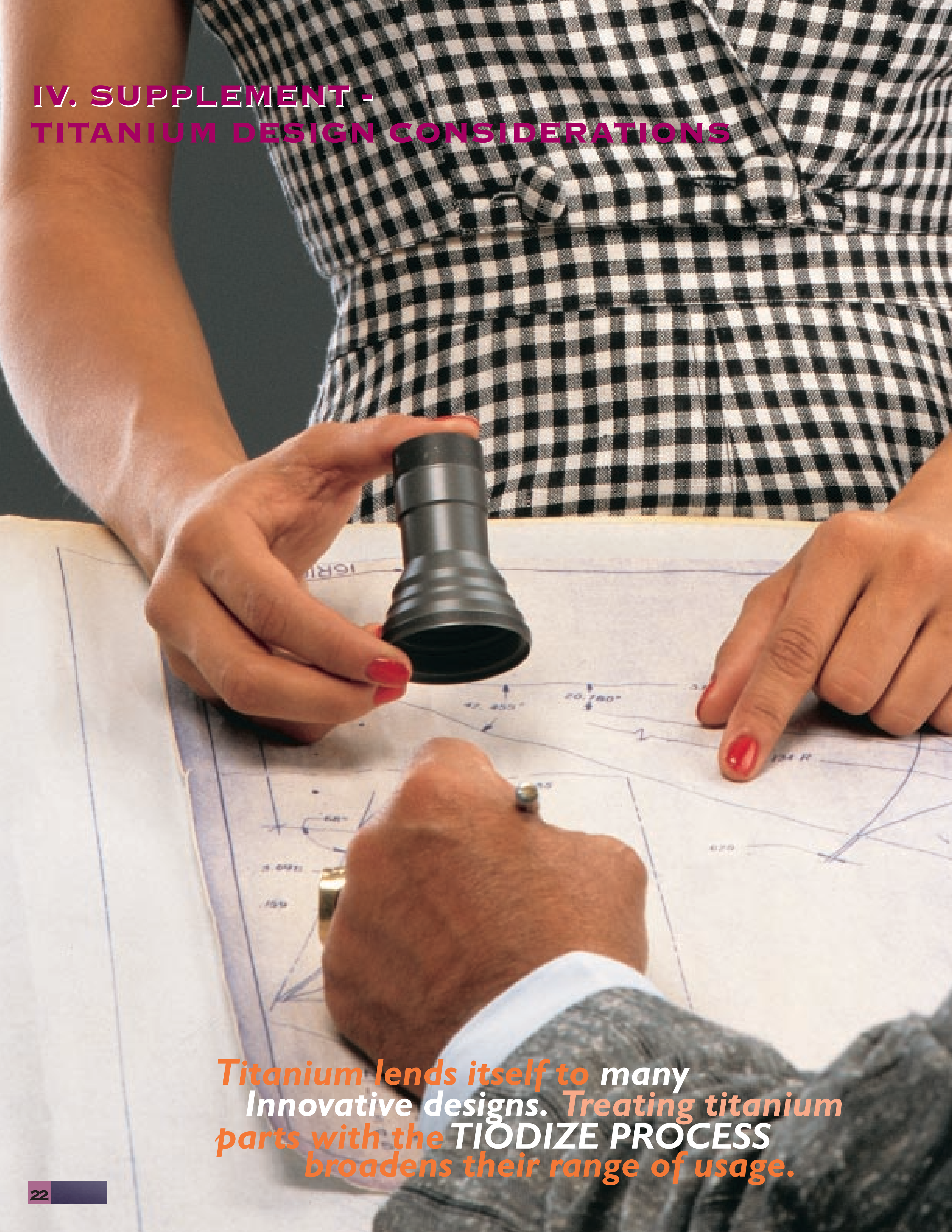
IV. SUPPLEMENT - TITANIUM DESIGN CONSIDERATIONS



Titanium lends itself to many Innovative designs. Treating titanium parts with the TIODIZE PROCESS broadens their range of usage.

IV. Supplement-Titanium Design Considerations

BASIC DESIGN FACTS ABOUT TITANIUM AND ITS ALLOYS

If you work with metals, you know about titanium. And, if you work with metals, chances are you daily encounter the common problems which must be met and conquered by all who design and engineer with metals.

These problems are easily categorized: strength-to-weight ratios, corrosion and erosion resistance, high temperature strength and resistance to oxidation, fatigue strength, creep resistance, cryogenic properties and weldability. But they are not always easily solved. Whenever the solution is difficult … whenever ordinary metals just don't offer enough advantages, you would do well to investigate the use of titanium, particularly for components which have a history of failure in severe environments.

Titanium has reversed its early position in the metals field. With a mushrooming history of success in a variety of fields, titanium is no longer the expensive metal limited to the "exotic" applications. It can, as you will find when you review the basic design facts presented herein, help you solve many common design and application problems, with greater efficiency and long-range economy.

TITANIUM IS VERSATILE

Though titanium first enjoyed wide usage by the military because of its exceptional combination of fatigue strength, creep resistance and weight-saving ability, it has proven itself extremely versatile in both military and non-military applications.

Commercially pure titanium and the various titanium alloys offer a range of mechanical properties that make them ideal for varied applications such as corrosive-fluid pump shafts, cryogenic storage vessels, rocket engine cases, heat exchangers, jet engine compressor wheels, blades and spacers, airframe skins and structures, chlorine anodes, saline water conversion units, deep diving under sea vehicles, tank armor, hydrofoil components and many more.

SUPERIOR STRENGTH-TO-WEIGHT RATIO

The high strengths and low densities of titanium and titanium alloys result in exceptionally favorable strength-to-weight ratios. Titanium bridges the design gap between aluminum and steel, offering a combination of the most desirable properties of each.

CORROSION RESISTANCE

Titanium is a highly reactive metal. Whenever it is exposed to air or other environments containing available oxygen, a thin surface film of oxide is formed. This film gives titanium its excellent corrosion resistance.

The most protective films on titanium are usually developed when water, even in trace amounts, is present. For example, if titanium and its alloys are exposed to some strongly oxidizing environments in the absence of moisture, the film that is formed is not protective, and rapid oxidation, often pyrophoric, may take place.

Titanium shows outstanding resistance to atmospheric corrosion in industrial and marine environments, and its resistance to sea water is relatively unsurpassed. It is also resistant to many acids and salt solutions.

UNUSUAL EROSION RESISTANCE

Titanium offers superior resistance to erosion, cavitation, or impingement attack, making it an ideal material for marine hydrofoils and high-velocity heat exchangers.

CHEMICAL ENVIRONMENTS

Titanium and its alloys corrode rapidly in environments that destroy the protective films. Hydrochloric, hydrofluoric, sulfuric, phosphoric and formic acids will attack titanium. However, attack by these acids, except hydrofluoric acids, is reduced by the addition of acid salts, oxidizing acids and other suitable inhibitors. Dry chlorine also attacks titanium, but it is quite resistant to wet chlorine (1% moisture) and other oxidizing gases, such as $S0_2$ and $C0_2$.

Titanium has excellent corrosion resistance to all concentrations of nitric acid up to 350ÞF. Even at 550ÞF, the rate of attack in 20% nitric acid is 12 mpy. Caution should be exercised, however, when titanium alloys are used in anhydrous fuming nitric acid because the reaction can be pyrophoric. The resistance of titanium to chromic

IV. Supplement- Titanium Design Considerations

Titanium has good resistance to dilute solutions of alkali. Hot, strong, caustic solutions attack unalloyed titanium and titanium alloys. Titanium is superior to stainless steel in its resistance to corrosion and pitting in marine environments and 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 will pit titanium alloys. At temperatures above 200ÞF, titanium may experience crevice corrosion in sea water and bromine. Titanium is not attacked by ferric chloride and sodium chloride solutions under conditions too severe for stainless steel.

Pure hydrocarbons are not considered corrosive to titanium. In addition, titanium shows corrosion resistance to most chlorinated and fluorinated hydrocarbons and other similar compounds used as hydraulic and/or heat exchange fluids. At elevated temperatures, hydrocarbons may decompose, liberating hydrogen, a portion of which may be absorbed by the titanium, resulting in loss of ductility. Chlorides may be released that can initiate elevated-temperature stress-corrosion cracking.

Titanium is not recommended for gaseous or liquid oxygen service since a violent reaction can occur. When a fresh titanium surface, such as a crack or a fracture, is exposed to gaseous oxygen, even at -250ÞF and at a pressure of about 50 to 100 psi (0.35 to 0.70 MPa), burning can begin. In liquid oxygen, titanium is impact sensitive at levels below those of many organic compounds. Titanium and its alloys also show pyrophoric reaction under impact in chlorine trifluoride, liquid fluorine and nitrogen tetroxide.

STRESS-CORROSION CRACKING RESISTANCE

CP titanium has not been found to fail by stress-corrosion cracking in any media except fuming nitric acid or methanol containing hydrochloric acid, sulfuric acid or bromine. However, under "plain stain" conditions, unalloyed titanium containing oxygen levels exhibits rapid crack propagation in sea water at low stress levels. The common aqueous stress-corrosion test solutions do not affect titanium alloys under normal conditions. Some common aqueous stress-corrosion solutions (distilled water, tap water, 3.5 sodium chloride solution) affect the fatigue life of sharp-notched test specimens (at high stress levels) and cause reduced stress rupture life in fatigue-cracked tension and bend specimens.

The susceptibility of pre-cracked titanium alloys to stress-corrosion cracking in salt water appears to be affected by the aluminum and tin content and isomorphous beta stabilizers. Susceptibility occurs with higher aluminum or aluminum-tin contents. An exception is Ti-8Mn alloy. The presence of molybdenum, vanadium and columbium reduces the sensitivity of titanium alloys.

Alloys that show some degrees of susceptibility to rapid crack propagation in salt water are unalloyed titanium, Ti-8Mn, Ti-3Al-11Cr-13V, Ti-5Al-2.5Sn, Ti-6Al-4V, Ti-8Al-1Mo-1V. Alloy Ti-4Al-3Mo-1V is insensitive to salt-water crack propagation.

The degree of susceptibility of some titanium alloys to stress-corrosion cracking in salt water can be changed by heat treatment. Rapid quenching from temperatures above the beta transus tends to improve resistance, while aging in the 900 to 1300ÞF range tends to decrease resistance to accelerated cracking.

Titanium alloys also suffer stress-corrosion cracking at ambient temperatures under certain other conditions. Failures have been encountered in red fuming nitric acid, in N_2O_4 and hydrochloric acid. Also, certain alloys show susceptibility to stress-corrosion cracking in chlorinated-hydrocarbon solvents. Cracks will initiate and propagate only if the right combination of stress, metallurgical history and environmental factors is present.

Methyl alcohol also initiates stress-corrosion cracking of titanium and its alloys. With small additions of bromine, hydrochloric acid or sulfuric acid to methanol, even unalloyed titanium can be made to crack. With chemically pure methanol the susceptibility of titanium alloys varies, depending on alloy, heat treatment and stress levels.

Most titanium alloys are susceptible to some degree of hot-salt stress-corrosion cracking. The alpha alloys are apparently most susceptible to attack. The alpha-beta alloys are less susceptible, but the degree of susceptibility increases with increases in aluminum content. Ti-8Al-1Mo-1V, both as mill and duplex annealed, is very susceptible. However, the Ti-8Mn alloy, which contains no aluminum, is also susceptible.

IV. Supplement – Titanium Design Considerations

Alloys with intermediate resistance are Ti6Al-4V, Ti-6Al-6V-2Sn and Ti-13V-11Cr-3Al. One of the most resistant to hot-salt stress-corrosion cracking is Ti-4Al-3Mo-1V. Variations in heat treatment affect the reactivity of many alloys.

Liquid-metal embrittlement is closely related to stress-corrosion cracking. Molten cadmium causes cracking in titanium alloys. Mercury and mercury amalgams also initiate cracking. However, here, plastic rather than elastic deformation is required to reduce cracking. Silver will cause cracking of stressed Ti-7Al-4MO and Ti-5Al-2.5Sn at temperatures of 650ÞF and above.

GALVANIC CORROSION

In most environments, the potential of passive titanium is similar to that for Monel(nickel-copper alloys) and stainless steel. Galvanic effects are not likely to occur when titanium alloys are coupled to these materials. Less noble materials, such as aluminum alloys, carbon steels and magnesium alloys, may suffer accelerated attack when coupled with titanium. Extent and degree of galvanic attack depends on the relative areas of the titanium and the other metal, e.g., where the area of the anodic material is small in relation to that of titanium, severe corrosion of the anodic materials occurs. Less attack is evident in the areas if the two metals are reversed. Attack is prevented or minimized in most cases by the TIODIZE PROCESS coatings, paints and other treatments.

CREVICE CORROSION

Crevice corrosion of titanium and its alloys occurs in chloride-salt solutions at elevated temperatures. Attack occurs above 200ÞF with increasing frequency from 300 to 400ÞF. Acid and neutral solutions cause the greatest susceptibility, whereas no attack has been observed at pH9 or more. Crevice attack occurs with about the same frequency among unalloyed titanium and the common titanium alloys. Titanium alloy with about 0.2% palladium provides increased resistance to crevice attack, but it too is attacked after a long-term exposure at elevated temperature.

BASIC TITANIUM METALLURGY

Effects of Alloying Elements

The selective addition of alloying elements to titanium enables a wide range of physical and mechanical properties to be obtained. Basic effects of a number of alloying elements are as follows:

1. Certain alloying conditions, notably aluminum, tend to stabilize the Alpha phase, i.e., raise the temperature at which the alloy will be transformed completely to the Beta phase. This temperature is known as the Beta transus temperature.

2. Most alloying additions such as chromium, columbium, copper, iron, manganese, molybdenum, tantalum, vanadium, stabilize the Beta phase by lowering the temperature of transformation (from Alpha to Beta).

3. Some elements, notably tin and zirconium, behave as neutral solutes in titanium and have little effect on the transformation temperature, acting as strengtheners of the Alpha, or room temperature phase.

Alpha Alloys

The single-phase microstructure of the Alpha alloys of titanium promotes good weldability. The stabilizing effect of the high aluminum content of this group of alloys assures excellent strength characteristics and oxidation resistance at elevated temperatures (in the range of 600-1100ÞF). Alpha alloys cannot be heat-treated since they are single-phase alloys.

Alpha-Beta Alloys

The addition of controlled amounts of Beta-stabilizing alloying elements causes the Beta phase to persist below the Beta transus temperature, down to room temperature, resulting in a two-phase system. Such two-phase titanium alloys can be significantly strengthened by heat treatment: a quench from a temperature in the Alpha-Beta range followed by an aging cycle at a somewhat lower temperature.

The transformation of the Beta phase, which would normally occur on slow cooling, is suppressed by the quenching. The aging cycle causes the precipitation of some fine Alpha particles from the metastable Beta, imparting a structure that is stronger than the annealed Alpha-Beta structure.

Beta Alloys

The high percentage of Beta-stabilizing elements in 13V-11Cr-3Al titanium alloy results in a microstructure that is substantially Beta,

FABRICATING PROPERTIES OF TITANIUM ALLOYS

GRADE OR ALLOY	ANNEAL TEMP. ÞF(K)	STRESS RELIEVE TEMP. ÞF(K)	SOLUTION TEMP. ÞF(K)	AGING TEMP. ÞF(K)	FORGING TEMP. ÞF(K)
Unalloyed grades 99.5 Ti, 99.2 Ti, and 99.0 Ti	*1000-1300 (811-978)*	*1000-1100 (811-866)*	*NHT*	*NHT*	*1200-1750 (922-1227)*
Alpha alloys Ti-0.15 to 0.20 Pd	*1250-1300 (950-978)*	*1000-1100 (811-866)*	*NHT*	*NHT*	*1550-1700 (1116-1200)*
Ti-5Al-2.55Sn	*1300-1600 (978-114)*	*1000-1200 (811-922)*	*NHT*	*NHT*	*1650-2150 (1144-1450)*
Near alpha Ti-2.25Al-11Sn-5Zr-1Mo-02Si	*1650 (1172)*	*930 (772)*	*1650 (1172)*	*930 (772)*	*1675-1825 (1185-1269)*
Ti-Al6Sn-2Zr-1Mo-0.25Si	*1800; 1100 [3] (1255,866)*	—	—	—	—
Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si	*1300; 1950 and 1300 [3] (978; 1339 and 978)*	—	—	—	—
Ti-6Al-2Cb-1Ta-0.8Mo	*1300-1700 (978-1200)*	*1100-1200 (866-922)*	*1850 (1283)*	—	*1800-1950 (1255-1339)*
Ti-9Al-1Mo-1V	*1400-1450 [5] (1033-1061)*	*1075- 1125 1450 [4] (1061)*	*NHT*	*NHT*	*1800-1950 (1255-1339)*
Alpha-beta Ti-8Mn	*1250-1350 (950-1005)*	*900-1100 (755-866)*	*Not recomm.*	*N/R*	*1450-1700 (1061-1200)*
Ti-3Al-2.5V	*1200-1300 (922-1033)*	*700-1200 (644-922)*	*1600-1700 (1144-1200)*	*900-950 (755-783)*	—
Ti-4Al-3Mo-1V	*1200-1400 (922-1033)*	*900-1100 (755-866)*	*1620-1775 [6] (1155-1241)*	*900-975 (755-797) 1050-1150 [3] (839-894)*	*1650-1750 (1172-1227)*
Ti-5A-2Sn-2Zr-4Mo-4Cr	—	—	*1475 [8] (1075)*	*1100-1200 (866-922)*	*1500-1700 (1088-1200)*
Ti-6Al-4V	*1350-1400 (1005-1033)*	*1000-1100 (811-866)*	*1650-1775 (1172-1241)*	*900-1050 (755-839) 1050-1300 [7] (839-978)*	*1775-18 (1241-1258)*
Ti-6Al6V-2Sn	*1300-1500 (978-1088)*	*1000-2000 (811-922)*	*1550-1650 (1116-1172)*	*875-1150 (741-894) 1100-1200 [7] (866-922)*	*1550-1710 (1116-1205)*
Ti-6Al-2Sn-4Zr-2Mo	*1300-1550 (978-1116)*	*900-1200 (755-922)*	*1525-1675 (1102-1352)*	*1100-1250 (866-950)*	*1750 max (1227 max)*
Ti-6Al-2Sn-4Zr-6Mo	*1100-1300 (866-978)*	*1100-1300 (866-978)*	*1550-1700 (1116-1200)*	*1100 (866)*	*1600-1825 (1144-1269)*
Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si	*1450 (1061)*	*1000-1100 (811-866)*	*1700-1740 (1200-1222)*	*1000-1100 (811-866)*	*1700-1050 (1200-1394)*
Ti-7Al-4Mo	*1425-1475 (1047-1075)*	*900-1300 (755-978)*	*1675-1775 (1352-1241)*	*950-1200 [2] (783-922)*	*1500-1850 (1088-1283)*
Beta Ti-2Al-11V-2Sn-11Zr	*1400-1600 (1033-1144)*	—	*1350-1700 [11] (1005-1200)*	*850-1250 (727-950)*	—
Ti-3Al-8V-6Cr-4Mo-4Zr	*1500-1700 (1088-1200)*	—	*1500-1700 (1088-1200)*	*800-1050 (700-839) 1050-1250 [7] (839-950)*	—
Ti-4.5Sn-6Zr-11.5Mo	*1275-1600 (963-1144)*	*900-1100 (755-866)*	*1275-1600 (963-1144)*	*900 (755) 1100 [3] (866)*	*1600-2000 (1144-1366)*
Ti-8Mo-8V-2Fe-3Al	*1450 (1061)*	*950-1100 (783-866)*	*1450-1475 (1061-1075)*	*900-950 (755-783) 1100-1200 (866-922)*	*1400-1700 (1033-1200)*
Ti-13V-11Cr-3Al	*1400-1500 (1033-1088)*	*900-1000 (758-811) 1400-1450 [12] (1033-1061)*	*1400-1500 (1033-1088)*	*825-1000 (713-811)*	—

[1] Numerical values based on AISI B1112 steel = 100. [2] Smaller radii above 300 F. [3] Both high and low temp steps required. Three steps required in triplex anneal. [4] Short exp. at full anneal temp may be used. Air cooling from this exp. results in simulating the duplex annealed cond. Slow cooling simulates mill annealed condition. [5] May be duplex annealed. [6] Bars and forgings at high end of temp range. [7] Overaging heat treatment. [8] Sol'n treatment for beta fabricated material. [9] Hot forming recomm. for complex structures. [10] Overaged condition may be achieved with higher temps of range indicated. [11] Section size determines temp. [12] Stress relief may be achieved using short time exp. at sol'n anneal temp.

FABRICATING PROPERTIES OF TITANIUM ALLOYS (continued)

FORMABILITY	WELDABILITY GENERAL	FUSION	RESIST	MACHINABILITY
3.5t [2]	Readily welded, high str, good duct	Shielded arc nearly 100% eff.	Spot, seam without gas shield	Similar to aust. stainless steel Ann.=40
1t-3t	Similar to unalloyed	Similar to unalloyed	Similar to unalloyed	Similar to unalloyed
3t-5t	Readily welded	MIG;TIG preferred	—	Similar to aust. stainless steel
—	—	—	—	Difficult due to high work hard rate
—	—	—	—	—
—	—	—	—	—
4t-6t	—	GTM; GMA	—	—
3t-5t	Joint efficiency 97-100%	TIG; MIG for thick sections	Readily done	Similar to Ti-6Al4V but needs stress relief; 22
3.5-4.0t	—	Not recomm	Spot, but poor sheer properties	25
2.5t-3.0t	Diff. bonded in honeycomb	—	—	—
3.5-4t	Ext. cleanliness reg.	MIG;TIG	Similar to aust. stainless steel	—
—	—	—	—	—
4.5-5.0t [9]	Ext. cleanliness reg	MIG;TIG EB very common	Similar to aust stainless steel	Similar to aust. stainless steel 22 Ann; 18 Ht
—	Very difficult; low ductility	MIT,TIG, but with caution	Not recomm.	20 Ann; 16 Ht
2.5t-4.0t	Joint prep very impt.	MIG,TIG	Inert gas protect. recomm.	—
—	Very little data available	Poor ductility	—	—
4-4.5t	Similar to Ti-6-6-2	—	—	Similar to 6-6-2
—	Not recomm.	—	—	Similar to unalloyed grades
—	—	GTA	—	—
—	—	—	—	—
2t-3.5t	—	GTA, EB	No gas shld. req. for spot	—
2t-4t	More weldable than	— Ti-13V-11Cr-3Al	—	—
2t-4t	—	—	—	16 Ann;~12 Ht

[1] Numerical values based on AISI B1112 steel = 100. [2] Smaller radii above 300 F. [3] Both high and low temp steps required. Three steps required in triplex anneal. [4] Short exp. at full anneal temp may be used. Air cooling from this exp. results in simulating the duplex annealed cond. Slow cooling simulates mill annealed condition. [5] May be duplex annealed. [6] Bars and forgings at high end of temp range. [7] Overaging heat treatment. [8] Sol'n treatment for beta fabricated material. [9] Hot forming recomm. for complex structures. [10] Overaged condition may be achieved with higher temps of range indicated. [11] Section size determines temp. [12] Stress relief may be achieved using short time exp. at sol'n anneal temp.