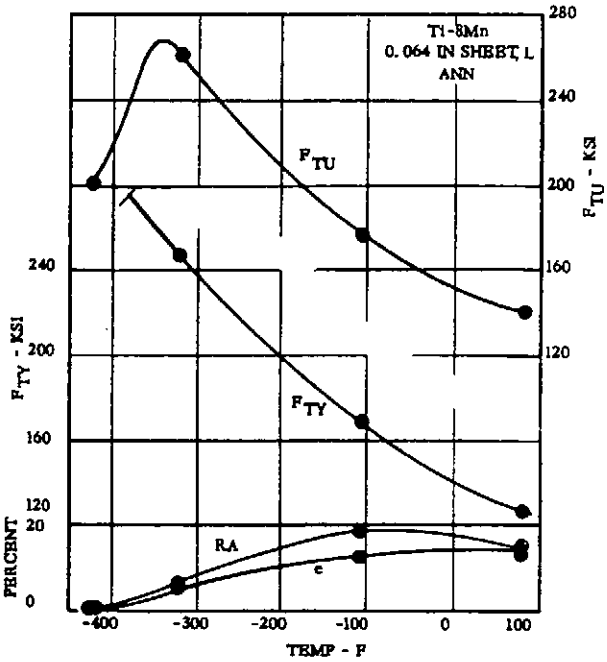


FIG. 3.0313 EFFECT OF LOW TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED SHEET

(7, p. 20)

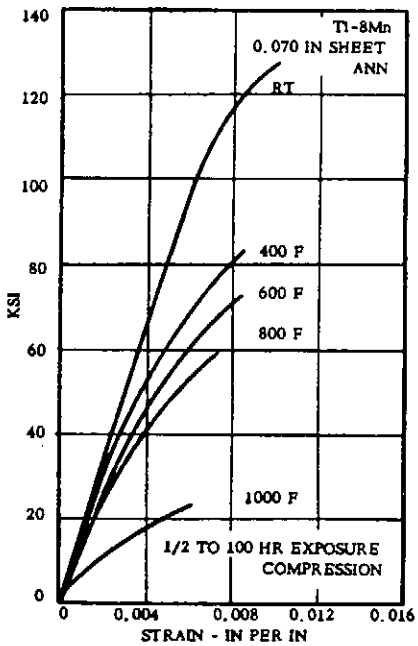


FIG. 3.0321 STRESS STRAIN CURVES IN COMPRESSION FOR ANNEALED SHEET

(8)

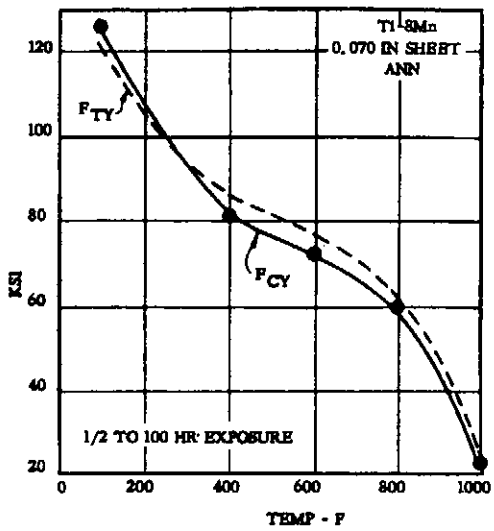


FIG. 3.0322 EFFECT OF TEST TEMPERATURE ON COMPRESSIVE YIELD STRENGTH OF ANNEALED SHEET (8)

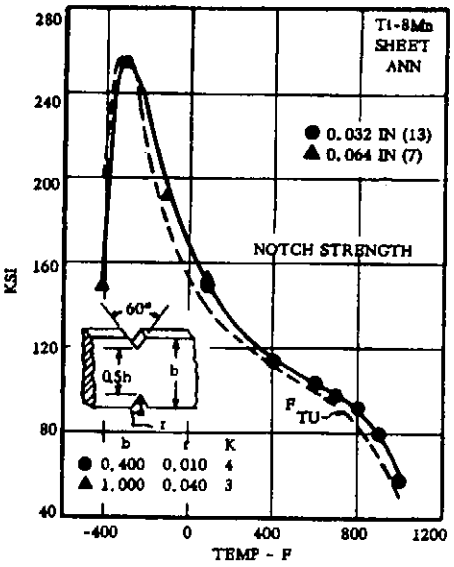


FIG. 3.033 EFFECT OF TEST TEMPERATURE ON NOTCH STRENGTH OF ANNEALED SHEET (7, p. 29)(13)

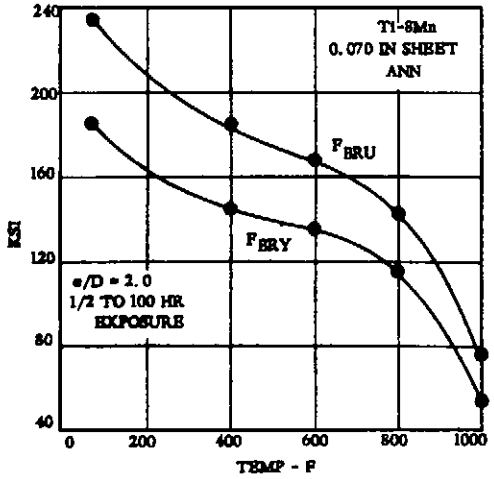


FIG. 3.0323 EFFECT OF TEST TEMPERATURE ON BEARING PROPERTIES OF ANNEALED SHEET (10)

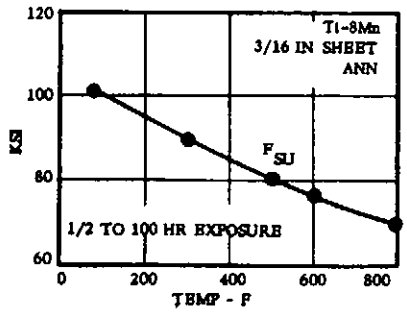


FIG. 3.0324 EFFECT OF TEST TEMPERATURE ON SHEAR STRENGTH OF ANNEALED SHEET (8)

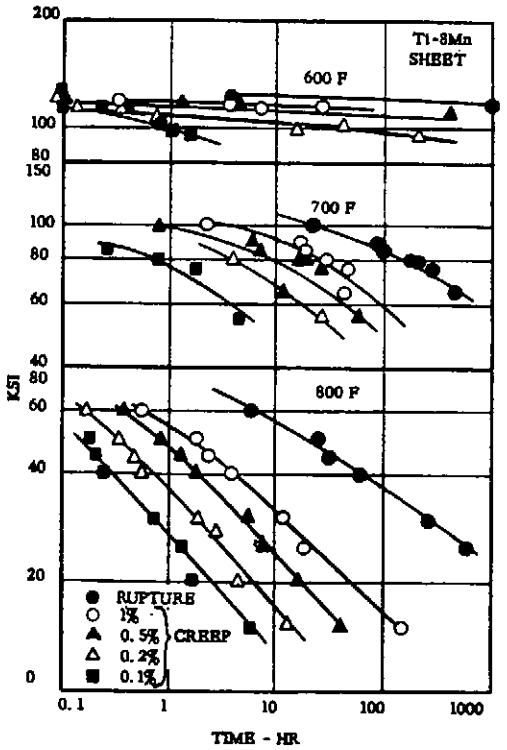


FIG. 3.041 CREEP AND CREEP RUPTURE CURVES AT 600 TO 800 F FOR ANNEALED SHEET (9)

Ti
8 Mn

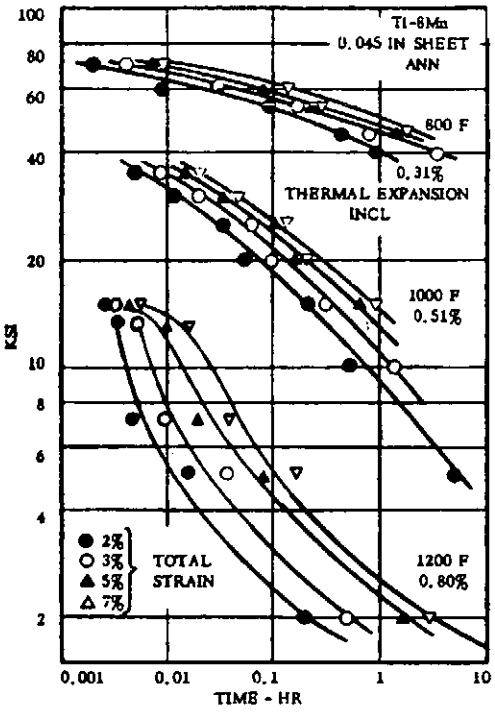


FIG. 3.042 SHORT TIME TOTAL STRAIN CURVES AT 800 TO 1200 F FOR ANNEALED SHEET (11)

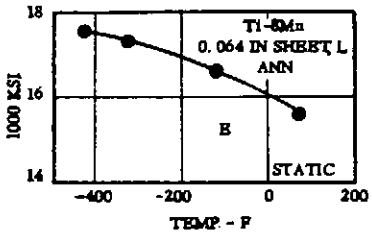


FIG. 3.062 MODULUS OF ELASTICITY AT ROOM AND LOW TEMPERATURES (7, p. 20)

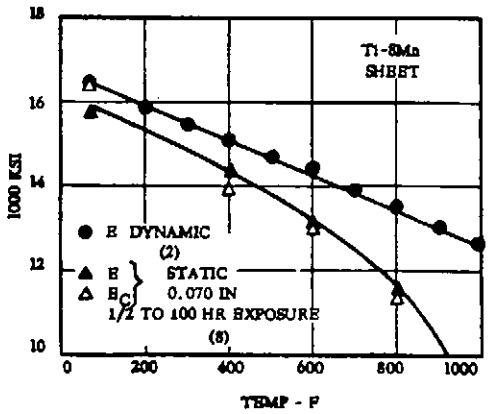


FIG. 3.061 MODULUS OF ELASTICITY AT ROOM AND ELEVATED TEMPERATURES (2)(8)

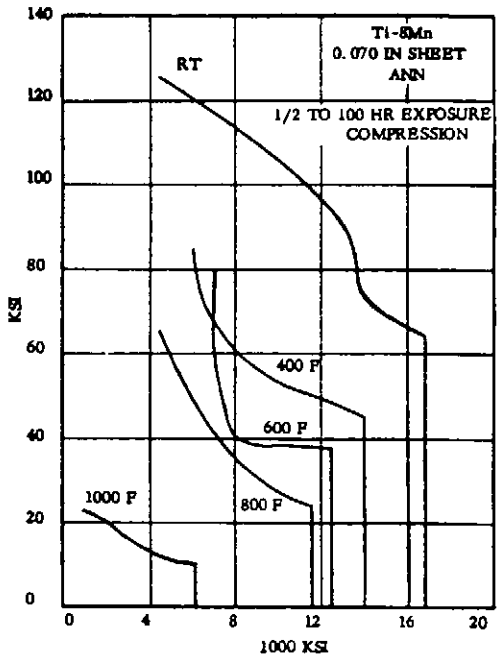


FIG. 3.063 TANGENT MODULUS CURVES IN COMPRESSION AT ROOM AND ELEVATED TEMPERATURES (8)

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1. General

This alloy was developed in the early 1970's by RMI Company under an Air Force Contract. The goal was to produce a composition which had higher hardenability than available α-β titanium alloys (e.g. Ti-6Al-4V) coupled with improved strength and good fracture toughness. By appropriate balance of the beta stabilizer elements Cr and Mo coupled with a small silicon addition, these goals were largely achieved. The resulting alloy had a modulus somewhat higher than widely used 6Al-4V. In 1988-1989 there was renewed interest in the alloy for applications in advanced military aircraft. Interest in these applications led to refinements in the composition and the development of thermomechanical processes designed to produce optimum combinations of strength and toughness. This Chapter presents both the old data and that resulting from recent investigations.

1.1 Commercial Designations

Ti-6Al-2Zr-2Mo-2Cr, Ti-6-2-2-2-2.

1.2 Alternate Designations

Ti-6-22-22, Ti-6-22-22Si, Ti-6Q2.

1.3 Specifications

1.3.1 *[Table]* Proposed design mechanical property values for α-β processed forgings and plate.

1.4 Composition

1.4.1 *[Table]* Chemical composition.

1.5 Heat Treatment

General. A range of mechanical properties can be developed by thermal-mechanical processes (TMP) which involve the interactive effect of forging conditions and subsequent heat treatment. The TMP determines the microstructure which in turn influences the mechanical properties in a complex manner.

Terminology. The following terminology is used when referring to the various steps in the TMP:

Finish forge temperature: the final soak temperature used prior to the last forging operation. Depending on the forging size and process, the part temperature will usually drop from the soak temperature during forging.

Beta forging: the finish forge temperature is above the beta transus (β_t) and the majority of the work is performed above β_t. This is sometimes referred to as through transus forging.

Alpha-beta forging: the final soak temperature is below the beta transus and the finish forge temperature is below the beta transus.

Beta solution treat: the solution temperature is above the beta transus.

Subtransus solution treat: the solution temperature is below the beta transus. This is sometimes referred to as an α-β heat treatment.

Conventional processing: finish forging below the beta transus followed by a single step subtransus solution treatment and aging at 1000F. This was the original processing schedule.

Mill anneal: 1350 to 1450F.

Duplex anneal: a two step subtransus solution treatment applied to α-β finished forging and plate used in some early development work.

Ti
6 Al
2 Sn
2 Zr
2 Mo
2 Cr
0.2 Si

Triplex heat treatment: a two step solution heat treatment where temperature in the first step is above the beta transus followed by rapid cooling to a subtransus temperature, air cooling and aging. This is presently the preferred heat treatment.

Effects of the TMP. It is obvious from the above that a wide range of microstructures and associated mechanical properties can be obtained from variations in the TMP. The majority of early data corresponded to α-β finish forging followed by a sub beta transus solution treatment (see Table 1.5.1.1). This TMP produced high strengths but relatively low fracture toughness.

A limited amount of the early data was produced using a duplex anneal of 1740F, AC to 1560F, WQ + 1000F, age.

More recently, studies of the effects of TMP variables have indicated that improved mechanical properties are associated with a transformed beta microstructure of acicular alpha containing little or no grain boundary alpha (Refs. 4, 6, 20). Data relating to one of these studies are summarized in Tables 1.5.1.1 and 1.5.1.2. The best combination of tensile properties and fracture toughness were produced by beta finish forging followed by solution treating somewhat below the beta transus and aging at 1000F (see Table 1.5.1.1, processes 1 and 2). The resulting microstructure was lamellar alpha with little or no grain boundary alpha. Alpha-beta finish forging followed by subtransus solution treating and aging at 1000F (see Table 1.5.1.1, processes 3 and 4) produced tensile strengths about equal to those resulting from beta finish forging but substantially reduced fracture toughness. The resulting microstructures consisted primarily of broken lamellar with equiaxed primary alpha. Processess 5 and 6 combine alpha-beta finish forging with a beta solution treatment. Process 6 employed a two step solution treatment producing tensile strengths and fracture toughness values nearly equal to those obtained by finish forging above the beta transus. This latter heat treatment is sometimes

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referred to as a triplex treatment. It has the advantage of producing desirable combinations of tensile strengths and fracture toughness without the very careful control of the forging process required by beta finish forging. The resulting microstructure was characterized by relatively coarse acicular alpha (Widmanstaten type). A triplex treatment is presently recommended (see Table 1.5.1.3) for forgings used in critical applications.

Highly acicular transformed microstructures would be expected to possess superior fatigue crack propagation resistance due to energy absorption associated with crack front splitting (Ref. 5). However, fatigue crack propagation data (see Figures 3.5.3.6 and 3.5.3.7) obtained for three TMPs did appear to correlate with the acicularity of the alpha platelets as judged from the TMP applied.

Cooling rate. The cooling rate from the solution treatment can alter the mechanical properties with the faster rates providing the higher tensile strengths. This cooling rate effect may be seen by comparing the tensile strengths and fracture toughness for the pancake and closed die forgings in Table 1.5.1.2. The fan cooled material had somewhat lower tensile strengths but higher fracture toughness than the oil quenched forging. The acicular alpha platelets increase in size with decrease in the cooling rate (Ref. 20). Another cooling rate study (see Figure 1.5.1.4) illustrated the variation of tensile strength with several quench methods from a subtransus solution temperature following beta finish forging (Ref. 20). As might be expected, the tensile strength falls with decreasing cooling rate which results in an increasing broadening of the alpha platelets. It appears that adequate fan cooling from the solution temperature can produce through hardening in section sizes up to three inches.

There is no assurance that a single TMP process can be defined as optimum for all forms of the alloy. However, based on available information, the triplex heat treatment shown in Table 1.5.1.3 is recommended for forgings and plates that have been alpha-beta finished forged.

1.5.1 Conventional Processing. Finish forge 1650 to 1700F + 1600 to 1700F, 0.5 hr, AC + 900 to 100F.

1.5.1.1 *[Table]* Effect of thermal mechanical processing on the tensile properties and fracture toughness of pancake forgings.

1.5.1.2 *[Table]* Effect of several thermal mechanical processes on the tensile properties and fracture toughness of forgings.

1.5.1.3 *[Table]* Triplex heat treatments specified for α-β finished forgings and plate.

1.5.1.4 *[Figure]* Effect of cooling rate on the tensile strength of a forging.

1.6 Hardness

Mill annealed – 39 RC.
α-β forged and triplex heat treated – 41-42 RC.

1.7 Forms and Conditions Available

Billets, forgings, plate, sheet and weld wire.

1.8 Melting and Casting Practice

1.9 Special Considerations

1.9.1 Effects of Silicon. The additions of Si increase the creep resistance of α-β titanium alloys and also increase the tensile strength. However, silicides of the form $(Ti,Zr)_5Si_3$ can precipitate at prior β grain boundaries and/or α-β platelet interfaces. This precipitation occurs on slow cooling from the solution temperature. These precipitates can substantially reduce the tensile ductility and the fracture toughness.

Recent work (Ref. 24) has systematically explored the influence of silicon on the tensile properties and fracture toughness of laboratory produced plate given several heat treatments. The results of this investigation are shown in Tables 1.9.1.1 through 1.9.1.3. For the triplex heat treatment (see Table 1.9.1.1) a substantial increase in tensile strength and a corresponding reduction in fracture toughness results from increasing the silicon level from 0.03 to 0.30 percent at an Oe of 0.18. Approximate TTT diagrams at different silicon levels indicate the maximum precipitation occurs between 1450 to 1500F. The deleterious effect of slow cooling through this temperature range is illustrated by the data in Table 1.9.1.2, which represent an intermediate hold at 1500F prior to aging. The result is low fracture toughness with the highest silicon level producing predominately intergranular fracture.

A regression analysis was used in an attempt to separate the effects of silicon from that of oxygen equivalent. The effect of silicon from this analysis was represented by the following expressions:

$$F_{ty} = 137.5 + 36.3 \text{ percent Si}$$
$$RA = 15.5 - 6.1 \text{ percent Si}$$
$$F_{tu} = 158.5 + 49.2 \text{ percent Si}$$
$$K_{Ic} = 91.6 - 49.5 \text{ percent Si.}$$

Increasing the aging temperature to 1150F (see Table 1.9.1.3) produced substantial loss in fracture toughness at the higher silicon levels. However, microstructure studies did not connect this loss with the appearance of silicides and its cause is presently unknown.

The above data are considered to support a specification maximum of 0.14 percent Si to avoid silicide embrittlement during fan cooling from the solution temperature for section sizes producing through hardening.

Some earlier work (Ref. 22) on conventionally processed Ti-6Al-2Sn-2Zr-1Mo-0.12O (see Table 1.9.1.4) showed similar effects of silicon on the tensile strength and fracture toughness but found no effect of silicon on the fatigue crack propagation rates.

1.9.1.1 *[Table]* Influence of silicon content on the tensile properties and fracture toughness of laboratory heats containing somewhat different equivalent oxygen contents.

1.9.1.2 *[Table]* Influence of silicon content on the tensile properties and fracture toughness of laboratory heats containing somewhat different equivalent oxygen contents and given an intermediate 1500F solution treatment.

1.9.1.3 *[Table]* Influence of silicon content on the tensile properties and fracture toughness of laboratory heats containing somewhat different oxygen equivalents and aged at 1150F.

1.9.1.4 *[Table]* Effect of silicon content on tensile properties and fracture toughness of a Ti-6Al-2Sn-2Zr-1Mo-0.12O alloy.

1.9.2 Solution temperatures in the range of 1500 to 1600F appears to produce a minimum in the tensile yield strength of sheet (see Figures 3.2.1.5 through 3.2.1.7).

1.9.3 Cooling rate from the solution temperature is critical for plate and forgings. Slow rates lead to reduced tensile strengths while very fast rates will increase tensile strength at the expense of reduced fracture toughness. Present recommendations follow the schedule given in Table 1.5.1.3 which specifies fan air cooling. Considering the possible variation in fan size and locations in respect to the part it would be wise to use thermocoupled test pieces to determine the actual cooling rate for a particular part shape and size.

1.9.4 Welding. Attempts to produce satisfactory welds for critical applications have been unsuccessful (see Section 4.3).

2. Physical Properties and Environmental Effects

2.1 Thermal Properties

2.1.1 Melting Range.

2.1.2 Phase Changes.

Beta transus – 1735 to 1785F, dependent upon composition variations given in Table 1.4.1.

2.1.2.1 Time-temperature-transformation diagrams.

2.1.3 Thermal Conductivity.
4 Btu ft per (hr ft^2 F) at room temperature (Ref. 16).

2.1.4 Thermal Expansion.
5.1×10^{-6} in./in./F.

2.1.5 Specific Heat.

2.1.6 Thermal Diffusivity.

2.2 Other Physical Properties

2.2.1 Density.
0.156 lb/cu in. (Refs. 6, 16).

2.2.2 Electrical Properties.

2.2.4 Emittance.

2.2.5 Damping Capacity.

2.3 Chemical Environments

2.3.1 General Corrosion.

2.3.2 Stress Corrosion.

The only data available at the time this Chapter was prepared related to the determination of the effects of stress intensity level on failure time in NaCl solutions. There are presently no published standards for these types of tests and therefore comparision with similar data should be approached with caution.

2.3.2.1 *[Figure]* Effect of applied K level on the failure time of conventionally processed billet in 3.5 percent NaCl.

A quantity designated as K_{Iscc} was recently reported (Ref. 26) for a variety of product forms from four producers. These forms included plates, forgings and forged block (up to 13-inch round corner block) from ingots having 0.23 percent silicon. Bolt-loaded compact specimens [MCT(W)] were cut from these forms and subjected to continuous immersion in 3.5 percent NaCl solution for 1000 hours. The procedures used in these tests have been described in a proposal for an ASTM test method (Ref. 25). While the K value based on the applied load and final crack length is designated as K_{Iscc} there is no assurance that further exposure to the NaCl solution would not have produced a lower value. The results of 35 tests gave an average value of 47.3 ksi $\sqrt{in.}$ with a standard deviation of 4.16. Additional tests on plate material with a 0.15 percent silicon content did not produce significantly different values from material containing 0.23 percent silicon (Ref. 27).

2.4 Nuclear Environments

3. Mechanical Properties

3.1 Specified Mechanical Properties

3.1.1 *[Table]* Producers typical mechanical properties for beta forged plate and billet.

3.2 Mechanical Properties at Room Temperature

3.2.1 Tensile Stress-strain Diagrams and Tensile Properties.

3.2.1.1 Tensile stress-strain diagrams (see Section 3.3.1).

3.2.1.2 *[Table]* Spread of tensile and yield strengths for α-β finished forgings and plates from several producers and different heats.

3.2.1.3 *[Figure]* Effect of oxygen content on the tensile properties of pancake forgings.

3.2.1.4 *[Figure]* Effect of thickness on the transverse tensile properties of conventionally processed sheet and plate.

3.2.1.5 *[Figure]* Effect of solution temperature on tensile properties of mill annealed unaged sheet.

3.2.1.6 *[Figure]* Effect of solution temperature on the transverse tensile properties of unaged sheet and plate.

3.2.1.7 *[Figure]* Effect of solution temperature on the tensile properties of sheet.

3.2.1.8 *[Figure]* Effect of aging temperature on tensile properties of sheet solution treated at 1600F.

3.2.1.9 *[Figure]* Effect of aging temperature on the tensile properties of sheet solution treated at 1700F.

3.2.1.10 *[Figure]* Effect of aging temperature on the tensile yield strength of sheet solution treated at several temperatures.

3.2.1.11 *[Figure]* Effect of 100-hour exposure temperature on the tensile properties of mill annealed sheet.

3.2.2 Compression Stress-strain Diagrams and Compressions Properties.

3.2.2.1 Compression stress-strain diagrams (see Section 3.3.2).

3.2.2.2 *[Table]* Spread of compressive yield strengths for α-β finished forgings and plates from several producers and different heats.

3.2.3 Impact.

3.2.3.1 *[Table]* Impact energy of a conventionally processed plate and a billet given a duplex anneal heat treatment.

3.2.4 Bending. Mill annealed material L and T limit: 3 x thickness at 105 degrees.

3.2.5 Torsion and Shear.

3.2.5.1 *[Table]* Spread of shear ultimate strengths for α-β finished forgings and plates from several producers and different heats.

3.2.5.2 *[Table]* Shear strength of a conventionally processed plate and a forged billet given a duplex anneal heat treatment.

3.2.6 Bearing.

3.2.6.1 *[Table]* Spread of bearing ultimate and yield strengths for α-β finished forgings and plates from several producers and different heats.

3.2.7 Stress Concentration.

3.2.7.1 Notch properties.

3.2.7.2 Fracture toughness. (See Tables 1.3.1, 1.5.1.1, and 1.5.1.2.)

3.2.7.2.1 *[Figure]* Effect of oxygen content on the fracture toughness of pancake forgings.

3.2.7.2.2 *[Figure]* Effect of aging temperature on plane strain fracture toughness of hot rolled plate given a triplex heat treatment.

3.2.8 Combined Loading.

3.3 Mechanical Properties at Various Temperatures

3.3.1 Tension Stress-strain Diagrams and Tensile Properties.

3.3.1.1 *[Figure]* Effect of temperature on longitudinal tensile stress-strain curves for conventionally processed plate.

3.3.1.2 *[Figure]* Effect of temperature on the transverse tensile stress-strain curves for conventionally processed plate.

3.3.1.3 *[Figure]* Effect of temperature on the longitudinal tensile stress-strain curves for α-β finished forged and duplex annealed billet.

3.3.1.4 *[Figure]* Effect of temperature on the transverse tensile stress-strain curves for α-β finished forged and duplex annealed billet.

3.3.1.5 *[Figure]* Effect of elevated temperature on tensile properties of specimens cut from a conventionally processed large billet.

3.3.1.6 *[Figure]* Effect of temperature on the tensile properties of conventionally processed plate.

3.3.1.7 *[Figure]* Effect of temperature on the tensile yield strength of a forging after 100-hour exposure at the test temperature.

3.3.1.8 *[Figure]* Effect of temperature on tensile strength of large forgings from three heats representing two producers (bars and/or points indicate 95 percent confidence intervals).

3.3.1.9 *[Figure]* Effect of temperature and elevated temperature exposure on tensile strength of a large wing strut die forging from one producer (bars indicate one sigma deviation from means).

3.3.2 Compression Stress-strain Diagrams and Compression Properties.

3.3.2.1 *[Figure]* Effect of temperature on the longitudinal compression stress-stain curves for conventionally processed plate.

3.3.2.2 *[Figure]* Effect of temperature on the transverse compression stress-strain curves for conventionally processed plate.

3.3.2.3 *[Figure]* Effect of temperature on the longitudinal compression stress-strain curves for duplex annealed billet.

3.3.2.4 *[Figure]* Effect of temperature on the transverse compression stress-strain curves for duplex annealed billet.

3.3.2.5 *[Figure]* Effect of temperature on the compression yield strength of conventionally processed plate.

3.3.3 Impact.

3.3.4 Bending.

3.3.5 Torsion and Shear.

3.3.6 Bearing.

3.3.7 Stress Concentration.

3.3.7 Notch Properties.

3.3.7.1 Fracture toughness.

3.3.8 Combined Loading.

3.4 Creep and Creep Rupture Properties

3.4.1 *[Figure]* Plastic creep and rupture data for conventionally processed plate and duplex annealed billet.

3.5 Fatigue Properties

3.5.1 Conventional High-cycle Fatigue.

3.5.1.1 *[Figure]* Effect of test temperature on the smooth fatigue strength of conventionally processed billet.

3.5.1.2 *[Figure]* Effect of test temperature on the notched fatigue strength of conventionally processed plate.

3.5.1.3 *[Figure]* Effect of test temperature on smooth fatigue strength of conventionally processed plate.

3.5.1.4 *[Figure]* Notch fatigue strength for conventionally processed solution treated unaged plate.

3.5.1.5 *[Figure]* Notch fatigue strength for conventionally processed plate.

3.5.1.6 *[Figure]* Notch fatigue strength of a conventionally processed forging.

3.5.1.7 *[Figure]* Smooth fatigue strength produced by two thermomechanical processes applied to Ti-6-2-2-2-2 forgings compared with fatigue strength of annealed Ti-6Al-4V forgings.

3.5.1.8 *[Figure]* Notch fatigue strength produced by two thermomechanical processes applied to Ti-6-2-2-2-2 forgings compared with fatigue strength of annealed Ti-6Al-4V forgings.

3.5.2 Low-cycle Fatigue.

3.5.2.1 *[Figure]* Effect of thermomechanical processing on low cycle fatigue crack initiation of forgings.

3.5.3 Fatigue Crack Propagation.

3.5.3.1 *[Figure]* Fatigue crack growth rates at 1 Hz for conventionally processed plate in humid air and in 3.5 percent NaCl.

3.5.3.2 *[Figure]* Fatigue crack growth rates at 20 Hz for conventionally processed plate in humid air and in 3.5 percent NaCl.

3.5.3.3 *[Figure]* Fatigue crack growth rates at 1 Hz for conventionally processed solution treated unaged plate in humid air and in 3.5 percent NaCl.

3.5.3.4 *[Figure]* Fatigue crack growth rates at 20 Hz for conventionally processed solution treated unaged plate in humid air and in 3.5 percent NaCl.

3.5.3.5 *[Figure]* Fatigue crack growth rates for conventionally processed forging in dry air and in 3.5 percent NaCl.

3.5.3.6 *[Figure]* Fatigue crack growth rates for Ti-6-2-2-2-2 forgings subjected to several thermomechanical processes compared with beta mill annealed Ti-6Al-4V forgings.

3.5.3.7 *[Figure]* Fatigue crack growth rates in 3.5 percent NaCl for hand forgings made from 8000-lb ingot and subjected to several thermomechanical processes.

3.5.3.8 *[Figure]* Fatigue crack growth rates for forgings subjected to several thermomechanical processes.

3.6 Elastic Properties

3.6.1 Poisson's Ratio.

3.6.2 Modulus of Elasticity.

For α-β finish forge + triplex heat treat = 17,200 ksi; for β finish forge + triplex heat treat = 16,000 ksi (Ref. 6).

3.6.2.1 *[Figure]* Effect of temperature on the tension and compression elastic modulus of conventionally processed plate.

3.6.2.2 *[Figure]* Effect of temperature on the tension and compression elastic modulus of conventionally processed forged billet.

3.6.3 Modulus of Rigidity.

3.6.4 Tangent Modulus.

3.6.5 Secant Modulus.

4. Fabrication

4.1 Forming

4.1.1 Superplastic Forming. Recent studies have shown that sheet can be superplastically formed using the same procedures as employed for Ti-6Al-4V and with no greater difficulties (Ref. 19).

4.1.2 *[Figure]* Effect of superplastic forming temperature on the tensile properties of sheet.

4.2 Machining and Grinding

4.3 Joining

4.3.1 Welding. There has been very little information published on the weldability of this alloy. Recent aircraft applications have not involved welding. Attempts to electron beam weld plate were reported as unsuccessful (Ref. 23). Weld tensile properties were essentially equal to the parent metal but the fracture toughness of the welds was low as evidenced by specimens fracturing during fatigue cracking. At the time of this Chapter preparation welding can not be recommended.

4.3.1.1 *[Table]* Tensile properties and fracture toughness of electron beam welds in conventionally processed plate.

4.4 Surface Treating

Table 1.3.1 Proposed design mechanical property values for α-β processed forgings and plate (Ref. 16)

Alloy	Ti-6-2-2-2-2			
Condition	Triplex Heat Treatment (see Table 1.5.1.3)			
Form	Die Forgings		Forged Block	Plate
Direction	**L, LT & ST**			**L & LT**
Size (in.)	**≤ 3-in.**		**13-in.[a]**	**≤ 3-in.**
Basis	**S**	**B**	**S**	
F_{tu} (ksi)	150[b]	156	150	150
F_{ty} (ksi)	135	138	135	135
F_{cy} (ksi)	146	150	146	146
F_{su} (ksi)	96	100	96	96
F_{bru} (ksi) e/D = 1.5 e/D = 2	 239 297	 248 309	 239 237	 239 237
F_{bry} (ksi) e/D = 1.5 e/D = 2	 217 260	 222 266	 217 260	 217 260
e (percent)	5	–	5	5
K_{Ic} (ksi $\sqrt{in.}$)	70	–	70	70
E (1000 ksi)	17.2	17.2	17.2	17.2
G (1000 ksi)	6.5	6.5	6.5	6.5
μ	0.33	0.33	0.33	0.33

[a] Heat treated size ≤ 3 inches.

[b] F_{tu} A value = 152 ksi.

Table 1.4.1 Chemical composition (Refs. 1, 28)

Alloy	Ti-6-2-2-2-2			
Composition	Conventional (Ref. 1)		Modified for Higher Toughness (Ref. 28)	
Element	**Min**	**Max**	**Min**	**Max**
Al	5.25	6.25	5.25	6.25
Sn	1.75	2.25	1.75	2.25
Zr	1.75	2.25	1.75	2.25
Mo	1.75	2.25	1.75	2.25
Cr	1.75	2.25	1.75	2.25
Si	0.20	0.27	0.12	0.20
C	–	0.04	–	0.04
N	–	0.03	–	0.03
Fe	–	0.25	–	0.15
O_2	–	0.14	–	0.13
H_2[a]	–	–	–	125 ppm

[a] Determined on finished parts.

Table 1.5.1.1 Effect of thermal mechanical processing on the tensile properties and fracture toughness of pancake forgings (Refs. 4, 7)

Alloy		Ti-6-2-2-2-2						
Composition		6Al - 2.2Sn - 1.8Zr - 2.1Cr - 1.9Mo - 0.16Si - 0.076O_2 - 0.01N - 0.02C - 0.06Fe						
Form		6-in. dia x 1.7-in. Thick Pancake Forgings						
Specimen Orientation		Tangential						
Process Forge	**Preform Forge**	**Finish Forge[a]**	**Heat / Heat Treatment[b]**	**F_{tu} (ksi)**	**F_{ty} (ksi)**	**e (percent)**	**RA (percent)**	**K_{Ic} (ksi $\sqrt{in.}$)**
1	α-β	β_t + 82F	β_t - 72F, 1 hr, FAC + 1000F, 8 hr, AC	161	144	11	21	82
2		β_t + 122F		162	145	12	21	80
3	β	α-β 25 percent		163	150	12	23	62
4		α-β 50 percent		162	149	12	25	53
5	α-β	α-β 50 percent	β_t + 82F, 0.5 hr, FAC + 1000F, 8 hr, AC	161	139	10	15	68
6		α-β 50 percent	β_t + 82F, 0.5 hr, FAC β_t - 122F, 1 hr, AC + 1000F, 8 hr, AC	159	141	10	17	77

[a] β_t = β transus temperature. Percentages = forge reduction.

[b] β_t = β transus temperature. FAC = fan air cool.

Table 1.5.1.2 Effect of several thermal mechanical processes on the tensile properties and fracture toughness of forgings (Refs. 6, 7)

Alloy	Ti-6-2-2-2-2								
Form	Forgings								
Forging Type	**Forge Process**[a]	**Heat Treatment**	**Section Thickness (in.)**	**Direction**	**F_{tu} (ksi)**	**F_{ty} (ksi)**	**e (percent)**	**RA (percent)**	**K_{Ic} (ksi $\sqrt{in.}$)**
Pancake 0.076 Oxygen	$>\beta_t$	$\alpha-\beta$[b] FAC[c]	0.5	L T	163 157	146 142	10 9	17 15	74 TL
	$\alpha-\beta$	Triplex[d] FAC	0.5	L T	159 155	141 137	10 9	16 15	78 TL
Pancake 0.13 Oxygen	$>\beta_t$	$\alpha-\beta$ FAC	–	L T	154 152	138 137	12 13	17 18	79 TL
	$\alpha-\beta$	Triplex Oil Quench	1.5	L T	176 169	154 152	8 7	12 11	63 TL
Closed Die 0.13 Oxygen	$>\beta_t$	$\alpha-\beta$ FAC	3 1 1 0.5	L L T T	163 161 160 165	146 144 148 147	12 11 13 17	21 19 24 26	71 SL
	$\alpha-\beta$	Triplex FAC	3 1 1 0.05	L L T T	154 159 154 159	138 141 137 144	10 19 9 14	17 24 16 18	74 SL

[a] $>\beta_t$ = finish forge above the β transus. $\alpha-\beta$ = through transus forge.

[b] ST β_t - 75F, 0.5 hour, FAC + 1000F, 8 hours, AC (conventional heat treat).

[c] FAC = fan air cool > 35 degrees per minute.

[d] ST β_t + 82F, 0.5 hour, FAC + β_t - 122F, 1 hour, AC + 1000F, 8 hours, AC.

Table 1.5.1.3 Triplex heat treatments specified for $\alpha-\beta$ finished forgings and plate (Ref. 16)

Alloy	Ti-6-2-2-2-2	
Form	Forgings and Plate (with maximum thickness or diameter up to 3-in.)	
β Solution Heat Treatment	**$\alpha-\beta$ Solution Treatment following β Solution Treatment**	**Aging**
Range: β transus[a] + 25F to β transus + 100F, 0.5 hr min, Fan Air Cool 36 to 120F/min to 900F max	Range: β transus - 25F to β transus - 115F, 1 hr min, Fan Air Cool 36 to 120F/min	925 to 1025F 8 to 10 hr, AC

[a] β transus to be determined to within +/- 25F.

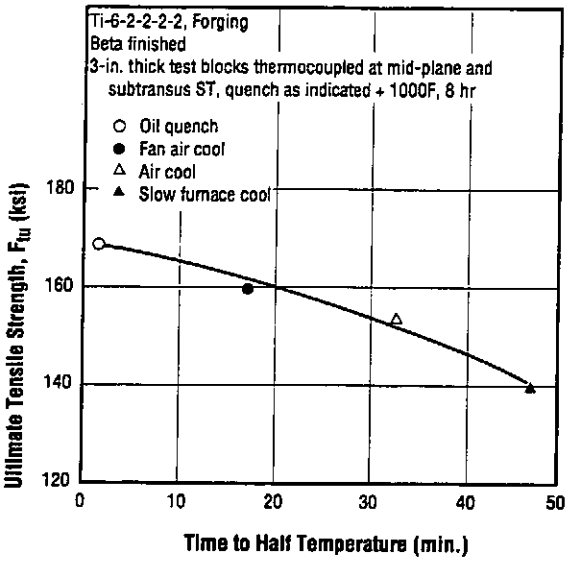


Fig. 1.5.1.4 Effect of cooling rate on the tensile strength of a forging (Ref. 20)

Table 1.9.1.1 Influence of silicon content on the tensile properties and fracture toughness of laboratory heats containing somewhat different equivalent oxygen contents (Ref. 24)

Alloy	Ti-6-2-2-2-2			
Form	65-lb Ingots Converted to 1.75-in. Thick Plate			
Heat Treatment	Triplex (see Table 1.5.1.3)			
Composition	**0.03 Si 0.18 Oe[a]**	**0.14 Si 0.13 Oe**	**0.24 Si 0.16 Oe**	**0.30 Si 0.18 Oe**
F_{tu} (ksi)[b]	163	164	174	176
F_{ty} (ksi)	145	143	152	155
e (percent)	8	9	9	8
RA (percent)	16	15	14	14
K_{Ic} (ksi $\sqrt{in.}$)[c]	79	88	73	63

[a] Oe = Oxygen equivalent = percent Oxygen + 1.5 percent Nitrogen.

[b] Average L and T.

[c] LT C(T) specimens.

Table 1.9.1.2 Influence of silicon content on the tensile properties and fracture toughness of laboratory heats containing somewhat different equivalent oxygen contents and given an intermediate 1500F solution treatment (Ref. 24)

Alloy	Ti-6-2-2-2-2			
Form	65-lb Ingots Converted to 1.75-in. Thick Plate			
Heat Treatment	β + 50F 1 hr, FAC[a] + β - 50F 1 hr, FAC + 1500F 2 hr, FAC + 1000F 8 hr, AC			
β Transus (F)	1805	1785	1810	1820
Composition	**0.03 Si 0.18 Oe[b]**	**0.14 Si 0.13 Oe**	**0.24 Si 0.16 Oe**	**0.30 Si 0.18 Oe**
F_{tu} (ksi)[c]	162	161	166	169
F_{ty} (ksi)	144	141	148	152
e (percent)	8	6	4	7
RA (percent)	15	8	7	13
K_{Ic} (ksi $\sqrt{in.}$)[d]	62	61	48	46

[a] FAC = fan air cool.

[b] Oe = Oxygen equivalent = percent Oxygen + 1.5 percent Nitrogen.

[c] Average L and LT.

[d] LT C(T) specimens.

Table 1.9.1.3 Influence of silicon content on the tensile properties and fracture toughness of laboratory heats containing somewhat different oxygen equivalents and aged at 1150F (Ref. 24)

Alloy	Ti-6-2-2-2-2			
Form	65-lb Ingots Converted to 1.75-in. Thick Plate			
Heat Treatment	β + 50F 1 hr, FAC[a] + β - 50F 1 hr, FAC + 1150F 8 hr, AC			
β Transus (F)	1895	1785	1810	1820
Composition	**0.03 Si 0.18 Oe[b]**	**0.14 Si 0.13 Oe**	**0.24 Si 0.16 Oe**	**0.30 Si 0.18 Oe**
F_{tu} (ksi)[c]	156	157	166	168
F_{ty} (ksi)	145	146	155	157
e (percent)	13	8	8	7
RA (percent)	19	12	10	9
K_{IC} (ksi $\sqrt{in.}$)[d]	78	68	49	43

[a] FAC = fan air cool.

[b] Oe = Oxygen equivalent = percent Oxygen + 1.5 percent Nitrogen.

[c] Average L and LT.

[d] LT C(T) specimens.

Table 1.9.1.4 Effect of silicon content on tensile properties and fracture toughness of a Ti-6Al-2Sn-2Zr-1Mo-0.12O alloy (Ref. 22)

Alloy	Ti-6Al-2Sn-2Zr-1Mo-0.12O + Si					
Form	1.26 x 5-in. Sheet Bar Rolled at 1950F					
Condition	ST 1950F, 15 min., AC + 1300F, 2 hr, AC					
Silicon (percent)	**0**		**0.25**		**0.5**	
Test Temperature (F)	**77**	**1000**	**77**	**1000**	**77**	**1000**
F_{tu} (ksi)	127	78	141	86	143	94
F_{ty} (ksi)	107	654	119	66	119	71
e (percent)	7.8	11.9	7	10	3.5	7
K_Q (ksi $\sqrt{in.}$)	112	103	86[a]	89	71[a]	87

[a] K_{IC} values.

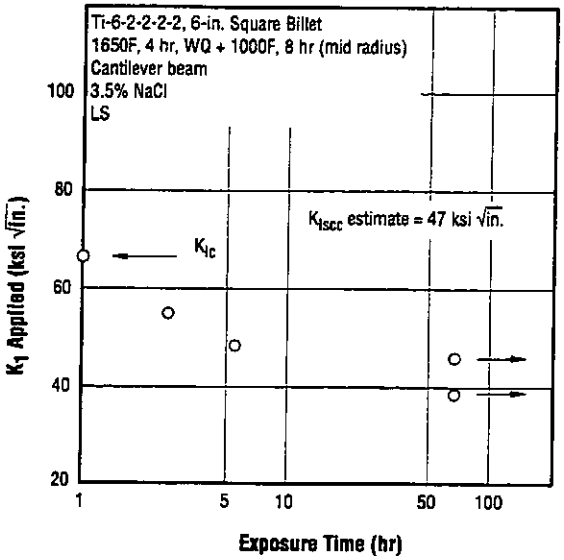


Fig. 2.3.2.1 Effect of applied K level on the failure time of conventionally processed billet in 3.5 percent NaCl (Ref. 3)

Table 3.1.1 Producers typical mechanical properties for beta forged plate and billet (Ref. 1)

Alloy	Ti-6-2-2-2-2		
Condition	Beta Forged + Subtransus ST + 1000F Age		
Form	**2-in. Plate**	**4-in. Plate**	**6-in. Rectangular Billet**
F_{tu} (ksi)	168	160	164
F_{ty} (ksi)	148	142	147
e (percent)	10	10	9
RA (percent)	16	14	13
K_{Ic} (ksi √in.)	77	81	89

Table 3.2.1.2 Spread of tensile and yield strengths for α-β finished forgings and plates from several producers and different heats (Ref. 16)

Alloy		Ti-6-2-2-2-2																				
Producer		Wyman Gordon			ALCOA			RMI		TIMET				RMI			TIMET					
Form[a]		Die Forging						2-in. Plate						6-in. Plate								
No. Lots[b]		3						1		2		3		1								
Heat		NS[c]			NS			882794		G6591				873190			882890			G6591		
Direction		L	LT	ST	L	LT	ST	L	LT	L	LT	L	LT	L	LT	ST	L	LT	ST	L	LT	ST
Tests / Lot		5	7	7	7	7	7	14	14	14	14	10	10	22	20	20	20	20	20	22	19	20
F_{tu} (ksi)	max	167	170	168	164	163	160	165	168	167	170	170	174	164	165	163	164	165	164	172	168	166
	min	162	160	161	156	157	153	161	163	161	162	162	165	169	160	159	159	160	169	155	159	157
F_{ty} (ksi)	max	146	146	146	143	143	141	146	147	148	151	148	151	145	145	144	144	145	143	144	147	145
	min	140	138	141	138	137	134	140	143	142	145	142	144	142	140	141	140	140	139	138	138	140

[a] Triplex heat treatment for all forms (see Table 1.5.1.3).

[b] A lot is an individual forging or plate.

[c] NS = not specified.

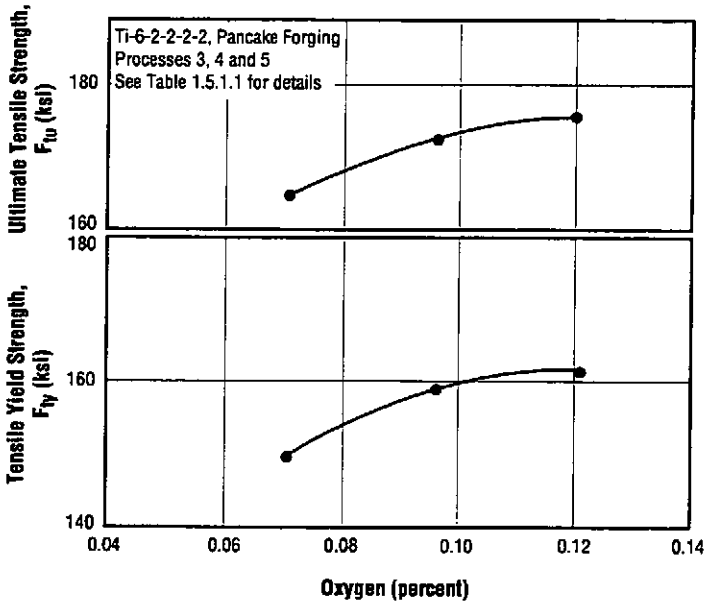


Fig. 3.2.1.3 Effect of oxygen content on the tensile properties of pancake forgings (Ref. 4)

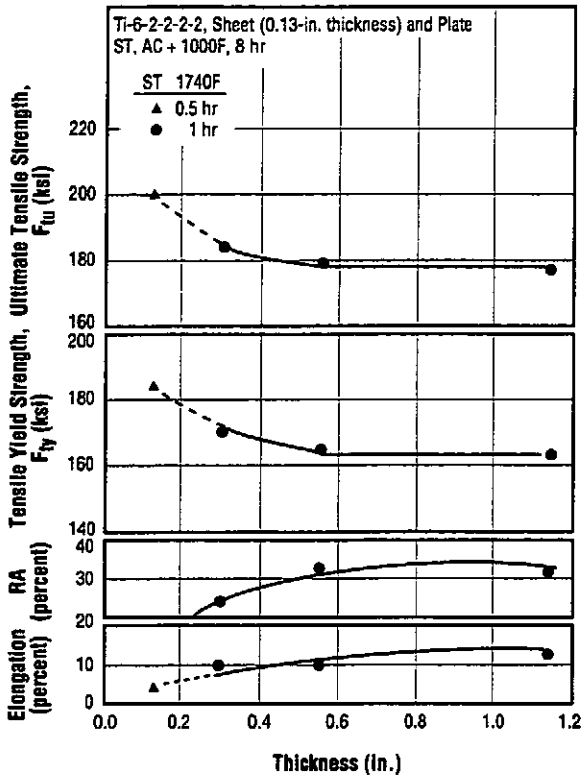


Fig. 3.2.1.4 Effect of thickness on the transverse tensile properties of conventionally processed sheet and plate (Ref. 14)

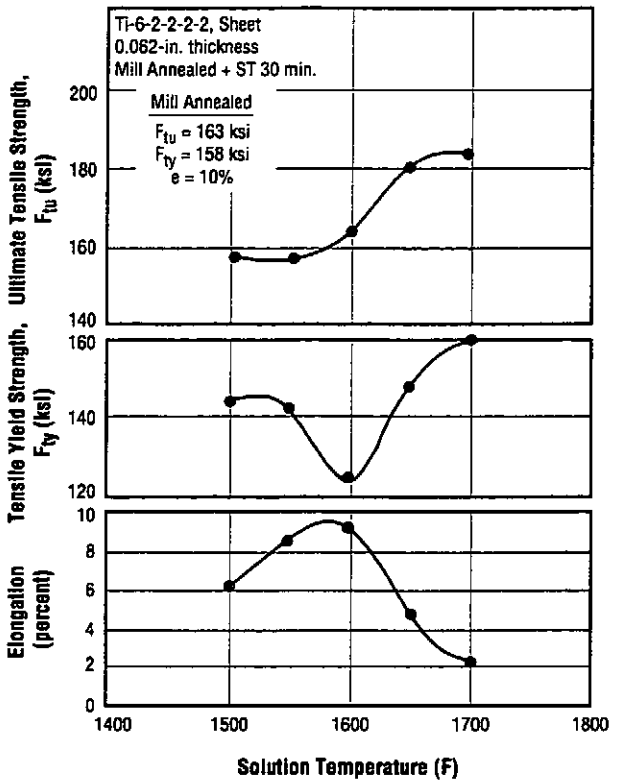


Fig. 3.2.1.5 Effect of solution temperature on tensile properties of mill annealed unaged sheet (Refs. 3, 19)

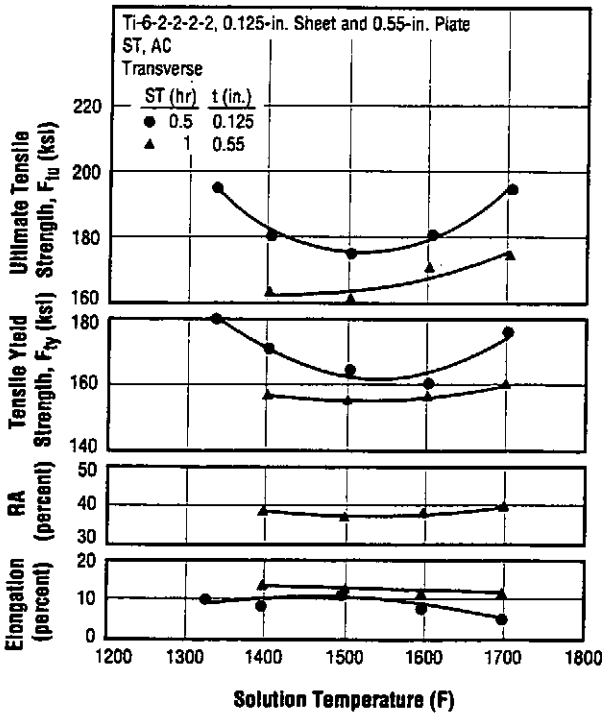


Fig. 3.2.1.6 Effect of solution temperature on the transverse tensile properties of unaged sheet and plate (Ref. 14)

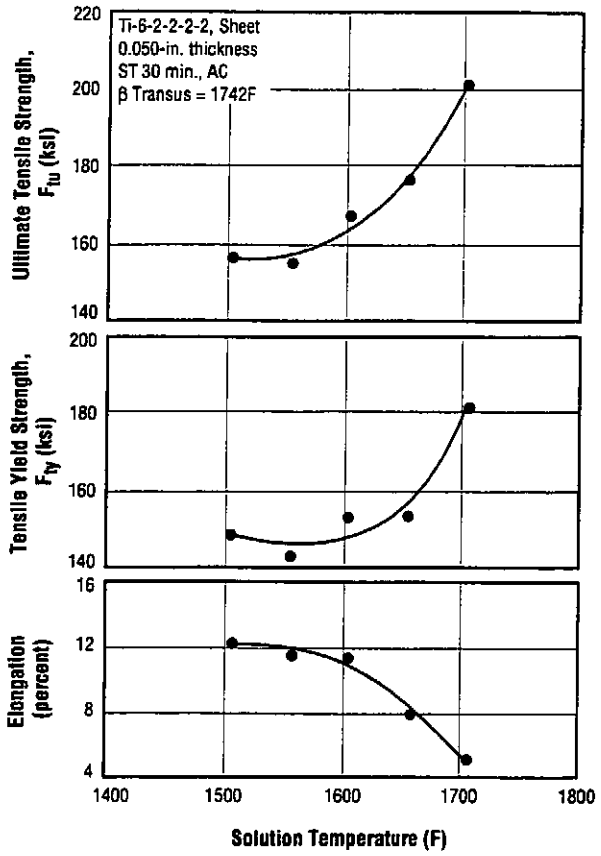


Fig. 3.2.1.7 Effect of solution temperature on the tensile properties of sheet (Ref. 21)

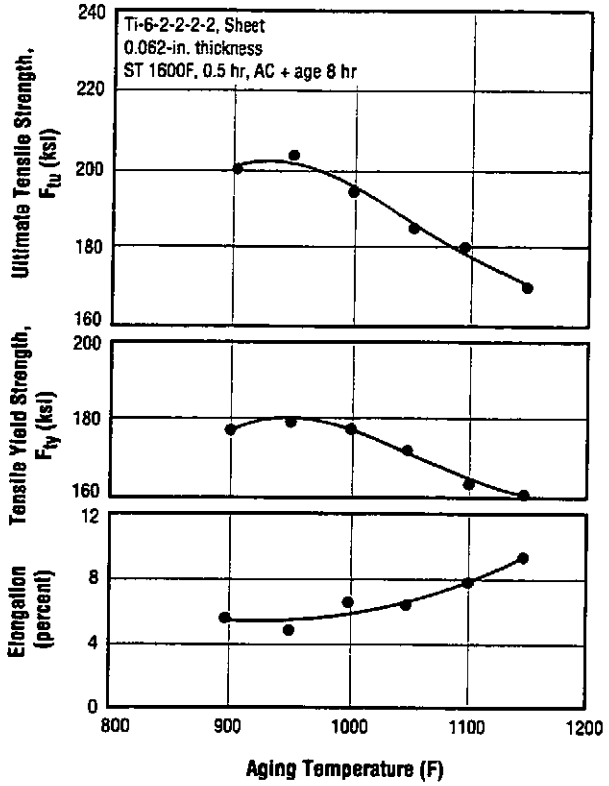


Fig. 3.2.1.8 Effect of aging temperature on tensile properties of sheet solution treated at 1600F (Refs. 3, 19)

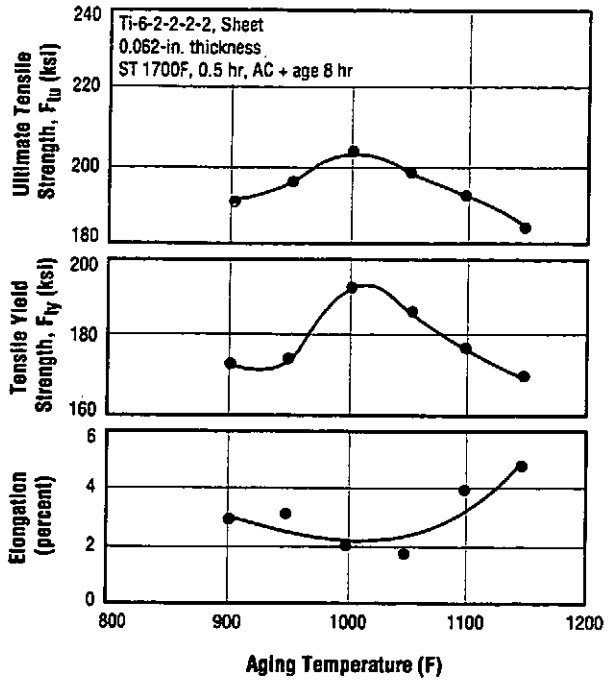


Fig. 3.2.1.9 Effect of aging temperature on the tensile properties of sheet solution treated at 1700F (Refs. 3, 19)

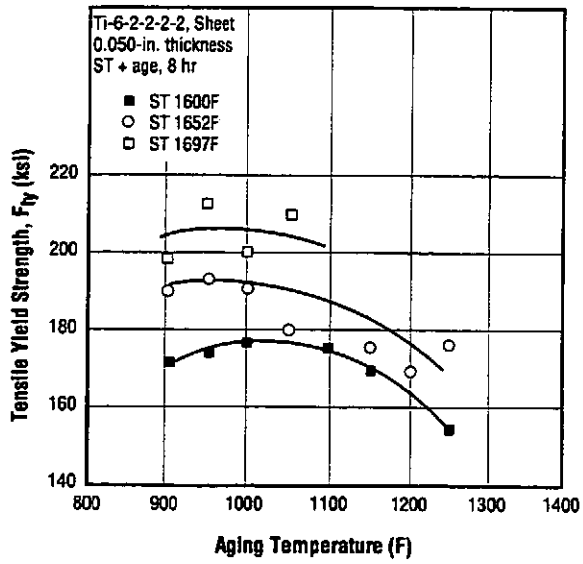


Fig. 3.2.1.10 Effect of aging temperature on the tensile yield strength of sheet solution treated at several temperatures (Ref. 21)

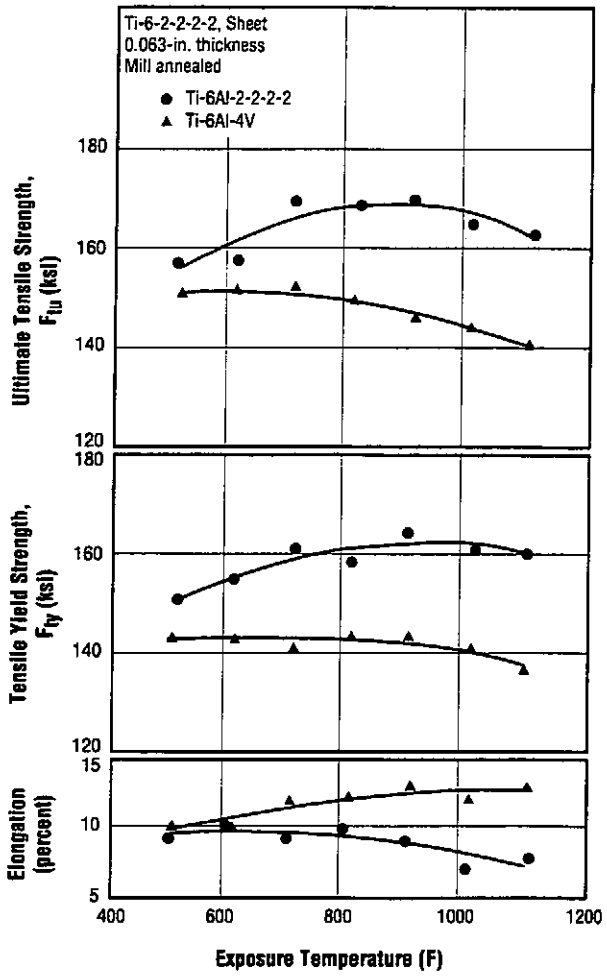


Fig. 3.2.1.11 Effect of 100-hour exposure temperature on the tensile properties of mill annealed sheet (Ref. 19)

Table 3.2.2.2 Spread of compressive yield strengths for α-β finished forgings and plates from several producers and different heats (Ref. 16)

Alloy		Ti-6-2-2-2-2																				
Producer		Wyman Gordon			ALCOA			RMI		TIMET				RMI						TIMET		
Form[a]		Die Forging						2-in. Plate						6-in. Plate								
No. Lots[b]		3						1		2		3		1								
Heat		NS[c]			NS			882794		G6591				873190			882890			G6591		
Direction		L	LT	ST	L	LT	ST	L	LT	L	LT	L	LT	L	LT	ST	L	LT	ST	L	LT	ST
Tests / Lot		2	2	2	2	1	1	2	2	3	3	2	2	3	3	3	3	3	3	3	3	3
F_{cy} (ksi)	max	160	156	160	153	153	152	159	159	169	169	157	160	157	154	156	155	157	157	163	155	158
	min	154	150	155	150	153	150	149	159	161	159	157	159	154	152	153	151	154	154	147	149	153

[a] Triplex heat treatment for all forms (see Table 1.5.1.3).

[b] A lot is an individual forging or plate.

[c] NS = not specified.

Table 3.2.3.1 Impact energy of a conventionally processed plate and a billet given a duplex anneal heat treatment (Refs. 8, 15)

Alloy	Ti-6-2-2-2-2			
Source	Table 32 (Ref. 8)		Table 34 (Ref. 15)	
Form	1-1/2-in. Plate		4 x 6-in. Billet	
Condition	**1740F, 1 hr, AC + 1000F, 8 hr**		**1745F, 1 hr, AC to 1560F, WQ + 1000F, 8 hr**	
Direction	**L**	**T**	**L**	**T**
Impact Energy (ft-lb)	14	16	15	–

Table 3.2.2.2 Spread of compressive yield strengths for α-β finished forgings and plates from several producers and different heats (Ref. 16)

Alloy		Ti-6-2-2-2-2																				
Producer		Wyman Gordon			ALCOA			RMI		TIMET				RMI						TIMET		
Form[a]		Die Forging						2-in. Plate						6-in. Plate								
No. Lots[b]		3						1		2		3		1								
Heat		**NS[c]**			**NS**			**882794**		**G6591**				**873190**			**882890**			**G6591**		
Direction		**L**	**LT**	**ST**	**L**	**LT**	**ST**	**L**	**LT**	**L**	**LT**	**L**	**LT**	**L**	**LT**	**ST**	**L**	**LT**	**ST**	**L**	**LT**	**ST**
Tests / Lot		**2**	**2**	**2**	**2**	**1**	**1**	**2**	**2**	**3**	**3**	**2**	**2**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
F_{cy} (ksi)	max	160	156	160	153	153	152	159	159	169	169	157	160	157	154	156	155	157	157	163	155	158
	min	154	150	155	150	153	150	149	159	161	159	157	159	154	152	153	151	154	154	147	149	153

[a] Triplex heat treatment for all forms (see Table 1.5.1.3).

[b] A lot is an individual forging or plate.

[c] NS = not specified.

Table 3.2.5.2 Shear strength of a conventionally processed plate and a forged billet given a duplex anneal heat treatment (Refs. 8, 15)

Alloy	Ti-6-2-2-2-2			
Source	Table 31 (Ref. 8)		Table 33 (Ref. 15)	
Form	1-1/2-in. Plate		4 x 6-in. Billet	
Condition	**1740F, 1 hr, AC + 1000F, 8 hr**		**1745F, 1 hr, AC to 1560F, WQ + 1000F, 8 hr**	
Direction	**L**	**T**	**L**	**T**
F_{su} (ksi)	108	180	103	105

Table 3.2.6.1 Spread of bearing ultimate and yield strengths for α-β finished forgings and plates from several producers and different heats (Ref. 16)

Alloy		Ti-6-2-2-2-2															
Producer		Wyman Gordon		ALCOA		RMI		TIMET				RMI				TIMET	
Form[a]		Die Forging				2-in. Plate						6-in. Plate					
No. Lots[b]		3				1										2	
Heat		NS[c]		NS		882794		G6591				873190		882890		G6591	
Direction		L								LT		L					
Tests / Lot		2				1		3				2	1	3			
e/D		1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2
F_{bu} (ksi)	max	270	334	259	322	277	323	259	331	260	308	270	340	266	345	273	334
	min	259	329	255	313	259	–	253	320	244	307	266	–	260	328	250	319
F_{by} (ksi)	max	241	286	232	275	238	268	243	278	225	260	239	290	237	286	243	288
	min	229	285	226	274	222	–	223	256	214	252	239	–	230	278	220	273

[a] Triplex heat treatment for all forms (see Table 1.5.1.3).

[b] A lot is an individual forging or plate.

[c] NS = not specified.

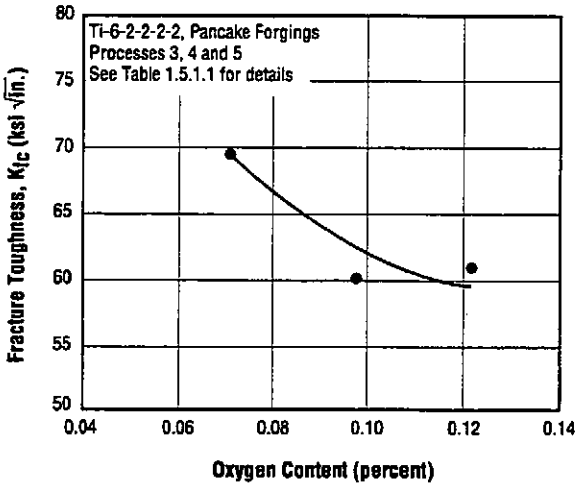


Fig. 3.2.7.2.1 Effect of oxygen content on the fracture toughness of pancake forgings (Ref. 4)

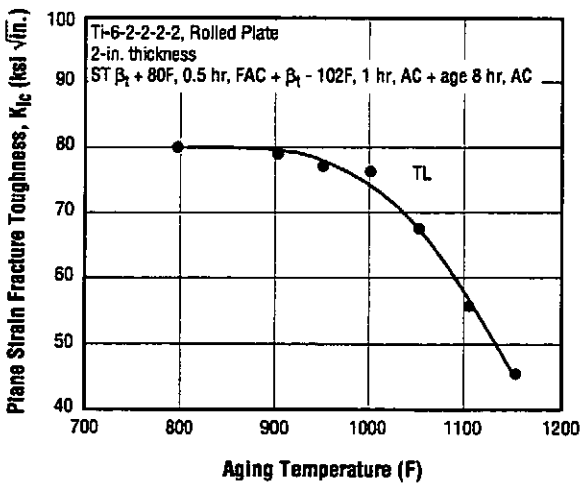


Fig. 3.2.7.2.2 Effect of aging temperature on plane strain fracture toughness of hot rolled plate given a triplex heat treatment (Ref. 5)

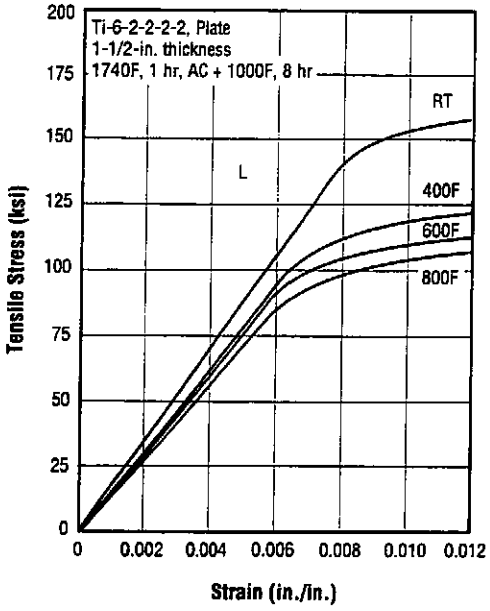


Fig. 3.3.1.1 Effect of temperature on longitudinal tensile stress-strain curves for conventionally processed plate (Ref. 8)

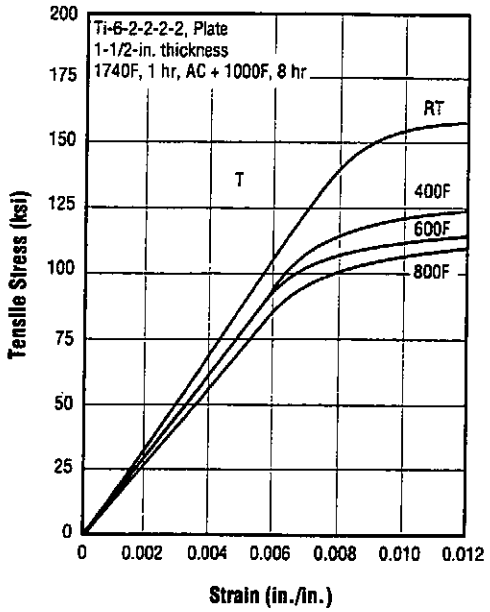


Fig. 3.3.1.2 Effect of temperature on the transverse tensile stress-strain curves for conventionally processed plate (Ref. 8)

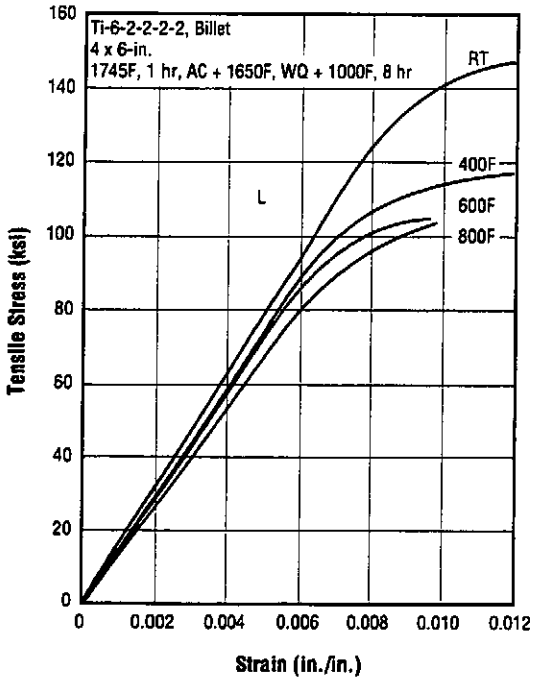


Fig. 3.3.1.3 Effect of temperature on the longitudinal tensile stress-strain curves for α-β finished forged and duplex annealed billet (Ref. 15)

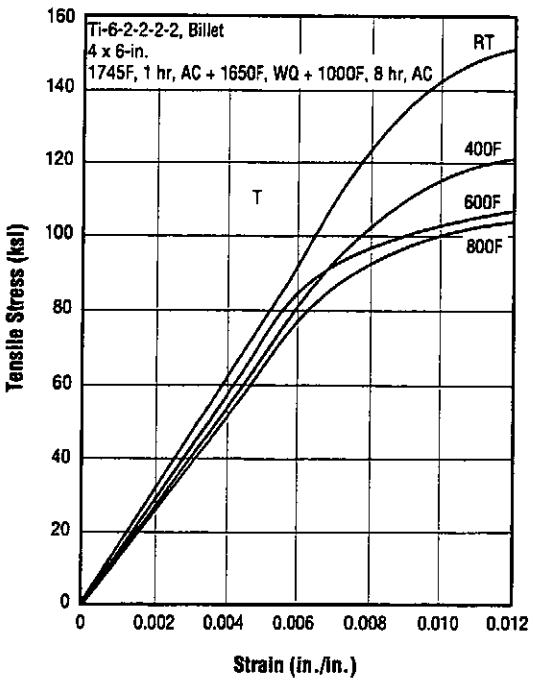


Fig. 3.3.1.4 Effect of temperature on the transverse tensile stress-strain curves for α-β finished forged and duplex annealed billet (Ref. 15)

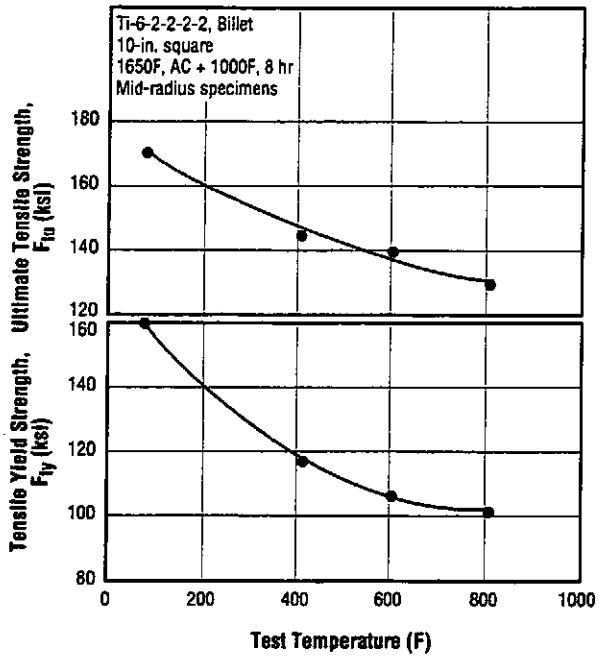


Fig. 3.3.1.5 Effect of elevated temperature on tensile properties of specimens cut from a conventionally processed large billet (Ref. 3)

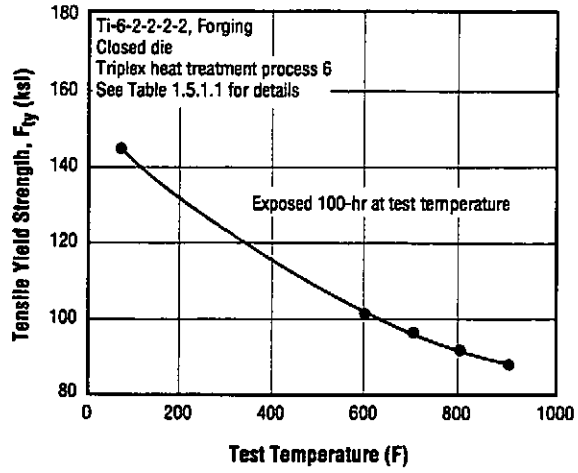


Fig. 3.3.1.7 Effect of temperature on the tensile yield strength of a forging after 100-hour exposure at the test temperature (Ref. 6)

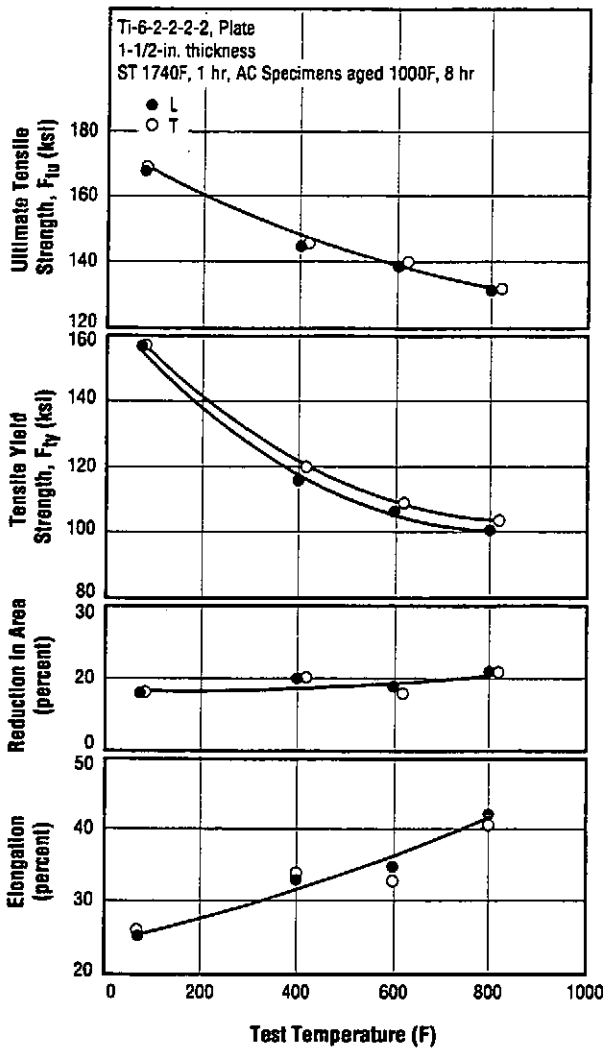


Fig. 3.3.1.6 Effect of temperature on the tensile properties of conventionally processed plate (Ref. 8)

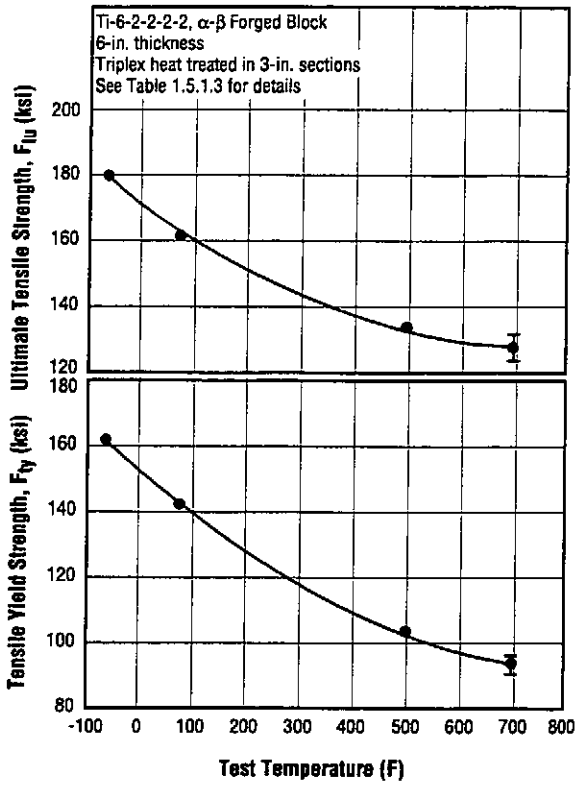


Fig. 3.3.1.8 Effect of temperature on tensile strength of large forgings from three heats representing two producers (bars and/or points indicate 95 percent confidence intervals) (Ref. 16)

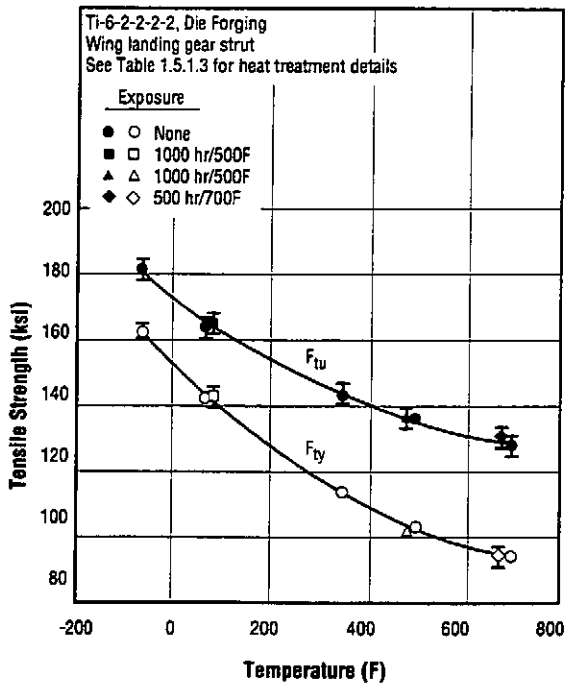


Fig. 3.3.1.9 Effect of temperature and elevated temperature exposure on tensile strength of a large wing strut die forging from one producer (bars indicate one sigma deviation from means) (Ref. 16)

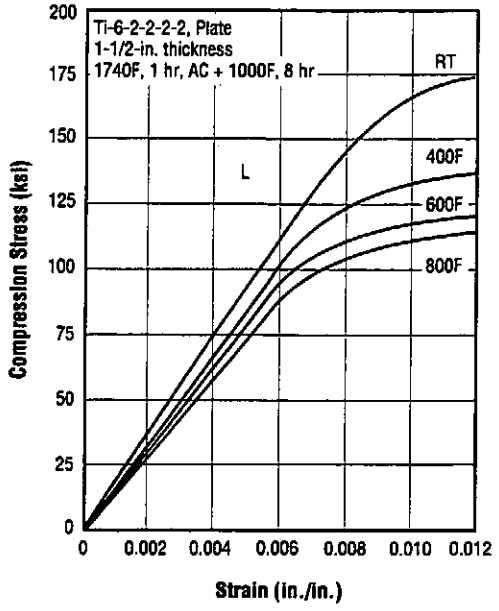


Fig. 3.3.2.1 Effect of temperature on the longitudinal compression stress-strain curves for conventionally processed plate (Ref. 8)

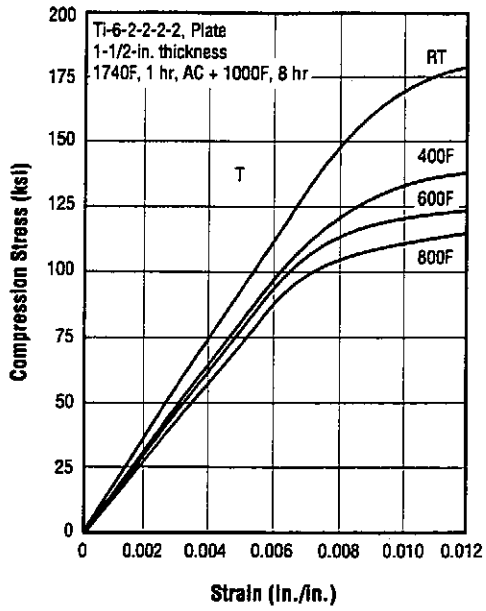


Fig. 3.3.2.2 Effect of temperature on the transverse compression stress-strain curves for conventionally processed plate (Refs. 8, 15)

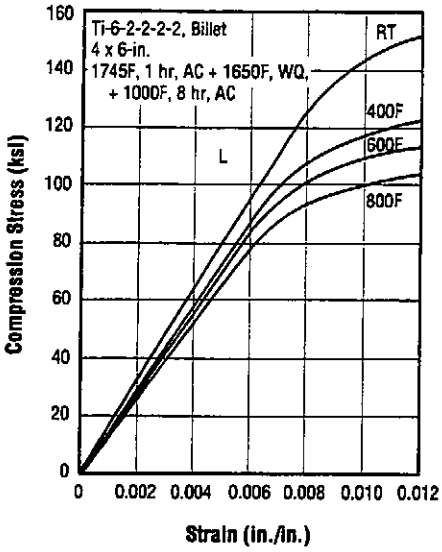


Fig. 3.3.2.3 Effect of temperature on the longitudinal compression stress-strain curves for duplex annealed billet (Ref. 15)

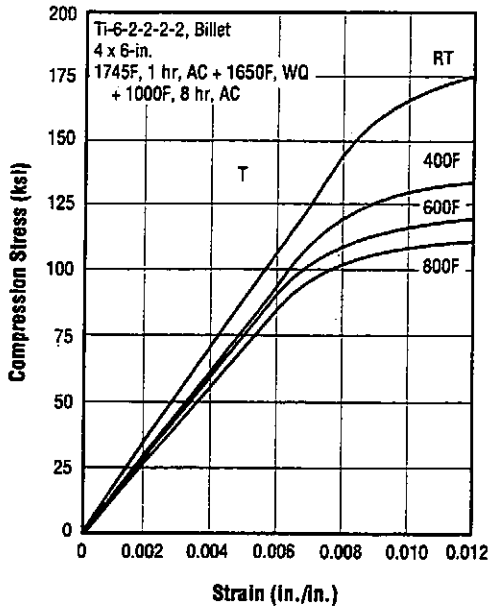


Fig. 3.3.2.4 Effect of temperature on the transverse compression stress-strain curves for duplex annealed billet (Ref. 15)

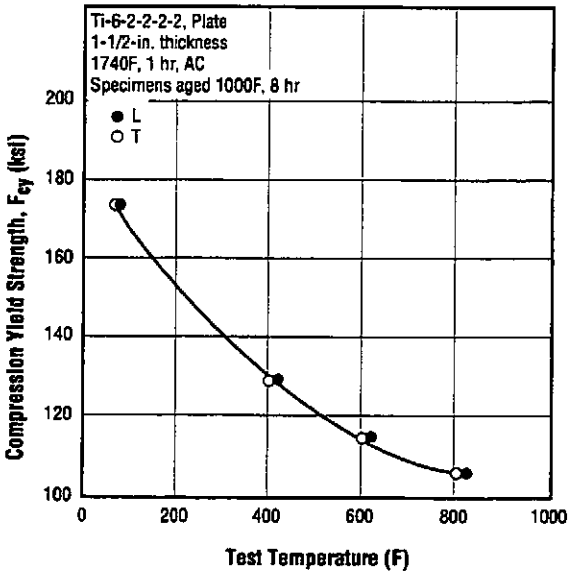


Fig. 3.3.2.5 Effect of temperature on the compression yield strength of conventionally processed plate (Ref. 8)

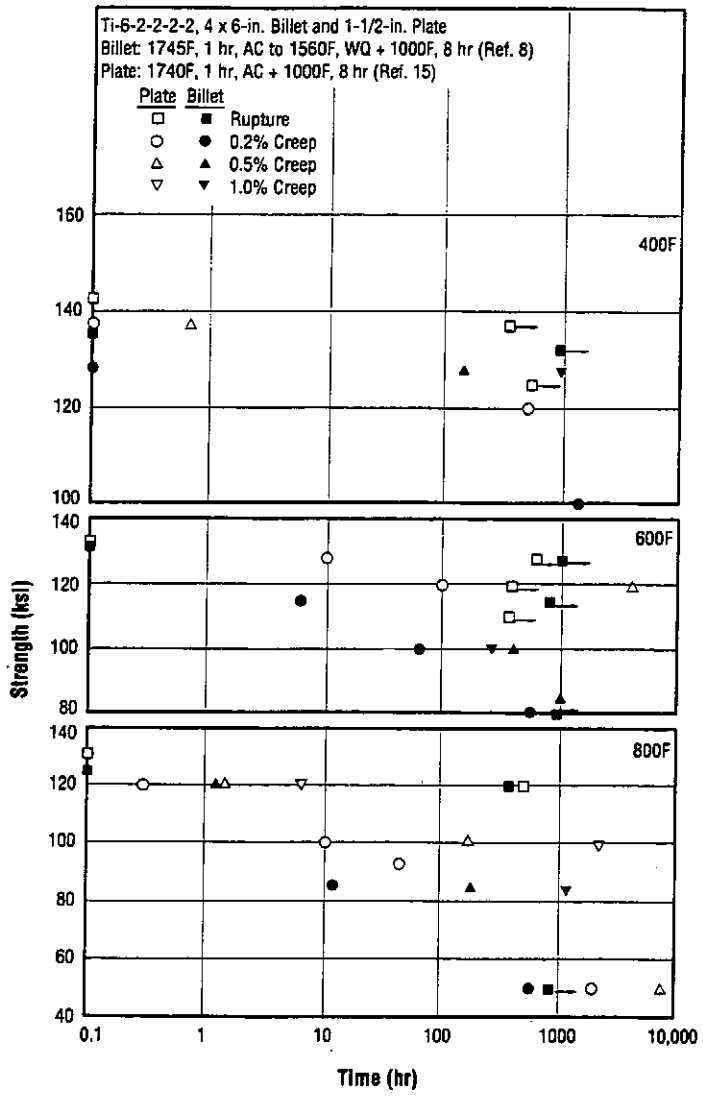


Fig. 3.4.1 Plastic creep and rupture data for conventionally processed plate and duplex annealed billet (Refs. 8, 15)

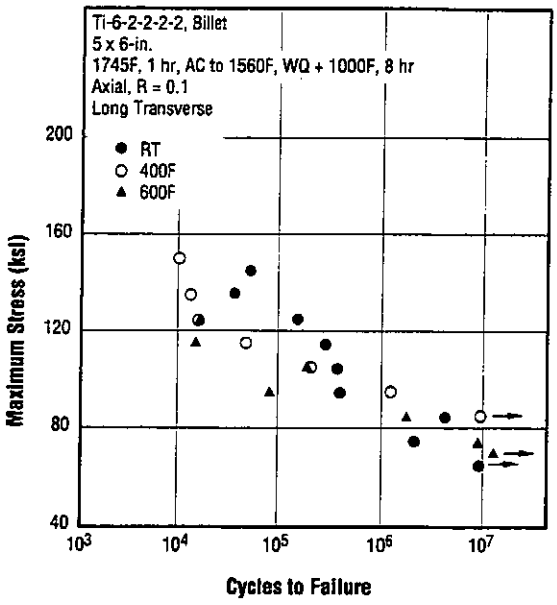


Fig. 3.5.1.1 Effect of test temperature on the smooth fatigue strength of conventionally processed billet (Ref. 15)

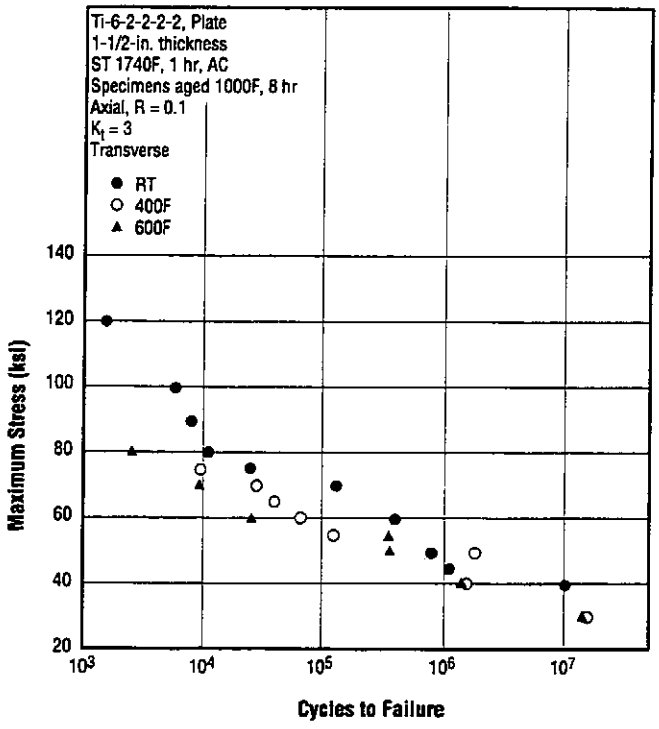


Fig. 3.5.1.2 Effect of test temperature on the notched fatigue strength of conventionally processed plate (Ref. 8)

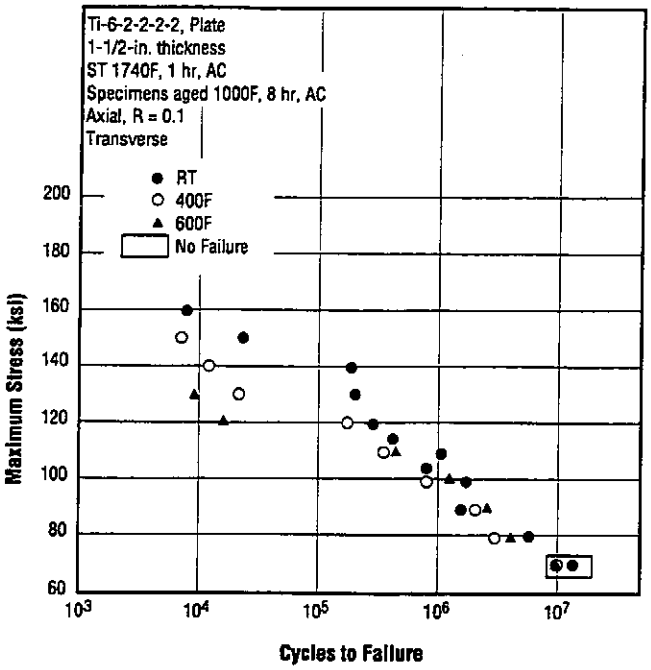


Fig. 3.5.1.3 Effect of test temperature on smooth fatigue strength of conventionally processed plate (Ref. 8)

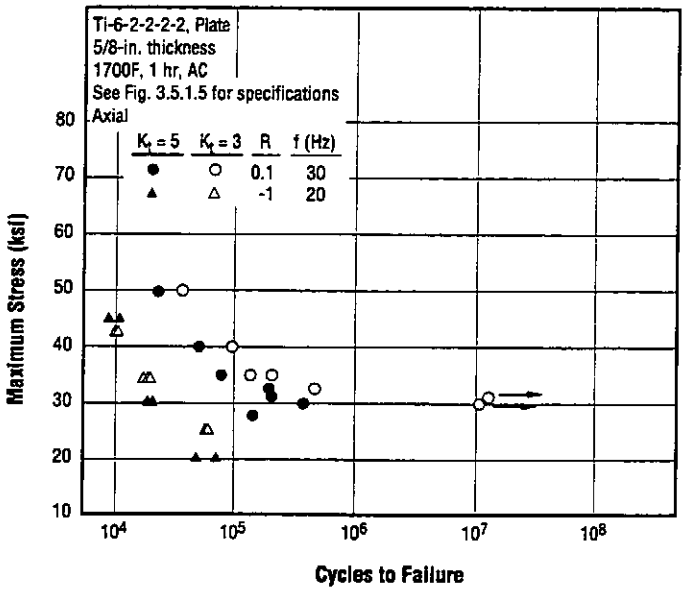


Fig. 3.5.1.4 Notch fatigue strength for conventionally processed solution treated unaged plate (Ref. 11)

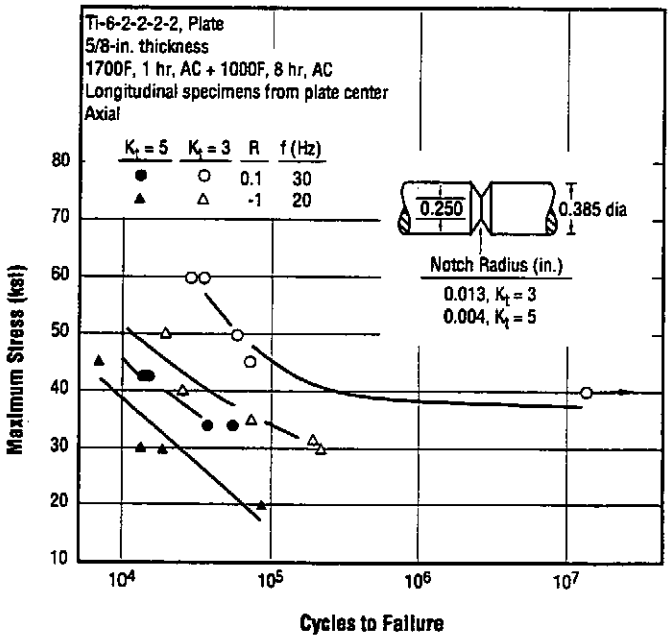


Fig. 3.5.1.5 Notch fatigue strength for conventionally processed plate (Ref. 11)

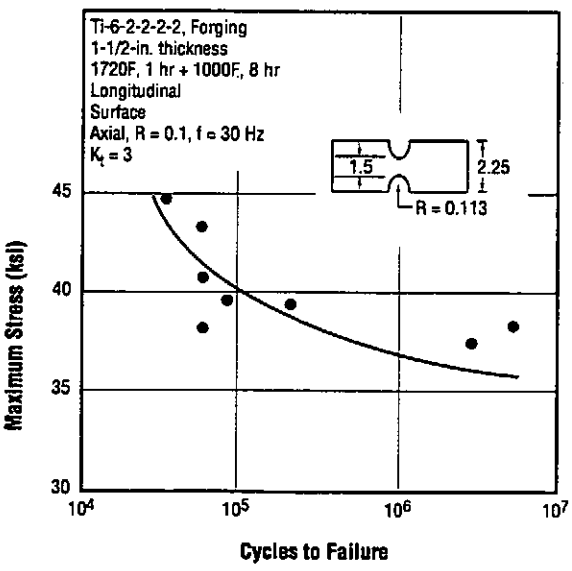


Fig. 3.5.1.6 Notch fatigue strength of a conventionally processed forging (Ref. 14)

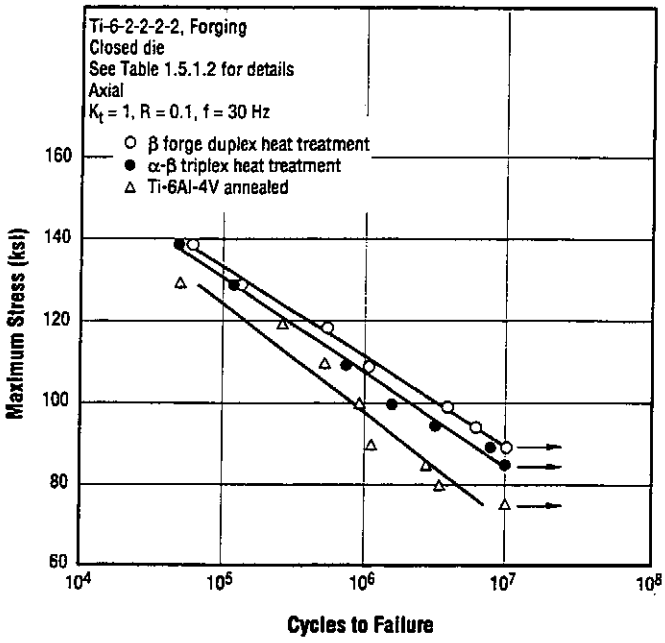


Fig. 3.5.1.7 Smooth fatigue strength produced by two thermomechanical processes applied to Ti-6-2-2-2-2 forgings compared with fatigue strength of annealed Ti-6Al-4V forgings (Ref. 6)

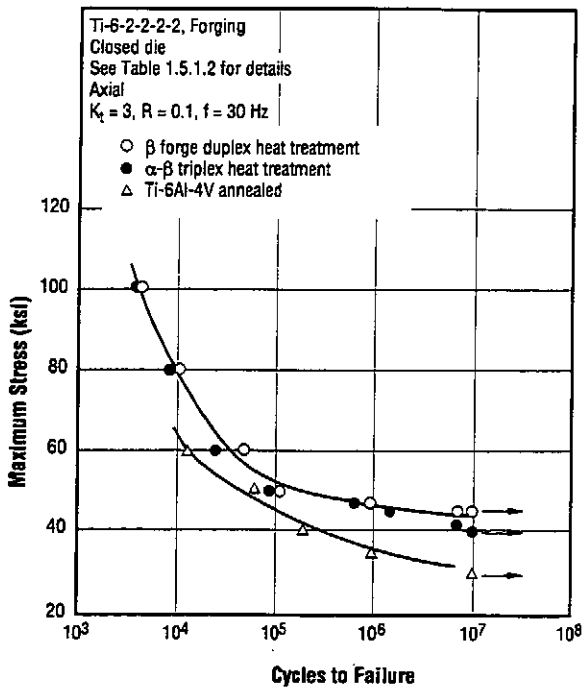


Fig. 3.5.1.8 Notch fatigue strength produced by two thermomechanical processes applied to Ti-6-2-2-2-2 forgings compared with fatigue strength of annealed Ti-6Al-4V forgings (Ref. 6)

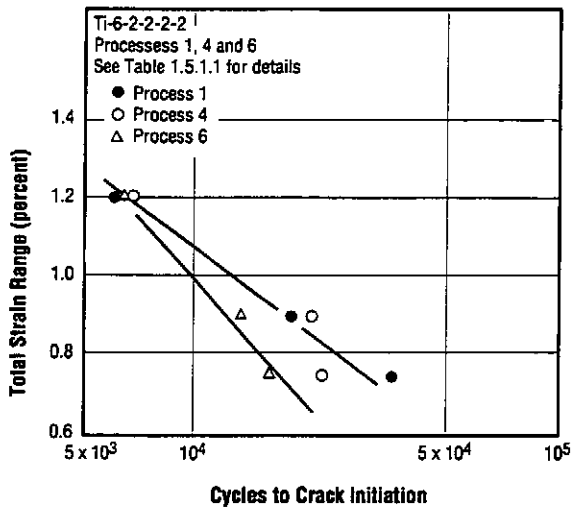


Fig. 3.5.2.1 Effect of thermomechanical processing on low cycle fatigue crack initiation of forgings (Refs. 4, 7)

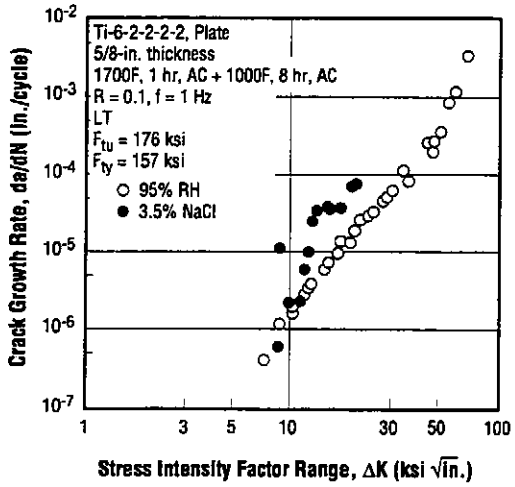


Fig. 3.5.3.1 Fatigue crack growth rates at 1 Hz for conventionally processed plate in humid air and in 3.5 percent NaCl (Refs. 10, 11)

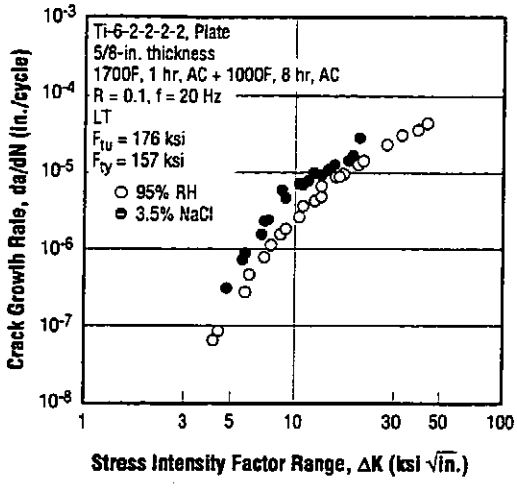


Fig. 3.5.3.2 Fatigue crack growth rates at 20 Hz for conventionally processed plate in humid air and in 3.5 percent NaCl (Refs. 10, 11)

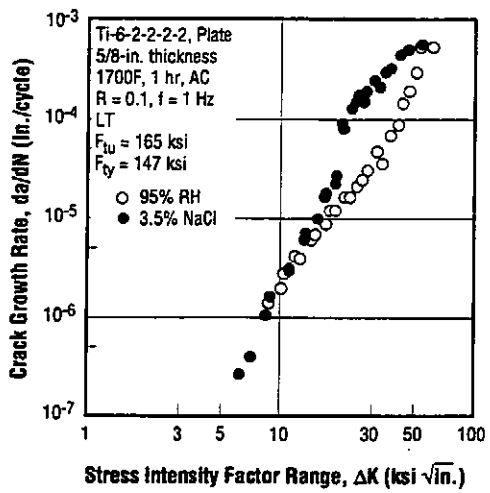


Fig. 3.5.3.3 Fatigue crack growth rates at 1 Hz for conventionally processed solution treated unaged plate in humid air and in 3.5 percent NaCl (Refs. 10, 11)

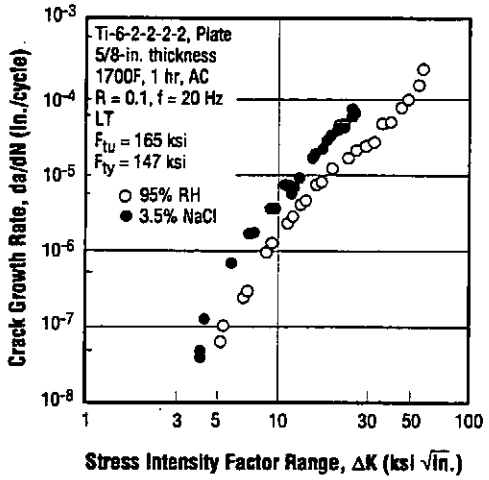


Fig. 3.5.3.4 Fatigue crack growth rates at 20 Hz for conventionally processed solution treated unaged plate in humid air and in 3.5 percent NaCl (Refs. 10, 11)

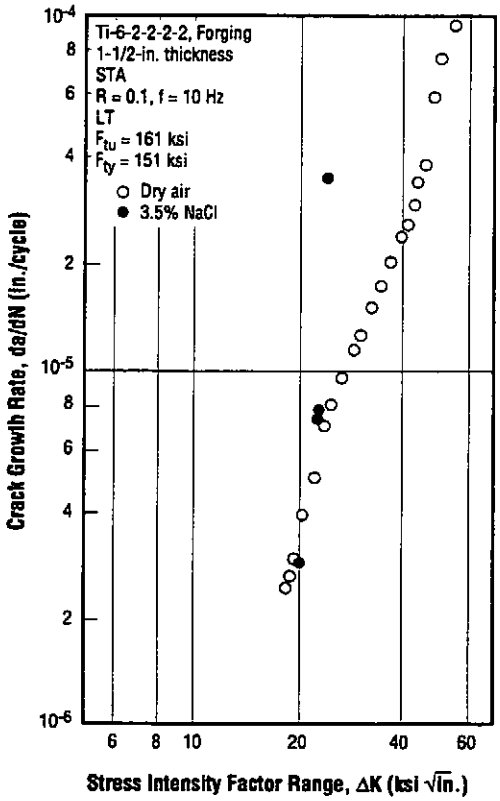


Fig. 3.5.3.5 Fatigue crack growth rates for conventionally processed forging in dry air and in 3.5 percent NaCl (Ref. 9)

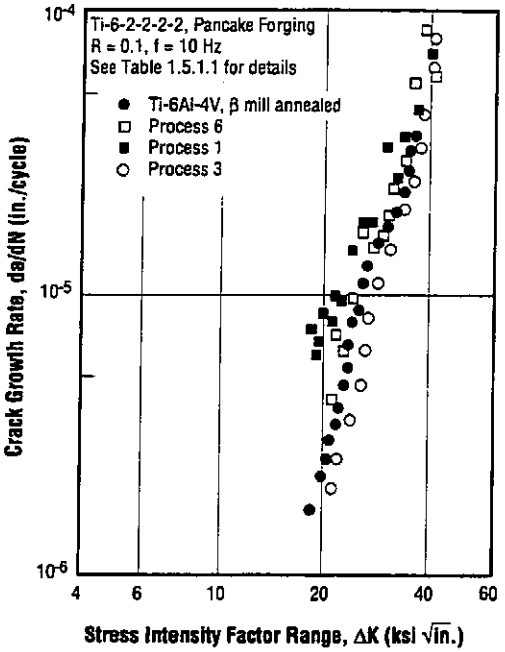


Fig. 3.5.3.6 Fatigue crack growth rates for Ti-6-2-2-2-2 forgings subjected to several thermomechanical processes compared with beta mill annealed Ti-6Al-4V forgings (Refs. 4, 7)

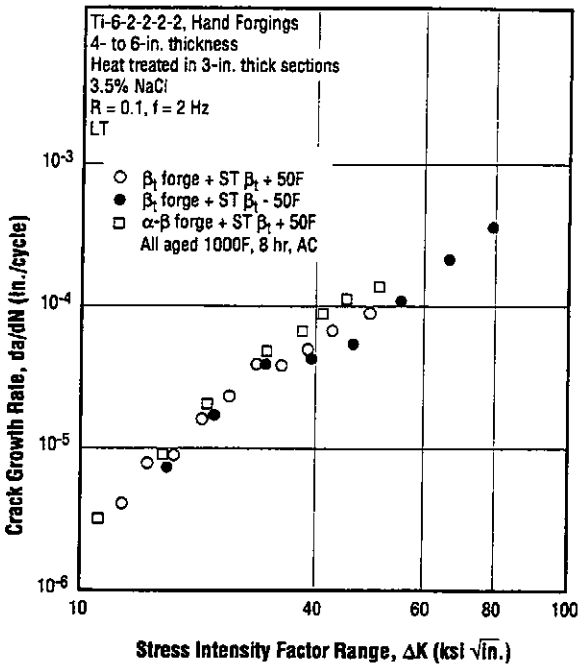


Fig. 3.5.3.7 Fatigue crack growth rates in 3.5 percent NaCl for hand forgings made from 8000-lb ingot and subjected to several thermomechanical processes (Ref. 20)

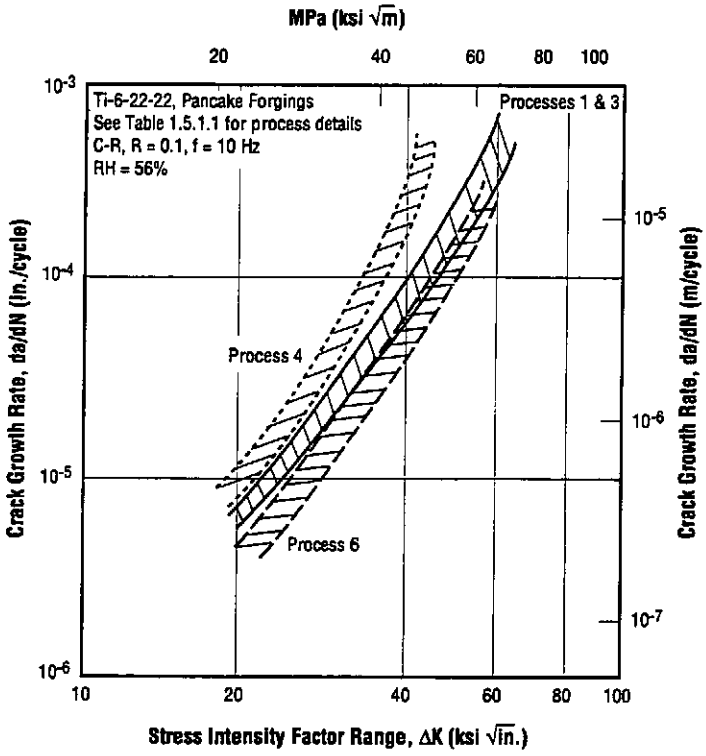


Fig. 3.5.3.8 Fatigue crack growth rates for forgings subjected to several thermomechanical processes (Ref. 4)

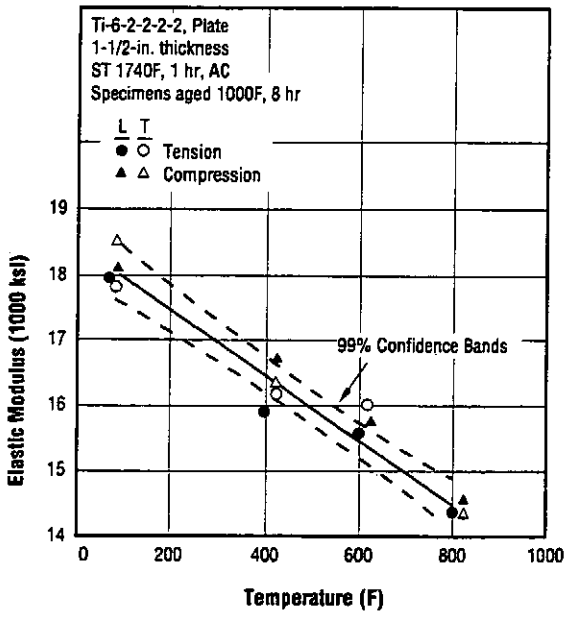


Fig. 3.6.2.1 Effect of temperature on the tension and compression elastic modulus of conventionally processed plate (Ref. 8)

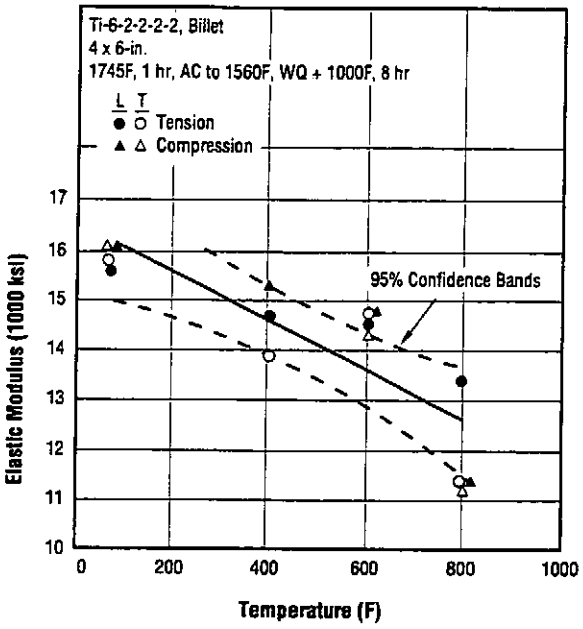


Fig. 3.6.2.2 Effect of temperature on the tension and compression elastic modulus of conventionally processed forged billet (Ref. 15)

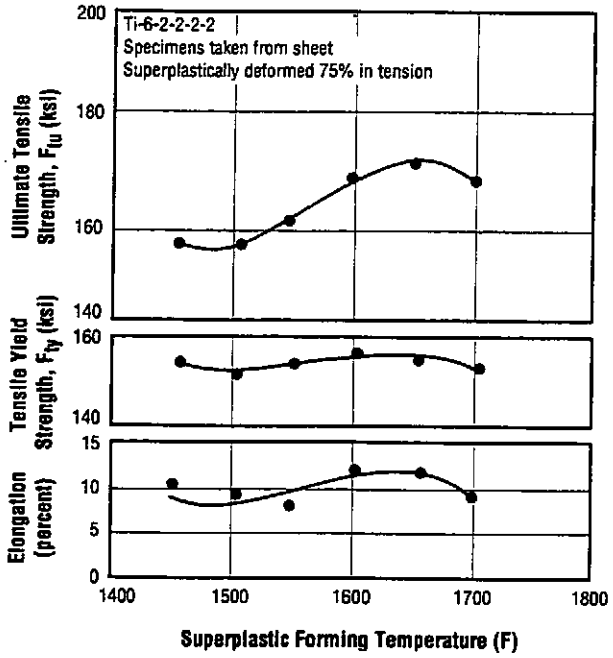


Fig. 4.1.2 Effect of superplastic forming temperature on the tensile properties of sheet (Ref. 19)

Table 4.3.1.1 Tensile properties and fracture toughness of electron beam welds in conventionally processed plate (Ref. 22)

Alloy	Ti-6Al-2-2-2-2 0.25Si, 0.12 Oxygen			
Form	0.625-in. Hot-Rolled Plate			
Condition	**ST 1725F, 1 hr, AC**		**ST 1750F, 1 hr, AC**	
Welding[a]	**No Weld + Age[b]**	**Weld + Age**	**No Weld + Age**	**Weld + Age**
F_{tu} (ksi)	182	180	180	178
F_{ty} (ksi)	156	166	165	164
e (percent)	13	17	17	17
RA (percent)	35	35	34	30
K_{Ic} (ksi $\sqrt{in.}$)[c]	44	_[d]	47	_[d]

[a] Electron beam welding parameters: beam current 300 ma, voltage 45 kV, energy input 20.4 kJ/inch, gun to work 8-inches. No filler metal.

[b] All specimens aged 1000F, 8 hours.

[c] CT specimens with crack at weld centerline.

[d] Specimens failed during fatigue cracking.

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