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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.

(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)

Ti
15 V
3 Cr
3 Sn
3 Al

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. However, 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 elec~~tron-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 x 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	

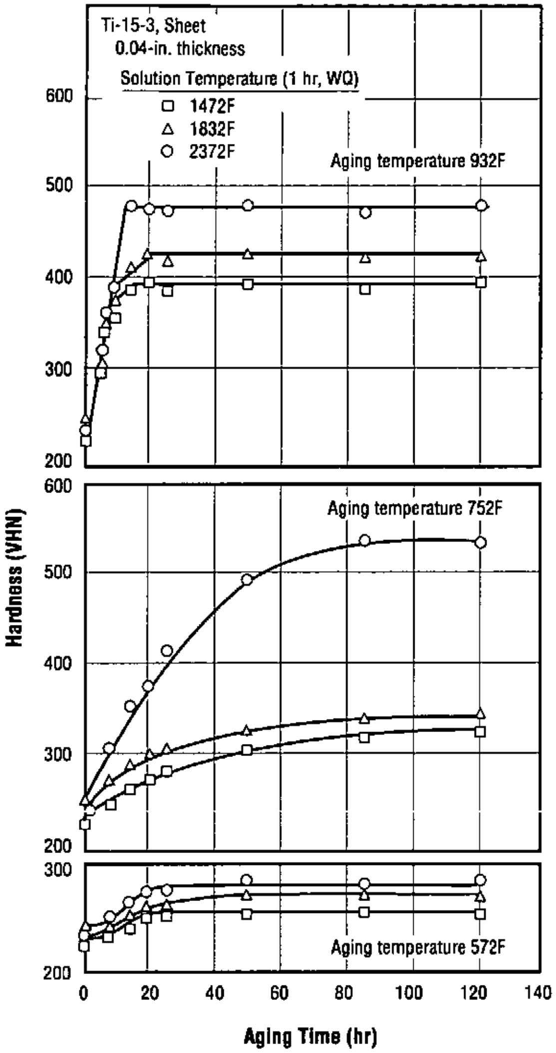

Figure 1.5.2.1 Effects of aging time and temperature on hardness of solution annealed alloy (Ref. 9)

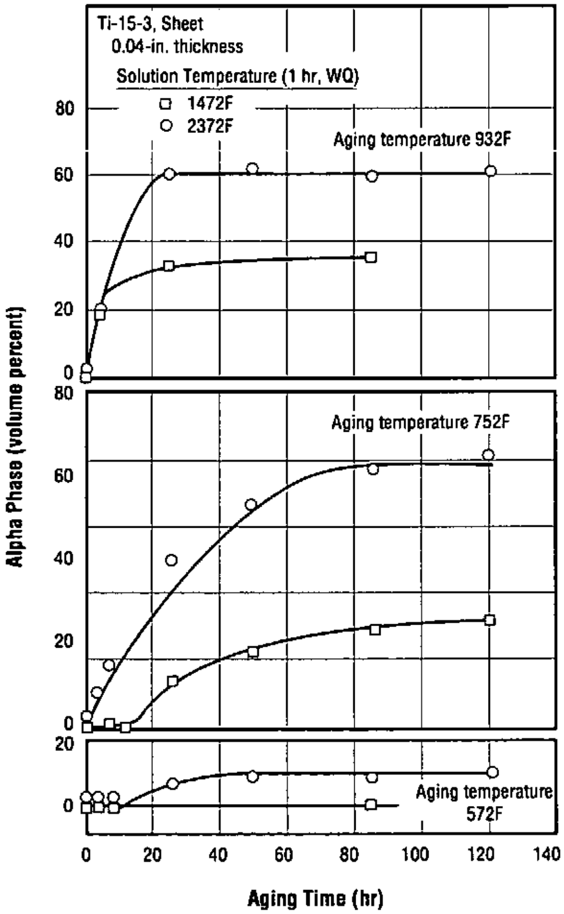

Figure 1.5.2.2 Effects of aging time and temperature on alpha phase precipitation in solution annealed sheet (Ref. 9)

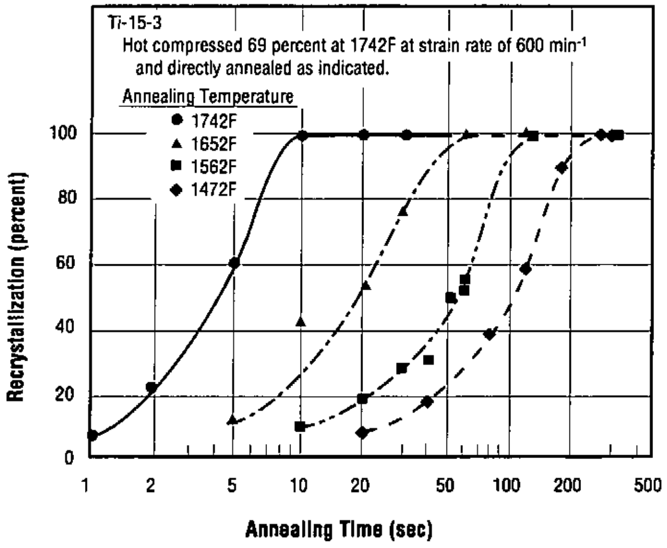

Figure 1.5.2.3 Effects of annealing time and temperature on recrystallization behavior of hot worked alloy (Ref. 11)

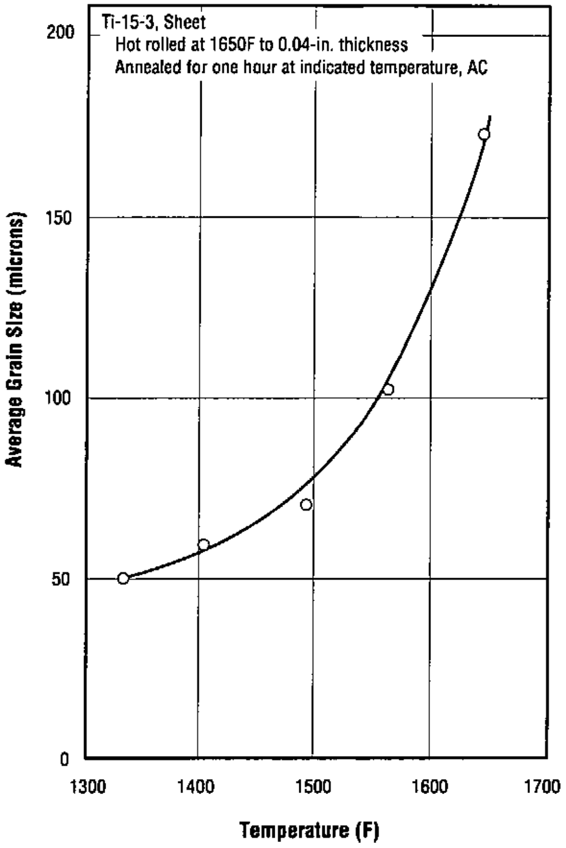

Figure 1.5.2.4 Effects of annealing temperature on grain size of hot rolled alloy (Ref. 10)

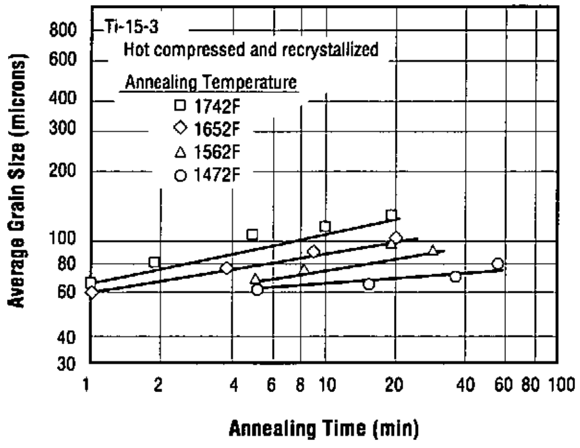

Figure 1.5.2.5 Effects of annealing time and temperature on grain growth behavior (Ref. 11)

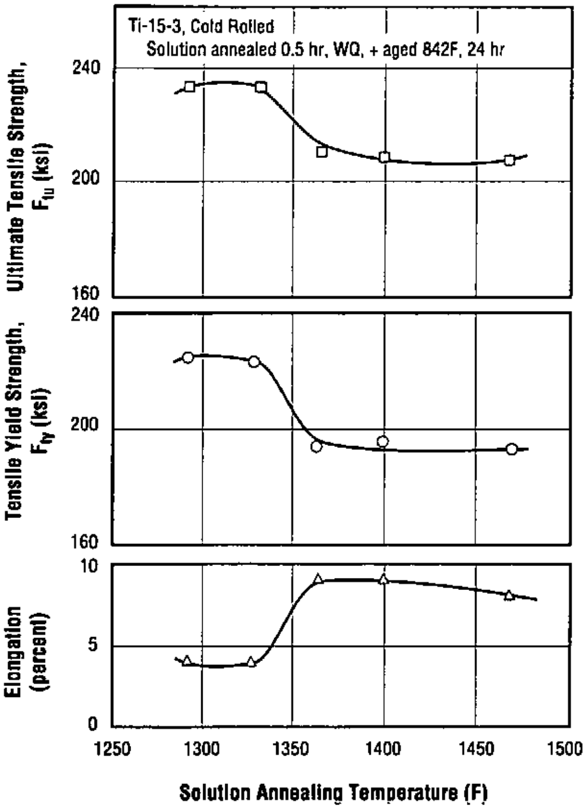

Figure 1.5.3.1 Effects of solution annealing temperature on tensile properties after aging at 842F (Ref. 12)

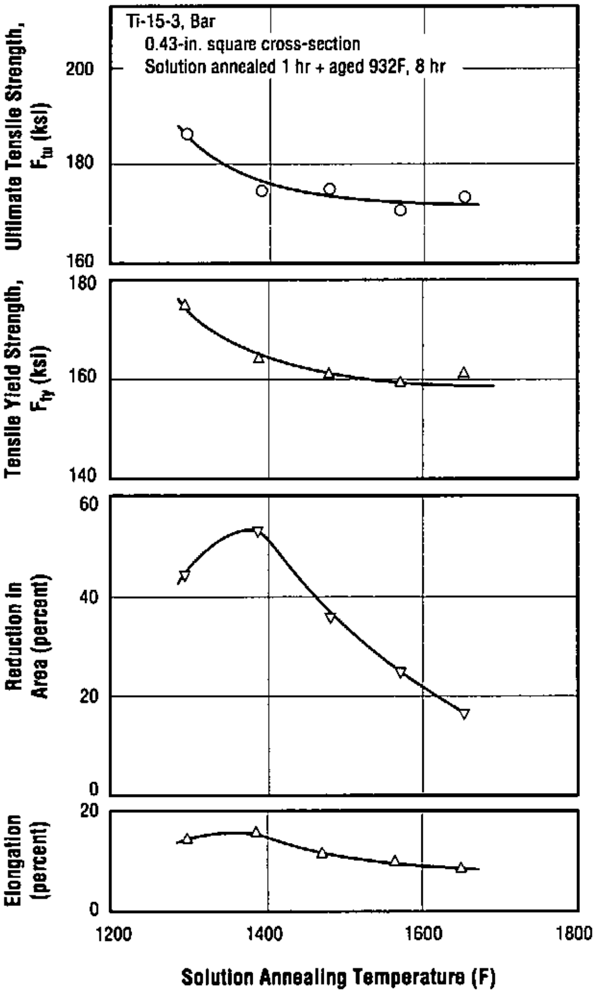

Figure 1.5.3.2 Effects of solution annealing temperature on tensile properties after aging at 932F (Ref. 13)

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.

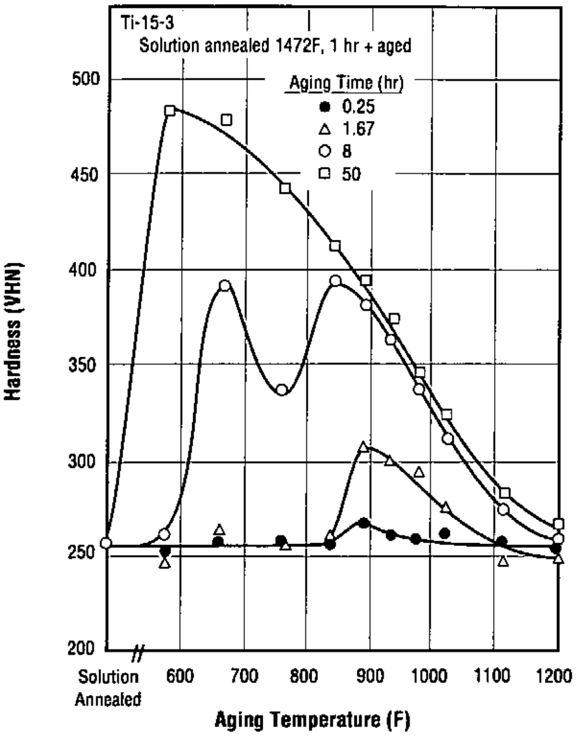

Figure 1.5.4.1 Effects of aging temperature and time on hardness of alloy solution annealed at 1472F (Ref. 13)

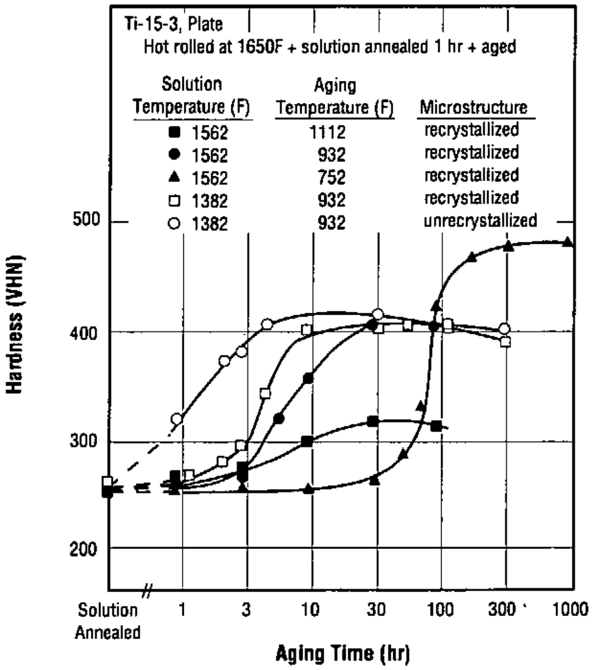

Figure 1.5.4.2 Effects of aging time and temperature on hardness of plate solution annealed at 1382 or 1562F (Ref. 10)

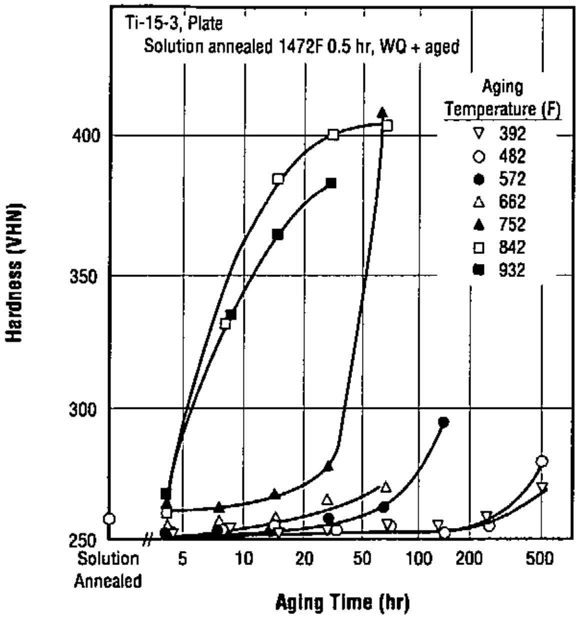

Figure 1.5.4.3 Effects of aging time and temperature on hardness of plate solution annealed at 1472F (Ref. 19)

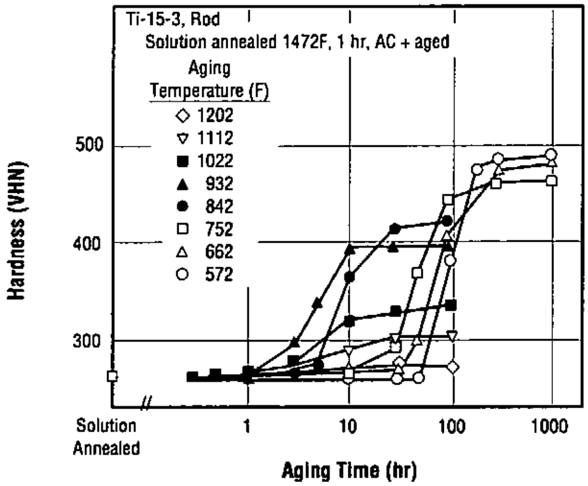

Figure 1.5.4.4 Effects of aging time and temperature on hardness of rod solution annealed at 1472F (Ref. 17)

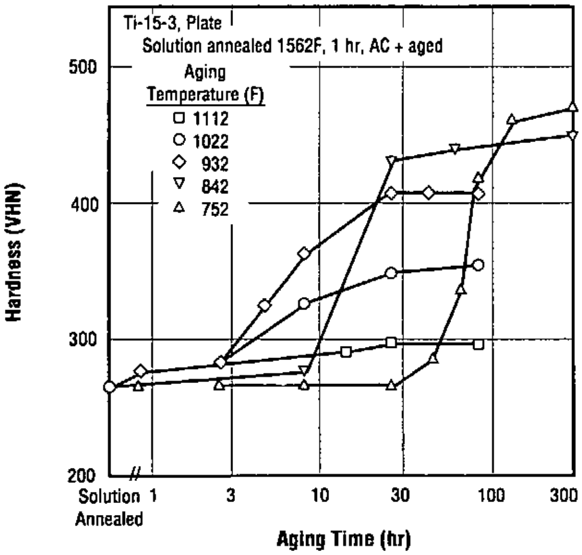

Figure 1.5.4.5 Effects of aging time and temperature on hardness of plate solution annealed at 1562F (Ref. 20)

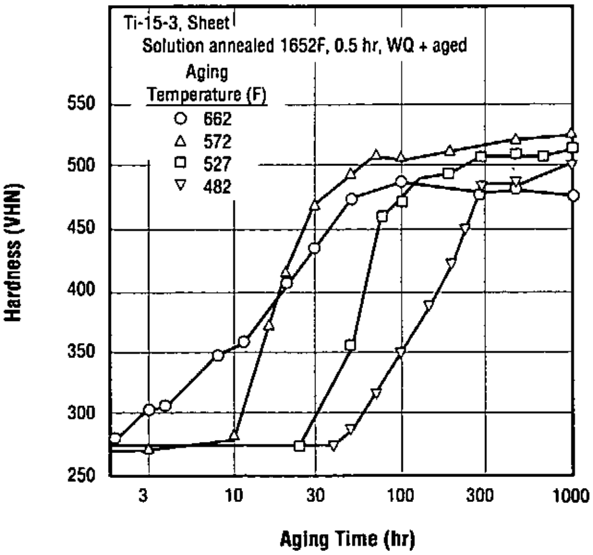

Figure 1.5.4.6 Effects of aging time and temperature on hardness of sheet solution annealed at 1652F (Ref. 18)

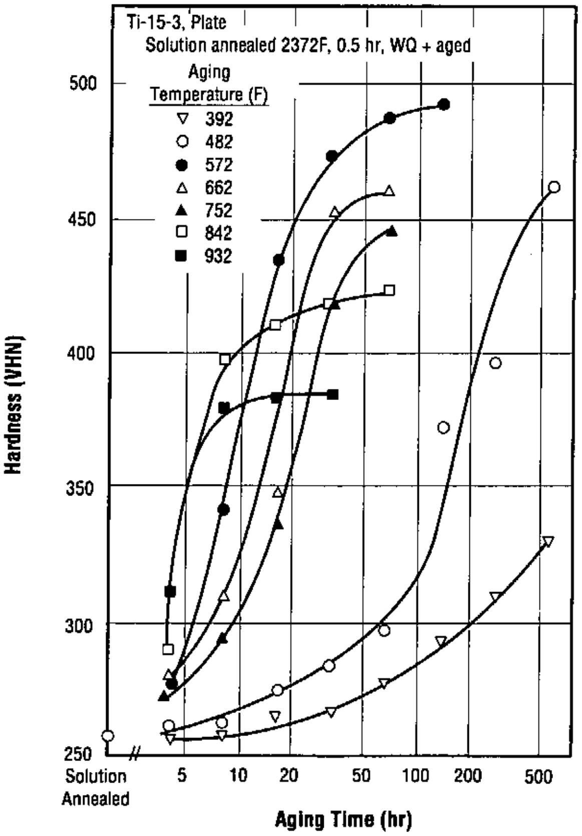

Figure 1.5.4.7 Effects of aging time and temperature on hardness of plate solution annealed at 2372F (Ref. 19)

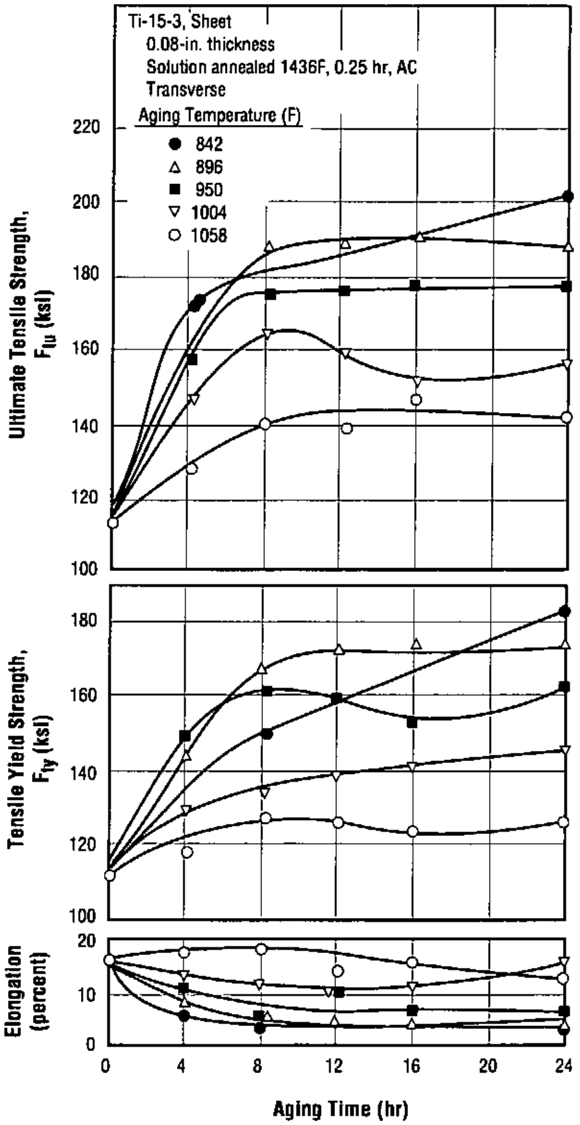

Figure 1.5.4.8 Effects of aging time at 842 to 1058F on tensile properties of sheet solution annealed at 1436F (Ref. 23)

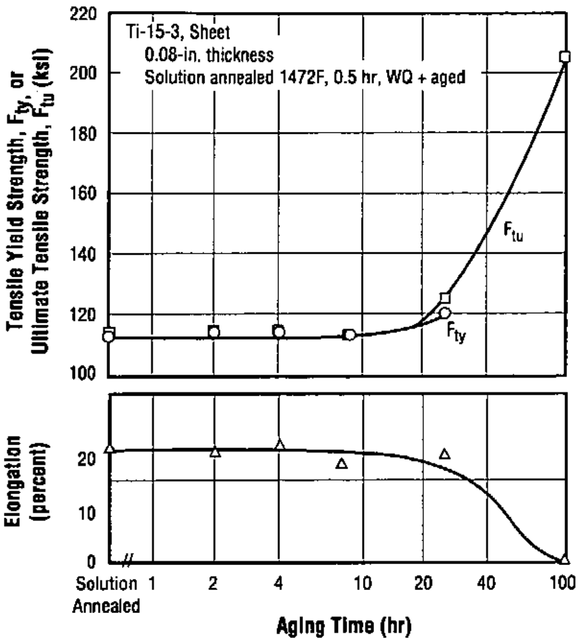

Figure 1.5.4.9 Effects of aging time at 572F on tensile properties of sheet solution annealed at 1472F (Ref. 21)

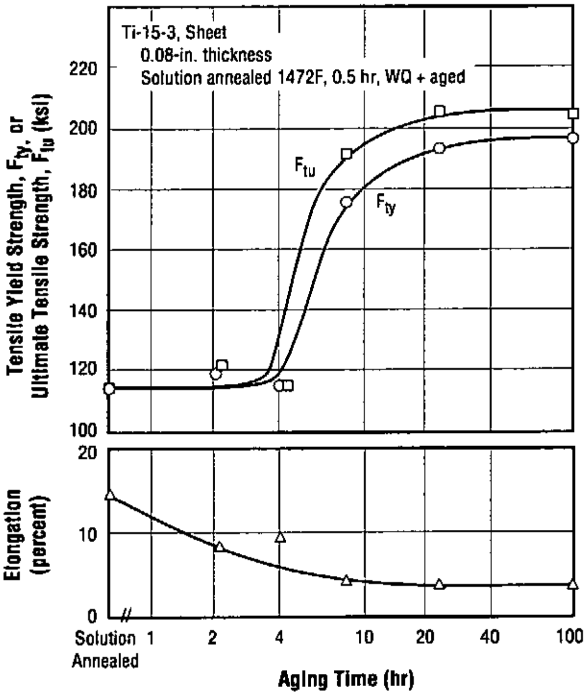

Figure 1.5.4.10 Effects of aging time at 842F on tensile properties of sheet solution annealed at 1472F (Ref. 21)

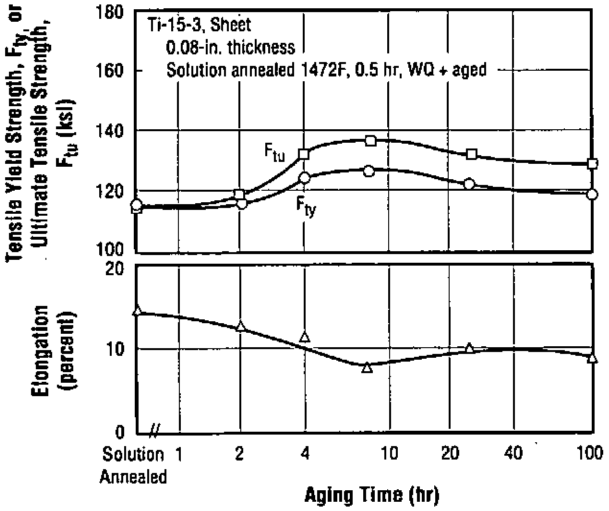

Figure 1.5.4.11 Effects of aging time at 1112F on tensile properties of sheet solution annealed at 1472F (Ref. 21)

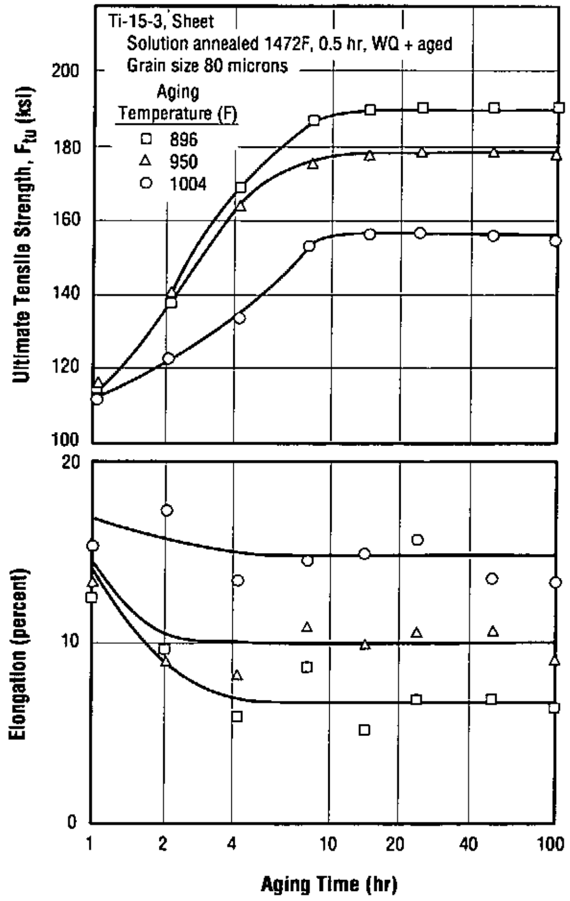

Figure 1.5.4.12 Effects of aging time at 896 to 1004F on tensile properties of sheet solution annealed at 1472F (Ref. 15)

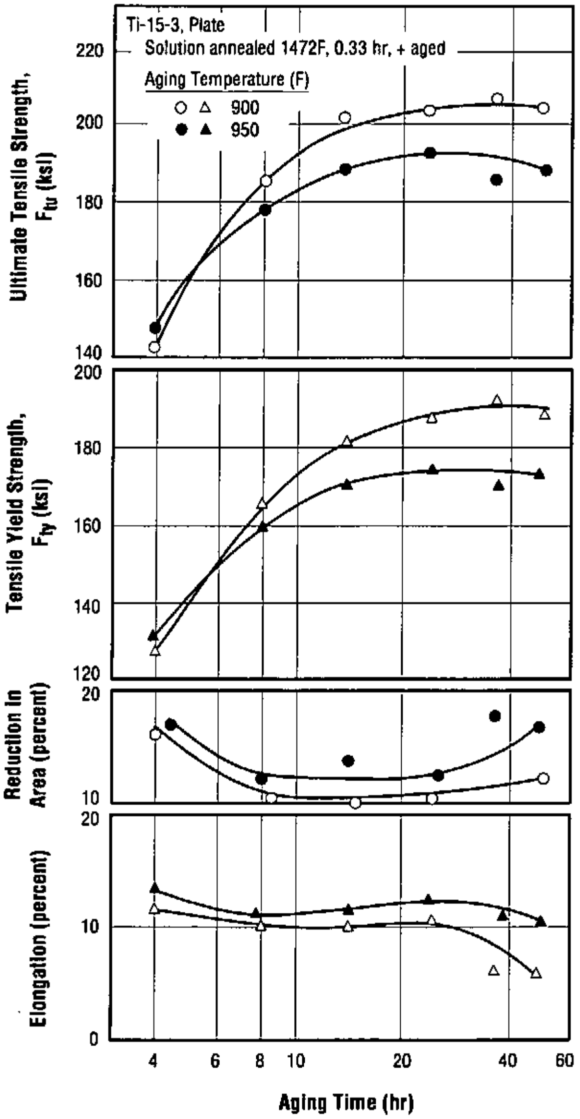

Figure 1.5.4.13 Effects of aging time at 900 and 950F on tensile properties of plate solution annealed at 1472F (Ref. 11)

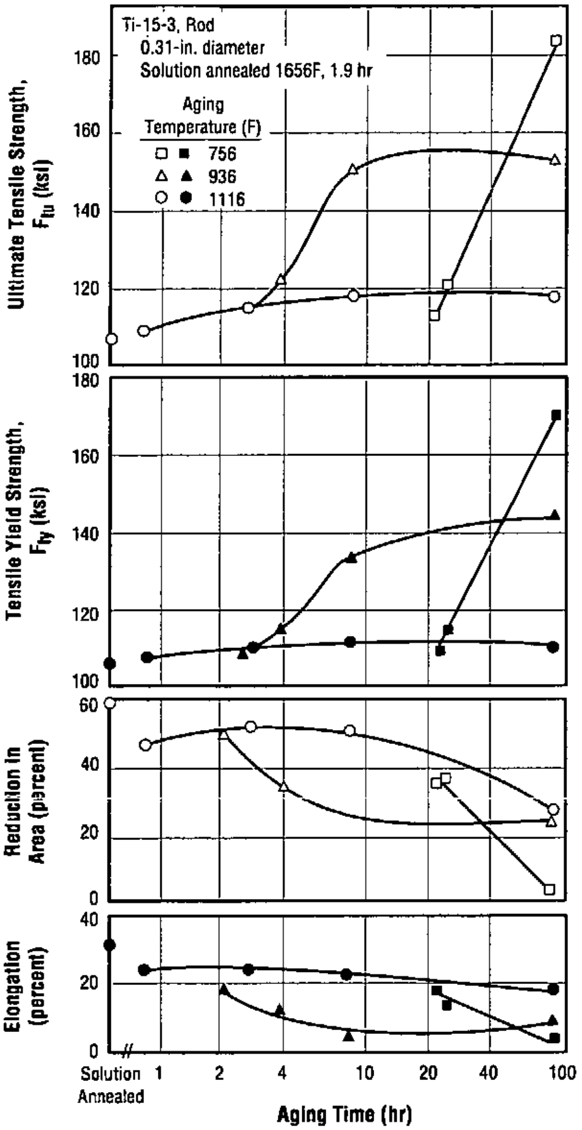

Figure 1.5.4.14 Effects of aging time at 756 to 1116F on tensile properties of rod solution annealed at 1656F (Ref. 22)

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.

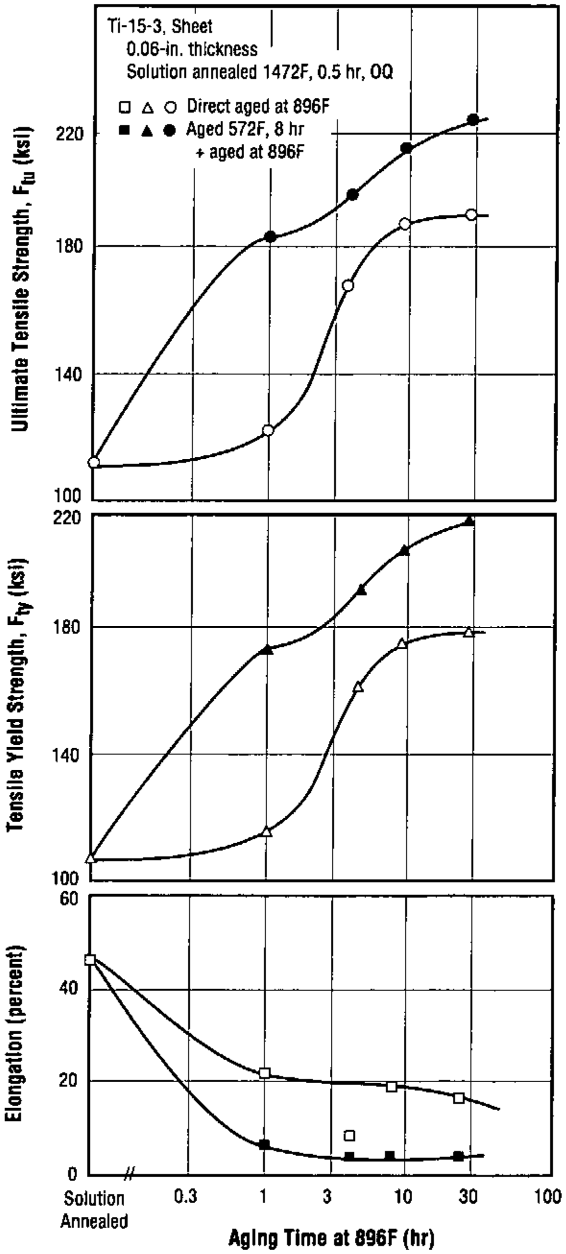

Figure 1.5.4.16 Effects of aging time at 896F on tensile properties of solution annealed alloy with and without aging at 572F (Ref. 24)

Table 1.5.4.17 Effects of aging treatments on fracture toughness and tensile properties (Ref. 25)

Alloy	Ti-15-3[a]			
	Tensile Properties			Fracture Toughness[c] (ksi $\sqrt{in}$)
Aging Conditions[b]	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.

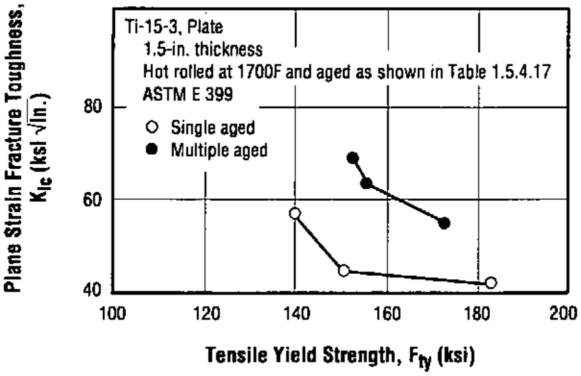

Figure 1.5.4.18 Variation of fracture toughness and yield strength with aging treatment (Ref. 25)

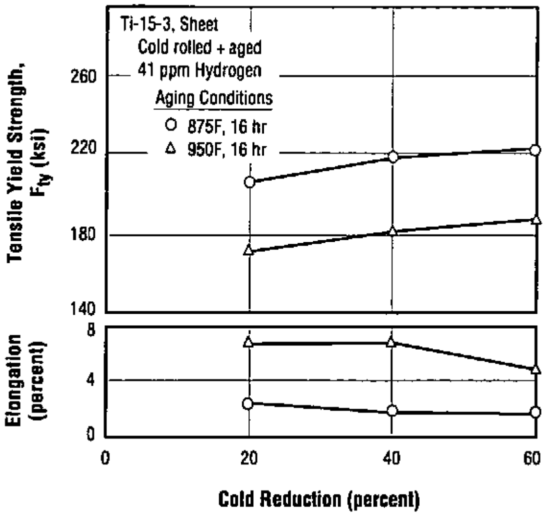

Figure 1.5.5.1 Effects of cold rolling and aging temperature on yield strength and elongation (Ref. 7)

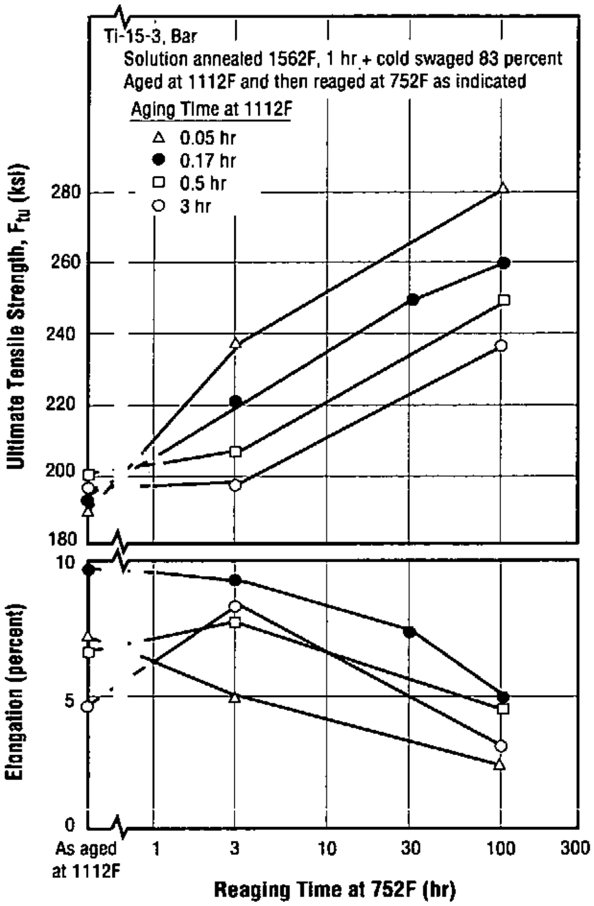

Figure 1.5.5.2 Effects of aging time at 752F on tensile properties of cold worked plus duplex aged alloy (Ref. 28)

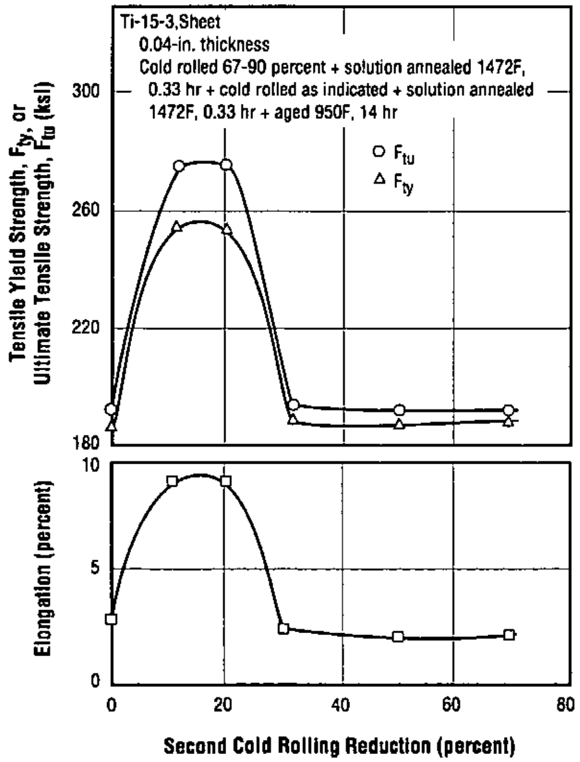

Figure 1.5.5.3 Effects of second rolling reduction on tensile properties of thermomechanically processed sheet (Ref. 29)

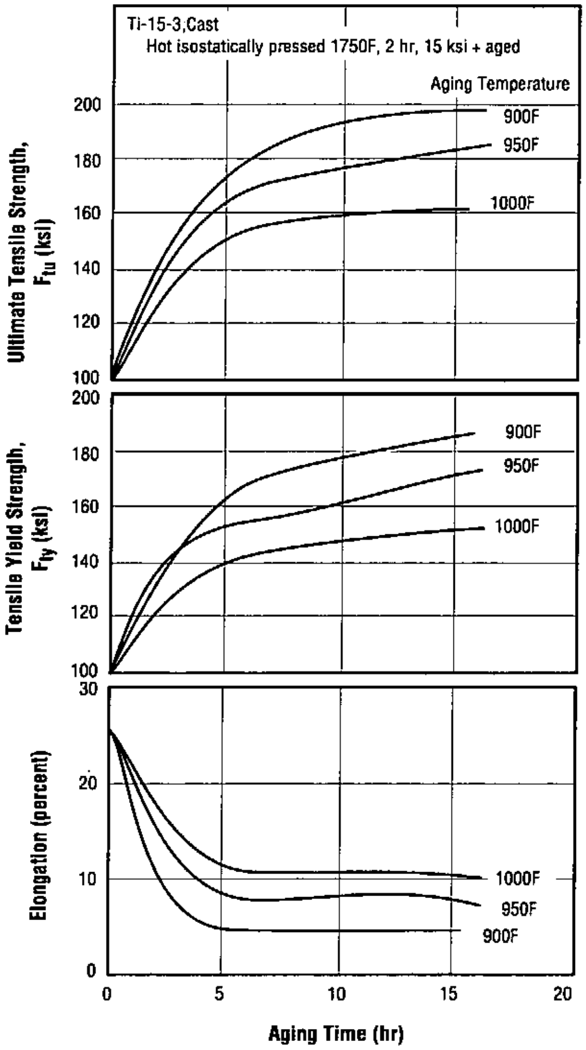

Figure 1.5.6.1 Effects of aging at 900 to 1000F on tensile properties of hot isostatically pressed cast alloy (Ref. 30)

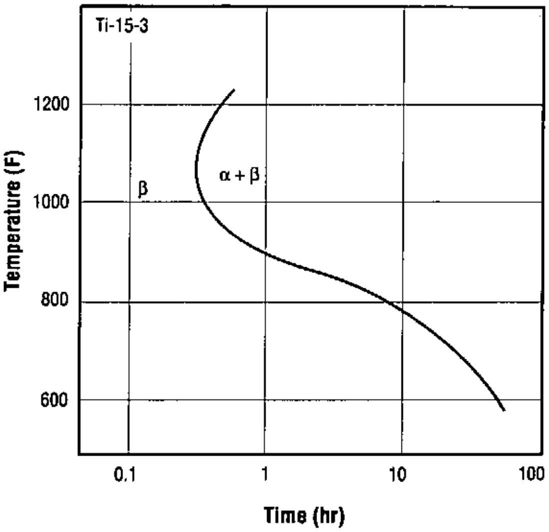

Figure 2.1.2.1.1 Time-temperature-transformation diagram (Ref. 17)

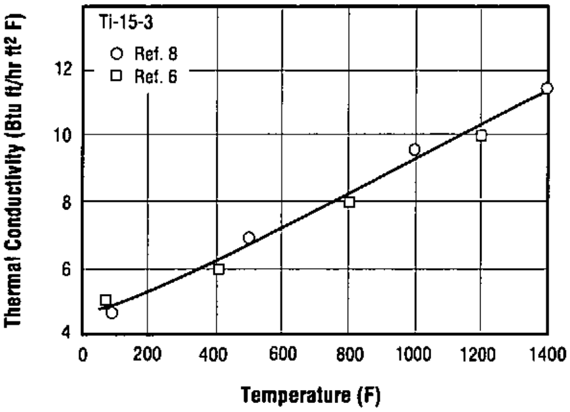

Figure 2.1.3.1 Thermal conductivity from RT to 1400F (Refs. 6, 8)

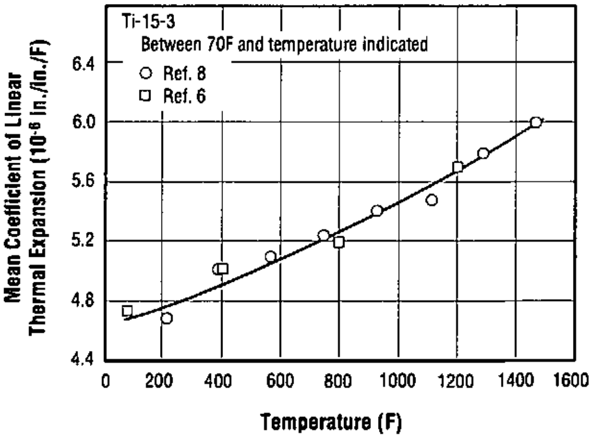

Figure 2.1.4.1 Thermal expansion from RT to 1472F (Refs. 6, 8)

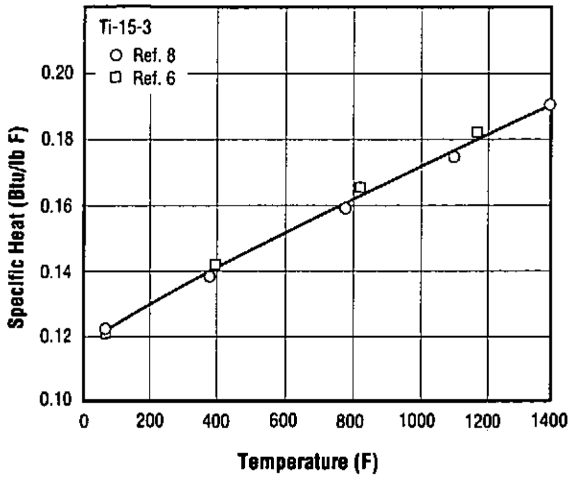

Figure 2.1.5.1 Specific heat from RT to 1400F (Refs. 6, 8)

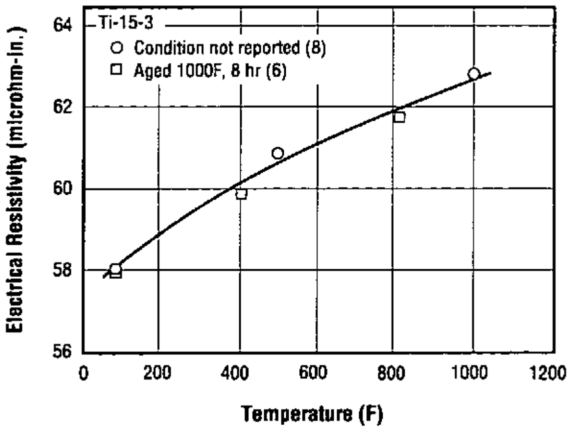

Figure 2.2.2.1 Electrical resistivity from RT to 1000F (Refs. 6, 8)

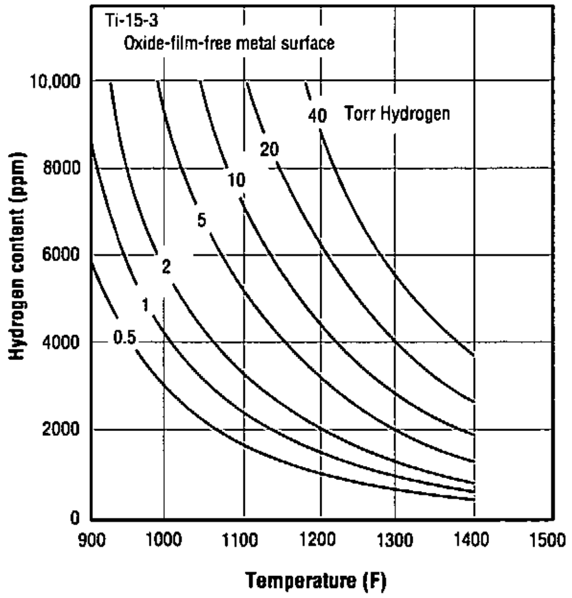

Figure 2.3.3.1 Effects of temperature and hydrogen pressure on solubility of hydrogen in Ti-15-3 (Ref. 35)

Table 2.3.3.2 Effects of hydrogen on room-temperature formability (Ref. 7)

Alloy	Ti-15-3[a]		
	0.035-in. thick		0.070-in. thick
Hydrogen Content (ppm)	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.

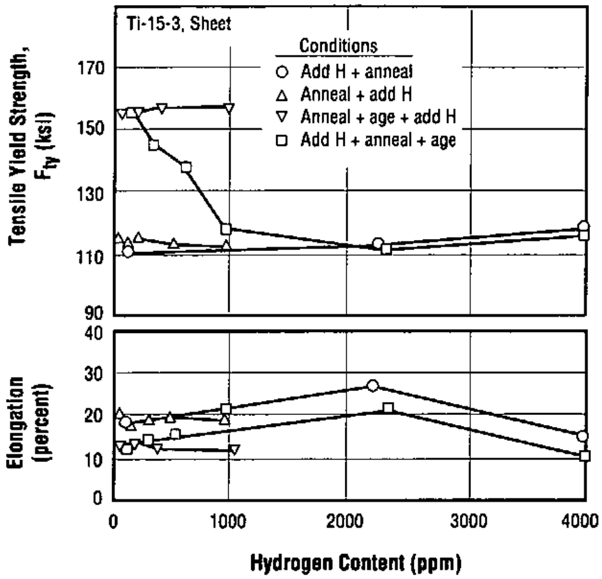

Figure 2.3.3.3 Effects of hydrogen on tensile properties of sheet (Ref. 7)

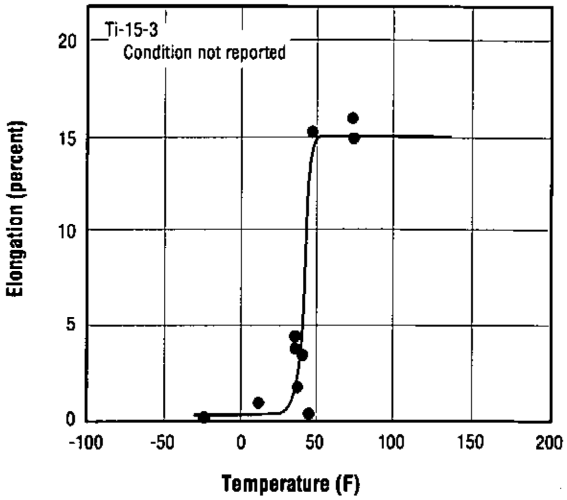

Figure 2.3.3.4 Ductile-brittle transition behavior of alloy containing 3900 ppm hydrogen (Ref. 35)

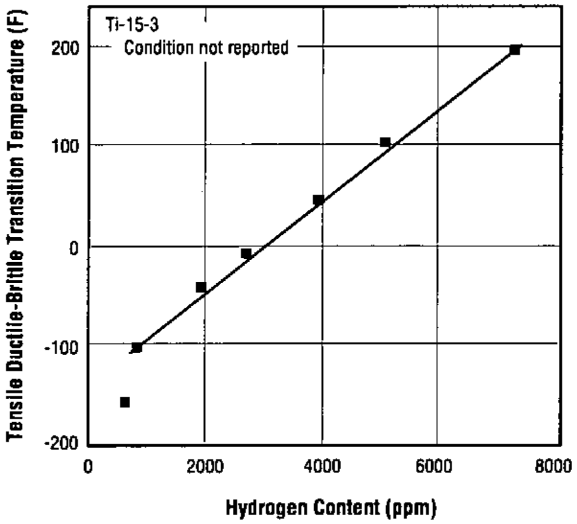

Figure 2.3.3.5 Effects of hydrogen on ductile-brittle transition temperature (Ref. 35)

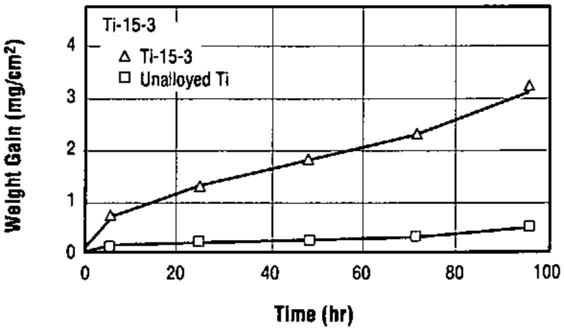

Figure 2.3.4.1 Oxidation weight gain behavior of Ti-15-3 alloy and unalloyed titanium in air at 1202F (Ref. 35)

Table 3.1.1 AMS specified room-temperature mechanical properties (Refs. 1, 2)

Alloy	Ti-15-3								
				Tensile Properties					
				F_{ty} (ksi)		F_{tu} (ksi)			
AMS Specification	Form	Condition	Thickness (in)	Minimum	Maximum	Minimum	Maximum	Elongation,[a] min (percent)	Bend Factor
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.

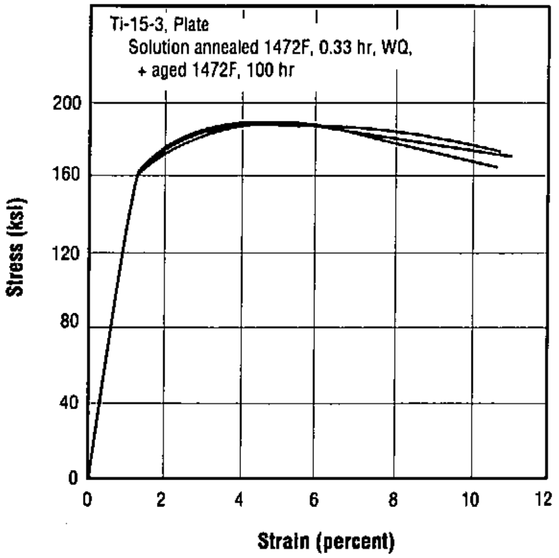

Figure 3.2.1.1 Stress-strain diagram for solution annealed and aged alloy at strain rate of 6 x 10^{-2} min^{-1} (Ref. 37)

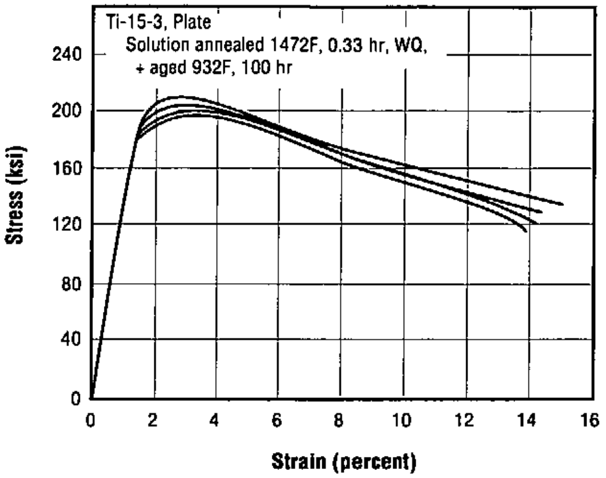

Figure 3.2.1.2 Stress-strain diagram for solution annealed and aged alloy at strain rate of 6 x 10^4 min^{-1} (Ref. 37)

Table 3.2.1.3 Effects of strain rate on tensile properties of solution annealed alloy (Ref. 8)

Alloy	Ti-15-3[a]		
	Tensile Properties		
Strain Rate (min^{-1})	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.

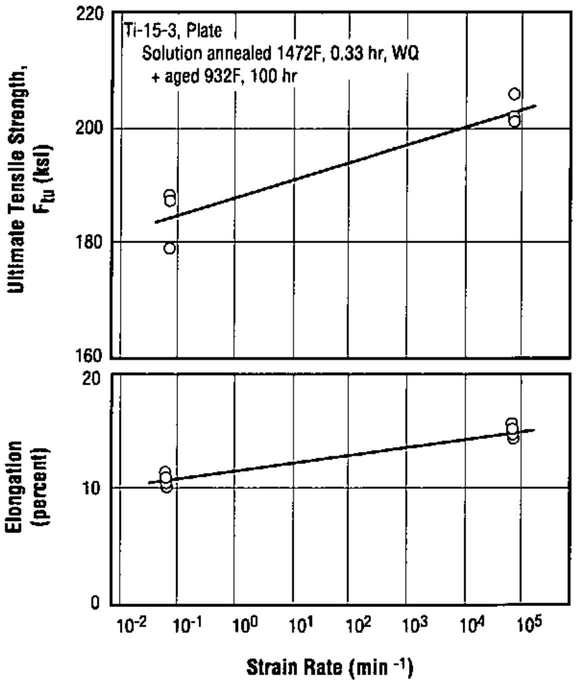

Figure 3.2.1.4 Effects of strain rate on tensile properties of solution annealed and aged alloy (Ref. 37)

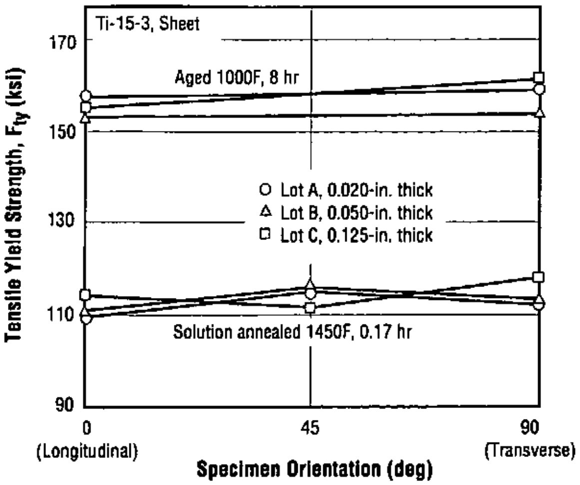

Figure 3.2.1.5 Effects of orientation and thickness on yield strength of heat treated alloy (Ref. 7)

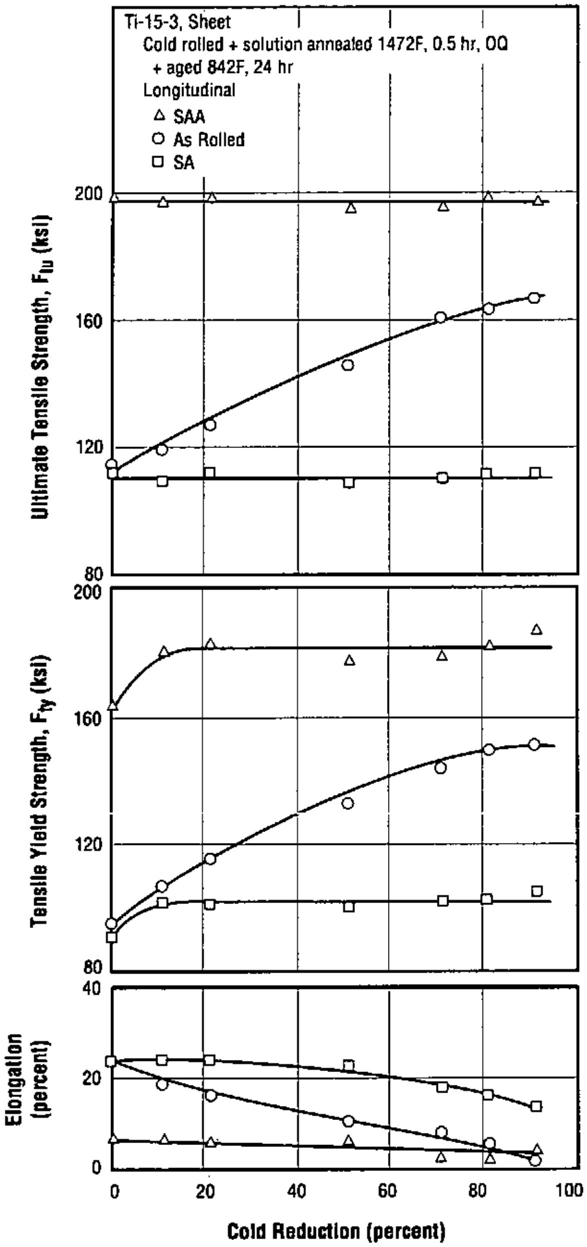

Figure 3.2.1.6 Effects of cold rolling and heat treatment on tensile properties in rolling direction (Ref. 38)

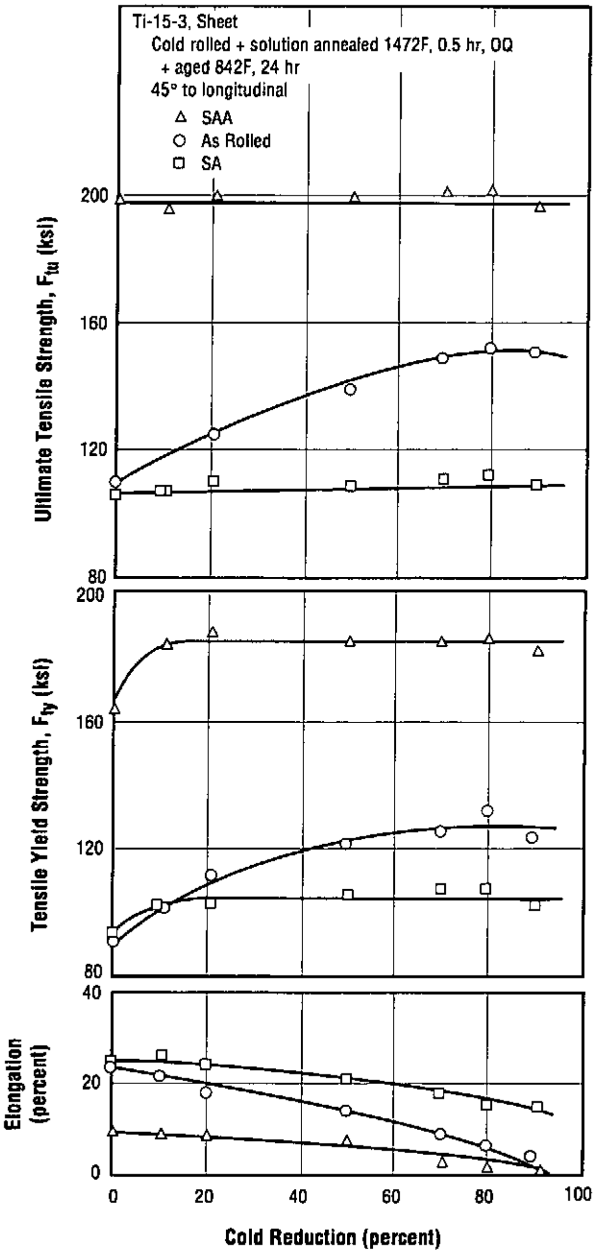

Figure 3.2.1.7 Effects of cold rolling and heat treatment on tensile properties 45 degrees to rolling direction (Ref. 38)

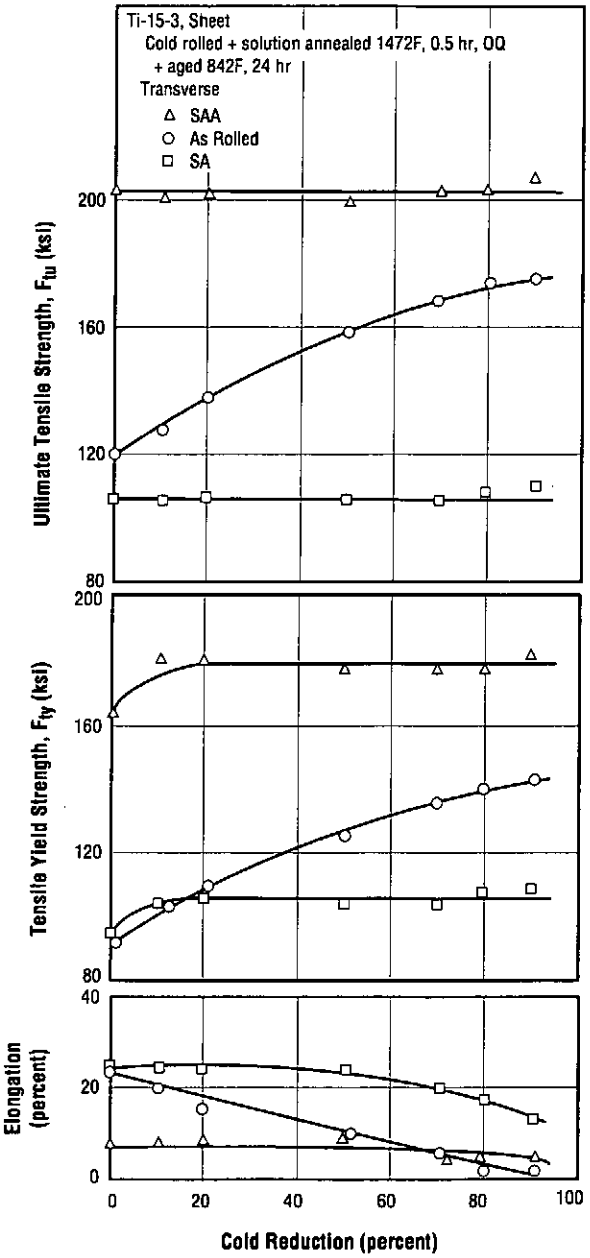

Figure 3.2.1.8 Effects of cold rolling and heat treatment on tensile properties transverse to rolling direction (Ref. 38)

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.

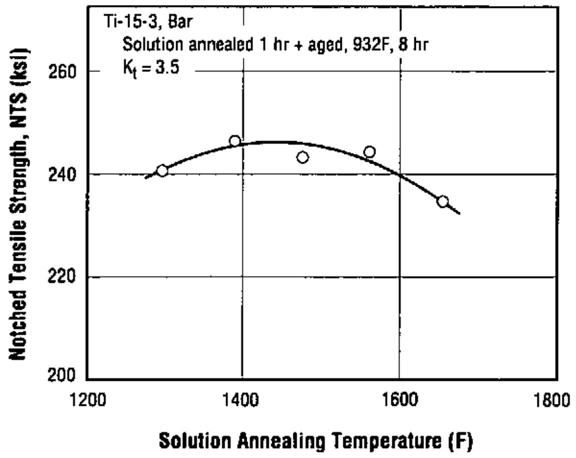

Figure 3.2.7.1.1 Effects of solution annealing temperature on notched tensile strength after aging at 932F (Ref. 13)

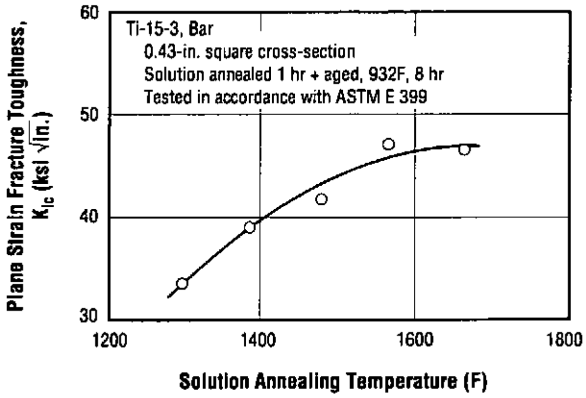

Figure 3.2.7.2.1 Effects of solution annealing temperature on fracture toughness after aging at 932F (Ref. 13)

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 √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.

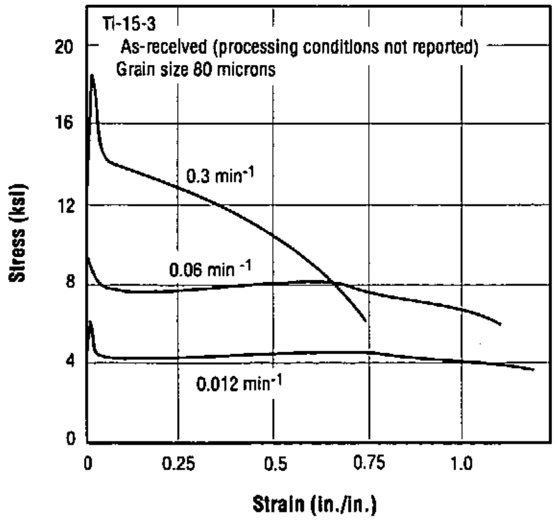

Figure 3.3.1.1 Effects of strain rate on flow curves at 1500F (Ref. 40)

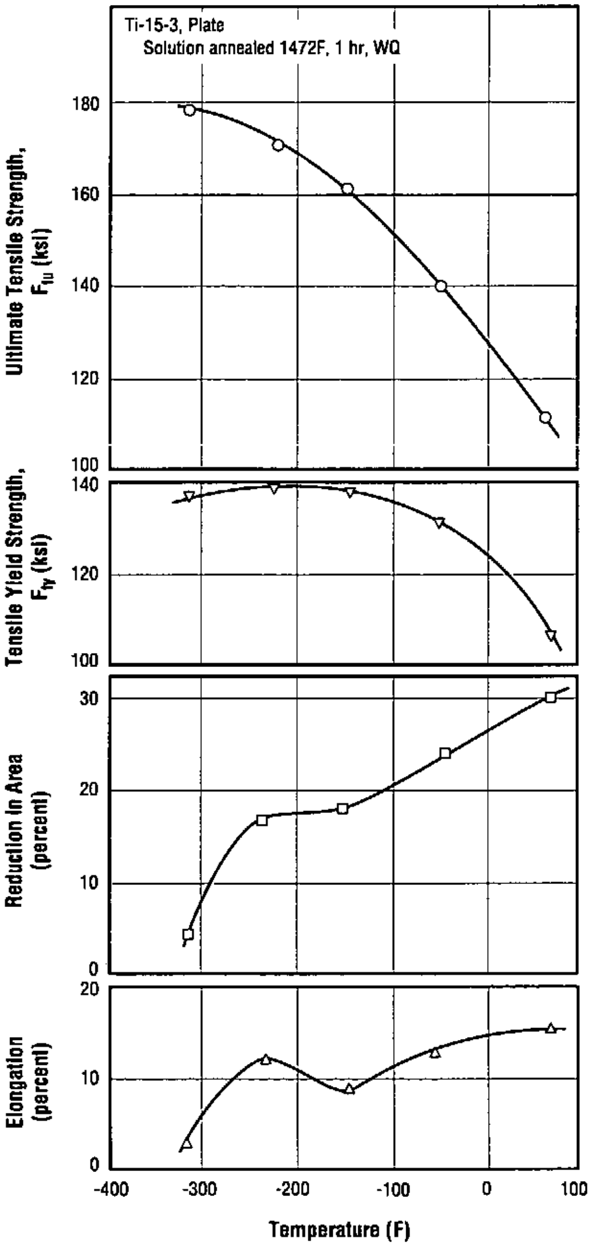

Figure 3.3.1.2 Tensile properties of solution annealed alloy at low temperatures (Ref. 41)

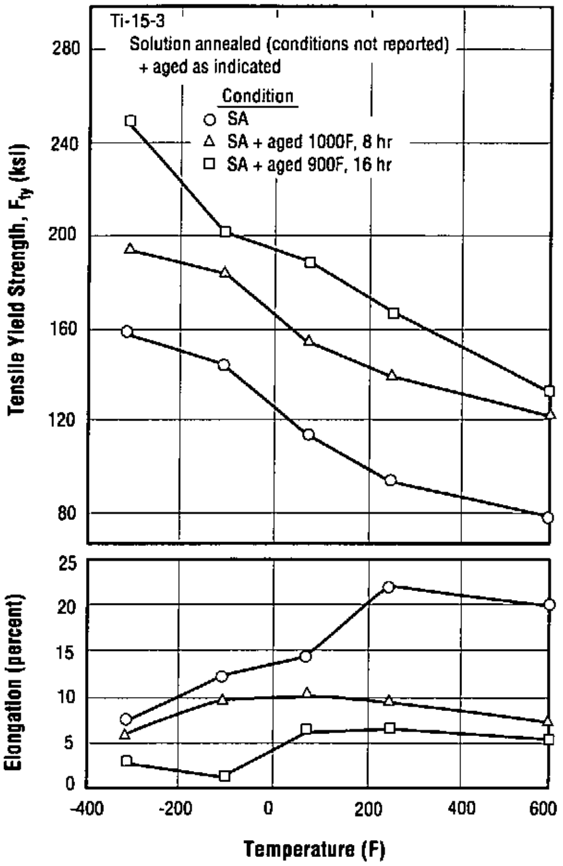

Figure 3.3.1.3 Effects of temperature on tensile properties in three heat treated conditions (Ref. 7)

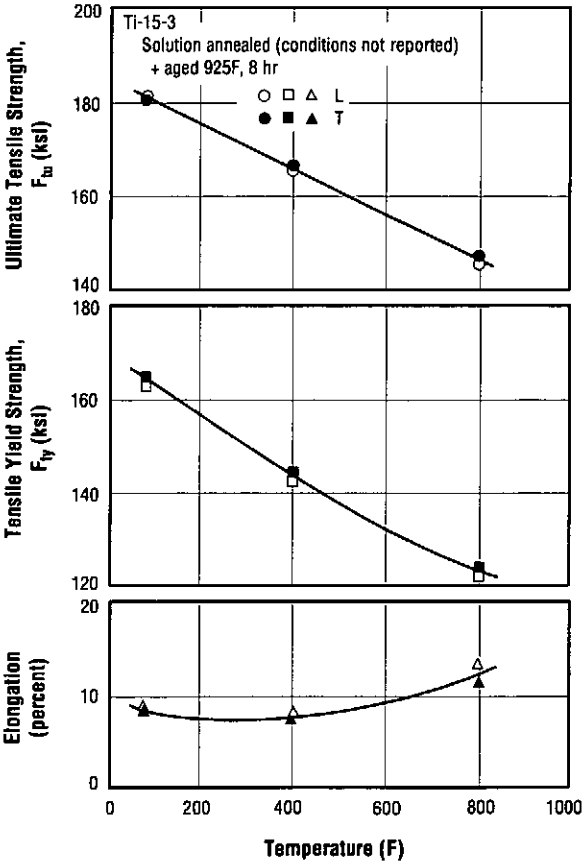

Figure 3.3.1.4 Tensile properties of solution annealed and aged alloy at room temperature to 800F (Ref. 8)

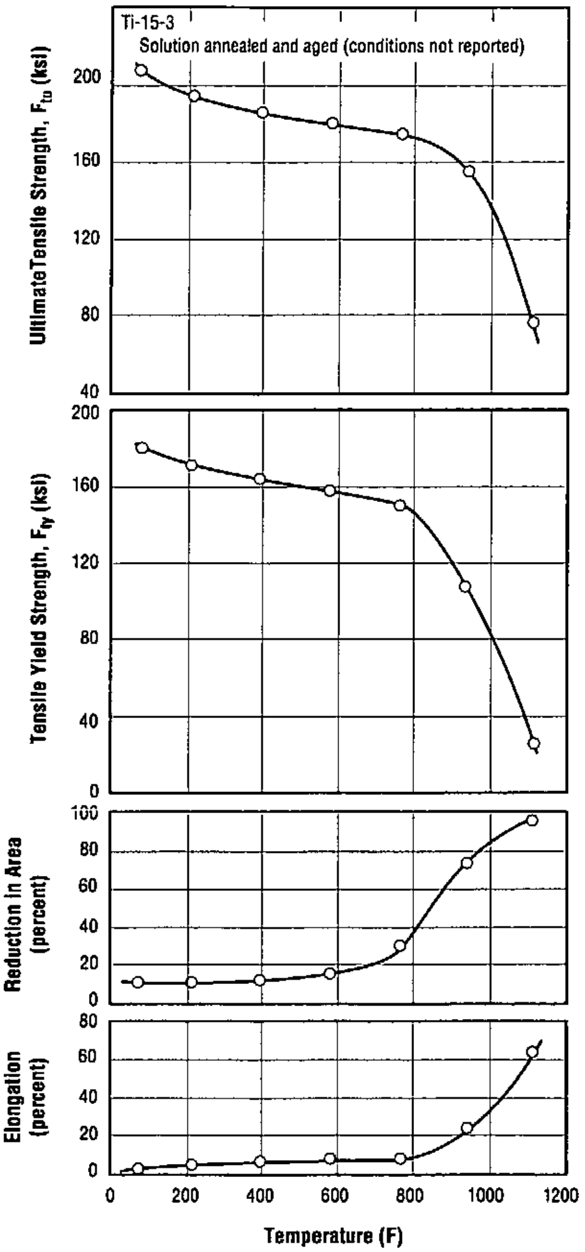

Figure 3.3.1.5 Tensile properties of solution annealed and aged alloy at room temperature to 1112F (Ref. 11)

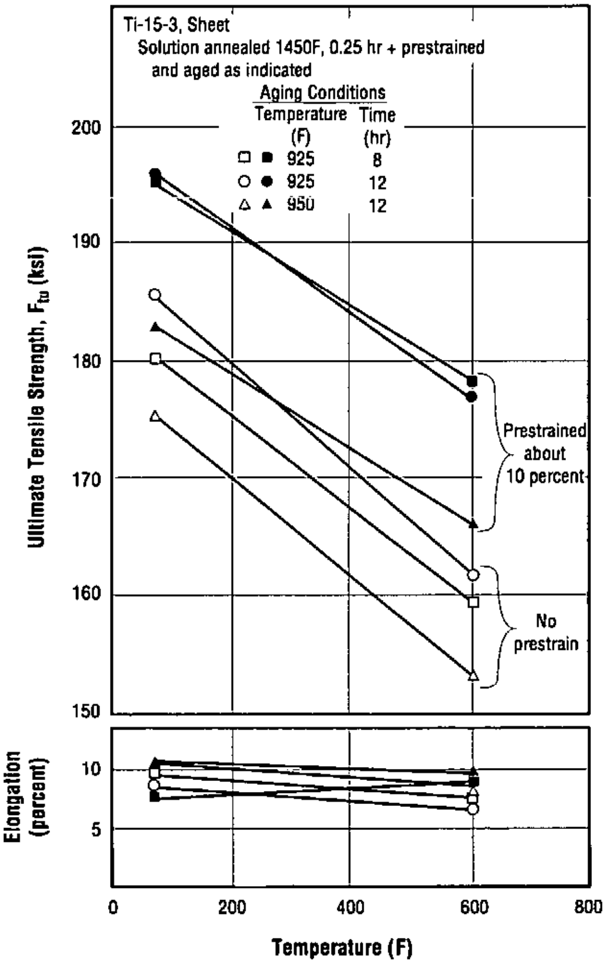

Figure 3.3.1.6 Effects of prestraining and aging on tensile properties of sheet at room temperature and 600F (Ref. 42)

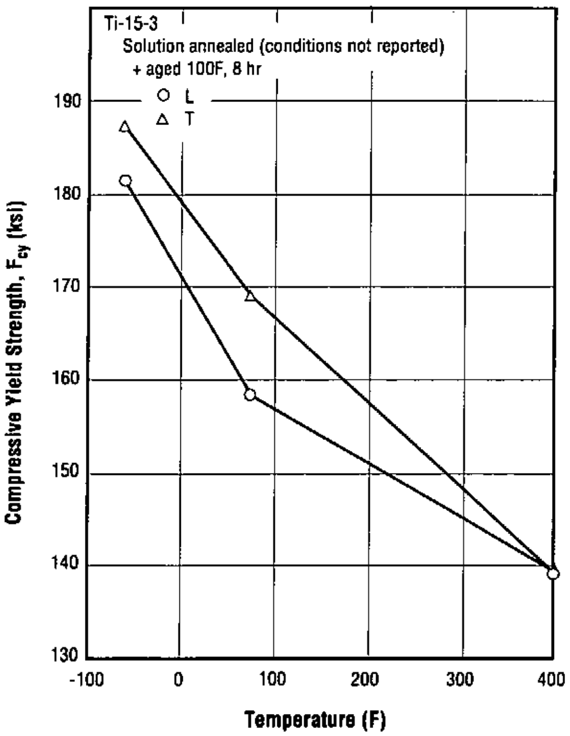

Figure 3.3.2.1 Effects of temperature and orientation on compressive yield strength (Ref. 8)

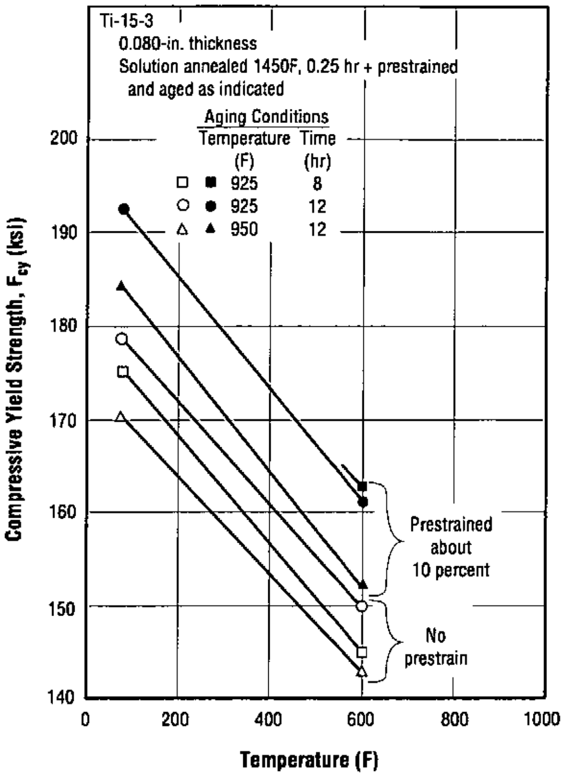

Figure 3.3.2.2 Effects of prestraining and aging on compressive yield strength of sheet at room temperature and 600F (Ref. 42)

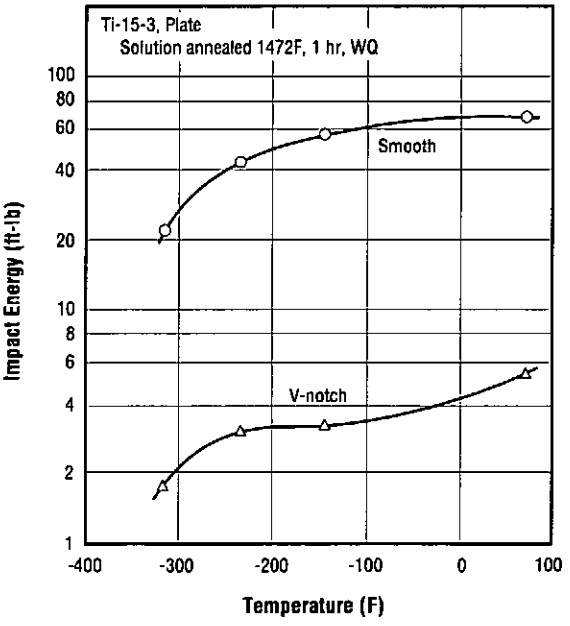

Figure 3.3.3.1 Effects of low temperatures on Charpy impact energy of solution annealed alloy (Ref. 41)

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.

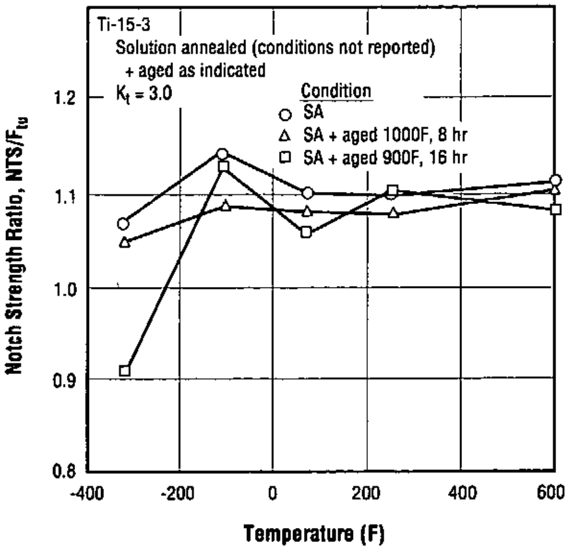

Figure 3.3.7.1.2 Effects of temperature on mild notch strength ratio for three heat treated conditions (Ref. 7)

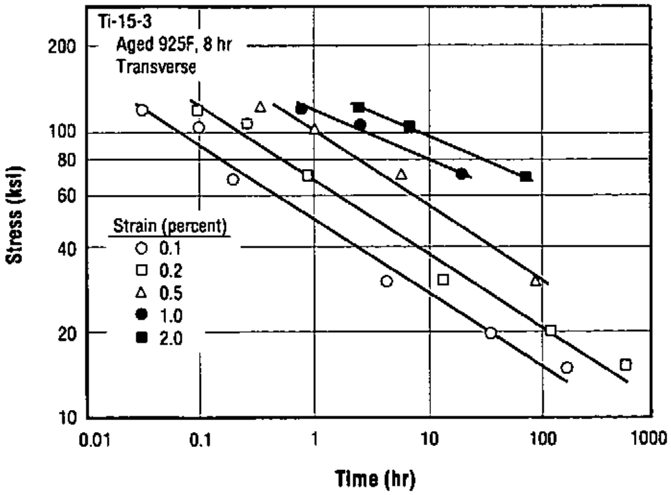

Figure 3.4.1 Times to various creep strains for aged alloy at 800F (Ref. 8)

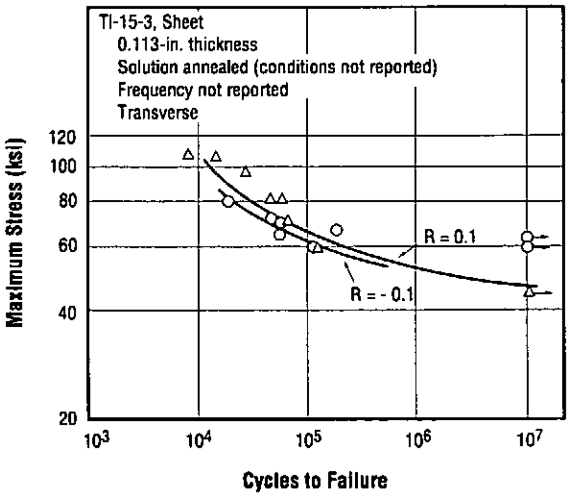

Figure 3.5.1.1 High-cycle fatigue behavior of sheet material (Ref. 39)

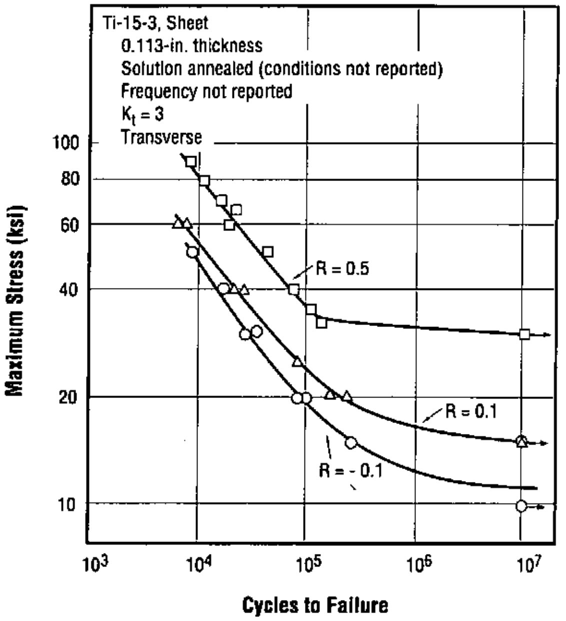

Figure 3.5.1.2 High-cycle fatigue behavior of notched sheet material (Ref. 39)

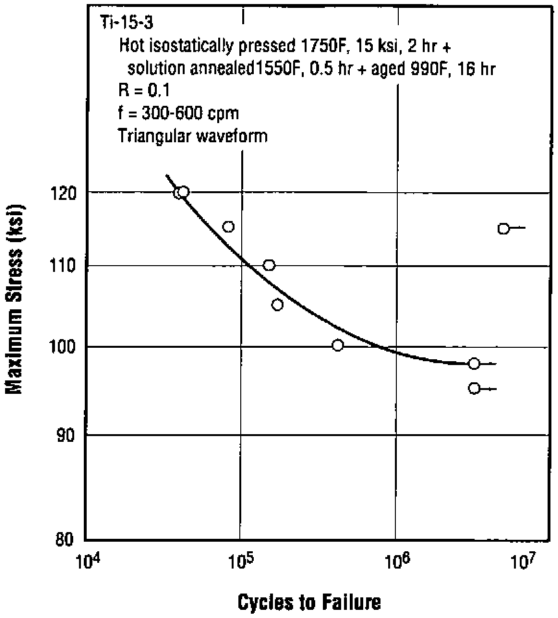

Figure 3.5.1.3 High-cycle fatigue behavior of cast alloy (Ref. 43)

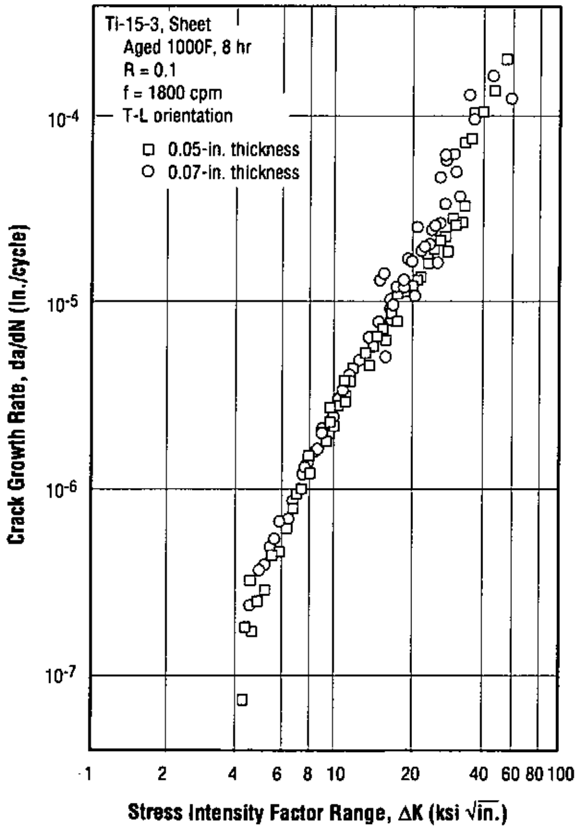

Figure 3.5.3.1 Fatigue crack growth behavior of heat treated alloy at room temperature (Ref. 7)

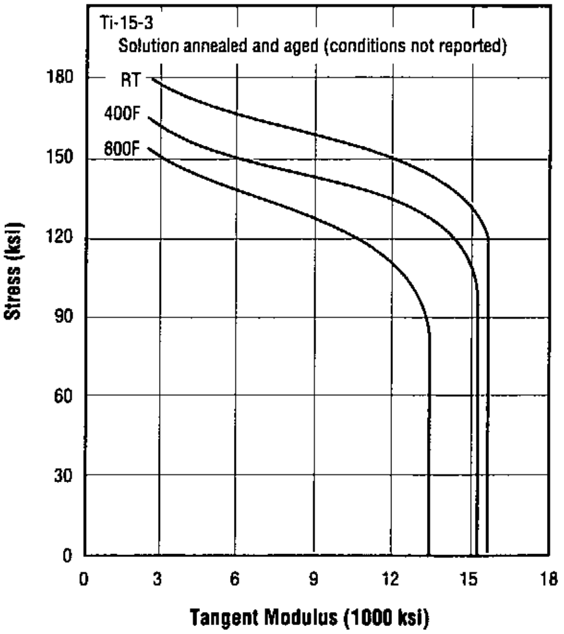

Figure 3.6.4.1 Effects of temperature on longitudinal compressive tangent-modulus curves (Ref. 8)

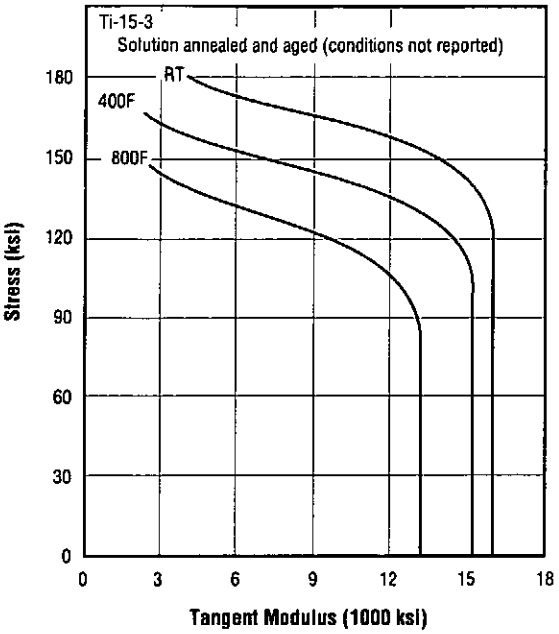

Figure 3.6.4.2 Effects of temperature on transverse compressive tangent-modulus curves (Ref. 8)

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.

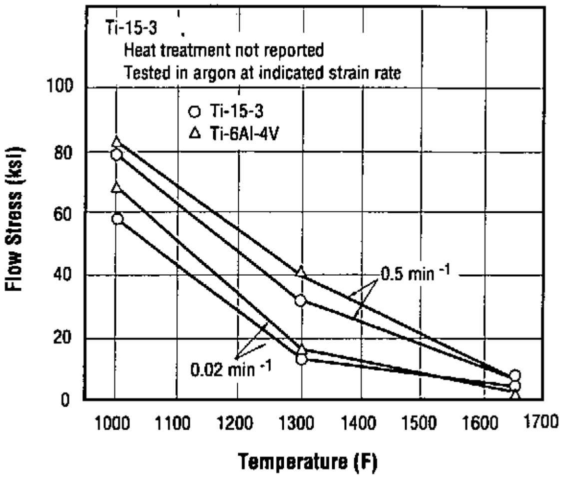

Figure 4.1.4 Effects of temperature and strain rate on flow stresses for Ti-15-3 and Ti-6Al-4V (Ref. 6)

Table 4.3.1.1 Effects of fusion welding and heat treatment on tensile properties (Ref. 47)

Alloy		Ti-15-3[a]							
Thickness (in.)	Pre-Age Weld Type	Age Conditions	Post-Age Weld Type	Tensile Properties					
				Longitudinal			Transverse		
				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 $\sqrt{\text{in}}$)
(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.

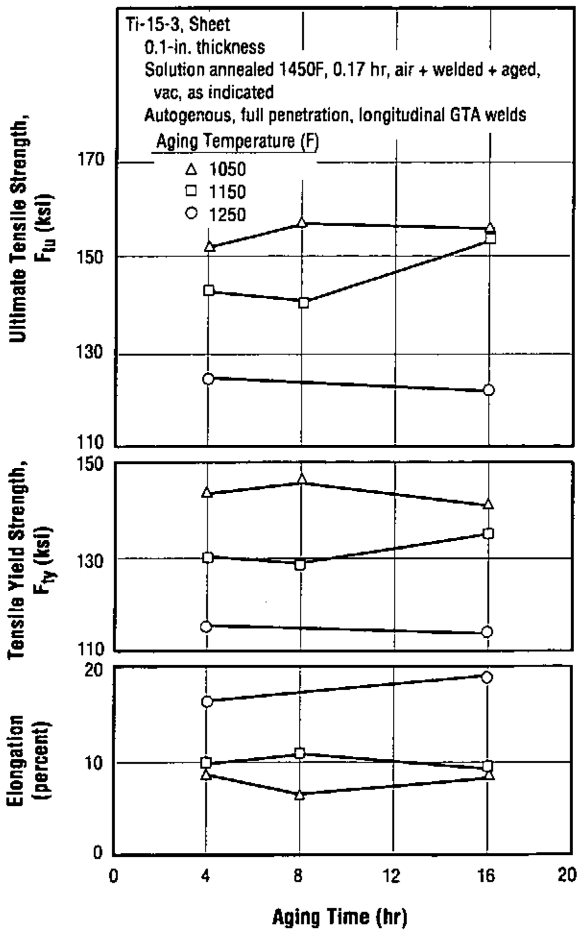

Figure 4.3.1.4 Effects of aging time and temperature on tensile properties of autogenous GTA weldments (Ref. 48)

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