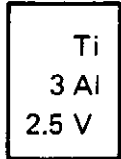
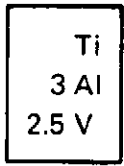


1	<p>GENERAL Ti-3Al-2.5V is a near alpha, alpha-beta alloy, sometimes referred to as "half 6-4". It offers 20 to 50 percent higher tensile strength than the strongest commercially pure grade of titanium at both room and elevated temperatures. It is much more amenable to cold working than Ti-6Al-4V, and 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.</p>	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 1/2 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).
1.01	<p><u>Commercial Designation</u> 3Al-2.5V Titanium alloy.</p>	1.054
1.02	<p><u>Alternate Designations</u> 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).</p>	1.055
	1.056	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.
	1.057	Solution treat and age. 1600-1700 F, 1/4-1/3 hour, WQ + 900-950 F, 2-8 hours, AC.
1.03	<p><u>Specifications</u> Table 1.03.</p>	1.058
	1.059	Effect of annealing (or stress relieving) temperature on hardness of full hard (50 percent cold worked) tubing, see Figure 1.061.
1.04	<p><u>Composition</u></p>	1.057
1.041	AMS specified composition for tubing, Table 1.041.	1.058
1.042	Users' specified composition for tubing and pipe, Table 1.042.	1.059
1.043	Users' specified composition for ingot and for aircraft quality bars (rolled or forged) and reforging stock, Table 1.043.	1.059
1.044	Users' specified composition for sheet, strip, and foil, Table 1.044.	1.059
1.045	AWS specified composition for welding rods and electrodes, Table 1.045.	1.059
1.05	<p><u>Heat Treatment</u></p>	1.059
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	1.059
	1.0513	Effect of annealing (or stress relieving) temperature on room temperature tensile properties of full hard (50 percent cold worked) tubing, see Figure 3.0213.
	1.0511	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.
	1.0512	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	<p><u>Hardness</u> The hardness of this alloy in the wrought condition will be directional because of differential working and crystallographic texturing.</p>



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- 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 mechanism 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 (ITT) 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, 4.4×10^{-6} (46), 5.5×10^{-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 Emission.
- 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 .

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.

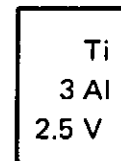
Titanium has good resistance to dilute solutions of alkali. Hot, strong, caustic solutions will attack unalloyed titanium and titanium alloys. On the other hand, titanium does not appear susceptible to caustic embrittlement as are carbon steels and stainless steels.

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.

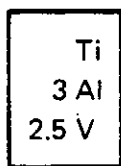
Titanium is remarkably resistant to pitting, stress corrosion, galvanic corrosion, crevice corrosion (below about 200 F), erosion-corrosion, and corrosion fatigue in marine environments.

Pure hydrocarbons are not considered corrosive to titanium, and titanium exhibits good corrosion behavior in most chlorinated and fluorinated hydrocarbons. However, such materials may hydrolyze 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



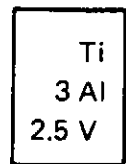
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- 2.032 impact in chlorine trifluoride, liquid fluorine and nitrogen tetroxide. Only in liquid and gaseous oxygen is the reaction sustained, once initiated.
- 2.0321 Stress Corrosion Cracking. There are no available stress corrosion cracking (SCC) 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.
- 2.03215 Some of the known environments in which titanium and its alloys have shown cracking susceptibility have been summarized by Brown (27) and are categorized 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, trichloroethylene, 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 N₂O₄ 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 N₂O₄ 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 experience with cadmium 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.	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.
2.034	Corrosion Fatigue. Aggressive environments will accelerate fatigue crack growth rates. This effect is predominately at high crack stress intensity factor ranges. (32)	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.
2.04	<u>Nuclear Environments</u>	3.022	Compression.
3	MECHANICAL PROPERTIES	3.023	Impact, see 3.033.
3.01	<u>Specified Mechanical Properties</u>	3.024	Bending.
3.011	AMS specified tensile properties for tubing, Table 3.011.	3.025	Torsion and Shear.
3.012	Users' specified tensile properties for bars (rolled or forged) and re forging stock, Table 3.012.	3.026	Bearing.
3.013	Users' specified tensile properties for sheet, strip and foil, Table 3.013.	3.027	Stress concentration.
3.014	Users' specified tensile properties for tubing and pipe, Table 3.014.	3.0271	Notch properties, see 3.0371.
3.015	AMS specified flarability for tubing, Table 3.015.	3.0272	Fracture toughness.
3.016	Users' specified tubing flarability requirements, Table 3.016.	3.028	Combined properties.
3.017	AMS specified bendability for tubing, Table 3.017.	3.03	<u>Mechanical Properties at Various Temperatures</u>
3.018	Users' specified bendability requirements for tubing and pipe, Table 3.018.	3.031	Tension.
3.019	Users' specified bendability requirements for sheet, strip and foil, Table 3.019.	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.
3.0110	AMS specified flattenability for tubing, Table 3.0110.	3.0312	Room temperature and 450 F tensile properties of cold worked, stress relieved tubing, Table 3.0312.
3.0111	Users' specified flattenability requirements for tubing and pipe, Table 3.0111.	3.0313	450 F tensile properties of tubing in hardness conditions ranging from full hard to fully annealed, Figure 3.0313.
3.0112	ASM specified pressurability for tubing, Table 3.0112.	3.0314	600 F tensile properties of tubing in hardness conditions ranging from full hard to fully annealed, Figure 3.0314.
3.0113	Users' specified pressurability requirements for tubing and pipe, Table 3.0113.	3.0315	Effect of test temperature on tensile properties of tubing in hardness conditions ranging from hard to fully annealed, Figure 3.0315.
3.02	<u>Mechanical Properties at Room Temperature</u>	3.0316	Tensile properties of tubing from room temperature to -453 F, Figure 3.0316.
3.021	Tension, see also 3.031.	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.
3.0211	Effect of anneal cycle on room temperature tensile properties of hot rolled sheet, Table 3.0211.	3.032	Compression.
3.0212	Effect of 1000 F age on room temperature tensile properties of strip, Figure 3.0212.	3.033	Impact.
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.	3.0331	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.
3.0214	Room temperature tensile properties of tubing in hardness conditions ranging from full hard to fully annealed, Figure 3.0214.	3.034	Bending.
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.	3.035	Torsion and shear.
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.	3.036	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	<u>Creep and Creep Rupture Properties</u>



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Ti
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- 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. 4.014
- 3.059 Effect of chafe depth (simulated service damage) on hydraulic impulse fatigue life of 3,000-psi system tubing, Figure 3.059. 4.015
- 3.0510 Effect of defect size (simulated service damage) on hydraulic impulse fatigue life of 3,000-psi system tubing, Figure 3.0510. 4.016
- 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 1/2-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. 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. Effect of homogenizing heat treat temperature and cooling rate from that temperature on microhardness of small samples taken from forged billet, Figure 4.015. 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:

$$RR = [(t_0 - t)/t_0] / [(D_0 - D)/D_0],$$

where t_0 and t are the initial and final wall thicknesses, respectively, and D_0 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 ($RR \rightarrow \infty$) 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 10⁵ 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. 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, how-

ever, increasingly stringent requirements for ductility and strength have resulted in an increase in the use of welding as a joining method.

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 HNO₃ + 5 percent HF + 60 percent H₂O solution. Either preparatory cleaning is apparently suitable for EB welding. 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 nomenclature in Figure 4.03134) constitutes the weakest part of the GTA as-welded joint for 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.

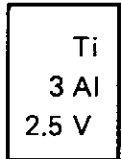
The uniaxial tension properties at slightly elevated temperature (248 F) of unwelded and GTA welded tubing are compiled in Table 4.03122 for three base metal conditions. All specimens failed in the transformation zone. However, the difference between base metal and weld properties lessens with increasing 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.

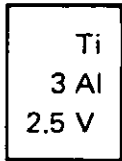
4.03122 Tensile properties at 248 F of cold worked and annealed tubes and as-welded strips from GTA welded portions of those tubes, Table 4.03122.

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-3Al-2.5V



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 anisotropy 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 $\Sigma_0:\Sigma_2 = 2:1$. 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.

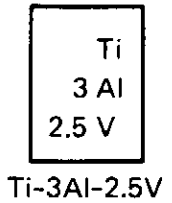
4.04

Surface Treating

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Ti
3 Al
2.5 V

Ti-3Al-2.5V

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 126OH (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	
	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
Vanadium	2.0	3.0	2.00	3.00	2.0	3.0	2.0	3.0
Iron	--	0.30	--	0.30	--	0.25	--	0.25
Oxygen	--	0.12	--	0.12	--	0.125	--	0.12
Carbon	--	0.05	--	0.05	--	0.05	--	0.05
Nitrogen	--	0.02	--	0.050	--	0.020	--	0.02
Hydrogen	--	0.015(a)	--	0.0150	--	0.0150	--	0.015
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	--	0.4(c)
Titanium	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 Reforging Stock, Aircraft Quality
Condition	As-Cast	Annealed
	Weight Percent	
	Min	Max
Aluminum	2.5	3.5
Vanadium	2.0	3.0
Iron	--	0.10
Oxygen	--	0.10
Carbon	--	0.05
Nitrogen	--	0.02
Hydrogen	--	0.010
Yttrium	--	0.005
Boron	--	0.05
Tungsten	--	--
Silicon	--	--
Residual Elements, Each	--	0.10
Residual Elements, Total	--	0.40(b)
Titanium	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	
	Min	Max
Aluminum	2.50	3.50
Vanadium	2.00	3.00
Iron	--	0.25
Oxygen	--	0.070
Carbon	--	0.070
Nitrogen	--	0.040
Hydrogen	--	0.015
Yttrium	--	--
Boron	--	--
Tungsten	--	--
Silicon	--	0.30
Residual Elements, Each	--	0.10(a)
Residual Elements, Total	--	0.40(a)
Titanium	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) Lockheed-Georgia STM08-303C (10) McDonnell MMS-1205D (36) Wolverine (38) AMS 4943A (2) Pratt & Whitney PWA-126OH (35) Zirtech (29) RMI (13)	700 F Min, ½-hour Min 600 F Min, ½-hour Min 600 F min, ½-hour Min; Except Rotary Straightened Tubing, 700 F Min, 2 hours Min 600 F Min 600-1000 F 700-1200 F, ½-2 hours, AC	1100-1450 F, ¼-1 hour, AC (or Slower) 1300 ± 25 F, 1-hour Min 1000-1350 F 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, ¼-½ 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

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	CWSR 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)	<u>Flarability</u> 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 \geq 0.125 inch	1.2 ^(b)
General Electric (14)	B50TF35-S7	Tubing, Seamless	Cold Drawn, Annealed	All	1.30 ^(c)
Pratt & Whitney (35)	PWA 126OH	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 \leq 3½ inches Wall \leq 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
Annealed* (2)	<u>Bendability</u> 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 \leq 2 inches	12.0 ^(c)
Pratt & Whitney (35)	PWA 126OH	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	2.5*
				0.010 to 0.187 inch	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										
Flattenability											
Annealed* (2)	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)	<p>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.</p> <table border="1"> <thead> <tr> <th>Outside Diameter to Wall Thickness Ratio OD/t</th> <th>Distance Between Plates Where t = Wall Thickness</th> </tr> </thead> <tbody> <tr> <td>10 or less</td> <td>8t</td> </tr> <tr> <td>11 to 16 incl</td> <td>12t</td> </tr> <tr> <td>17 to 30 incl</td> <td>15t</td> </tr> <tr> <td>31 to 50 incl</td> <td>17t</td> </tr> </tbody> </table> <p>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.</p>	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
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										

* 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	12(b)
ANSI/ASTM (17)	B337-78	Pipe, Seamless, and Welded	Annealed and Cold Worked, Stress Relieved	≤ 1.15 x OD 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 11 ≤ OD/t < 16 17 ≤ OD/t < 30 31 ≤ OD/t < 50	g(h) 12(h) 15(h) 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
	<u>Pressuribility</u>
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)*** sufficient 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

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)
General Electric (14)	B50TF35-S7	Tubing, Seamless	Cold Drawn, Annealed	OD > 3/8 inch	95(b)(c) 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 F _{ty} , min = 95 ksi F _{ty} , min = 105 ksi	All	70 (g)(i)(j) 95 (g)(i)(j) 105 (g)(i)(j)

Ti-3Al-2.5V

- (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	F _{tu} , ksi	F _{ty} , ksi	e, percent
	Direction			
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} ,	F _{ty} ,	e,
	ksi	ksi	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	F _{tu} ,	F _{ty} ,	e (2-inches),
	Temp/Time			
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: RA 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 1/2-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	182×10^3
			(2)	25.4	145×10^3
			(3)	24.6	92×10^3
		Rotary Straightened	(1)	24.6	141×10^3
(2)	24.9		127×10^3		
(3)	25.7		93×10^3		
1 x 0.066	Annealed ($F_{tu} = 99.5$ ksi)	Cold-Stretch Straightened	(1)	35.2	233×10^3
			(2)	34.8	115×10^3
			(3)	36.3	220×10^3
		Rotary Straightened	(1)	32.5	249×10^3
			(2)	34.8	304×10^3
			(3)	33.1	251×10^3

*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.

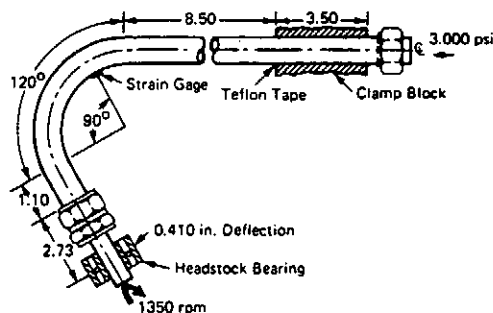
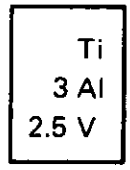


DIAGRAM OF ROTARY FLEXURE TEST SET-UP

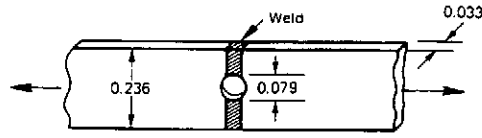
TABLE 3.056. INFLUENCE OF STRAIGHTENING PROCEDURE, HEAT TREATMENT, AND SURFACE CONDITIONING ON ROTARY FLEXURE FATIGUE LIFE OF TUBING (44)

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



Ti-3Al-2.5V

- (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.

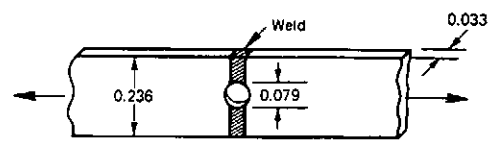


STRIP SPECIMEN

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)

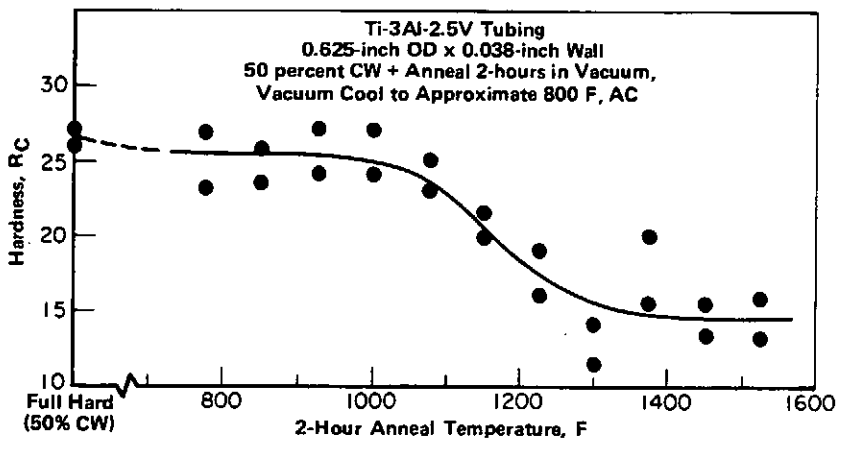


FIGURE 1.061. EFFECT OF ANNEALING (OR STRESS RELIEVING) TEMPERATURE ON HARDNESS OF FULL HARD (50 PERCENT COLD WORKED) TUBING (17)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

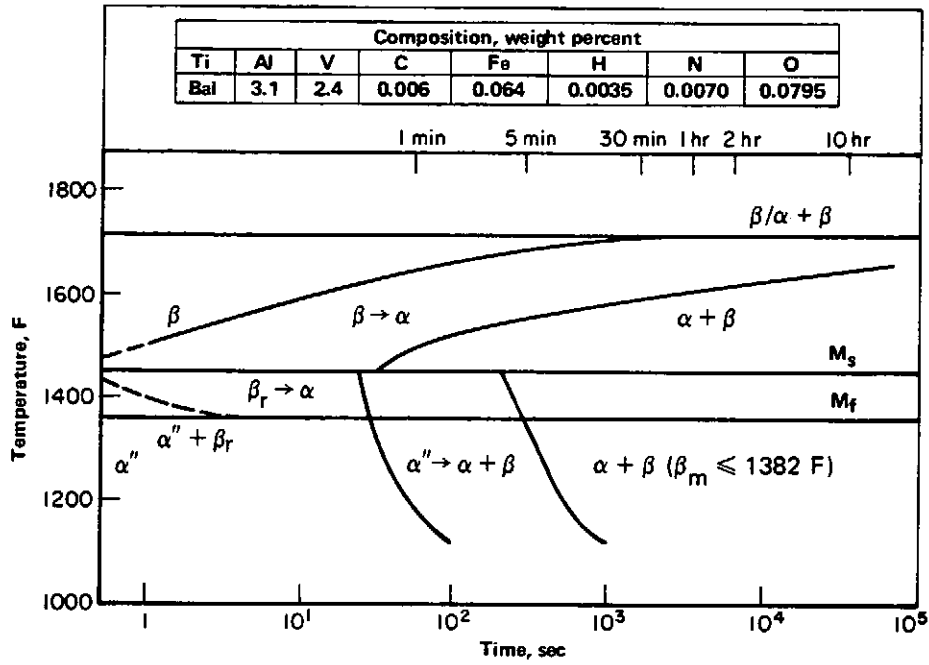


FIGURE 2.0121. Ti-3Al-2.5V ISOTHERMAL TRANSFORMATION (TTT) DIAGRAM (6)

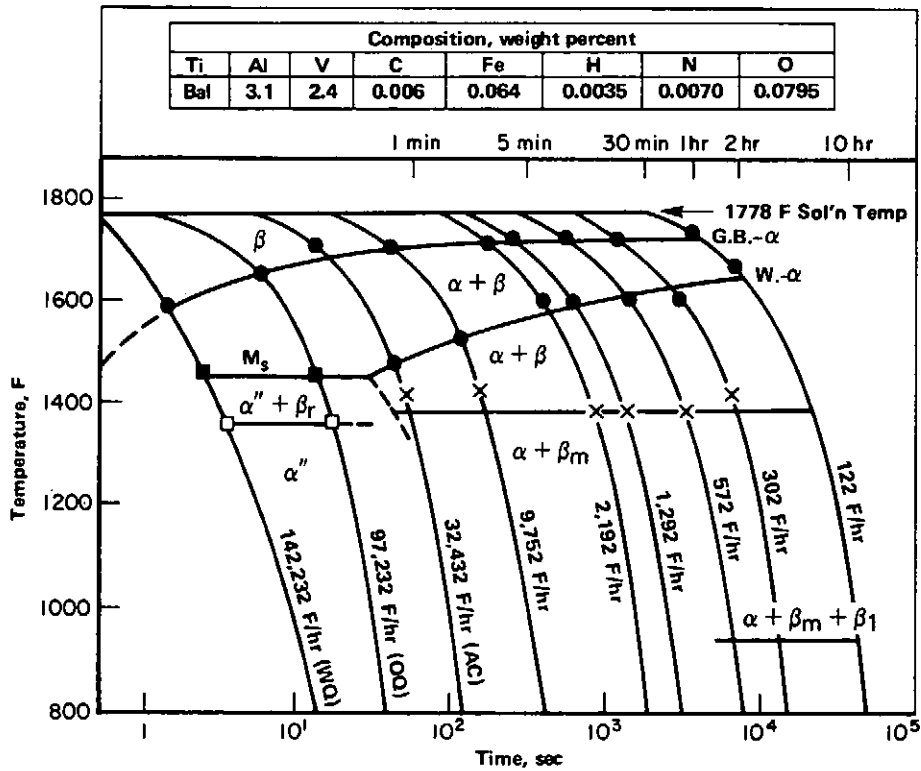


FIGURE 2.0122. Ti-3Al-2.5V CONTINUOUS COOLING TRANSFORMATION (CCT) DIAGRAM (6)

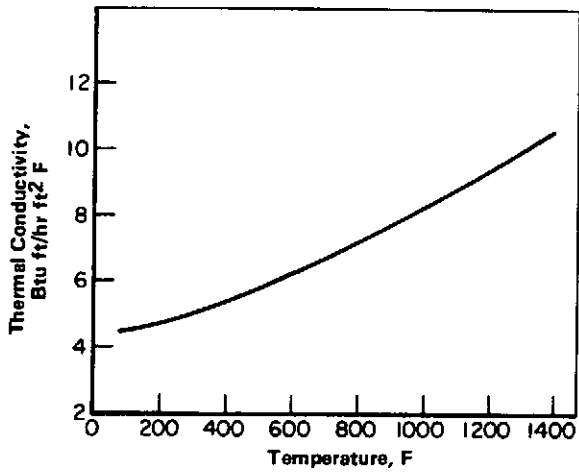


FIGURE 2.013. THERMAL CONDUCTIVITY (29)

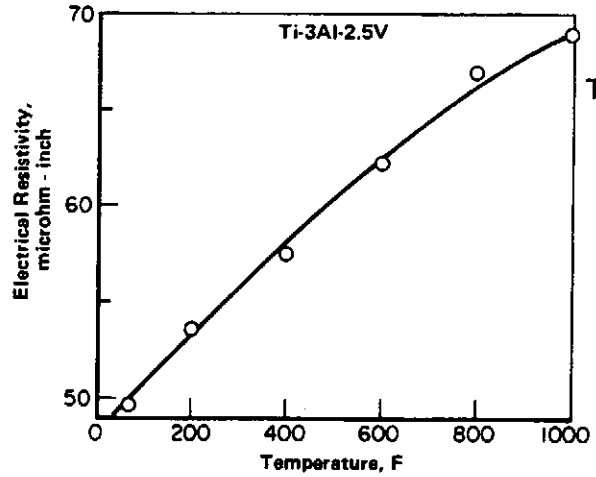


FIGURE 2.0221. ELECTRICAL RESISTIVITY (29)

Ti
3 Al
2.5 V

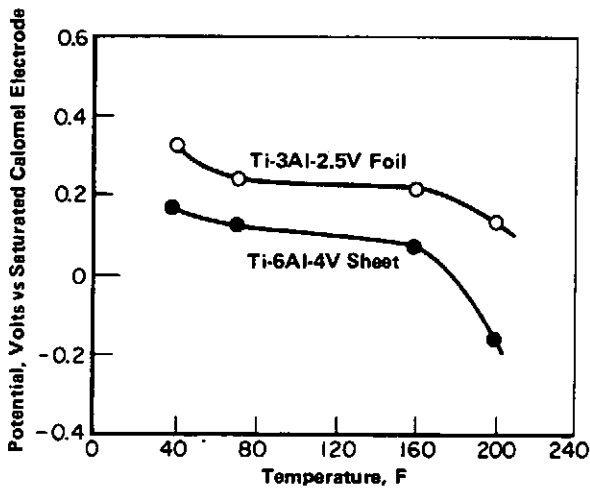


FIGURE 2.0311. EFFECT OF TEMPERATURE ON ELECTRODE POTENTIAL FOR Ti-3Al-2.5V FOIL AND Ti-6Al-4V SHEET IN 3.5 PERCENT NaCl SOLUTION (26)

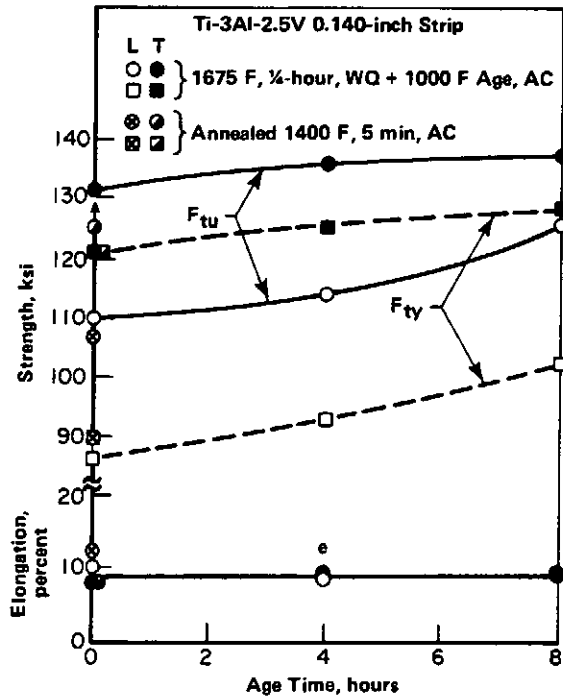


FIGURE 3.0212. EFFECT OF 1000 F AGE ON ROOM TEMPERATURE TENSILE PROPERTIES OF STRIP (12)

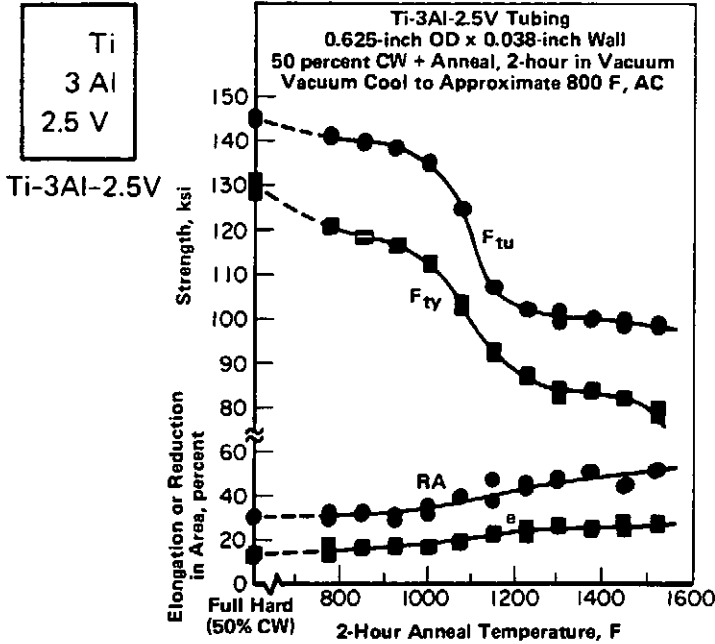


FIGURE 3.0213. EFFECT OF ANNEALING (OR STRESS RELIEVING) TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF FULL HARD (50 PERCENT COLD WORKED) TUBING (19)

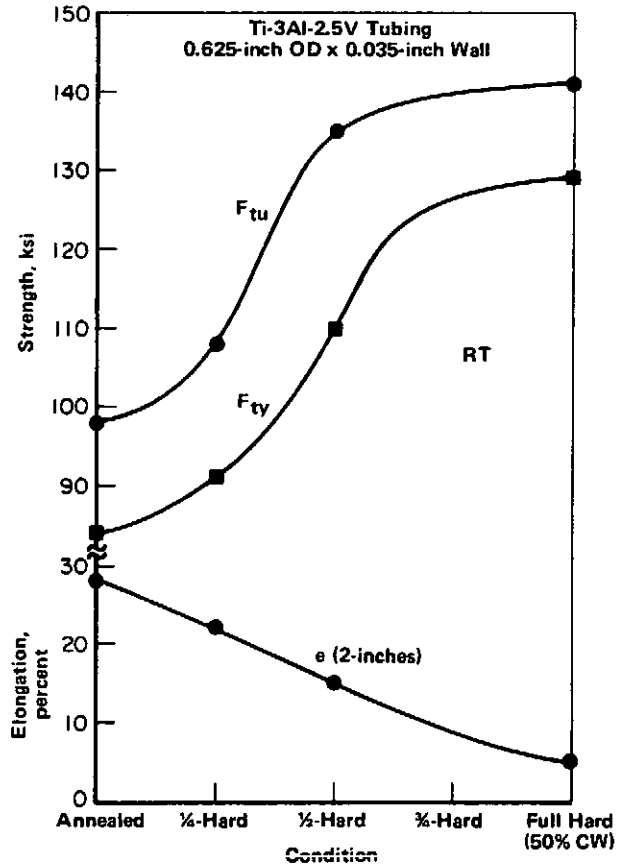


FIGURE 3.0214. ROOM TEMPERATURE TENSILE PROPERTIES OF TUBING IN HARDNESS CONDITIONS RANGING FROM FULL HARD TO FULLY ANNEALED (12)

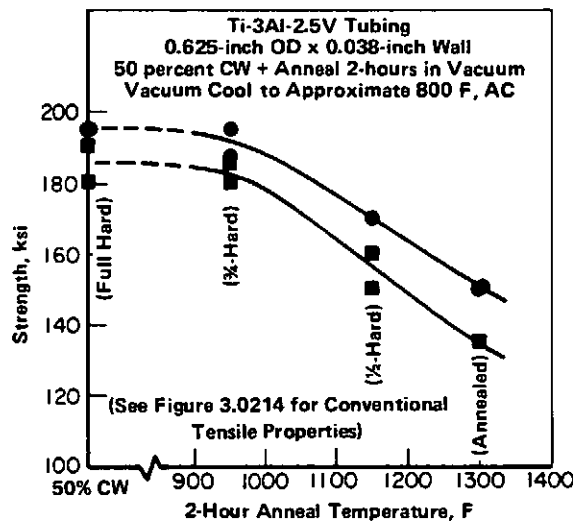


FIGURE 3.0215. EFFECT OF ANNEALING (OR STRESS RELIEVING) TEMPERATURE ON ROOM TEMPERATURE YIELD AND BURST STRENGTHS OF INTERNALLY PRESSURIZED FULL HARD (50 PERCENT COLD WORKED) TUBING (19)

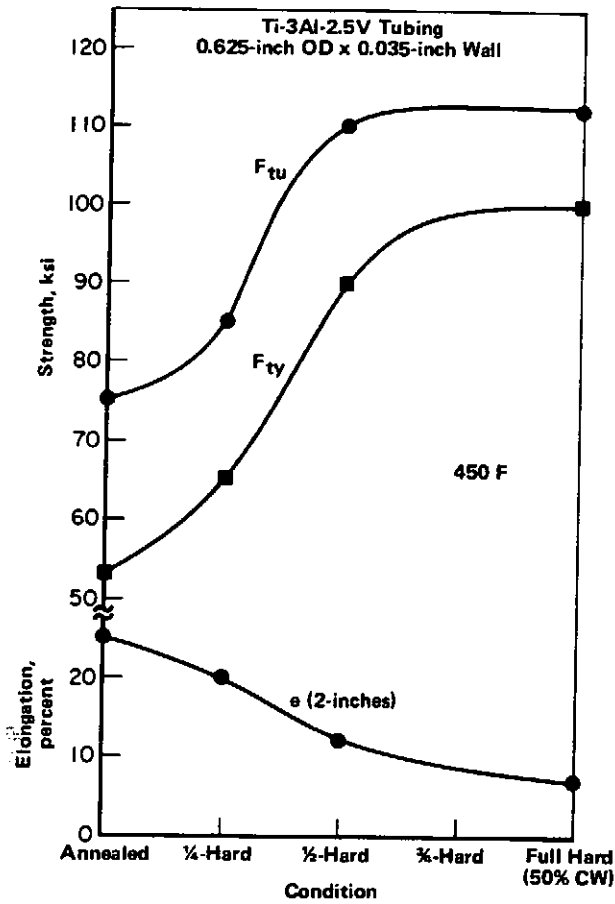


FIGURE 3.0313. 450 F TENSILE PROPERTIES OF TUBING IN HARDNESS CONDITIONS RANGING FROM FULL HARD TO FULLY ANNEALED (12)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

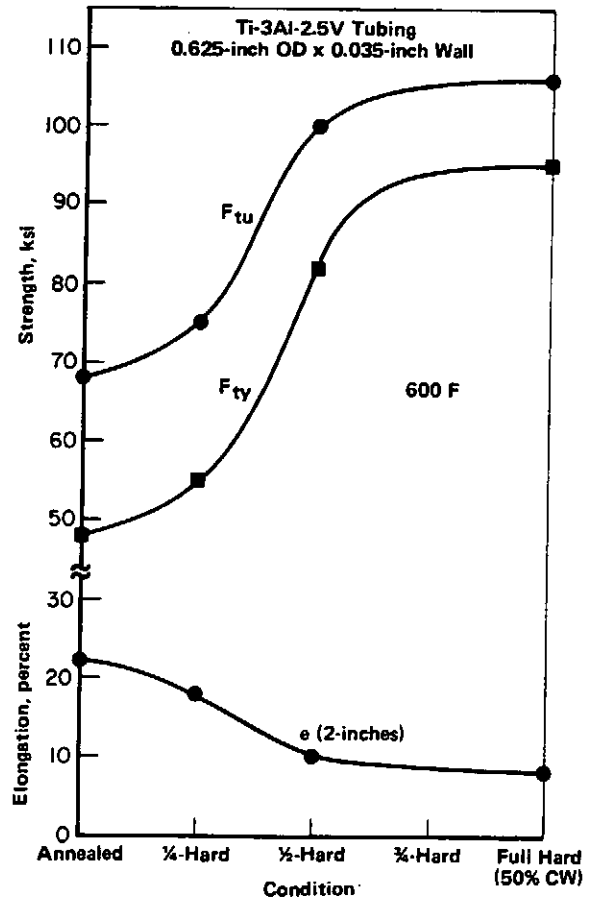


FIGURE 3.0314. 600 F TENSILE PROPERTIES OF TUBING IN HARDNESS CONDITIONS RANGING FROM FULL HARD TO FULLY ANNEALED (12)

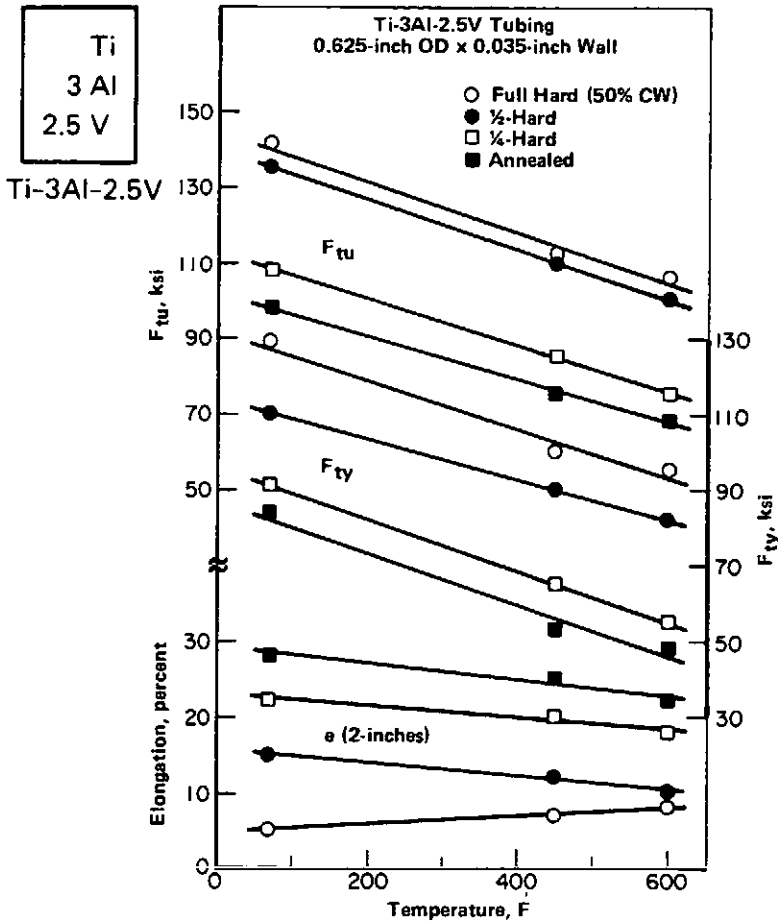


FIGURE 3.0315. EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF TUBING IN HARDNESS CONDITIONS RANGING FROM FULL HARD TO FULLY ANNEALED (12)

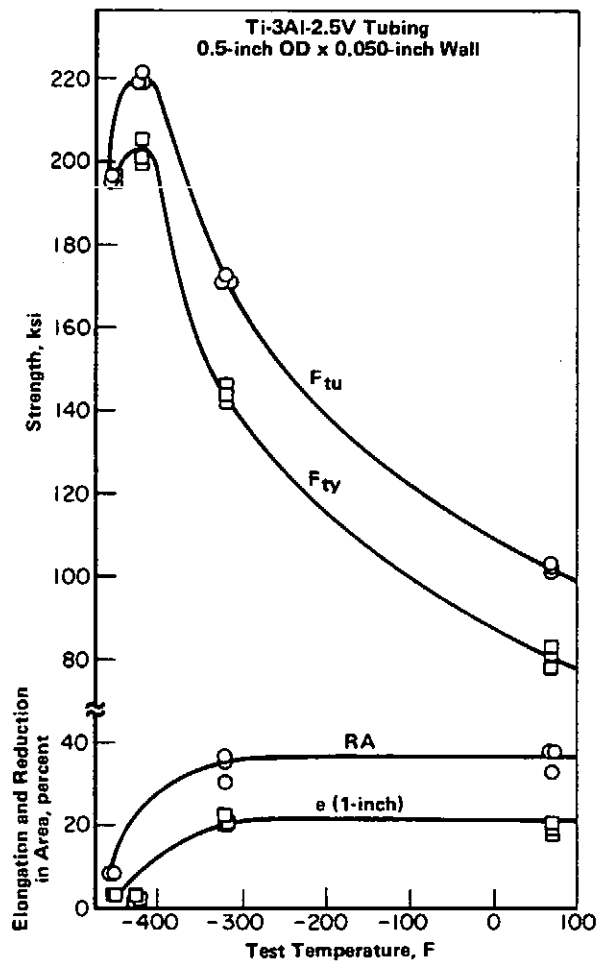


FIGURE 3.0316. TENSILE PROPERTIES OF TUBING FROM ROOM TEMPERATURE TO -453 F (45)

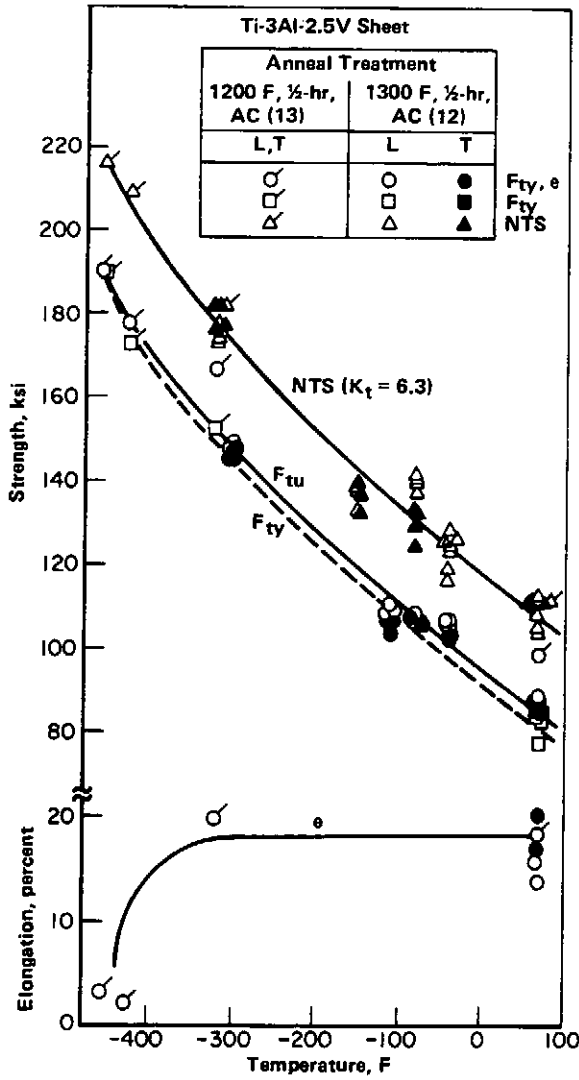


FIGURE 3.03711. EFFECT OF CRYOGENIC TEMPERATURE ON SMOOTH AND MILD NOTCH TENSILE PROPERTIES OF ANNEALED SHEET (12) (13)

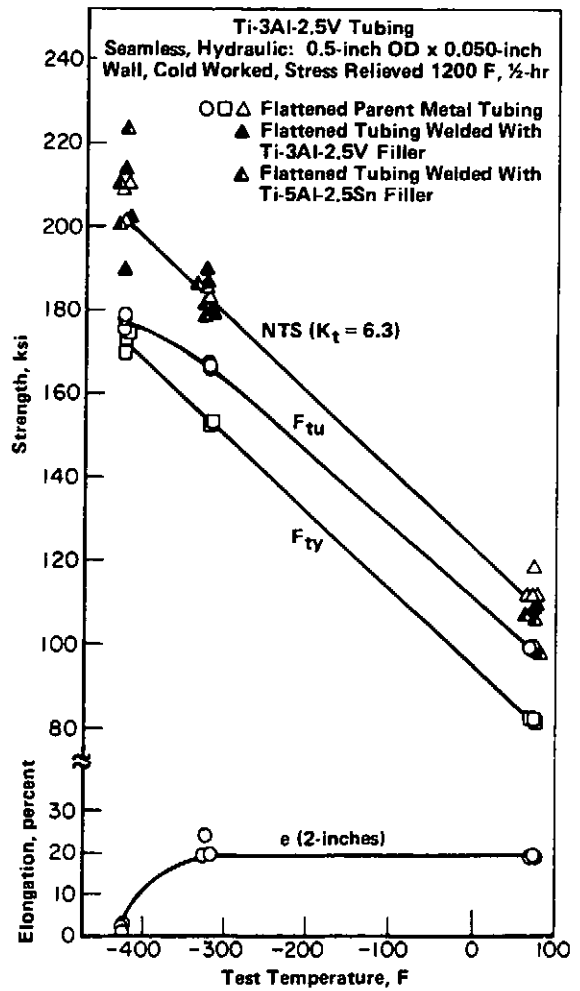
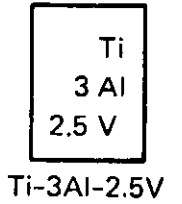


FIGURE 3.03712. SMOOTH AND MILD NOTCH TENSILE PROPERTIES OF PARENT METAL AND WELDED FLATTENED TUBING FROM ROOM TEMPERATURE TO -423 F (45)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

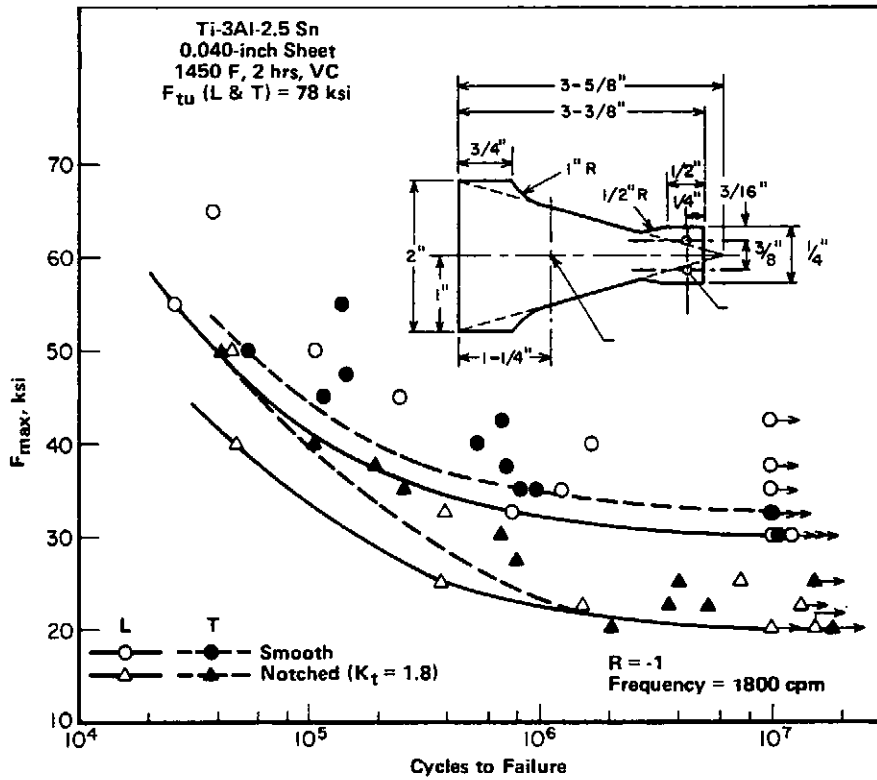


FIGURE 3.051. ROOM TEMPERATURE SMOOTH AND MILD NOTCH BENDING FATIGUE STRENGTH OF VARIOUS ANNEALED SHEET (1)

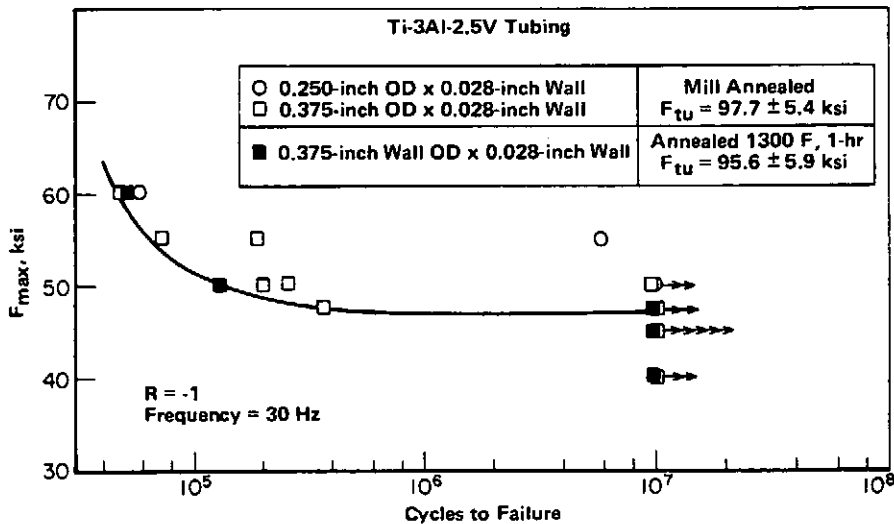


FIGURE 3.052. ROOM TEMPERATURE HIGH CYCLE FATIGUE STRENGTH OF ANNEALED TUBING PRODUCED BY TWO TUBING PRODUCERS FROM STOCK FURNISHED BY THREE METAL PRODUCERS (34)

Ti
 3 Al
 2.5 V

Ti-3Al-2.5V

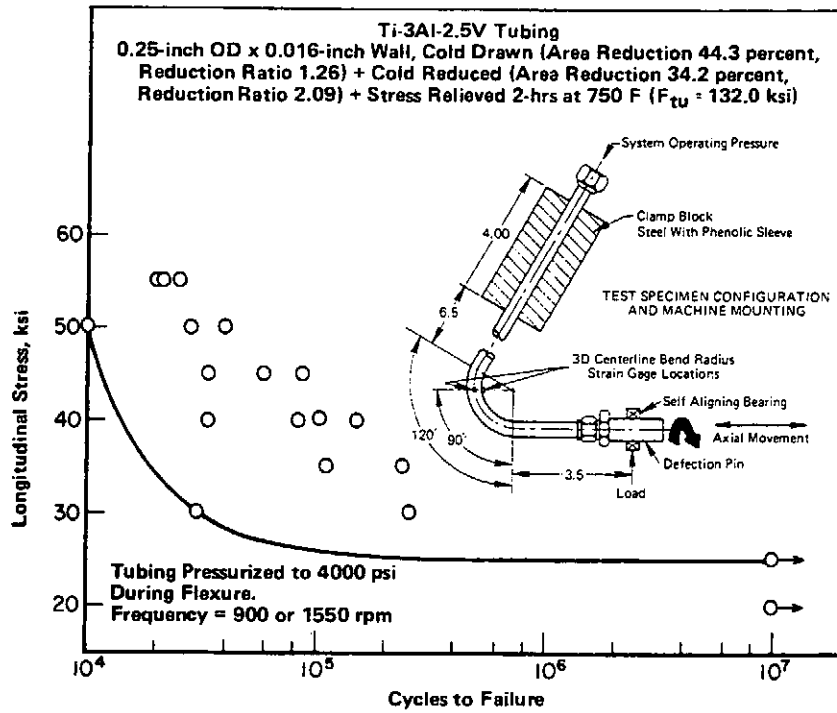


FIGURE 3.053. ROOM TEMPERATURE ROTARY FLEXURE FATIGUE STRENGTH OF COLD WORKED, STRESS RELIEVED TUBING (37)

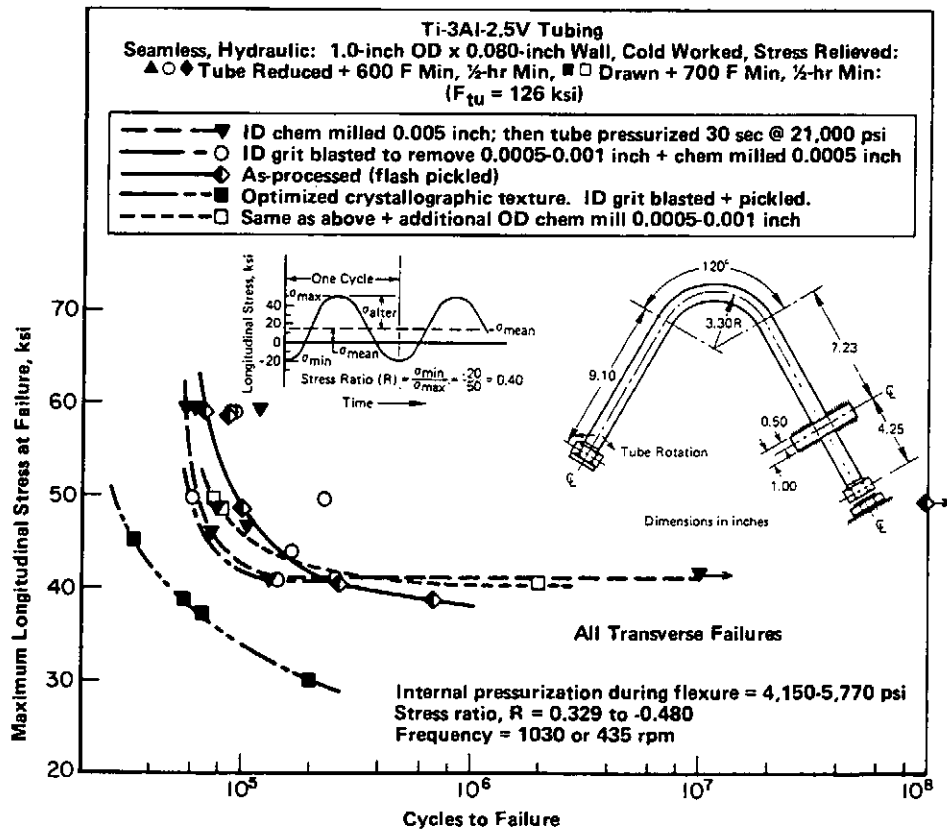


FIGURE 3.054. ROTARY FLEXURE FATIGUE STRENGTH OF 1.0-INCH OD X 0.080-INCH WALL, COLD WORKED PLUS STRESS RELIEVED, 4,150-PSI SYSTEM PRESSURE-LINE TUBING (43)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

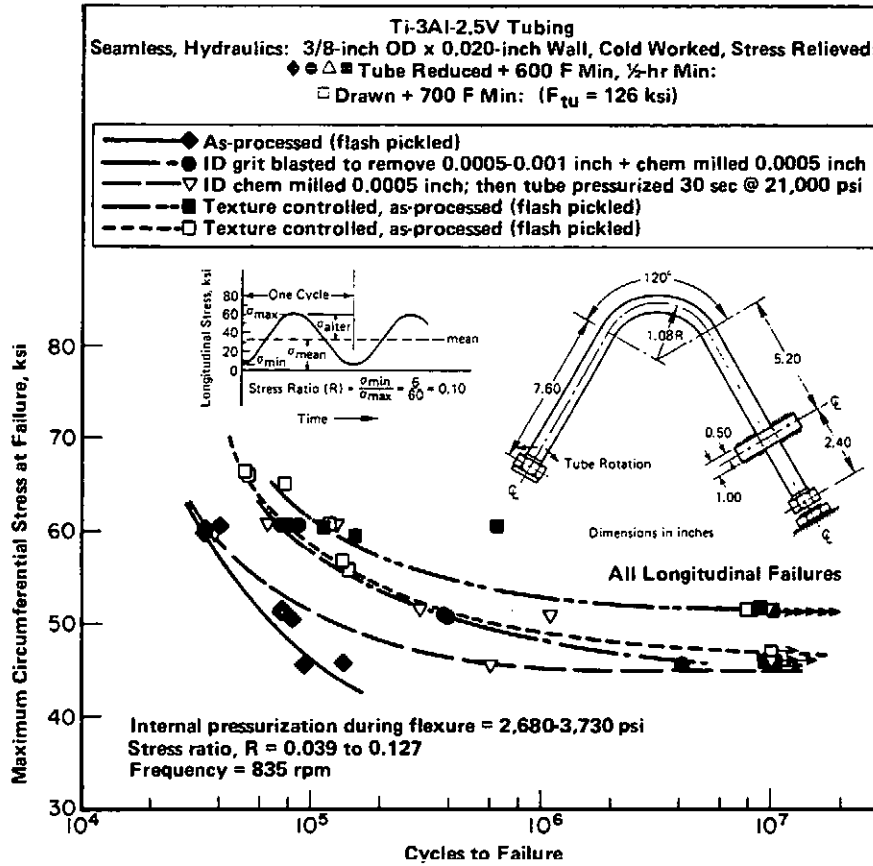


FIGURE 3.055. ROTARY FLEXURE FATIGUE STRENGTH OF 3/8-INCH OD X 0.020-INCH WALL, COLD WORKED PLUS STRESS RELIEVED, 4,150-PSI SYSTEM RETURN-LINE TUBING (41)

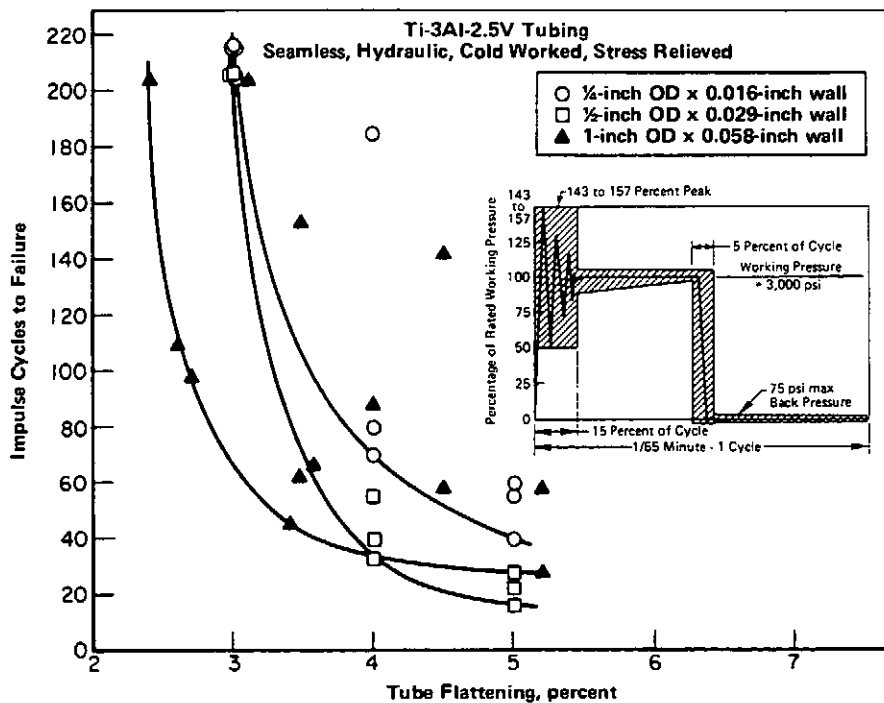


FIGURE 3.057. EFFECT OF TUBE OVALITY ON HYDRAULIC IMPULSE FATIGUE LIFE OF 90°-BENT, 3,000-PSI SYSTEM TUBING (40)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

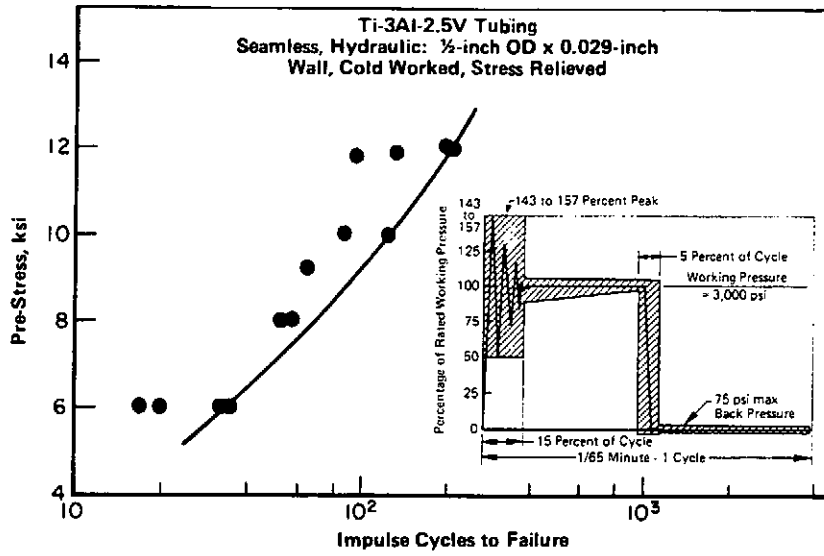


FIGURE 3.058. EFFECT OF OVERPRESSURIZATION ON IMPULSE FATIGUE LIFE OF DEFECTIVE, 3,000-PSI SYSTEM TUBING CONTAINING TWO 90° BENDS (Z-SHAPE) (40)

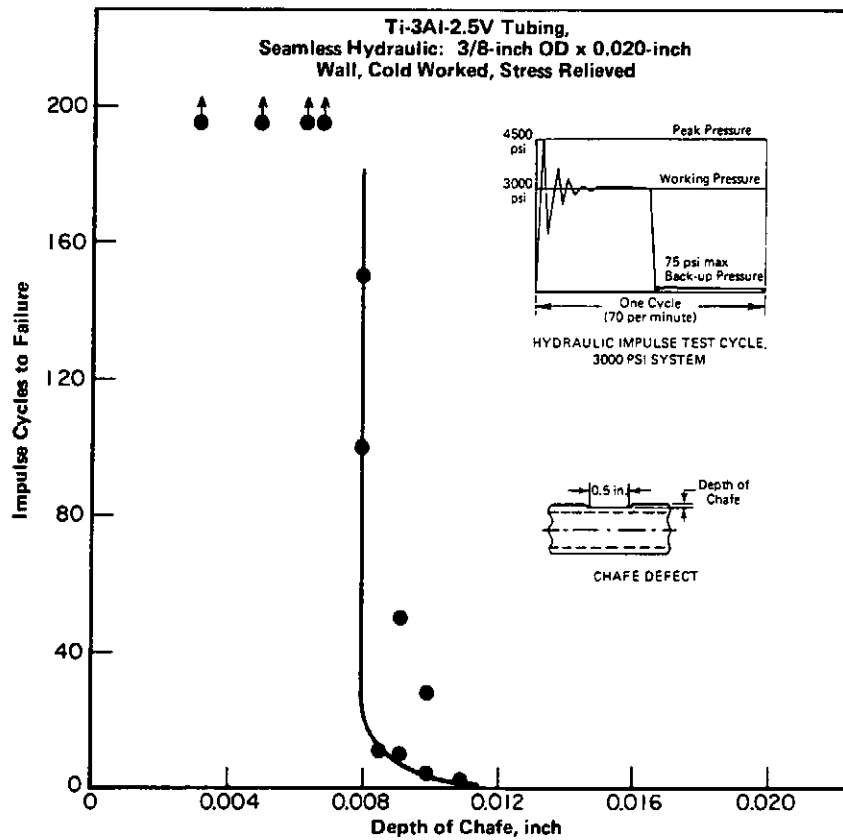


FIGURE 3.059. EFFECT OF CHAFE DEPTH (SIMULATED SERVICE DAMAGE) ON HYDRAULIC IMPULSE FATIGUE LIFE OF 3,000-PSI SYSTEM TUBING (39)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

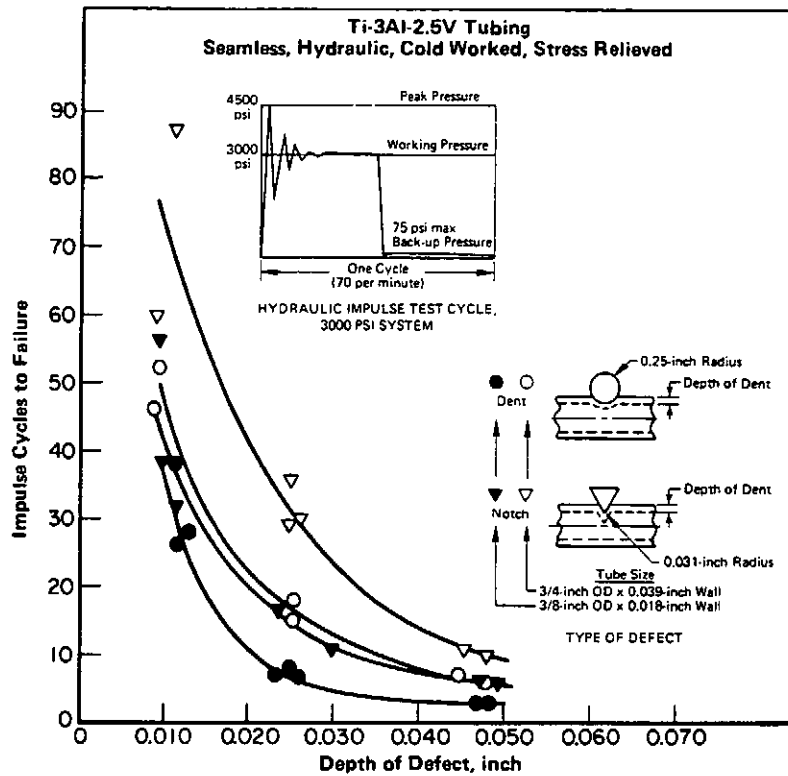


FIGURE 3.0510. EFFECT OF DEFECT SIZE (SIMULATED SERVICE DAMAGE) ON HYDRAULIC IMPULSE FATIGUE LIFE OF 3,000 PSI SYSTEM TUBING (39)

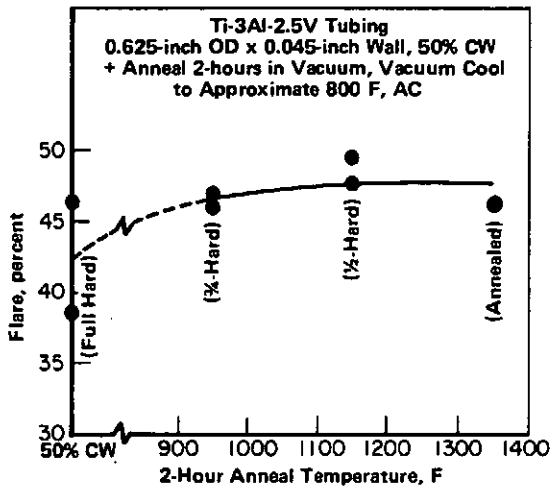


FIGURE 4.011. EFFECT OF ANNEALING (OR STRESS RELIEVING) TEMPERATURE ON ROOM TEMPERATURE FLARING OF FULL HARD (50 PERCENT COLD WORKED) TUBING (19)

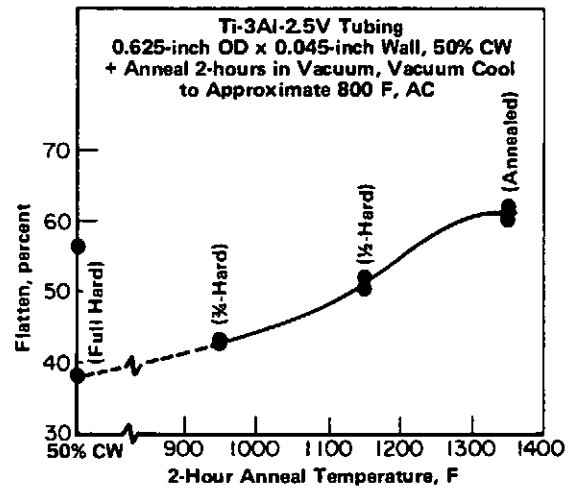


FIGURE 4.012. EFFECT OF ANNEALING (OR STRESS RELIEVING) TEMPERATURE ON ROOM TEMPERATURE FLATTENING OF FULL HARD (50 PERCENT COLD WORKED) TUBING (19)

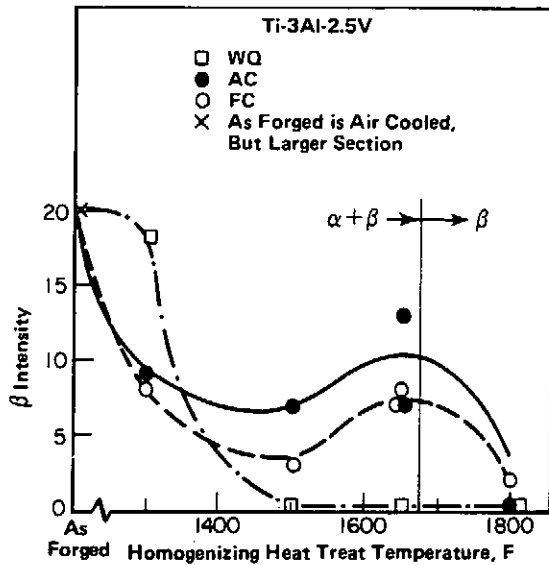


FIGURE 4.014. EFFECT OF HOMOGENIZING HEAT TREAT TEMPERATURE ON β INTENSITY (CONTENT) DETERMINED ON SMALL SAMPLES TAKEN FROM FORGED BILLET (41)

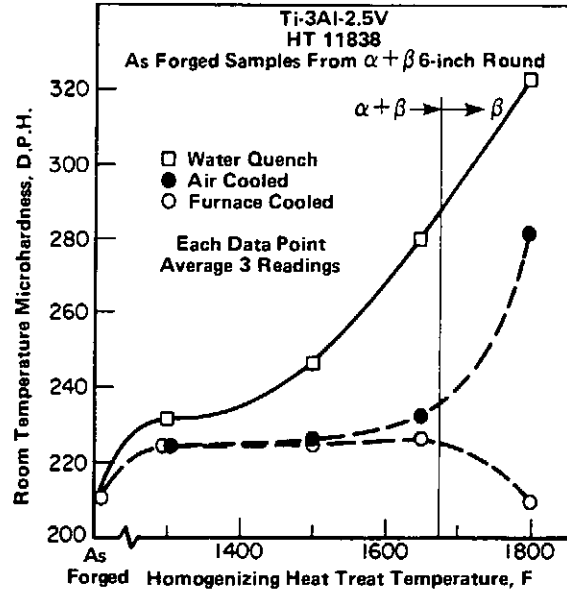


FIGURE 4.015. EFFECT OF HOMOGENIZING HEAT TREAT TEMPERATURE AND COOLING RATE FROM THAT TEMPERATURE ON MICROHARDNESS OF SMALL SAMPLES TAKEN FROM FORGED BILLET (41)

Ti
3 Al
2.5 V
Ti-3Al-2.5V

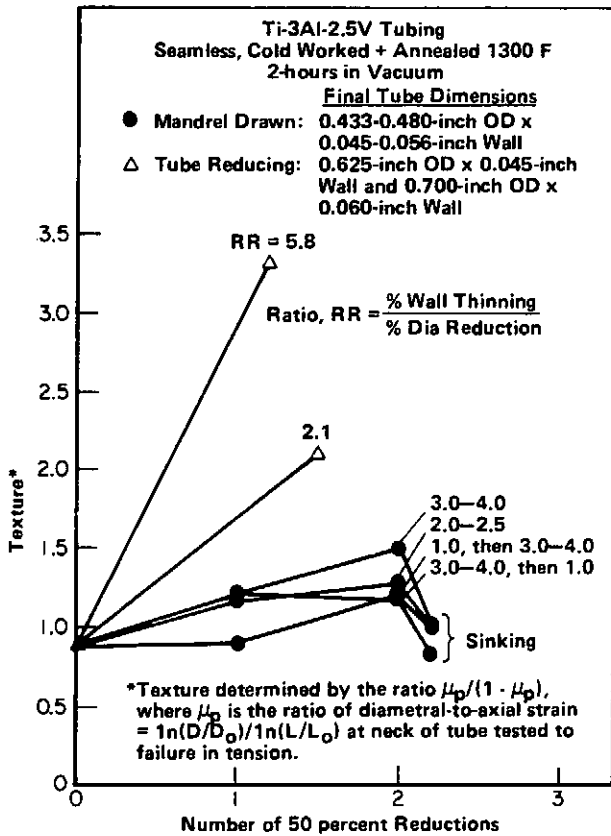


FIGURE 4.017. EFFECT OF COLD REDUCTION SCHEDULE ON CRYSTALLOGRAPHIC TEXTURE OF COLD WORKED, ANNEALED TUBING (42)

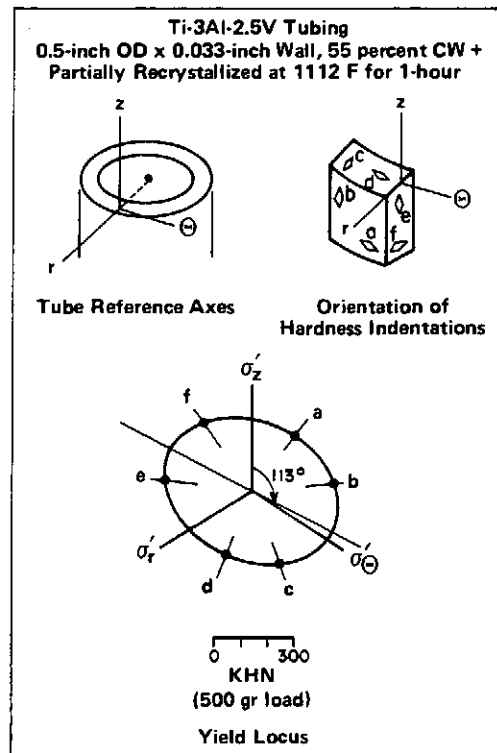


FIGURE 4.03131. MECHANICAL ANISOTROPY OF COLD WORKED AND PARTIALLY RECRYSTALLIZED TUBING AS ILLUSTRATED BY DISTORTION OF THE YIELD LOCUS DETERMINED FROM HARDNESS MEASUREMENTS ACCORDING TO THE TECHNIQUE OF WHEELER AND IRELAND (24)

Ti
3 Al
2.5 V

Ti-3Al-2.5V

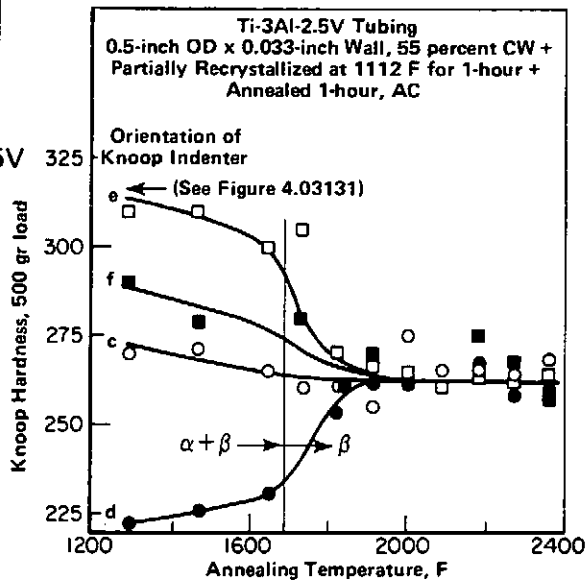


FIGURE 4.03132. EFFECT OF 10-SECOND ANNEALING TEMPERATURE ON KNOOP HARDNESS OF COLD WORKED AND ANNEALED (PARTIALLY RECRYSTALLIZED) TUBING, SIMULATING HARDNESS PROFILE OF EB WELD (24)

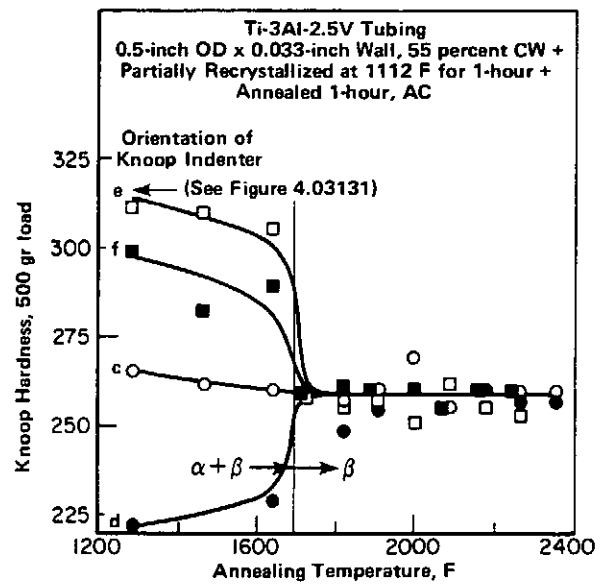


FIGURE 4.03133. EFFECT OF 30-SECOND ANNEALING TEMPERATURE ON KNOOP HARDNESS OF COLD WORKED AND ANNEALED (PARTIALLY RECRYSTALLIZED) TUBING, SIMULATING HARDNESS PROFILE OF GTA WELD (24)

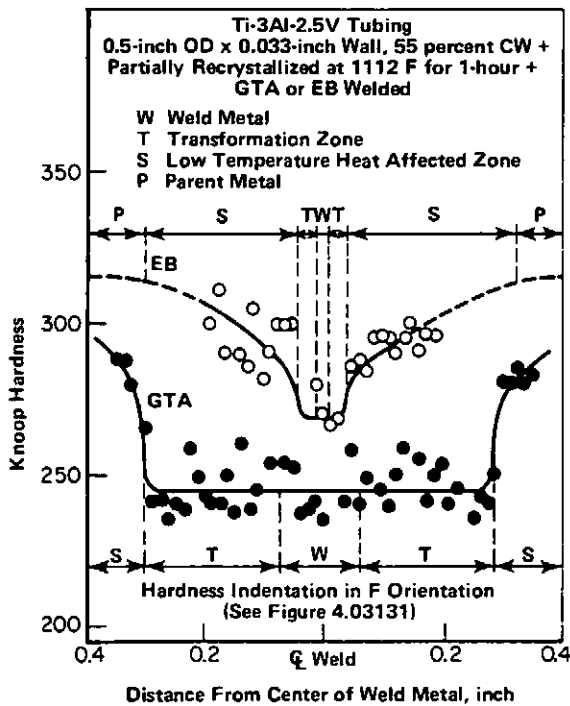


FIGURE 4.03134. KNOOP HARDNESS TRAVERSE OF GTA AND EB WELDS IN 55 PERCENT COLD WORKED AND PARTIALLY RECRYSTALLIZED TUBING (24)

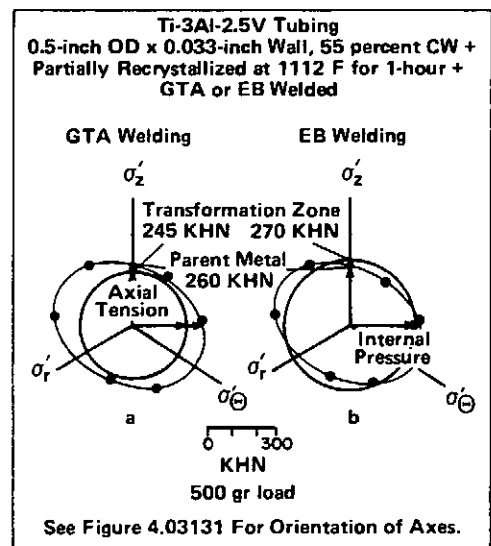


FIGURE 4.03135. YIELD LOCI OF BASE METAL AND TRANSFORMATION ZONE OF COLD WORKED AND PARTIALLY RECRYSTALLIZED TUBING AFTER GTA AND WELDING (24)