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# MILITARY HANDBOOK

# TITANIUM AND TITANIUM ALLOYS

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

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Titanium and Titanium Alloys
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1. This standardization handbook was developed for the Department of Defense in accordance with established procedure.

2. This publication was approved on 1 June 1974 for printing and inclusion in the military standardization handbook series.

3. This handbook provides basic and fundamental information on titanium and titanium alloys for the guidance of engineers and designers of military materiel. This handbook is not intended to be referenced in purchase specifications except for informational purposes, nor shall it supersede any specification requirements.

4. Every effort has been made to reflect the latest information on titanium and titanium alloys. It is the intent to review this document periodically to insure its completeness and currency. Users of this document are encouraged to report any errors discovered and recommendations for changes or inclusions to the Director, US Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172, ATTN: AMXMR-MS.

# PREFACE

This is one of a group of handbooks covering metallic and nonmetallic materials used in the design and construction of military equipment.

The purpose of this handbook is to provide, in condensed form, technical information and data of direct usefulness to design engineers. The data, especially selected from a number of government and industrial publications, have been checked for suitability for use in design. Wherever practicable, the various types, classes, and grades of materials are identified with applicable government specifications. The corresponding technical society specifications and commercial designations are shown for information.

The numerical values for properties listed in this handbook, which duplicate specification requirements, are in agreement with the values in issues of the specifications in effect at the date of this handbook. Because of revisions or amendments to specifications taking place after publication, the values may, in some instances, differ from those shown in current specifications. In connection with procurement, it should be understood that the governing requirements are those of the specifications of the issue listed in the contract.

This revision of the handbook was prepared by the Metals and Ceramics Information Center of Battelle Columbus Laboratories and the Army Materials and Mechanics Research Center. Comments on this handbook are invited. They should be addressed to Director, US Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172, ATTN: AMXMR-MS.

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# GENERAL INFORMATION

## Titanium in Engineering Design

1. General Characteristics. Titanium and titanium alloys are used in engineering design chiefly for their excellent combination of mechanical properties coupled with low density and their corrosion resistance. Other advantages of titanium for specific applications include: low coefficient of thermal expansion, good oxidation resistance at intermediate temperatures, low magnetic permeability, high toughness, and low heat-treating temperature during hardening. Alloying may be used to enhance selected properties of titanium and many alloys can be strengthened by processing and heat treatment. Although about 40 percent lighter than steel, certain titanium alloys can be equated on a strength-to-weight basis to steels having yield strength levels of about 300 ksi. Compared to aluminum, titanium alloys (60 percent heavier than aluminum) are much stronger, are useful to much higher temperatures and show higher fatigue resistance and greater hardness. A wide range of physical and mechanical properties are available from titanium and its alloys.

Table I compares some of the physical properties of titanium with those of other pure metals. As mentioned above, a low density, intermediate to aluminum and steel, and a low coefficient of thermal expansion are properties of titanium that can be used to afford unique advantages for some applications. The elastic modulus of titanium, also intermediate to aluminum and steel, can be used to advantage in certain applications (e.g. torsion bars and springs). Another physical characteristic of titanium is its transformation from one crystal morphology, body-centered-cubic to another hexagonal-close-packed (hcp) at about 1625 F (885 C). The transformation is reversible. The hcp form is the stable structure at room temperature although the bcc form can be stabilized by alloying. The processing and heat treatment of titanium alloys are inevitably involved with the transition behavior and the two basic structures or phases, hcp (alpha) and bcc (beta).

The secondary processing of titanium or alloys that might be required by the fabricator of end-use items usually may be accomplished without difficulty by the experienced shop. There are of course certain precautions to be observed which are described in more detail in later sections. For example, the preservation of properties imparted by primary processing (at the titanium producers shop) must be a consideration during any secondary fabrication, heat treatment, and finishing operations. Forming, joining (titanium can be welded or joined by several other methods), heat treatment, and machining operations must follow procedures which allow for the physical characteristics common to the metal.

Titanium is strain-rate sensitive. For example, mechanical properties may vary greatly with different speeds of testing. Strain-rate sensitivity also must be given consideration in part-forming operations. For example some complex parts can be formed at a low strain rate which would be impossible to form at a high strain rate. A strain rate of 0.005 in./in./min. is generally accepted as standard for tensile testing.

## TABLE I. PHYSICAL PROPERTIES OF TITANIUM AND OTHER PURE METALS

| Properties | Titanium (99.9%) | Iron (99.9+%) | Aluminum (99.996%) | Magnesium (99.98%) | Copper (99.95%) |
|---|---|---|---|---|---|
| Atomic Number | 22 | 26 | 13 | 12 | 29 |
| Atomic Weight (based on Carbon = 12) | 47.90 | 55.85 | 26.98 | 24.312 | 63.54 |
| Density (lb/cu. in) at 68°F (20°C) | 0.163 | 0.284 | 0.098 | 0.063 | 0.323 |
| Liquidus Temperature, °F | 3035±18 | 2797.7±1.8 | 1220.4 | 1202 | 1981.4±0.2 |
| Liquidus Temperature, °C | 1668±10 | 1536.5±1 | 660.2 | 650 | 1083.0±0.1 |
| Transformation Temperature, °F | 1625(a) | 1670(b) | None | None | None |
| Magnetic Susceptibility(c) | Para(d) | Ferro | Para | Para | Dia |
| Tensile Modulus, psi x $10^6$ | 14.7 | 29.7 | 10.0 | 6.25 | 16.0 |
| Shear Modulus, psi x $10^6$ | 5.0 | 10.0 | 3.8 | 2.4 | 6.0 |
| Thermal Expansion ($10^{-6}$ in./in./°F at 68°F) | 4.67 | 6.8 | 13.1 | 14.0 | 9.4 |
| Thermal Conductivity (Btu/Hr/ft$^2$/°F/ft) | 9 | 46 | 117 | 56 | 226 |
| Specific Heat (Btu/lb/°F) at RT | 0.126 | 0.107 | 0.215 | 0.246 | 0.092 |
| Electric Resistivity (microhm–cm at RT) | 47.8 | 10.0 | 2.824 | 4.6 | 1.724 |
| % IACS(e) | 3.6 | 17.2 | 61.1 | 38.7 | 100 |

Note:

(a) Titanium is hcp at <1625 F and bcc at >1625 F.

(b) Iron is bcc at <1670 F and fcc between 1670 and 2535 F.

(c) Paramagnetic = slightly more permeable than a vacuum and independent of magnetizing force.
Diamagnetic = less permeable than a vacuum and *weakly repelled* by magnetic force.
Ferromagnetic = strongly magnetic and dependent of magnetizing force.

(d) Susceptibility of titanium is 3.17 x $10^{-6}$ emu/g. Permeability is 1.00005 at 20 oersteds.

(e) Percent International Annealed Copper Standard at 20°C. (Measure of electrical conductivity)

The high friction characteristics of titanium and associated wear can present somewhat of a problem in certain applications. However, specialized coatings and lubricants have been developed to greatly alleviate galling and other difficulties in selected applications. Each application, where titanium would be subject to friction wear, should be analyzed to determine the optimum system to be used.

Normally, protective coatings to eliminate corrosion effects are not required for titanium. The ever present oxide surface affords ample protection in most ambient environments and in a wide range of corrosive media. In cases where coatings are needed, such as for protection against friction wear, erosion, and elevated temperature corrosion, specific materials and techniques have been employed for specific applications. Decorative or other nonservice required coatings can also be applied.

The relative price of titanium and its alloys is an important consideration in design applications. Although the initial unit price of titanium may be considered high, weight savings, superior corrosion resistance, and other design factors may warrant its selection over other structural materials for a given job. Indeed, for certain applications, weight savings resulting in increased payload can more than offset initial costs and perhaps in the long run prove less costly than lower priced materials.

2. Titanium Alloy Availability — Designations. The titanium industry of the United States did not achieve significant size until the late 1950's. However, it was an important industry from the viewpoint of its military potential and received considerable industrial and governmental research and development funding. This support stimulated steady growth and generated an advanced titanium technology. During the course of its existence, the industry has developed about 50 different grades and compositions which have been described as commercial. Approximately 30 alloy compositions and unalloyed grades of titanium are currently commercially viable. These are listed in Table II. Table III gives typical producer company designations for these alloys.

As shown in Table II, the major types of titanium alloys are: alpha, alpha-beta, and beta. Other types are known as near-alpha, near-beta, and alpha-dispersoid types. As the type names suggest, the classification is based on the dominant microstructural features of the alloys. For example, unalloyed titanium grades are predominantly of hcp (alpha phase) structure, beta alloys are bcc (beta phase), and a host of compositions are of mixed hcp and bcc structure (alpha plus beta phases). Alpha-dispersoid types have intermetallic compound phase interspersed with the alpha matrix phase. Several other alloys (notably those containing silicon) also can exhibit intermetallic phase in the microstructure.

Aluminum and oxygen are the alloy additions capable of stabilizing the alpha phase in titanium and in general increasing amounts of these elements result in the stabilization of increasing amounts of the alpha phase. Beta stabilizing additions such as vanadium, molybdenum, manganese, iron and chromium, cause the stabilization of the beta phase generally proportional to the amount of beta addition used but subject to modification by the amount of alpha stabilizers combined in the alloy. Most of the commercial alloys have combinations of alpha stabilizing and beta stabilizing additions to impart the characteristics desired.

The many alloys available collectively provide a very wide range of mechanical and physical properties suitable for many applications. Some alloys, for example 5621S, were formulated specifically to have good elevated temperature characteristics (e.g. creep strength). Others for example Beta III and Ti-8Mo-8V-2Fe-3Al, were designed for improved combinations of formability, deep hardenability, and high strength. Some alloys, for example Ti-6Al-4V, are very versatile,

## TABLE II. TITANIUM ALLOYS OF CURRENT GENERAL INTEREST

| Nominal Composition, wt % | Alloy Type | Common Name(a) |
|---|---|---|
| Unalloyed Ti, ~99.5(b) | Alpha | CP |
| Unalloyed Ti, ~99.2(b) | Alpha | CP |
| Unalloyed Ti, ~99.01(b) | Alpha | CP |
| Ti-0.15 to 0.20 Pd | Alpha | Pd alloy |
| Ti-5A1-2.5Sn(c) | Alpha | A-110 |
| Ti-1 to 2Ni | Alpha-dispersoid | —— |
| Ti-2Cu | Alpha-dispersoid | —— |
| Ti-2.25A1-11Sn-5Zr-1Mo-0.2Si | Near-alpha | 679 |
| Ti-5A1-6Sn-2Zr-1Mo-0.25Si(d) | Near-alpha | 5621S |
| Ti-6A1-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si | Near-alpha | Ti-11 |
| Ti-6A1-2Cb-1Ta-0.8Mo | Near-alpha | 6-2-1-1 |
| Ti-8A1-1Mo-1V | Near-alpha | 8-1-1 |
| Ti-8Mn | Alpha-beta | 8Mn |
| Ti-3A1-2.5V | Alpha-beta | 3-2.5 |
| Ti-4A1-3Mo-1V | Alpha-beta | 4-3-1 |
| Ti-5A1-2Sn-2Zr-4Mo-4Cr | Alpha-beta | Ti-17 |
| Ti-6A1-4V(c) | Alpha-beta | 6-4 |
| Ti-6A1-6V-2Sn | Alpha-beta | 6-6-2 |
| Ti-6A1-2Sn-4Zr-2Mo(e) | Alpha-beta | 6-2-4-2 |
| Ti-6A1-2Sn-4Zr-6Mo | Alpha-beta | 6-2-4-6 |
| Ti-6A1-2Sn-2Zr-2Mo-2Cr-0.2Si | Alpha-beta | 6-2-2-2-2 |
| Ti-7A1-4Mo | Alpha-beta | 7-4 |
| Ti-1A1-8V-5Fe | Near-beta | 185 |
| Ti-2A1-11V-2Sn-11Zr | Beta | Transage 129 |
| Ti-3A1-8V-6Cr-4Mo-4Zr | Beta | Beta C |
| Ti-4.5Sn-6Zr-11.5Mo | Beta | Beta III |
| Ti-8Mo-8V-2Fe-3A1 | Beta | 8-8-2-3 |
| Ti-13V-11Cr-3A1 | Beta | 13-11-3 |

Note:

(a) Producer nomenclature varies since some companies use a code for designating products while others use logical symbols such as the company name followed by the composition in alphanumeric form. See Table 3 for guidance.
(b) Several grades of unalloyed titanium are produced which differ in impurity level, hence strength and ductility.
(c) High-purity grades of these alloys are available and are designated with the suffix ELI, meaning Extra Low Interstitials.
(d) A modification of this alloy, Ti-5A1-5Sn-2Zr-2Mo-0.25Si, may become commercial.
(e) A silicon-containing grade of 6-2-4-2 is also available.

## TABLE III. TYPICAL DESIGNATIONS FOR TITANIUM ALLOYS OF COMMERCIAL INTEREST

| Nominal Composition, wt % | Crucible[a] | Martin[b] | RMI[c] | TIMET[d] | Other |
|---|---|---|---|---|---|
| Unalloyed Ti, ~99.5 | A-40 | MMA-1940 | RMI 40 | Ti-35A | Armco Ti-40[e] |
| Unalloyed Ti, ~99.2 | A-55 | MMA-1950 | RMI 55 | Ti-65A | -- |
| Unalloyed Ti, ~99.0 | A-70 | MMA-1970 | RMI 70 | Ti-75A | -- |
| Ti-0.15 to 0.20 Pd | -- | MMA-1942 | RMI 0.2 Pd | Ti-0.20 Pd | TiTech 0.2 Pd[f] |
| Ti-5Al-2.5Sn | A-110AT | MMA-5137 | RMI 5Al-2.5Sn | Ti-5Al-2.5Sn | -- |
| Ti-1 to 2 Ni | -- | -- | -- | Ti-2Ni | Company name preceding alloy composition or Company name symbol preceding alloy composition |
| Ti-2Cu | -- | -- | RMI 2Cu | -- | |
| Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si | -- | -- | -- | Ti-679 | |
| Ti-5Al-6Sn-2Zr-1Mo-0.25Si | -- | -- | RMI 5Al-6Sn-2Zr-1Mo-Si | -- | |
| Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si | -- | -- | -- | Ti-11 | |
| Ti-6Al-2Cb-1Ta-0.8Mo | -- | -- | RMI 6Al-2Cb-1Ta-1Mo | -- | |
| Ti-8Al-1Mo-1V | 8Al-1Mo-1V | MMA-8116 | RMI 8Al-1Mo-1V | Ti-8Al-1Mo-1V | |
| Ti-8Mn | C-110M | -- | RMI 8 Mn | Ti-8Mn | |
| Ti-3Al-2.5V | 3Al-2.5V | MMA-3138 | RMI 3Al-2.5V | Ti-3Al-2.5V | |
| Ti-4Al-3Mo-1V | -- | -- | RMI 4Al-3Mo-1V | -- | |
| Ti-5Al-2Sn-2Zr-4Mo-4Cr | -- | -- | -- | Ti-17 | -- |
| Ti-6Al-4V | C-120AV | MMA-6510 | RMI 6Al-4V | Ti-6Al-4V | Tel-Ti-6Al-4V[g] |
| Ti-6Al-6V-2Sn | C-125AVT | MMA-5158 | RMI 6Al-6V-2Sn | Ti-6Al-6V-2Sn | -- |
| Ti-6Al-2Sn-4Zr-2Mo | 6Al-2Sn-4Zr-2Mo | MMA-9744 | RMI 6Al-2Sn-4Zr-2Mo | Ti-6Al-2Sn-4Zr-2Mo | Sometimes alloy designation is entirely in symbols |
| Ti-6Al-2Sn-4Zr-6Mo | -- | MMA-6246 | RMI 6Al-2Sn-4Zr-6Mo | Ti-6Al-2Sn-4Zr-6Mo | |
| Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si | -- | -- | RMI 62222S | -- | |
| Ti-7Al-4 Mo | -- | MMA-7146 | RMI 7Al-4Mo | Ti-7Al-4Mo | |
| Ti-1Al-8V-5Fe | -- | -- | RMI 1Al-8V-5Fe | -- | |
| Ti-2Al-11V-2Sn-11Zr | -- | -- | -- | -- | Transage 129, Experimental |
| Ti-3Al-8V-6Cr-4Mo-4Zr | -- | -- | RMI 38-6-44 | -- | Allvac Ti-3-8-6-4-4[h] |
| Ti-4.5Sn-6Zr-11.5Mo | Beta III | -- | -- | -- | -- |
| Ti-8Mo-8V-2Fe-3Al | -- | -- | -- | Ti-8Mo-8V-2Fe-3Al | -- |
| Ti-13V-11Cr-3Al | B-120VCA | -- | RMI 13V-11Cr-3Al | Ti-13V-11Cr-3Al | OMC-VCA[i] |

Note:

(a) Crucible, Inc., subsidiary of Colt Industries.
(b) Martin Marietta Aluminum, Titanium Division.
(c) RMI Company (formerly Reactive Metals, Inc.).
(d) TIMET Division, Titanium Metals Corporation of America (TMCA).
(e) Armco Steel Corporation, Advanced Materials Division (Armco).
(f) TiTech International, Inc. (TiTech).
(g) Teledyne Titanium, Inc. (Teledyne Ti).
(h) Teledyne Allvac (Allvac).
(i) Oregon Metallurgical Corporation (Oremet).
(j) The companies providing the high-purity grades of Ti-5Al-2.5Sn and Ti-6Al-4V alloys (and sometimes others) designate such grades with the suffix ELI, meaning Extra Low Interstitials.

having properties intermediate to some of the specialty alloys but having broad utility in part due to the intermediacy. The Ti-6Al-4V alloy is in fact the most widely used titanium alloy (>50%) with the next most used titanium materials being the unalloyed grades (~20%). The next most used materials are the Ti-5Al-2.5Sn and Ti-6Al-6V-2Sn alloys (~7% each) and all other alloys are used to a lesser extent. In selecting an alloy for a particular application, it is good practice to not only examine and match the properties available for a material with the requirements but to discuss the selection with producers.

3. Availability of Titanium-Forms and Sizes. A wide range of unalloyed and alloyed titanium mill products, castings, and powder-metallurgy products are produced by the industry. However, not all forms and sizes of products are available for each alloy or grade of titanium available and no single company produces a full range of products. On the other hand, individual product forms are usually available from a number of sources. Thus this section is offered to afford the titanium user guidance in determining certain limitations and restrictions concerning product availability.

The basic titanium product is called sponge titanium because lumps of metal extracted from the primary titanium ore (rutile, $TiO_2$) have the porosity of sponges. (Other ores such as ilmenite, are used in addition to rutile by foreign sponge producers.) The Kroll Process (named for Dr. Wilhelm Kroll) is used by the commercial producers to win titanium from rutile. This process is a batch operation requiring stringent control in order to maintain purity. Titanium sponge is subject to atmospheric contamination unless suitably protected. Sponge is subsequently purified and compacted into electrodes for melting and remelting in the production of ingot (or casting). Titanium metal production, from ore to final ingot, usually follows the basic steps outlined below and is shown schematically in the illustration of Figure 1.

Chlorination—Rutile ore is reacted with chlorine gas and carbon at elevated temperatures to yield titanium tetrachloride ($TiCl_4$), a colorless liquid, and the carbon gases ($CO$, $CO_2$) according to the following reactions:

$$TiO_2 \quad + \quad 2Cl_2 \quad + \quad C \qquad\qquad TiCl_4 \quad + \quad CO_2 \quad + \quad \text{heat}$$

$$TiO_2 \quad + \quad 2Cl_2 \quad + \quad 2C \qquad\qquad TiCl_4 \quad + \quad 2CO \quad + \quad \text{heat}$$

As indicated, these reactions are exothermic and are carefully conducted in large reaction vessels to produce as pure an intermediate product ($TiCl_4$, sometimes called "tickle") as possible. Additional purification of "tickle" in distillation towers is usually necessary.

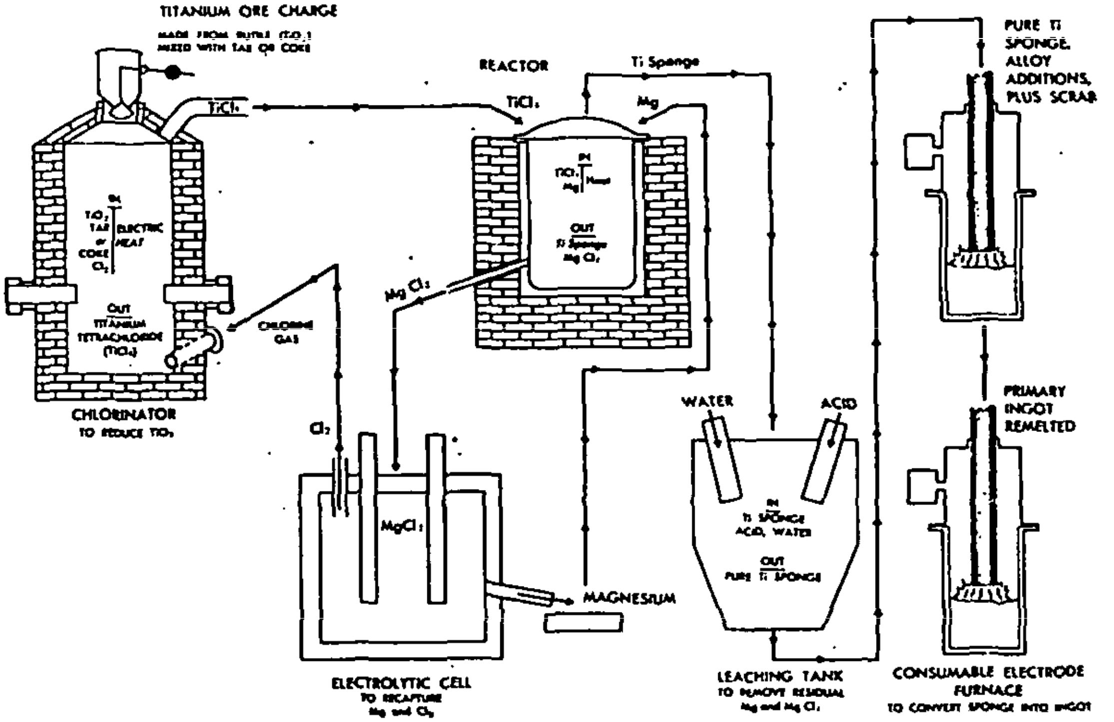
Magnesium Reduction—The $TiCl_4$ is combined with molten magnesium metal in a steel reactor under a controlled atmosphere to yield titanium metal in sponge form. Magnesium chloride ($MgCl_2$) is a byproduct. (The $MgCl_2$ is electrolyzed to recapture chlorine gas and magnesium metal, both of which are recycled through the process). The reactions are:

$$TiCl_4 \quad + \quad 2Mg \qquad\qquad Ti \quad + \quad 2MgCl_2$$

$$MgCl_2 \text{ (by electrolysis)} \qquad\qquad Mg \quad + \quad Cl_2$$

Sodium instead of magnesium is used in the same type of reactions by some producers of titanium.

Purification. Titanium sponge is placed in leaching tanks where acid and water remove trace quantities of magnesium chloride and residual magnesium. Another method of removing these impurities from sponge is vacuum distillation. Producers of titanium sponge in the Soviet Union



Courtesy of Titanium Metals Corporation of America

FIGURE 1. Titanium Processing from Ore to Ingot

and Japan make a very high quality product by this method. Considerable quantities of foreign produced sponge titanium are imported by the United States.

Melting. — Sponge titanium may be compacted as the only constituent to make electrodes for producing ingots, or, if an alloy is desired, sponge is mixed with other metallic ingredients before compacting electrodes for the melting operation. An electric arc-melting process converts the compacted electrode (consumable electrode) into a primary ingot which, in turn, is remelted into a final ingot (triple melting may be used to produce a premium quality ingot). Another method of making primary ingot, that of melting sponge, alloy additions, or scrap, by continuously feeding small uncompacted particles of the charge into the molten pool of metal created by the arc, is used by some ingot producers. In either method, melting is accomplished in vacuum furnaces which removes volatile impurities such as hydrogen and residual $MgCl_2$.

The typical titanium product forms manufactured from domestic and foreign sponge by the U. S. industry are listed in Table IV. It is to be noted that this is a typical listing and does not include all products that can be made, for example, on special order. To illustrate some exceptions, wire of Ti-5Al-2.5Sn and Ti-8Al-1Mo-1V alloys, extrusions of Ti-4Al-3Mo-1V alloy, and castings of Ti-11.5Mo-6Zr-4.5Sn alloy can and have been produced. Inquiries to producers should be made to determine current availability of unlisted products for any desired material.

## TABLE IV. TYPICAL TITANIUM PRODUCT FORMS

| Nominal Composition, wt % | Typical Product Forms$^{(a)}$ |
|---|---|
| Unalloyed Ti, ~99.5$^{(b)}$ | All forms are available in unalloyed grades |
| Unalloyed Ti, ~99.2$^{(b)}$ | |
| Unalloyed Ti, ~99.0$^{(b)}$ | |
| Ti-0.15 to 0.20 Pd | All forms |
| Ti-5Al-2.5Sn$^{(c)}$ | I, B, b, P, S, E, C |
| Ti-1 to 2 Ni | B, b, P, S |
| Ti-2Cu | B, b, P, S |
| Ti-2.25 Al-11Sn-5Zr-1Mo-0.2Si | I, B, b, P, S |
| Ti-5Al-6Sn-2Z4-1Mo-0.25Si | I, B, b, P, S |
| Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si | I, B, b |
| Ti-6Al-2Cb-1Ta-0.8Mo | I, B, b, P |
| Ti-8Al-1Mo-1V | I, B, b, P, S, E |
| Ti-8Mn | I, S, s |
| Ti-3Al-2.5V | S, s, f, T |
| Ti-4Al-3Mo-1V | P, S, s |
| Ti-5Al-2Sn-2Zr-4Mo-4Cr | I, B, b |
| Ti-6Al-4V$^{(c)}$ | All forms |
| Ti-6Al-6V-2Sn | I, B, b, P, S, E |
| Ti-6Al-2Sn-4Zr-2Mo | I, B, b, P, S, E |
| Ti-6Al-2Sn-4Zr-6Mo | I, B, b, P, S |
| Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si | B, b, P |
| Ti-7Al-4Mo | I, B, b, P |
| Ti-1Al-8V-5Fe | I, B, b, w |
| Ti-2Al-11V-2Sn-11Zr | B, b, P |
| Ti-3Al-8V-6Cr-4Mo-4Zr | B, b, w, P, S, s, f, T |
| Ti-4.5Sn-6Zr-11.5Mo | B, b, w, P, S, s, f, T |
| Ti-8Mo-8V-2Fe-3Al | I, B, b, w, P, S, s, f, T |
| Ti-13V-11Cr-3Al | I, B,b, w, P, S, s, f, T |

Note:

(a) I = ingot bloom, B = billet, b = bar, w = wire,
P = plate, S = sheet, s = strip, f = foil,
E = extrusion, T = tubing, C = casting.

(b) There are several unalloyed titanium grades available.

(c) High purity grades of these alloys are available and are designated with the suffix ELI, meaning Extra Low Interstitials.

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Ingots. – The largest titanium ingot produced to date was about 40 inches in diameter and weighed about 11 tons (Krupp, West Germany in 1966). However, more commonly, ingots of ~30 inches in diameter x ~10,000 pounds and ~15,000 pounds are produced domestically. Smaller ingots are also produced. Ingots are usually converted into castings or mill product forms prior to sale to the major users of titanium.

Castings. — Titanium castings are produced by remelting ingot or billet (used as electrode) in so-called skull-type vacuum furnaces having the general arrangement shown in Figure 2. The casting producing companies differ in their operations and capabilities due to types of molds used and equipment size. They may be considered in two categories: (1) those that use investment molds, and (2) those that use rammed graphite molds. Investment casting techniques can potentially produce more intricate parts, closer tolerances, and better as-cast surface finishes. The rammed graphite process, because of greater flexibility in gating and risering, is potentially capable of producing castings having better internal quality, higher mechanical properties, larger cast configurations, and lower costs. However, no one process is superior to the other; both have their place and both fill specific needs.

Rammed-graphite-mold castings can and have been made in quite large sizes. A 2400-pound pour can be made to yield castings of up to 2000 pounds (balance of metal in gates and risers). Large castings have a maximum dimension of 100 inches. The more common size limitations of rammed-graphite-mold castings are 400 pounds with dimensions fitting within a 52-inch diameter x 32 inch high envelope. Intricate shapes as well as preform shapes for forgings (e.g., engine rings) are made in this type mold.

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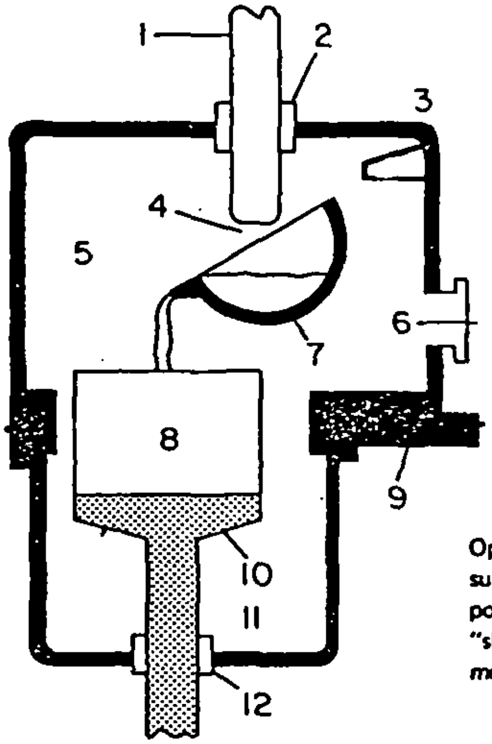

1. Consumable or nonconsumable electrode
2. Vacuum seal
3. Material feed
4. Arc
5. Furnace chamber
6. Vacuum
7. Tiltable melting crucible
8. Mold
9. Valve body
10. Mold table
11. Mold chamber
12. Vacuum seal

Operation. Electrode is rapidly melted into 7. to obtain a superheated titanium or alloy pool which is then immediately poured. About one-quarter of the melt is retained as a "skull", lining the interior of 7. Hence the name, "skull melting".

FIGURE. 2. General Arrangement and Operation of Melting Furnace and Casting Apparatus Used by Titanium Casting Foundries

Investment-mold castings have been produced in much smaller sizes than rammed-graphite-mold castings. Maximum weights of about 50 pounds and maximum envelopes of about 2 x 2 x 2 feet are offered. Wall thickness limitations of investment-mold castings are about half of rammed-graphite-mold castings (0.050-inch compared with 0.10 inch) and surface finish potential is better for investment-mold castings. Intricate shapes with good dimensional tolerances are possible with investment-mold castings. The mechanical properties of castings produced by either of the available techniques are not quite as good as those of most wrought mill products.

Forgings, Billets. — Ingots are converted to ingot-bloom, billet, or bar, and these are offered by the primary titanium producers (the melters) for secondary processing. While each of the major titanium producers has forging capability, most of the forgings produced are made by companies specializing in this aspect of the titanium business (e.g., Wyman-Gordon Company). Forged billets generally have a cross-sectional area of 16 square inches or more and are available in rounds, squares, rectangles, and octagons. Forged shapes may be produced by hammer, press, or ring-roll type operations and are usually classified into four dimensional tolerance groups. (1) blocker, (2) conventional, (3) close, and (4) precision. Table V gives examples of the types of forging shapes commonly produced and the availability of such shapes in the various tolerance categories. Forgings as large as 4000 pounds and 22 feet long or as small as under one pound have been made. Details for determining shape, size, and tolerance limitations can be obtained from numerous forging companies experienced in working with titanium.

### TABLE V. AVAILABILITY OF TITANIUM ALLOYS IN FORGINGS BY SHAPE AND TOLERANCES

[Forgings classified by dimensional tolerance]

| Forged Shape | Availability[(a)] | | | |
|---|---|---|---|---|
| | Blocker-Type Tolerances | Conventional Tolerances | Close Tolerances | Precision Tolerances |
| Disks | A | A | L | LS |
| Cones | A | A | L | U |
| Hemispheres | A | A | L | U |
| Cylinders | A | A | L | U |
| Blades | A | A | A | A |
| Airframe (fittings) | A | A | A | LS |
| Airframe (rib and web) | A | A | L | LS |
| Rings | A | A | L | U |

Note:

(a) Code:
A = Readily available
L = Limited availability
LS = Limited availability = small parts only
U = Virtually unavailable

Bar, Rod and Wire. – Bar and rod are available in rounds, hexagonals, squares, and rectangles. Rolled bar, which has a cross-sectional area ranging from 16 square inches down to about 1.4 square inches, has a length restriction because of annealing-furnace limitations. Lengths up to 90 feet are possible, but the usual lengths produced are 16 to 25 feet. Round bars having diameters less than 0.3125 inch are priced as wire: coil lengths in the smaller diameters range between 300 and 500 feet.

Rods and bars are frequently converted to end-use items by forging and machining or simply by machining. Wire is produced for use as weld-filler and for such end-use items as springs and fasteners. Most alloys are available in bar and rod form but several alloys are not routinely available in wire form.

Plate, Sheet, Strip and Foil. – Plate, sheet, and strip are flat-rolled products available in many alloy grades and from several producers. Foil is a specialty product available in just a few alloys and unalloyed titanium. Plate is generally defined as 0.1875 inch or more in thickness and commonly in sizes listed below.

| Thickness, inch | Width x Length, inches |
|---|---|
| 0.1875-0.249 | 100 x 420 |
| 0.250-0.374 | 110 x 420 |
| 0.375-0.499 | 120 x 450 |
| 0.500-0.749 | 130 x 480 |
| 0.750-0.999 | 140 x (a) |
| 1.0 and up | 145 x (a) |

*(a) Any practical length within ingot size limitations.*

The thickness and flatness tolerances of alloy plate are given in Table VI.

Flat-rolled titanium products are priced as sheet if width is 24 inches or greater and thickness is less than 0.1875 inch. The product is priced as strip when it is less than 24 inches in width. The availability of sheet and strip with regard to size and some alloy limitations is indicated by the data of Table VII. Note that in the thinner gages, and this is especially true for foil gages (<0.008 inch thickness), only unalloyed titanium and a few of the alloys are available in this form.

Extruded Shapes. – Extruded shapes are currently supplied in a wide variety of configurations, although most of these are basic angle, tee, or channel shapes. Section thicknesses generally vary from 0.125 to 1.25 inches within circumscribing circles of 1.50 to 11.0 inches in diameter. Most shapes, however, fit within a 3- to 5-inch-diameter circle. Lengths usually supplied in the annealed condition vary between 20 and 75 feet. Lengths up to 40 feet can be supplied in the solution-treated-and-aged (STA) condition. In the present state of development, as-extruded titanium alloys are not of requisite quality for direct use because of surface roughness or surface contamination. Thus, extruders supply product in an oversize condition to allow a suitable envelope for machining to final size and acceptable surface finish. Minimum envelope requirements vary with users. Some allow as little as 0.020 inch excess per surface while others require as much as 0.125 inch excess per surface. Part design and application influence these requirements. Research and development efforts are continuing towards the goal of supplying net extrusions of acceptable surface finish and precision dimensional tolerances. Redrawing, straightening, and heat treatment techniques are a part of this development effort.

## TABLE VI. TYPICAL THICKNESS AND FLATNESS TOLERANCES OF CURRENT TITANIUM PLATE

| | Thickness Tolerance, in. | | Variation from Flat Surface, in.[a] | |
|---|---|---|---|---|
| Plate Thickness, in. | Width | Thickness Overage | Width | Variation in 15 feet |
| 0.1875 to 0.375 | Max available | 0.050 | Up to 48 | 0.75 |
| 0.375 to 1.00 | Max available | 0.060 | Up to 48 | 0.50 |
| | | | 48 to 76 | 0.62 |
| 1.00 to 2.00 | Max available | 0.070 | Up to 48 | 0.5 to 0.2[b] |
| | | | 48 to 76 | 0.6 to 0.3[b] |

Note:

(a) Plate of special flatness (0.060 inch measured anywhere) is available by the Vacuum Creep Flattening (VCF) process.

(b) Flatness increases with increasing thickness and decreases with increasing plate size.

## TABLE VII. AVAILABILITY OF TITANIUM-ALLOY SHEET AND STRIP[a,b]

| Thickness, in. | Maximum Width, in. | Maximum Length, in. |
|---|---|---|
| 0.008-0.012 | 26 | Coil[c] |
| 0.012-0.016 | 30 | Coil[c] |
| 0.016-0.020 | 36 | Coil[c] |
| 0.020-0.032 | 44 | Coil[c] |
| | 48 | 120-144 |
| 0.032-0.060 | 44 | Coil[c] |
| | 48 | 144 |
| 0.060.-0.187 | 48 | 144 |

Note:

(a) Unalloyed grades are generally available in greater widths at thinner gages than alloy grades.

(b) Tolerances for all gages meet AMS 2242 specifications.

(c) Coil only available in select grades, i.e., unalloyed Ti, Ti–5Al–2.5Sn, Ti–6Al–4V, and beta alloys.

Tubing. – Seamless tubing is produced in unalloyed titanium, Ti-3Al-2.5V and Ti-6Al-4V (in some sizes) commercially, and in such beta alloys as Ti-11.5Mo-6Zr-4.5Sn and Ti-3Al-8V-6Cr-4Mo-4Zr on a developmental basis. Seamless tubing is produced from extruded tube hollows and is sized to finish dimensions by drawing or tube reducing operations (usually cold worked with intermediate annealing).

Unalloyed titanium seamless tubing is available in diameters ranging from 0.062 inch to several inches (>8<36) with wall thickness as low as 0.004 inch in the smaller diameters (large diameter tubes can only be supplied in thick wall sizes). Diameters of 0.75 to 1.00 inch with wall thicknesses ranging from 0.03 to 0.04 inch are the most used. Seamless alloy tubing is supplied in a more restricted size range: the Ti-3Al-2.5V alloy, for example, is available in tube form in diameters of 0.25 inch to 1.75 inch with wall thicknesses between 0.012 to 0.030 inch. Lengths up to 34 feet as vacuum annealed are available. The Ti-3Al-2.5V alloy is available in quality sufficient to meet aircraft hydraulic tubing specifications.

In addition to seamless tubing, an important supply of rolled and welded tube (with longitudinal seam weld) is available. Suppliers can provide both unalloyed and alloyed (Ti-6Al-4V is common) rolled and welded tubing in sizes ranging from 1 to 10 inches diameter with wall thicknesses between 0.012 to 0.168 inch. Generally only the most weldable and stable-after-welding titanium alloys are available such as Ti-6Al-4V, Ti-3Al-2.5V, Ti-5Al-2.5Sn, Ti-8Al-1Mo-1V, and Ti-6Al-2Sn-4Zr-2Mo compositions. Structural members and corrosion resistant piping commonly utilize roll and weld tubing.

Powder Metallurgy Products. – Unalloyed and alloy titanium powders are made by several different processes including mechanical attrition, gas attrition, chemical reduction, hydride-dehydride, and comminution from the molten state – e.g., powder-size droplets from a rotating electrode. Alloy powders also may be obtained by blending unalloyed titanium powder with powders of the desired elements. End-use products are made by die pressing the powders to shape and subsequently sintering such compacts or by simultaneously hot pressing and sintering the powders. Research also has been conducted in producing forged products from pressed and sintered powder preforms. The latter products approach full theoretical density and have mechanical properties equivalent to wrought metal properties provided the powder used is of highest quality (oxygen as a contaminant is one of the problems with powders). The principal reason for the quest for product via powder metallurgy is cost reduction since net shapes can be produced without high associated scrap losses and machining time. However, except for some specialized purposes and parts such as porous titanium filtering elements, titanium hardware via powder metallurgy techniques has never materialized as a major segment of the titanium industry. Currently, quality titanium end-use items can be made at reasonable costs but the method is not popular for producing hardware.

# SECTION II

# SPECIFICATIONS AND PROPERTIES

## Titanium Materials Specifications

4. General. Both the Government and nongovernment technical societies issue specifications for titanium and titanium alloys. This section covers the current specifications for titanium materials prepared by the Government (MIL specifications), by the American Society for Testing and Materials (ASTM specifications), the Aerospace Materials Specifications (AMS) issued by the *Society of Automotive Engineers (SAE) and by the American Welding Society (AWS specifications).*

5. Military Specifications. Specifications prepared by the Government on titanium materials are listed in Table VIII, and are described in the following paragraphs. It should be noted that military specifications currently in force have different preparation and coordination dates, include limited coordination specifications as well as fully coordinated specifications, and are inconsistent one from another in alloy coverage and composition designations. Further, some of the titanium materials *currently being produced are not included in any military specification.* Additionally, specifications include alloys not now being produced or much used. Therefore, in an effort to relate currently available titanium materials with the descriptions and designations offered in some of the important military specifications, the correlation tabulation of Table IX is given. This table does not include composition designations from MIL-T-46035 and MIL-T-46038 because no specific compositions are described therein. Similarly, titanium materials (sponge and powder) are described generally in MIL-T-13405C. The table also does not include designations from MIL-T-46077 since it refers specifically to the Ti-6Al-4V alloy which is not otherwise designated. Specifications, standards, etc., required by suppliers in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.

a. MIL-R-81588 (22 July 1970). — Rods and Wire, Welding, Titanium and Titanium Alloys. This specification covers the requirements for bare titanium and titanium alloy filler rods and wire suitable for use with gas-tungsten arc (GTA) or gas-metal-arc (GMA) welding processes. Alloy types and compositions are given in Table IX. Chemical composition requirements and form, size and weight requirements are given.

*b. MIL-T-13405C (27 May 1966) — Titanium Powder. This specification covers one type* and one grade of titanium powder which is intended for use in pyrotechnic mixtures. This grade of titanium powder is not intended for use in manufacturing structural titanium parts by powder metallurgy techniques.

c. MIL-T-009047F (25 March 1971) and Amendment No. 1 (19 September 1972) — Titanium and Titanium Alloy Bars and Forging Stock. This specification has not been approved *for promulgation as a coordinated revision of MIL-T-9047E (i.e., it is subject to modification).* However it may be used in procurement of aircraft quality wrought titanium and titanium alloy bars, billets, slabs and forging stock in lieu of MIL-T-9047E since it describes the same materials under identical designations (see Table IX). MIL-T-009047F was prepared to specifically cover macrostructural and microstructural aspects of the titanium materials included in MIL-T-9047E.

TABLE VIII. MILITARY SPECIFICATIONS – TITANIUM AND TITANIUM ALLOYS

| Specification No. | Date | Title |
|---|---|---|
| MIL-R-81588 | 22 July 1970 | Rods and Wire, Titanium and Titanium Alloys |
| MIL-T-13405C | 27 May 1965 | Titanium Powder |
| MIL-T-009047F<br>Amendment No. 1 | 25 March 1971<br>19 September 1972 | Titanium and Titanium Alloy Bars and Forging Stock |
| MIL-T-9047E | 15 June 1970 | Titanium and Titanium Alloy Bars and Forging Stock |
| MIL-F-83142A | 1 December 1969 | Forging, Titanium Alloys, Premium Quality |
| MIL-T-46038A<br>Amendment No. 1<br>Amendment No. 2 | 28 October 1966<br>14 March 1967<br>5 October 1972 | Titanium Alloy, Wrought, Rods, Bars and Billets (for Critical Applications) |
| MIL-T-81556 | 20 March 1968 | Titanium and Titanium Alloys, Bars, Rods, and Special Shaped Sections, Extruded |
| MIL-T-9046H | 14 March 1974 | Titanium and Titanium Alloy, Sheet, Strip and Plate |
| MIL-T-46035A<br>Amendment No. 1 | 28 October 1966<br>5 October 1972 | Titanium Alloy, High Strength, Wrought, (for Critical Applications) |
| MIL-T-46077A | 28 June 1968 | Titanium Alloy Armor Plate, Weldable |
| MIL-H-81200A<br>Amendment No. 1 | 12 September 1968<br>24 March 1969 | Heat Treatment of Titanium and Titanium Alloys |
| MIL-W-6858C<br>Amendment No. 1 | 20 October 1964<br>28 June 1965 | Welding, Resistance: Aluminum, Magnesium, Nonhardening Steels or Alloys, Nickel Alloys, Heat Resisting Alloys and Titanium Alloys; Spot and Seam |

d. MIL-T-9047E (15 June 1970) – Titanium and Titanium Alloy Bars and Forging Stock. This specification covers bars, billets, and blooms of several of the materials included in superseded MIL-T-9047D, less four compositions which are no longer much used, plus three new alloys currently being produced. Table X gives the correlation of MIL-T-9047C, MIL-T-9047D and MIL-T-9047E (same as MIL-T-009047F) designations. The specification gives the composition

TABLE IX. MILITARY SPECIFICATION CORRELATION

| Nominal Composition, wt % | MIL-T-9047E | MIL-T-009047F[a] | MIL-F-83142A | MIL-T-9046H | MIL-T-81556 | MIL-R-81588 |
|---|---|---|---|---|---|---|
| *Unalloyed Ti, ~99.5* | Composition 1 | Composition 1 | Composition 1 | Type I, Composition A Unalloyed (40KSI-Y.S.) | Type I, Composition B[a] | -- |
| Unalloyed Ti, ~99.2 | (All unalloyed grades are in this category) | (All unalloyed grades are in this category) | (All unalloyed grades are in this category) | Type I, Composition C Unalloyed (55KSI-Y.S.) | Type I, Composition C | -- |
| Unalloyed Ti, ~99.0 | | | | Type I, Composition B Unalloyed (70KSI-Y.S.) | Type I, Composition D | |
| Ti-0.15 to 0.20Pd | -- | -- | -- | -- | -- | -- |
| *Ti-5Al-2.5Sn* | *Composition 2* | *Composition 2* | Composition 2 | Type II, Composition A | Type II, Composition A | -- |
| Ti-5Al-2.5Sn ELI | Composition 3 | Composition 3 | Composition 3 | Type II, Composition B | Type II, Composition B | -- |
| Ti-1 to 2 Ni | -- | -- | -- | -- | -- | -- |
| Ti-2Cu | -- | -- | -- | -- | -- | -- |
| Ti-2.15Al-11Sn-5Zr-1Mo-0.2Si | Composition 10 | Composition 10 | Composition 10 | -- | -- | -- |
| Ti-2.25Al-6Sn-2Zr-1Mo-0.25Si | -- | -- | -- | -- | -- | -- |
| Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si | -- | -- | -- | -- | -- | -- |
| Ti-6Al-2Cb-1Ta-0.8Mo | -- | -- | -- | Type II, Composition G | -- | Type II, Composition D |
| *Ti-8Al-1Mo-1V* | Composition 5 | Composition 5 | Composition 5 | Type II, Composition F | Type II, Composition C | Type II, Composition C |
| Ti-8Mn | -- | -- | -- | Type III, Composition A | -- | -- |
| Ti-3Al-2.5V | -- | -- | -- | -- | -- | -- |
| Ti-4Al-3Mo-1V | -- | -- | -- | Type III, Composition B | -- | -- |
| Ti-5Al-2Sn-2Zr-4Mo-4Cr | -- | -- | -- | -- | -- | -- |
| *Ti-6Al-4V* | *Composition 6* | Composition 6 | Composition 6 | Type III, Composition C | Type III, Composition A | Type III, Composition A |
| Ti-6Al-4V ELI | Composition 7 | Composition 7 | Composition 7 | Type III, Composition D | Type III, Composition B | Type III, Composition B |
| Ti-6Al-4V SPL | -- | -- | -- | Type III, Composition H | -- | -- |
| Ti-6Al-6V-2Sn | Composition 8 | Composition 8 | Composition 8 | Type III, Composition E | Type III, Composition C | |
| Ti-6Al-2Sn-4Zr-2Mo | Composition 11 | Composition 11 | Composition 11 | Type III, Composition G | -- | -- |
| Ti-6Al-2Sn-4Zr-6Mo | *Composition 14* | *Composition 14* | -- | -- | -- | -- |
| Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si | -- | -- | -- | -- | -- | -- |
| Ti-7Al-4Mo | Composition 9 | Composition 9 | Composition 9 | -- | Type III, Composition D | |
| Ti-1Al-8V-5Fe | -- | -- | -- | -- | -- | -- |
| Ti-2Al-11V-2Sn-11Zr | -- | -- | -- | -- | -- | -- |
| Ti-3Al-8V-6Cr-4Mo-4Zr | -- | -- | -- | -- | -- | -- |
| Ti-4.5Sn-6Zr-11.5Mo | Composition 13 | Composition 13 | Composition 13 | -- | -- | -- |
| Ti-8Mo-8V-2Fe-3Al | -- | -- | -- | -- | -- | -- |
| Ti-13V-11Cr-3Al | Composition 12 | Composition 12 | Composition 12 | Type IV, Composition A | -- | Type IV, Composition A |
| Ti-11.5Mo-6Zr-4.5Sn | -- | -- | -- | Type IV, Composition B | -- | -- |
| Ti-3Al-8V-6Cr-4Mo-4Zr | -- | -- | -- | Type IV, Composition C | -- | -- |
| Ti-8Mo-8V-2Fe-3Al | -- | -- | -- | Type IV, Composition D | -- | -- |
| Ti-5Al-5Zr-5Sn[c] | -- | -- | Composition 4 | -- | -- | -- |

Note:

(a) Type I, Composition A, is a high-purity unalloyed titanium grade.

(b) The following alloys have limited current use and are described in the heat treatment specification MIL-H-81200A:

Ti-7Al-12Zr[c]
*Ti-7Al-2Cb-1Ta*[c]
Ti-4Al-4V[c]
Ti-5Al-1.5Cr-1.5Fe-1Mo[c]
*Ti-2Fe-2Cr-2Mo*[c]

} *These alloys are not described in current specifications except for the Heat Treatment Specification MIL-H-81200A*

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MIL-R-81588

Type I – Commercial pure titanium
Composition A - unalloyed
Composition B – unalloyed

Type II – Alpha titanium alloy
Composition A – 5 Al – 2.5 Sn
*Composition B – 5 Al – 2.5Sn ELI*
Composition C – 8 Al – 1 Mo – 1 V
Composition D – 6 Al – 2 Cb - 1 Ta – 0.8 Mo

Type III – Alpha-beta titanium alloy
Composition A – 6 Al – 4 V
Composition B – 6 Al – 4 V ELI

Type IV – Beta titanium alloy
Composition A-13 V-11 Cr-3 Al

## TABLE X. CORRELATION TABLE: MIL-T-9047

| MIL-T-9047E | MIL-T-9047D | MIL-T-9047C[a] |
|---|---|---|
| Alpha Alloys | Type I—Commercially pure titanium | |
| Composition 1 - unalloyed | Composition A — unalloyed | Class 1 |
| | Type II—Alpha titanium alloys | |
| Composition 2 - 5Al-2.5Sn | Composition A (5Al-2.5Sn) | Class 2 |
| Composition 3 - 5Al-2.5Sn ELI | Composition B (5Al-2.5Sn ELI) | — |
| | Composition C (5Al-5Zr-5Sn)[b] | — |
| Composition 5 - 8Al-1Mo-1V | Composition D (8Al-1Mo-1V) | — |
| Alpha beta alloys | Type III-Alpha beta titanium alloys | |
| Composition 6 - 6Al-4V | Composition A (6Al-4V) | Class 5 |
| Composition 7 - 6Al-4V ELI | Composition B (6Al-4V ELI) | — |
| Composition 8 - 6Al-6V-2Sn | Composition C (6Al-6V-2Sn) | — |
| Composition 9 - 7Al-4Mo | Composition D (7Al-4Mo) | — |
| | Composition E (4Al-4Mn)[b] | Class 6 |
| | Composition F (5Al-1.5Fe-1.5Cr-1.5Mo)[b] | Class 7 |
| Composition 10 - 11Sn-5Zr-2Al-1Mo | Composition G (11Sn-5Zr-2Al-1Mo) | — |
| | Composition H (4Al-3Mo-1V)[b] | — |
| Composition 11 - 6Al-2Sn-4Zr-2Mo | Composition I (6Al-2Sn-4Zr-2Mo) | — |
| Composition 14 - 6Al-2Sn-4Zr-6Mo | | |
| Beta Alloys | Type IV—Beta titanium alloys | |
| Composition 12 - 13V-11Cr-3Al | Composition A (13V-11Cr-3Al) | — |
| Composition 13 - 11.5Mo-6Zr-4.5Sn | | |

Note:

(a) Class 3, 3Al-5Cr and Class 4, 2Fe-2Cr-2Mo, of MIL-T-9047C were deleted in the "D" revision.

(b) Commercially unavilable.

limits and mechanical property requirements (minimums) for all materials covered in the annealed condition per various thickness ranges where that is applicable. In addition, the solution-treated and aged (STA) mechanical properties of compositions 6 through 13 are given for the thickness ranges applicable to the specific alloys.

e. MIL-F-83142A (l December 1969) – Forging, Titanium Alloys, Premium Quality. This specification covers unalloyed titanium and titanium alloy forgings suitable for aircraft and aerospace components and supersedes MIL-F-83142. Table XI gives the correlation of MIL-F-83142 and -83142A designations. It is to be noted that the alloy lists reflect alloy availability at the time of specification preparation and that composition categories were changed (Type I, II, III, and IV category nomenclature dropped). Composition designation correlation between MIL-F-83142A and MIL-T-9047E is given in Table IX. Specification MIL-F-83142A gives the composition limits and mechanical property requirements (minimums) for all materials covered in the annealed condition per various thickness ranges where that is applicable and also the solution-treated and aged (STA) mechanical properties of compositions 6 through 13 for the thickness ranges applicable to these alloys. In addition, mechanical property requirements for various conditions of the alpha alloys, Ti-5Al-2.5Sn and Ti-5Al-5Zr-5Sn, are given.

f. MIL-T-46038A (28 October 1966), Amendment No. 1 (14 March 1967) and Amendment No. 2 (5 October 1972) – Titanium Alloy, Wrought, Rods, Bars and Billets (for Critical Applications). This specification covers wrought-titanium alloy rods, bars, and billets which are suitable for processing by hot forming and heat treatment or by heat treatment only, or for direct application to highly stressed critical components, and it is required for use with Specification MIL-T-46035A. Specification MIL-T-46038A describes mechanical property ranges for bars and billets of various section sizes. MIL-T-46035A covers high strength wrought titanium alloys, in annealed or heat-treated shapes, having a critical section thickness of one-quarter to two and one-half inches, for critical components other than armor, such as tubes, chambers, and nozzles.

g. MIL-T-81556 (20 March 1968) – Titanium and Titanium Alloys, Bars, Rods and Special Shaped Sections, Extruded. This specification covers extruded titanium and titanium alloy bars, rods, and special shaped sections. The compositions covered by MIL-T-81556 have the designations given in Table IX. The composition requirements and the mechanical property requirements in the mill annealed condition per various thickness ranges where that is applicable are given. The mechanical property requirements for various section thicknesses of Ti-6Al-4V, Ti-6Al-6V-2Sn, and Ti-7Al-4Mo alloys, are given also for the solution treated and aged (STA) condition. Dimensional tolerance requirements also are given.

h. MIL-T-9046H (14 March 1974) – Titanium and Titanium Alloy, Sheet, Strip and Plate. This specification gives composition (see Table IX), mechanical property (see Table XIX), and dimensional tolerance requirements for the compositions covered in the appropriate section size and heat treatment condition. The materials procurable under the specification are intended for structural and engineering applications in airborne vehicles and equipment based upon the combination of excellent mechanical properties coupled with low density and corrosion resistance. Table XII gives the correlation of the "D", "E", "F", "G", and "H" versions.

i. MIL-T-46035A (28 October 1966) and Amendment No. 1 (5 October 1972) – Titanium Alloy, High-Strength, Wrought (for Critical Components). This specification covers high strength wrought titanium alloys, in annealed or heat-treated shapes, having a critical section thickness of ¼ to 2-½ inches, for critical components other than armor, such as tubes, chambers and nozzles. Mechanical property requirements are given.

## TABLE XI. CORRELATION TABLE: MIL-F-83142

| MIL-F-83142 | MIL-F-83142A |
|---|---|
| Type I — Commercially pure | Alpha Alloys |
| Composition 1 — unalloyed | Composition 1 — unalloyed |
| Type II — Alpha alloys | |
| Composition 2 - 5Al-2.5Sn | Composition 2 — 5Al-2.5Sn |
| Composition 3 — 5Al-2.5Sn ELI | Composition 3 — 5Al-2.5Sn ELI |
| Composition 4 — 5Al-5Zr-5Sn(a) | Composition 4 — 5Al-5Zr-5Sn |
| Composition 5 — 8Al-1Mo-1V | Composition 5 — 8Al-1Mo-1V |
| Type III — Alpha beta alloys | Alpha beta alloys |
| Composition 6 — 6Al-4V | Composition 6 — 6Al-4V |
| Composition 7 — 6Al-4V- ELI | Composition 7 — 6Al-4V ELI |
| Composition 8 — 6Al-6V-2Sn | Composition 8 — 6Al-6V-2Sn |
| Composition 9 — 7Al-4Mo | Composition 9 — 7Al-4Mo |
| Composition 10 — 5Al-1.5Fe-1.5Cr-1.5Mo(a) | |
| Composition 11 — 11Sn-5Zr-2Al-1Mo | Composition 10 — 11Sn-5Zr-2Al-1Mo |
| Composition 12 — 4Al-3Mo-1V(a) | |
| Composition 13 — 6Al-2Sn-4Zr-2Mo | Composition 11 — 6Al-2Sn-4Zr-2Mo |
| Type IV — Beta alloys | Beta alloys |
| Composition 14 — 13V-11Cr-3Al | Composition 12 — 13V-11Cr-2Al |
| | Composition 13 — 11.5Mo-6Zr-4.5Sn |

Note:

(a) Commercially unavailable or not much used.

TABLE XII. CORRELATION TABLE: MIL-T-9046

| Type | Comp. | MIL-T-9046D | MIL-T-9046E | MIL-T-9046F | MIL-T-009046G | MIL-T-9046H |
|---|---|---|---|---|---|---|
| | | 17 June 1964 | 29 Sep 1965 | 3 April 1967 | 12 Oct 1970 | 14 March 1974 |
| I | A | Unalloyed | Unalloyed | Unalloyed | ---- | Unalloyed (40 KSI-YS) |
| | B | Unalloyed | Unalloyed | Unalloyed | ---- | Unalloyed (40 KSI-YS) |
| | C | Unalloyed | Unalloyed | Unalloyed | ---- | Unalloyed (55 KSI-YS) |
| II | A | 5Al-2.5Sn | 5Al-2.5Sn | 5Al-2.5Sn | ---- | 5Al-2.5Sn |
| | B | 5Al-2.5Sn ELI | 5Al-2.5Sn ELI | 5Al-2.5Sn ELI | ---- | 5Al-2.5Sn ELI |
| | C | 5Al-5Zr-5Sn | 5Al-5Zr-5Sn | ---- | ---- | ---- |
| | D | 7Al-12Zr | 7Al-12Zr | ---- | ---- | ---- |
| | E | 7Al-2Cb-1Ta | 7Al-2Cb-1Ta | ---- | ---- | ---- |
| | F | 8Al-1Mo-1V | 8Al-1Mo-1V | 8Al-1Mo-1V | ---- | 8Al-1Mo-1V |
| | G | ---- | ---- | 6Al-2Cb-1Ta-0.8Mo | ----- | 6Al-2Cb-1Ta-0.8Mo |
| III | A | 8Mn | 8Mn | 8Mn | ---- | ---- |
| | B | 4Al-3Mo-1V | 4Al-3Mo-1V | 4Al-3Mo-1V | ---- | ---- |
| | C | 6Al-4V | 6Al-4V | 6Al-4V | 6Al-4V (No. 6) | 6Al-4V |
| | D | 6Al-4V ELI | 6Al-4V ELI | 6Al-4V ELI | 6Al-4V ELI (No. 7) | 6Al-4V ELI |
| | E | 6Al-6V-2Sn | 6Al-6V-2Sn | 6Al-6V-2Sn | 6Al-6V-2Sn (No. 8) | 6Al-6V-2Sn |
| | F | 7Al-4Mo | 7Al-4Mo | ---- | ---- | ---- |
| | G | ---- | ---- | 6Al-2Sn-4Zr-2Mo | 6Al-2Sn-4Zr-2Mo (No. 11) | 6Al-2Sn-4Zr-2Mo |
| | H | ---- | ---- | ---- | ---- | 6Al-4V SPL (Special Low, .005 H) |
| IV | A | 13V-11Cr-3Al | 13V-11Cr-3Al | 13V-11Cr-3Al | ---- | 13V-11Cr-3Al |
| | B | ---- | ---- | ---- | ---- | 11.5Mo-6Zr-4.5Sn |
| | C | ---- | ---- | ---- | ---- | 3Al-8V-6Cr-4Mo-4Zr |
| | D | ---- | ---- | ---- | ---- | 8Mo-8V-2Fe-3Al |

j. MIL-T-46077A (28 June 1968) – Titanium Alloy Armor Plate, Weldable. This specification covers a weldable wrought-titanium alloy 6Al-4V ELI, armor plate in the mill-annealed condition with composition ranges or maximum values as shown below (values in weight percent):

| Al | V | C | O* | N | H | Fe | Ti |
|---|---|---|---|---|---|---|---|
| 5.5-6.5 | 3.5-4.5 | .04 | .14 | .02 | .0125 | .25 | Remainder |

The nominal thicknesses of armor plate covered by this specification are ¼ to 2-¼ inches, inclusive. Mechanical properties and ballistic requirements are given. Ballistic properties are contained in the Supplement which has a security classification of confidential.

k. MIL-H-81200A (12 September 1968) and Amendment No. 1 (24 March 1969) – Heat Treatment of Titanium and Titanium Alloys. This specification covers furnace equipment requirements and test procedures, heat treating procedures, heat treating temperatures, and general information for the heat treatment of titanium and titanium alloy items used in the construction of military equipment. It also describes procedures which, when followed, have produced the desired properties within the limitation of the respective alloys. Several compositions included in this specification are not now in production. Therefore, representative alloys listed in Table III are the compositions described in the Heat Treatment section of this handbook.

l. MIL-W-6858C (20 October 1964) and Amendment No. 1 (28 June 1965) – Welding, Resistance, Aluminum, Magnesium, Non-hardening Steels or Alloys, Nickel Alloys, Heat Resisting Alloys, and Titanium Alloys, (Spot and Seam). This specification covers requirements for resistance spot and seam welding of the following nonhardening materials:

(a) Aluminum, aluminum alloys, magnesium alloys
(b) Steels, heat resisting alloys, nickel and cobalt alloys
(c) Titanium and titanium alloys.

MIL-W-6858C covers welding machine qualification, and certification of the welding process or schedule. Radiographic, shear strength and metallurgical test requirements are given.

6. AMS Specifications. The Aerospace Materials Specifications (AMS) for titanium materials issued by the Society for Automotive Engineers (SAE) are listed in Table XIII. Since the AMS titles accurately describe the titanium materials covered, no individual descriptions are necessary. However, as an aid in relating AMS specifications with the alloy coverage and material forms described in this handbook, Table XIV is offered. This table includes alloys which are too new to be covered by specifications and alloys that are no longer much used or produced as well as those covered by Current AMS specifications.

7. ASTM Specifications. The American Society for Testing and Materials (ASTM) specifications for titanium materials are listed in Table XV. The Standards are issued under fixed designations, for example B299 in Table XV and the year of last revision or year of adoption, whichever is most recent, is given as a suffix, for example, B299-69. The ASTM Specification titles are descriptive with regard to product form but do not describe material coverage except in general terms. Therefore Table XVI is offered to show more specifically the compositions and their ASTM designations included in individual specifications. As is the usual practice in

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*Other military and nonmilitary specifications for ELI (extra low interstitial content) grade Ti-6Al-4V call out lower maximum oxygen contents.

TABLE XIII. AEROSPACE MATERIALS SPECIFICATIONS FOR TITANIUM MATERIALS

| AMS No. | Title of Specification |
|---|---|
| 4900D | Plate, Sheet and Strip-Annealed-55,000 psi Yield (Unalloyed Ti) |
| 4901E | Sheet, Strip and Plate-Annealed-70,000 psi Yield " |
| 4902B | Plate, Sheet and Strip-Annealed-40,000 psi Yield " |
| 4906 | Sheet and Strip-6Al 4V, Continuously Rolled, Annealed |
| 4907B | *Plate, Sheet, and Strip--6Al 4V, Extra Low Interstitial, Annealed* |
| 4908B | Sheet and Strip--8Mn, Annealed--110,000 psi Yield |
| 4909B | Plate, Sheet, and Strip--5Al 2.5Sn, Extra Low Interstatial, Annealed |
| 4910F | Plate, Sheet, and Strip--5Al 2.5Sn, Annealed |
| 4911C | Plate, Sheet, and Strip--6Al 4V, Annealed |
| 4912A | Sheet and Strip--4Al 3Mo 1V Solution Heat Treated |
| 4913A | Sheet and Strip--4Al 3Mo 1V Solution and Prec. Tr. |
| 4915B | Plate, Sheet and Strip--8Al 1Mo 1V, Single Annealed |
| 4916B | *Plate, Sheet and Strip--8Al 1Mo 1V, Duplex Annealed* |
| 4917B | Plate, Sheet and Strip--13.5V 11Cr 3Al, Solution Treated |
| 4918C | Plate, Sheet and Strip--6Al 6V 2Sn, Annealed |
| 4921B | Bars, Forgings and Rings--Annealed--70,000 psi Yield (Unalloyed Ti) |
| *---4923A | Bars and Forgings--2Cr 2Fe 2Mo, Annealed--120,000 psi Yield |
| 4924B | Bars, Forgings, and Rings, 5Al 2.5 Sn, Extra Low Interstitial Annealed, 90,000 psi Yield |
| *---4925B | *Bars and Forgings--4Al 4Mn, Annealed--130,000 psi Yield* |
| 4926D | Bars and Rings--5Al 2.5Sn, Annealed--110,000 psi Yield |
| *---4927 | Bars and Forgings--5Cr 3Al |
| 4928G | Bars and Forgings--6Al 4V, Annealed--120,000 psi Yield |
| *---4929 | Bars--5.4Al 1.4Cr 1.3Fe 1.15Mo, Annealed--135,000 psi Yield |
| 4930A | Bars, Forgings and Rings--6Al 4V, Extra Low Interstitial, Annealed |
| 4935B | Extrusions--6Al 4V Annealed |
| 4936 | Extrusions--6Al 6V 2Sn |
| 4941 | Tubing, Welded-Annealed--40,000 psi Yield (Unalloyed Ti) |
| 4942 | Tubing, Seamless-Annealed--40,000 psi Yield (Unalloyed Ti) |
| 4943 | Tubing Seamless-Annealed, 3.0Al 2.5V |
| 4951C | Wire, Welding (Unalloyed Ti) |
| 4953 | Wire, Welding--5Al 2.5Sn, Annealed |
| 4954B | Wire, Welding--6Al 4V |
| 4955 | Wire, Welding, 8Al 1Mo 1V |
| 4956 | Wire, Welding--6Al 4V, Extra Low Interstitial, Environment Controlled |
| 4965B | Bars, Forgings, and Rings--6Al 4V, Sol. & Precip. Heat Treated |
| 4966D | Forgings--5Al 2.5Sn, Annealed--110,000 psi Yield |
| 4967D | Bars and Forgings--6Al 4V, Annealed, Heat Treatable |
| *---4968A | Bars and Forgings--5Zr 5Al 5Sn, Annealed |
| *---4969 | *Forgings--5.4Al 1.4Cr 1.3Fe 1.2Mo, Annealed 135,000 psi Yield* |
| 4970C | Bars and Forgings, 7Al 4Mo, Sol. & Precip. Treated |
| 4971A | Bars, Forgings, and Rings--6Al 6V 2Sn, Annealed, Heat Treatable |
| 4972A | Bars and Rings--8Al 1Mo 1V, Solution Treated and Stabilized |
| 4973A | Forgings--8Al 1Mo 1V, Solution Treated and Stabilized |
| 4974 | Bars and Forgings--11Sn 5.0Zr 2.3Al 1.0Mo 0.21Si, Sol. and Precip. Treated |
| 4975B | Bars and Rings--6Al 2Sn 4Zr 2Mo, Solution and Precipitation Heat Treated |
| 4976 | Forgings--6Al 2Sn 4Zr 2Mo, Solution and Precipitation Heat Treated |
| 4977A | Bars and Wire--11.5Mo 6.0Zr 4.5Sn, Solution Heat Treated |
| 4978A | Bars, Forgings and Rings--6Al 6V 2Sn, Annealed, 140,000 Yield |
| 4979 | Bars, Forgings and Rings--6Al 6V 2Sn, Sol. and Precip. Heat Treated |
| 4980A | Bars and Wire--11.5Mo 6.0Zr 4.5Sn, 1375F Solution Heat Treated |
| 4981 | Bars and Forgings--6Al 2Sn 4Zr 6Mo, Sol. & Precip. Heat Treated |

Note: *--- Not current. Materials which have been widely used in the past but which are not now generally recommended for use in new designs.

TABLE XIV. AMS MATERIALS AND PRODUCT FORM CORRELATION

| Composition, wt % | Forgings | Bars | Rings | Wire | Plate | Sheet | Strip | Tubing | Extrusions |
|---|---|---|---|---|---|---|---|---|---|
| Unalloyed Ti, ~99.5, Ann. 40 ksi YS | -- | -- | -- | 4951C (welding) | 4902B | 4902B | 4902B | 4941 (welded) | -- |
| Unalloyed Ti, ~99.5, Ann. 40 ksi YS | -- | -- | -- | -- | -- | -- | -- | 4942 (seamless) | -- |
| Unalloyed Ti, ~99.2, Ann. 55 ksi YS | -- | -- | -- | -- | 4900D | 4900D | 4900D | -- | -- |
| Unalloyed Ti, ~99.0, Ann. 70 ksi YS | 4921B | 4921B | 4921B | -- | 4901E | 4901E | 4901E | -- | -- |
| Ti-0.15 to 0.20 Pd | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Ti-5Al-2.5Sn, Ann. 110 ksi YS | 4966D | 4926D | 4926D | 4953 (welding) | 4910F | 4910F | 4910F | -- | -- |
| Ti-5Al-2.5Sn ELI, Ann. 90 ksi YS | 4924B | 4924B | 4924B | -- | 4909B | 4909B | 4909B | -- | -- |
| Ti-1 to 2Ni | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Ti-2Cu | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si, STA | 4974 | 4974 | -- | -- | -- | -- | -- | -- | -- |
| Ti-5Al-6Sn-2Zr-1Mo-0.25Si | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Ti-6Al-2Cb-1Ta-0.8Mo | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Ti-8Al-1Mo-1V, Single Ann. | -- | -- | -- | 4955 (welding) | 4915B | 4915B | 4915B | -- | -- |
| Ti-8Al-1Mo-1V, Duplex Ann. | -- | -- | -- | -- | 4916B | 4916B | 4916B | -- | -- |
| Ti-8Al-1Mo-1V, Sol. Treated & Stabilized | 4973A | 4972A | 4972A | -- | -- | -- | -- | -- | -- |
| Ti-8Mn, Ann. 110 ksi YS | -- | -- | -- | -- | -- | 4908B | 4908B | -- | -- |
| Ti-3Al-2.5V, Ann. | -- | -- | -- | -- | -- | -- | -- | 4943 (seamless) | -- |
| Ti-4Al-3Mo-1V, Sol. Treated | -- | -- | -- | -- | -- | 4912A | 4912A | -- | -- |
| Ti-4Al-3Mo-1V, STA | -- | -- | -- | -- | -- | 4913A | 4913A | -- | -- |
| Ti-5Al-2Sn-2Zr-4Mo-4Cr | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Ti-6Al-4V, Ann. 120 ksi YS | 4928G | 4928G | -- | 4954B (welding) | 4911C | 4911B | 4911B | -- | 4935B |
| Ti-6Al-4V, Continuously Rolled, Ann. | -- | -- | -- | -- | -- | 4906 | 4906 | -- | -- |
| Ti-6Al-4V, Ann. Heat Treatable | 4967D | 4967D | -- | -- | -- | -- | -- | -- | -- |
| Ti-6Al-4V, STA | 4965B | 4965B | 4965B | -- | -- | -- | -- | -- | -- |
| Ti-6Al-4V ELI, Ann. | 4930A | 4930A | 4930A | 4956 (welding) | 4907B | 4907B | 4907B | -- | -- |
| Ti-6Al-6V-2Sn, Ann. 140 ksi YS | 4978A | 4978A | 4978A | -- | 4918C | 4918C | 4918C | -- | 4936 |
| Ti-6Al-6V-2Sn, Ann. Heat Treatable | 4971A | 4971A | 4971A | -- | -- | -- | -- | -- | -- |
| Ti-6Al-6V-2Sn, STA | 4979 | 4979 | 4979 | -- | -- | -- | -- | -- | -- |
| Ti-6Al-2Sn-4Zr-2Mo, STA | 4976 | 4975B | 4975B | -- | -- | -- | -- | -- | -- |
| Ti-6Al-2Sn-4Zr-6Mo, STA | 4981 | 4981 | -- | -- | -- | -- | -- | -- | -- |
| Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Ti-7Al-4Mo, STA | 4970C | 4970C | -- | -- | -- | -- | -- | -- | -- |
| Ti-1Al-8V-5Fe | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Ti-2Al-11V-2Sn-11Zr | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Ti--3Al-8V-6Cr-4Mo-4Zr | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Ti-11.5Mo.6Zr-4.5Sn, Sol. Treated | -- | 4977A | -- | 4977A | -- | -- | -- | --- | -- |
| Ti-11.5Mo-6Zr-4.5Sn, 1375F Sol. Treated | -- | 4980A | -- | 4980A | -- | -- | -- | -- | -- |
| Ti-8Mo-8V-2Fe-3Al | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Ti-13V-11Cr-3Al, Sol. Treated | -- | -- | -- | -- | 4917B | 4917B | 4917B | -- | -- |
| Ti-5Al-5Sn-5Zr, Not current | 4968A | 4968A | -- | -- | -- | -- | -- | -- | -- |
| Ti-2Cr-2Fe-2Mo, Not Current | 4923A | 4923A | -- | -- | -- | -- | -- | -- | -- |
| Ti-4Al-4Mn, Not Current | 4925B | 4925B | -- | -- | -- | -- | -- | -- | -- |
| Ti-3Al-5Cr, Not Current | 4927 | 4927 | -- | -- | -- | -- | -- | -- | -- |
| Ti-5.4Al-1.4Cr-1.3Fe-1.25Mo, Not Current | 4969 | 4929 | -- | -- | -- | -- | -- | -- | -- |

Note: Ann. = annealed, YS = yield strength, STA = solution and precipitation heat treated (i.e., aged), Sol. = solution.

TABLE XV. AMERICAN SOCIETY FOR TESTING AND MATERIALS SPECIFICATIONS — TITANIUM AND TITANIUM ALLOYS

| ASTM No. | Specification Title |
|---|---|
| B299-69 | Titanium Sponge |
| B348-72 | Titanium and Titanium Alloy Bars and Billets |
| B381-69 | Titanium and Titanium Alloy Forgings |
| B265-72 | Titanium and Titanium Alloy Strip, Sheet, and Plate |
| B337-73 | Seamless and Welded Titanium Pipe |
| B338-73 | Seamless and Welded Titanium and Titanium Alloy Tubes for Condensers and Heat Exchangers |
| B363-71 | Seamless and Welded Unalloyed Titanium Welding Fittings |
| B367-69 | Titanium and Titanium Alloy Castings |
| F67-66 | Titanium for Surgical Implants |
| F136-70 | Specification for Titanium 6Al-4V ELI Alloy for Use in Clinical Evaluations as a Surgical Implant Material |

specifications, the ASTM Standards include requirements for composition, mechanical properties, dimensions of product, testing, and marking.

The ASTM Specification B382-64 entitled "Titanium and Titanium Alloy Bare Welding Rods and Electrodes" was discontinued in 1969.and replaced by the American Welding Society (AWS) Specification AWSA5.16—70. The AWS Classification designations and impurity composition limitations are given for such materials in Table XVII.

8. Specification and Designation Correlation. The proliferation of unalloyed titanium grades and titanium alloys by modification with interstitial and solid solution alloying additions has led to a bewildering array of nomenclature for these materials. The producers have their trade names, there are common names, and each military and society specification has its code for describing particular titanium materials. As an example for one material, several of the designations for various forms and grades of the Ti-6Al-4V alloy are shown below.

Armco Ti-6Al-4V
C-120AV
MMA-6510
RMI-6Al-4V
Tel-Ti6Al-4V
Ti Tech 6Al-4V

AMS-4906
AMS-4907B
AMS-4911B
AMS-4928G
AMS-4935B
AMS-4965B

TABLE XVI: ASTM SPECIFICATION COMPOSITION AND DESIGNATION CORRELATIONS

| Nominal Composition wt % | B348-72 Bars and Billets | B381-69 Forgings | B265-72 Strip, Sheet and Plate | B337-73 Pipe | B338-73 Tubing | B363-71 Welding Fittings | B367-69 Castings | F67-66 Wrought Forms | F136-70 Wrought Forms |
|---|---|---|---|---|---|---|---|---|---|
| Unalloyed Titanium (Low iron, low interstitials) | Grade 1 | Grade F-1 | Grade 1 | Grade 1 | Grade 1 | WPT1[a] | Grade C-1 | -- | -- |
| Unalloyed Titanium (Intermediate iron and interstitials) | Grade 2 | Grade F-2 | Grade 2 | Grade 2 | Grade 2 | WPT2[a] | Grade C-2 | -- | -- |
| Unalloyed Titanium (Intermediate iron, high interstitials) | Grade 3 | Grade F-3 | Grade 3 | Grade 3 | Grade 3 | WPT3[a] | Grade C-3 | Grade 3[b] | -- |
| Unalloyed Titanium (High iron and intersitials) | Grade 4 | Grade F-4 | Grade 4 | Grade 4 | Grade 4 | -- | Grade C-4 | Grade 4[c] | -- |
| Ti-6Al-4V | Grade 5 | Grade F-5 | Grade 5 | -- | -- | -- | Grade C-5 | -- | -- |
| Ti-6Al-4V ELI (High Purity) | -- | -- | -- | -- | -- | -- | -- | -- | Ti-6Al-4V ELI |
| Ti-5Al-2.5Sn | Grade 6 | Grade F-6 | Grade 6 | -- | -- | -- | Grade C-6 | -- | -- |
| Ti-0.12 to 0.25 Pd (Low iron, low interstitials) | -- | -- | -- | -- | -- | -- | Grade C-7A | -- | -- |
| Ti-0.12 to 0.25 Pd (Intermediate iron and interstitials) | Grade 7 | Grade F-7 | Grade 7 | Grade 7 | Grade 7 | -- | Grade C-7B | -- | -- |
| Ti-0.12 to 0.25 Pd (Intermediate iron, high interstitials) | -- | -- | -- | Grade 8 | Grade 8 | -- | Grade C-8A | -- | -- |
| Ti-0.12 to 0.25 Pd (High iron and interstitials) | -- | -- | -- | -- | -- | -- | Grade C-8B | -- | -- |
| Ti-11.5Mo-6Zr-4.5Sn | Grade 10 | -- | Grade 10 | -- | -- | -- | -- | -- | -- |

Note:

(a) When fittings are of welded construction, the symbol shown shall be supplemented by the letter "W". The designated grades correspond to Grades 1, 2, and 3 of B348, B265, B337, B338, and Grades C-1, C-2 and C-3 of B367.

(b) Corresponds to Grade 3 of B348, B381, and B265.

(c) Corresponds to Grade 4 of B381 and B265.

TABLE XVII. COMPOSITIONS AND DESIGNATIONS OF MATERIALS DESCRIBED IN AWS A5.16-70, SPECIFICATION FOR TITANIUM AND TITANIUM ALLOY BARE WELDING RODS AND ELECTRODES

| Nominal Composition, wt.% | AWS Classification | Interstitial and Iron Contents, weight percent[a] | | | | |
|---|---|---|---|---|---|---|
| | | C | O | H | N | Fe |
| Unalloyed Titanium[b] | ERTi-1 | 0.03 | 0.10 | 0.005 | 0.012 | 0.10 |
| Unalloyed Titanium | ERTi-2 | 0.05 | 0.10 | 0.008 | 0.020 | 0.20 |
| Unalloyed Titanium | ERTi-3 | 0.05 | 0.10-0.15 | 0.008 | 0.020 | 0.20 |
| Unalloyed Titanium | ERTi-4 | 0.05 | 0.15-0.25 | 0.008 | 0.020 | 0.30 |
| Ti-0.15 to 0.25 Pd | ERTi-0.2 Pd | 0.05 | 0.15 | 0.008 | 0.020 | 0.25 |
| Ti-3Al-2.5V | ERTi-3Al-2.5V | 0.05 | 0.12 | 0.008 | 0.020 | 0.25 |
| Ti-3Al-2.5V[b] | ERTi-3Al-2.5V-1 | 0.04 | 0.10 | 0.005 | 0.012 | 0.25 |
| Ti-5Al-2.5Sn | ERTi-5Al-2.5Sn | 0.05 | 0.12 | 0.008 | 0.030 | 0.40 |
| Ti-5Al-2.5Sn[b] | ERTi-5Al-2.5Sn-1 | 0.04 | 0.10 | 0.005 | 0.012 | 0.25 |
| Ti-6Al-2Cb-1Ta-0.8Mo | ERTi-6Al-2Cb-1Ta-1Mo | 0.04 | 0.10 | 0.005 | 0.012 | 0.15 |
| Ti-6Al-4V | ERTi-6Al-4V | 0.05 | 0.15 | 0.008 | 0.020 | 0.25 |
| Ti-6Al-4V[b] | ERTi-6Al-4V-1 | 0.04 | 0.10 | 0.005 | 0.012 | 0.15 |
| Ti-8Al-1Mo-1V | ERTi-8Al-1Mo-1V | 0.05 | 0.12 | 0.008 | 0.03 | 0.25 |
| Ti-13V-11Cr-3Al | ERTi-13V-11Cr-3Al | 0.05 | 0.12 | 0.008 | 0.03 | 0.25 |

Note:

(a) Analyses to meet interstitial content requirements are made after the welding rod or electrode is reduced to the final diameter. Single values are maximum values allowed.

(b) Very high purity compositions.

MIL-T-9046H, Type III, Composition C
MIL-T-9047E, Composition 6
MIL-T-81556, Type III, Composition A
MIL-F-83142A, Composition 7
MIL-T-009047F, Composition 7
MIL-T-46077A

AMS-4967D
B348-72, Grade 5
B381-69, Grade F-5
B265-72, Grade 5
B367-69, Grade C-5
AWS A5.16-70 ERTi-6Al-4V-1

A number of titanium users and producers, government agencies and metals-oriented societies have recognized that the nomenclature problem is not unique for titanium. Personnel from these groups have met to sponsor a Unified Numbering System (UNS) for all metals and alloys produced and used in North America. The UNS effort has become a joint activity of the SAE and ASTM where the purpose of the activity is to develop and promulgate for adoption a unified system for the identification of metals and alloys. A proposed SAE/ASTM Standard entitled, "Recommended Practice for Numbering Metals and Alloys", has emerged as a result of this activity. In part, the scope of this Standard reads:

"The UNS provides a means of correlating many nationally used numbering systems currently administered by societies, trade associations, and individual users and producers of metals and alloys, thereby avoiding confusion caused by use of more than one identification number for the same material — and by the opposite situation of having the same number assigned to two or more entirely different materials. It provides, also, the uniformity necessary for efficient indexing, record keeping, data storage and retrieval, and cross referencing."

Part A of the Specification describes the alpha-numeric numbers (or codes) established for each family of metals and alloys. The code consists of a letter (which identifies a metal family) followed by five numerals (which identify compositions). For example, nickel and nickel alloys are the N-series (Nxxxxx), rare earth metals are in the E-series (Exxxxx), and reactive and refractory metals are in the R-series. Within the R series titanium materials are assigned the Numeral 5 (R5xxxx) and the various grades of titanium are identified by the remaining numerals of the six-place code. The numbers R50001—R59999 have been reserved for titanium and titanium alloys.

Considerable effort will be required to complete the details of this activity and finally to promote it and to achieve its adoption by the metals community. However, since it appears as the logical activity to achieve an ultimate correlation of metals nomenclature, the UNS assigned to titanium and its alloys is presented in this handbook with the expectation that it will eventually be adopted.

9. General Specification Requirements. Specifications prepared by the Government or metals-oriented societies have the basic aim of establishing uniformity in prescribed materials under selected conditions. Such parameters as metal composition, manufacturing technique, thermal processing, mechanical properties, product sampling and testing, dimensional tolerances, workmanship, and finishes, marking, packaging, and certification are identified and described in terms of restrictions and limitations designed to standardize product. As shown in previous sections, all commercial titanium-base materials are not covered by specifications but most are included in at least one specification and some products are covered by several. In the case of such multiple coverage, the specifications while using different language, basically define the same limitations for the product, usually concerning the parameters of prime interest to users. The parameters are those of interest to titanium producers as well since specification requirements may serve as the authority to limit responsibility for product improperly utilized. Most specifications call out material composition ranges or maximums and tensile property limitations in the descriptions of the

TABLE XVIII. TYPICAL-MINIMUM MECHANICAL PROPERTY REQUIREMENTS – MIL-T-9047E SPECIFICATION

| *Nominal Composition, wt %* | Designation | Thickness, in. | Tensile Strength, ksi | Yield Strength[a], ksi | Elongation[b] % | Red. in Area[c], % | Charpy Impact[d], ft-lb |
|---|---|---|---|---|---|---|---|
| | | Annealed Bars and Forging Stock[e] | | | | | |
| Unalloyed titanium | Composition 1 | — | 80 | 70 | 15 | 30 | 20 |
| Ti-5Al-2.5Sn | Composition 2 | — | 115 | 110 | 10 | 25 | 10 |
| Ti-5Al-2.5Sn ELI | Composition 3 | ≤2.0 | 100 | 90 | 10 | 20 | — |
| | | 2.0-4.0 | 100 | 90 | 10 | 15 | — |
| Ti-8Al-1Mo-1V | Composition 5 | ≤2.5 | 130 | 120 | 10 | 20 | 15 |
| | | 2.5-4.0 | 120 | 110 | 10 | 20 | — |
| Ti-6Al-4V | Composition 6[f] | — | 130 | 120 | 10 | 25 | 10 |
| Ti-6Al-4V ELI | Composition 7 | ≤1.5 | 120 | 110 | 10 | 20 | — |
| | | 1.5-2.0 | 125 | 115 | 10 | 25 | 15 |
| Ti-6Al-6V-2Sn | Composition 8[f] | ≤1.5 | 150 | 140 | 8 | — | — |
| | | 1.5-3.0 | 145 | 135 | 8 | 15 | — |
| | | 3.0-4.0 | 140 | 130 | 8 | 20 | — |
| Ti-7Al-4Mo | Composition 9[f] | ≤2.0 | 145 | 135 | 10 | 20 | 10 |
| | | 2.0-3.0 | 140 | 130 | 10 | 20 | — |
| Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si | Composition 10[g] | — | 140 | 130 | 10 | 20 | — |
| Ti-6Al-2Sn-4Zr-2Mo | Composition 11 | — | 130 | 120 | 10 | 25 | — |
| Ti-13V-11Cr-3Al | Composition 12[f] | — | 125 | 120 | 10 | 25 | 15 |
| Ti-11.5Mo-6Zr-4.5Sn | Composition 13 | ≤1.675 | 100 | 90 | 15 | 50 | — |
| | | 1.68-3.0 | 100 | 90 | 15 | 50 | — |
| | | Heat Treated (STA) Bars and Forging Stock | | | | | |
| Ti-6Al-4V (≤ 8 in. width) | Composition 6 | ≤0.5 | 160 | 150 | 10 | 15 | — |
| (≤4 in. width) | | 0.5-1.0 | 155 | 145 | 10 | 15 | — |
| (4-8 in. width) | | 0.5-1.0 | 150 | 140 | 10 | 15 | — |
| (≤ 4 in. width) | | 1.0-1.5 | 150 | 140 | 10 | 15 | — |
| (4-8 in. width) | | 1.0-1.5 | 145 | 135 | 10 | 15 | — |
| (≤4 in. width) | | 1.5-2.0 | 145 | 135 | 10 | 15 | — |
| (4-8 in. width) | | 1.5-2.0 | 140 | 130 | 10 | 15 | — |
| (≤8 in. width) | | 2.0-3.0 | 135 | 125 | 8 | 15 | — |
| (≤8 in. width) | | 3.0-4.0 | 130 | 120 | 6 | 15 | — |
| Ti-6Al-4V ELI (≤8 in. width) | Composition 7 | ≤0.5 | 150 | 140 | 12 | 20 | — |
| (≤4 in. width) | | 0.5-1.0 | 145 | 135 | 12 | 20 | — |
| (4-8 in. width) | | 0.5-1.0 | 140 | 130 | 12 | 20 | — |
| (≤4 in. width) | | 1.0-1.5 | 140 | 130 | 12 | 20 | — |
| (4-8 in. width) | | 1.0-1.5 | 135 | 125 | 12 | 20 | — |
| (≤4 in. width) | | 1.5-2.0 | 135 | 125 | 12 | 20 | — |
| (4-8 in. width) | | 1.5-2.0 | 130 | 120 | 12 | 20 | — |
| (≤8 in. width) | | 2.0-3.0 | 125 | 115 | 10 | 20 | — |
| (≤8 in. width) | | 3.0-4.0 | 120 | 110 | 8 | 20 | — |
| Ti-6Al-6V-2Sn | Composition 8 | ≤1.0 | 175 | 160 | 6 | 15 | — |
| | | 1.0-2.0 | 170 | 155 | 8 | 15 | — |
| | | 2.0-3.0 | 155 | 145 | 6 | 15 | — |
| | | 3.0-4.0 | 150 | 140 | 6 | 15 | — |
| Ti-7Al-4Mo | Composition 9 | ≤1.0 | 170 | 160 | 8 | 15 | — |
| | | 1.0-2.0 | 160 | 150 | 8 | 15 | — |
| | | 2.0-4.0 | 160 | 140 | 8 | 15 | — |
| Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si | Composition 10 | ≤1.0 | 145 | 135 | 12 | 25 | — |
| | | 1.0-2.0 | 145 | 130 | 12 | 25 | — |
| | | 2.0-3.0 | 140 | 125 | 12 | 25 | — |
| Ti-6Al-2Sn-4Zr-2Mo | Composition 11 | ≤1.0 | 150 | 138 | 10 | 25 | — |
| Ti-13V-11Cr-3Al | Composition 12 | ≤2.0 | 170 | 160 | 4 | 10 | — |
| | | 2.0-7.0 | 170 | 160 | 2 | 10 | — |
| Ti-11.5Mo-6Zr-4.5Sn | Composition 13 | ≤1.625 | 180 | 175 | 8 | 22 | — |
| | | 1.62-3.0 | 180 | 170 | 4 | 10 | — |

Note:

(a) 0.2% offset yield strength.
(b) Elongation in 4D.
(c) Transverse reduction in area minimums.
(d) Room temperature, transverse, V-notch values are shown. Longitudinal values shall be 20 percent higher.
(e) Properties apply to sections up to 3 inches thick with a maximum of 10 square inches.
(f) Materials shall be capable of meeting the mechanical property requirements after being heated to any temperature up to 1200 F for approximately 30 minutes in air and then cooled in air.
(g) Properties are for section sizes up to 2.25 inches in thickness or 5 square inches.

materials covered. Several specifications have been prepared for specific products, for example, Ti-6Al-4V ELI material for medical implants or unalloyed titanium tubing for heat exchanger utilization, and such specifications describe specific requirements for these materials.

10. Properties Specification Requirements. Tables XVIII, XIX, XX, and XXI summarize the typical mechanical property requirements specified for the various titanium materials by Government, ASTM, and SAE (AMS) specifications. The tensile and impact toughness minimums for bars and forging stock described in MIL-T-9047E for ranges of thicknesses in either the annealed or heat treated (STA) conditions are given in Table XVIII. Note that as thickness of stock increases, strength and ductility requirements generally decrease. Table XIX, typical minimum tensile and bend properties as described in MIL-T-9046H for plate, sheet, and strip, reflects the same stipulations regarding flat-rolled product thickness. Typically, tensile property requirements are described in ASTM and AMS specifications, Tables XX and XXI respectively, without reference to product thickness. The ASTM specification for castings, B367-69, includes reference hardness values. The total requirements for any alloy, form, thickness, and heat treated condition are described in the particular specifications of interest. Tables XVIII through XXI merely present the salient features of the total requirements.

## Nonspecification Mechanical Properties

11. General. There are many important properties and characteristics of titanium and its alloys that are not described in specifications. Tensile requirements appear to be the properties emphasized in government, public, and private specifications, which when met, afford a reasonably good description of the material for intended applications. However, there are a host of other properties which are not usually described in specifications but which are important for design considerations. These include such properties as elevated temperature strength, compressive strength, modulus of elasticity, creep and stress-rupture, fracture toughness, fatigue, and stability characteristics such as the behavior of a material after exposures at various temperatures and for various times. The intent of this section is to briefly present some of the typical properties and characteristics of selected alloys which might serve to describe various titanium materials somewhat beyond the descriptions afforded by specifications. Obviously complete descriptions require a separate handbook for each material, and often such handbooks for a material are available from producers. Typical nonspecification properties and characteristics for the major types of titanium alloys, alpha, alpha-beta, and beta, are described in the following paragraphs.

12. Tension and Compression Properties—Temperature Effects. The high elevated-temperature strength of titanium alloys has been one of the attractive features of these materials from the time of their first utilization. More recently, their high low-temperature strength also has been exploited. Figure 3 shows the tensile yield strength range of the alpha-beta Ti-6Al-4V alloy at the low to high temperatures commonly encountered in various devices. It is quite apparent that the higher temperature usefulness for Ti-6Al-4V is limited by a rapid decrease in tensile yield strength above about 800 F. This is representative of the behavior of titanium alloys although several compositions have higher strength than Ti-6Al-4V at high temperatures. In general, the upper service temperature limit for titanium alloys is 1000 F. However, the limit for any one alloy depends largely on composition, mill product form, heat treatment condition, and the time, temperature, and stress combinations of the application.

TABLE XIX. TYPICAL MINIMUM MECHANICAL PROPERTY REQUIREMENTS – MIL-T-9046 SPECIFICATION

| MATERIAL | DESIGNATION | THICKNESS INCH | THERMAL CONDITION<br>A – Annealed<br>ST – *Solution Treated*<br>STA – Solution Treated and Aged<br>DA – Duplex Annealed | TENSILE STRENGTH KSI | YIELD STRENGTH [1] (0.2% Offset, KSI, Min. *Unless Range Indicated*) | ELONGATION % in 2 in. [2] | MINIMUM BEND RADIUS XT ≤0.07 in. | MINIMUM BEND RADIUS XT >0.07 in. to 0.1875 |
|---|---|---|---|---|---|---|---|---|
| | | SHEET AND STRIP (≤0.1875 inch) | | | | | (Annealed or ST) | |
| TYPE I | COMMERCIALLY PURE TITANIUM | | | | | | | |
| | Composition A–Unalloyed (40 KSI Y.S.) | – | A | 60 | 40-65 | 20 | 2.0 | 2.5 |
| | Composition B–Unalloyed (70 KSI Y.S.) | – | A | 80 | 70-95 | 15 | 2.5 | 3.0 |
| | Composition C–Unalloyed (55 KSI Y.S.) | – | A | 65 | 55-80 | 18 | 2.0 | 2.5 |
| TYPE II | ALPHA TITANIUM ALLOY | | | | | | | |
| | Composition A–5Al-2.5Sn | – | A | 120 | 113 | 10 | 4.0 | 4.5 |
| | Composition B–5Al-2.5Sn (ELI) | – | A | 100 | 95 | 10③ | 4.0 | 4.5 |
| | Composition F–8Al-1Mo-1V | – | A | 145③ | 135③ | 10③③ | 5.4⑤ | 6.0⑤ |
| | Composition G–6Al-2Cb-1Ta-0.8Mo | – | – | — | — | — | — | — |
| TYPE III | ALPHA–BETA–TITANIUM ALLOY | | | | | | | |
| | Composition C–6Al-4V | – | A/ST | 134/③ | 126/150 | 8④/10.0④ | 4.5 | 5.0 |
| | | – | STA | 160 | 145 | 6.0⑤ | | |
| | Composition D–6Al-4V ELI | – | A/ST | 130/ | 120/ | 10 [3] | 4.5 | 5.0 |
| | | – | STA | | | | | |
| | Composition E–6Al-6V-2Sn | – | A/ST | 155/③ | 145/180 | 10③/10.0 | 4.0 | 4.5 |
| | | – | STA | 170 | 160 | 8③ | | |
| | Composition G–6Al-2Sn-4Zr-2Mo | – | A/ST | 135③ | 125③/– | 8④⑤ | 4.5 | 6.0 |
| | | – | STA | | | | | |
| | Composition H–6Al-4V SPL | – | A/ST | 130/– | 120/– | 10③ | 4.5 | 5.0 |
| | | – | STA | | | | | |
| TYPE IV | BETA TITANIUM ALLOY | | | | | | | |
| | Composition A–13V-11Cr-3Al⑥ | – | ST | 125⑥ | 120⑥⑦ | 10⑥ | 3.0 | 3.5 |
| | | – | STA | 170 | 160 | 4⑥ | 3.0 | 3.5 |
| | Composition B–11.5Mo-6Zr-4.5Sn⑥ | – | ST | 100 | 90⑥ | 12⑥ | 3.0 | 3.0 |
| | | – | STA | 180 | 170 | 6⑥ | | |
| | Composition C–3Al-8V-6Cr-4Mo-4Zr⑥ | – | ST | 125 | 120 | 6⑥ | 3.5 | 4.0 |
| | | – | STA | 180 | 170 | 6 | | |
| | Composition D–8Mo-8V-2Fe-3Al⑥ | – | ST | 125 | 120 | 8 | 3.5 | 3.5 |
| | | – | STA | 175 | 155 | 10⑥ | | |
| | | | PLATE (>0.1875 inch) | | | | | |
| TYPE I | COMMERCIALLY PURE TITANIUM | | | | | | | |
| | Composition A–Unalloyed (40 KSI Y.S.) | 0.1875–1.0 | A | 60 | 40-65 | 20 | | |
| | Composition B–Unalloyed (70 KSI Y.S.) | 0.1875–1.0 | A | 80 | 70-95 | 15 | | |
| | Composition C–Unalloyed (55 KSI) | 0.1875–1.0 | A | 65 | 55-80 | 18 | | |
| TYPE II | ALPHA TITANIUM ALLOY | | | | | | | |
| | Composition A–5Al-2.5Sn | – | A | 120⑥ | 113⑥ | 10 | | |
| | Composition B–5Al-2.5Sn ELI | 0.1875-10 | A | 100 | 95 | 10 | | |
| | Composition F–8Al-1Mo-1V | 3/16–1/4 | A | 145 | 125 | 10 | | |
| | | 3/16–1/4 | DA | 130 | 120 | 10 | | |
| | | >1/4–1/2 | A | 145 | 125 | 10 | | |
| | | >1/4–1/2 | DA | 130 | 120 | 10 | | |
| | | >1/2–3/4 | A | 140 | 130 | 10 | | |
| | | >1/2–3/4 | DA | 130 | 120 | 10 | | |
| | | >3/4–1 | A | 140 | 130 | 10 | | |
| | | >3/4–1 | DA | 130 | 120 | 10 | | |
| | | >1–1-1/2 | A | 130 | 120 | 10 | | |
| | | >1–1-1/2 | DA | 125 | 115 | 10 | | |
| | | >1-1/2–2 | A | 130 | 120 | 10 | | |
| | | >1-1/2–2 | DA | 125 | 115 | 10 | | |
| | | >2–2-1/2 | A | 130 | 120 | 10 | | |
| | | >2–2-1/2 | DA | 120 | 110 | 8 | | |
| | | >2-1/2–4 | A | 120 | 110 | 8 | | |
| | | >2-1/2–4 | DA | 120 | 110 | 8 | | |
| | Composition G–6Al-2Cb-1Ta-0.8Mo | 0.1875–2.750 | A | 103 | 95 | 10 | | |
| TYPE III | ALPHA BETA TITANIUM ALLOY | | | | | | | |
| | Composition C–6Al-4V | 0.1875–4.0 | A | 130 | 120 | 10 | | |
| | | 3/16–1/4 | STA | 160 | 145 | 8 | | |
| | | >1/4–1/2 | STA | 160 | 145 | 8 | | |
| | | >1/2–3/4 | STA | 160 | 145 | 8 | | |
| | | >3/4–1.0 | STA | 150 | 140 | 6 | | |
| | | >1.0–1-1/2 | STA | 145 | 135 | 6 | | |
| | | >1-1/2–2.0 | STA | 145 | 135 | 6 | | |
| | | >2.0–2-1/2 | STA | 130 | 120 | 6 | | |
| | | >2-1/2 4.0 | STA | 120 | 120 | 6 | | |
| | Composition D–6Al-4V ELI | 1.0–3.0 | A | 130⑥ | 120⑥ | 10 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Composition E–6Al-6V-2Sn | | A | 150 [illegible] | 140 [illegible] | 10 [illegible] [illegible] |
| | | 3/16–1/4 | STA | 170 | 160 | 8 |
| | | >1/4–1/2 | STA | 170 | 160 | 8 |
| | | >1/2–3/4 | STA | 170 | 160 | 8 |
| | | >3/4–1.0 | STA | 170 | 160 | 8 |
| | | >1.0–1-1/2 | STA | 170 | 160 | 8 |
| | | >1-1/2–2.0 | STA | 160 | 150 | 6 |
| | | >2.0–2-1/2 | STA | 160 | 150 | 6 |
| | | >2-1/2–4.0 | STA | 150 | 140 | 6 |
| | Composition H–6Al-4V-SPL | | | 130 [illegible] | 120 [illegible] | 10 |
| TYPE IV | BETA TITANIUM ALLOY<br>Composition A–13V-11Cr-3Al ⑨ | 0.1875–4.0 | A | 125 | 120 | 10 |
| | | 3/16–1/4 | STA | 170 | 160 | 4 |
| | | >1/4–1/2 | STA | 170 | 160 | 4 |
| | | >1/2–3/4 | STA | 170 | 160 | 4 |
| | | >3/4–1.0 | STA | 170 | 160 | 4 |
| | | >1.0–1-1/2 | STA | 170 | 160 | 4 |
| | | >1-1/2–2.0 | STA | 170 | 160 | 4 |
| | | >2.0–2-1/2 | STA | 170 | 160 | 4 |
| | | >2-1/2–4.0 | STA | 170 | 160 | 4 |
| | Composition B–11.5Mo-6Zr-4.5Sn ⑨ | 0.1875–4.0 | A | 100 | 90 | 10 |
| | | 3/16–1/4 | STA | 180 | 170 | 6 |
| | | >1/4–1/2 | STA | 180 | 170 | 6 |
| | | >1/2–3/4 | STA | 180 | 170 | 6 |
| | | >3/4–1.0 | STA | 180 | 170 | 6 |
| | | >1.0–1-1/2 | STA | 180 | 170 | 6 |
| | | >1-1/2–2.0 | STA | 180 | 170 | 6 |
| | | >2.0–2-1/2 | STA | 180 | 170 | 8 |
| | | >2-1/2–4.0 | STA | 180 | 170 | 6 |
| | Composition C–3Al-8V-6Cr-4Mo-4Zr ⑨ | | A | 125 [illegible] | 120 [illegible] | 10 [illegible] |
| | | 3/16–1/4 | STA | 180 | 170 | 8 |
| | | >1/4–1/2 | STA | 180 | 170 | 8 |
| | | >1/2–3/4 | STA | 180 | 170 | 8 |
| | | >3/4–1.0 | STA | 180 | 170 | 8 |
| | | >1.0–1-1/2 | STA | 180 | 170 | 8 |
| | | >1-1/2–2.0 | STA | 180 | 170 | 8 |
| | | >2.0–2-1/2 | STA | 180 | 170 | 6 |
| | | >2-1/2–4.0 | STA | 180 | 170 | 6 |
| | Composition D-8Mo-8V-2Fe-3Al | | A | 125 [illegible] | 120 [illegible] | 10 [illegible] |
| | | 3/16–1/4 | STA | 170 | 160 | 8 |
| | | >1/4–1/2 | STA | 170 | 160 | 8 |
| | | >1/2–3/4 | STA | 170 | 160 | 8 |
| | | >3/4–1.0 | STA | 170 | 160 | 8 |
| | | >1.0–1-1/2 | STA | 170 | 160 | 6 |
| | | >1-1/2–2.0 | STA | 170 | 160 | 6 |
| | | >2.0–2-1/2 | STA | 170 | 160 | 6 |
| | | >2-1/2–4.0 | STA | 170 | 160 | 6 |

Notes:

1. The rate of strain shall be 0.003 to 0.007 inch per minute through the yield strength, and then is increased so as to product failure in approximately one additional minute. In case of dispute, a strain rate of 0.005 shall be used to the yield point and from yield to fracture a minimum crosshead speed of 0.10 inch per minute shall be used.
2. For 0.025 inch and heavier. For 0.008 inch and up to 0.014 inch, a minimum of 6 percent elongation is required. For 0.015 inch and up to 0.024 inch, a minimum of 8 percent elongation is required.
3. For Duplex annealed, a minimum of 135 ksi for ultimate tensile strength, a minimum of 120 ksi for yield strength, and a minimum of 10 percent elongation is required.
4. For 0.063 inch and heavier, a minimum of 10 percent elongation is required.
5. Spread between ultimate tensile strength and yield strength shall be 15 ksi minimum.
6. For 0.033 inch and heavier, a minimum of 8 percent elongation is required.
7. For elongation in longitudinal direction. Elongation in the transverse direction shall require a minimum of 8 percent. For less than 0.025 inch, a minimum of 6 percent elongation in longitudinal direction and 6 percent elongation in transverse direction is required.
8. For duplex annealed, a minimum of 8 percent elongation is required for less than 0.020 inch and a minimum of 10 percent elongation for 0.020 inch and greater. For triplex annealed, a minimum of 145 ksi for ultimate tensile strength, a minimum of 135 ksi for yield strength, a minimum of 8 percent elongation for less than 0.020 inch and a minimum of 10 percent elongation for 0.020 inch and greater is required.
9. For this all–beta alloy, solution heat treated condition properties are synonymous with annealed.
10. For material less than 0.050 inch, a minimum of 132 ksi for ultimate tensile strength, a minimum of 126 ksi for yield strength, and a minimum of 8 percent elongation is required.
11. For this material, the value for yield strength is minimum.
12. For material less than 0.025 inch, a minimum of 10 percent elongation is required.
13. ~~For material less than 0.030 inch, a minimum of 6 percent elongation is required.~~
14. For 0.050 inch and over, 4 percent for 0.033 inch to 0.049 inch and 3 percent for 0.032 inch and below.
15. For elongation in longitudinal direction. Elongation in transverse direction shall require a minimum of 6 percent.
16. For 0.025 inch and over, 3 percent below 0.025 inch.
17. When specified, the following shall be required:
    - (a) For aging at 1000°F, a minimum of 165 ksi for ultimate tensile strength, a minimum of 155 ksi for yield strength, and a minimum of 8 percent elongation.
    - (b) For aging at 1100°F of material 0.012 inch and greater, a minimum of 130 ksi for ultimate tensile strength, a minimum of 125 ksi for yield strength, and a minimum of 8 percent elongation
18. When specified, the following shall be required for aging at 1100°F, a minimum of 150 ksi for ultimate tensile strength, a minimum of 140 ksi for yield strength and a minimum of 15 percent elongation.
19. Requirement for mill–annealed. For Duplex annealed, a minimum of 4.0T for nominal thickness of 0.070 inch and under, and a minimum of 4.5T for nominal thickness of over 0.070 to 0.1875 inch.
20. For sections from 1.500 to 4.000 inches, a minimum of 116 ksi for ultimate tensile strength and a minimum of 110 ksi for yield strength is required.
21. For section from 1.000 to 3.000 inches, a minimum of 125 ksi for ultimate tensile strength and a minimum of 115 ksi for yield strength is required.
22. For sections from 0.1875 to 2.000 inches. For sections 2.001 to 4.000 inches, a minimum of 145 ksi for ultimate tensile strength, a minimum of 135 ksi for yield strength, and a minimum of 8 percent elongation in longitudinal direction, 6 percent elongation in transverse direction is required.
23. For elongation in longitudinal direction. Elongation in the transverse direction shall require a minimum of 8 percent.
24. For sections from 0.1875 to 2.000 inches. For sections 2.001 to 4.000 inches a minimum of 120 ksi for ultimate tensile strength, a minimum of 115 ksi for yield strength and a minimum of 8 percent elongation in the longitudinal direction, 6 percent elongation in the transverse direction and 3 percent elongation in the short transverse direction is required.

TABLE XX. TYPICAL TENSILE PROPERTY REQUIREMENTS – ASTM SPECIFICATIONS

| Nominal Composition, wt % | Grade | Tensile Strength, ksi[a] | Yield Strength, ksi[a] | | Min. Elongation, % in 2 inches[b] | Min. Red in Area, % | Min. Bend Radius, T[c] | |
|---|---|---|---|---|---|---|---|---|
| | | Min. | Min. | Max. | | | ≤0.07 in. | >0.07 in. |
| | | **Strip, Sheet, and Plate (B265 - 72)[d]** | | | | | | |
| Unalloyed Titanium (Low iron and interstitials) | 1 | 35 | 25 | 45 | 24 | -- | 3 | 4 |
| Unalloyed Titanium (Intermediate iron and interstitials) | 1 | 50 | 40 | 65 | 20 | -- | 4 | 5 |
| Unalloyed Titanium (Intermediate Iron, high interstitials) | 3 | 65 | 55 | 80 | 18 | -- | 4 | 5 |
| *Unalloyed Titanium (High iron and interstitials)* | 4 | 80 | 70 | 95 | 15 | -- | 4 | 6 |
| Ti-6Al-4V | 5[e] | 130 | 120 | -- | 10 | -- | 9 | 10 |
| Ti-5Al-2.5Sn | 6[e] | 120 | 115 | -- | 10 | -- | 8 | 9 |
| Ti-0.12 to 0.25 Pd (Intermediate iron and interstitials) | 7 | 50 | 40 | 65 | 20 | -- | 4 | 5 |
| Ti-11.5Mo-6Zr-4.5Sn | 10[d,e] | 100 | 90 | -- | 10 | -- | 6 | 6 |
| | | **Seamless and Welded Tube For Condensers and Heat Exchangers (B338 - 65) and Seamless and Welded Titanium Pipe (B337 - 65)** | | | | | | |
| Unalloyed Titanium (Low iron and interstitials) | 1 | 35 | 25 | 45 | 24 | -- | -- | -- |
| Unalloyed Titanium (Intermediate iron and interstitials) | 2 | 50 | 40 | 60 | 20 | -- | -- | -- |
| Unalloyed Titanium (Intermediate iron, high interstitials) | 3 | 65 | 55 | 75 | 18 | -- | -- | -- |
| Unalloyed Titanium (High iron and interstitials) | 4 | 80 | 70 | 90 | 15 | -- | -- | -- |
| Ti-0.12 to 0.25 Pd (Intermediate iron and interstitials) | 7 | 50 | 40 | 60 | 20 | -- | -- | -- |
| Ti-0.12 to 0.25 Pd (Intermediate iron, high interstitials) | 8 | 65 | 55 | 75 | 18 | -- | -- | -- |
| | | **Bars and Billets (B348 - 72)[f]** | | | | | | |
| Unalloyed Titanium (Low Iron and Interstitials) | 1 | 35 | 25 | -- | 24 | 30 | -- | -- |
| *Unalloyed Titanium (Intermediate iron and interstitials)* | 2 | 50 | 40 | -- | 20 | 30 | -- | -- |
| Unalloyed Titanium (Intermediate iron, high interstitials) | 3 | 65 | 55 | -- | 18 | 30 | -- | -- |
| Unalloyed Titanium (High iron and interstitials) | 4 | 80 | 70 | -- | 15 | 25 | -- | -- |
| Ti-6Al-4V | 5 | 130 | 120 | -- | 10 | 25 | -- | -- |
| Ti-5Al-2.5Sn | 6 | 120 | 115 | -- | 10 | 25 | -- | -- |
| Ti-0.12 to 0.25 Pd (Intermediate iron and interstitials) | 7 | 50 | 40 | -- | 20 | 25 | -- | -- |
| Ti-11.5Mo-6Zr-4.5Sn | 10[e] | 100 | 90 | -- | 15 | 50 | -- | -- |
| | | **Forgings (B381 - 69)[g]** | | | | | | |
| Unalloyed Titanium (Low iron and interstitials) | F-1 | 35 | 25 | -- | 24 | 30 | -- | -- |
| Unalloyed Titanium (Intermediate iron and interstitials) | F-2 | 50 | 40 | -- | 20 | 30 | -- | -- |
| Unalloyed Titanium (Intermediate iron, high interstitials) | F-3 | 65 | 55 | -- | 18 | 30 | -- | -- |
| Unalloyed Titanium (High iron and interstitials) | F-4 | 80 | 70 | -- | 15 | 25 | -- | -- |
| Ti-6Al-4V | F-5 | 130 | 120 | -- | 10 | 25 | -- | -- |
| Ti-5Al-2.5Sn | F-6 | 120 | 115 | -- | 10 | 25 | -- | -- |
| Ti-0.12 to 0.25 Pd (Intermediate iron and interstitials) | F-7 | 50 | 40 | -- | 20 | 30 | -- | -- |
| | | **Castings (B367 - 69)[i]** | | | | | | |
| Unalloyed Titanium (Low Iron and interstitials) | C-1 | 35 | 25 | (190 HB)[j] | 24 | -- | -- | -- |
| Unalloyed Titanium (Intermediate Iron and interstitials) | C-2 | 50 | 40 | (210 HB) | 20 | -- | -- | -- |
| Unalloyed Titanium (Intermediate Iron, high interstitials) | C-3 | 65 | 55 | (235 HB) | 15 | -- | -- | -- |
| Unalloyed Titanium (High iron and interstitials) | C-4 | 80 | 70 | (245 HB) | 12 | -- | -- | -- |
| Ti-6Al-4V | C-5 | 130 | 120 | (365 HB) | 6 | -- | -- | -- |
| Ti-5Al-2.5Sn | C-6 | 115 | 105 | (335 HB) | 8 | -- | -- | -- |
| Ti-0.12 to 0.25 Pd (Low iron and interstitials) | C-7A | 35 | 25 | (190 HB) | 24 | -- | -- | -- |
| Ti-0.12 to 0.25 Pd (Intermediate iron and interstitials) | C-7B | 50 | 40 | (210 HB) | 20 | -- | -- | -- |
| Ti-0.12 to 0.25 Pd (Intermediate iron, high interstitials) | C-8A | 65 | 55 | (235 HB) | 15 | -- | -- | -- |
| Ti-0.12 to 0.25 Pd (High iron and interstitials) | C-8B | 80 | 70 | (245 HB) | 12 | -- | -- | -- |

Note:

(a) Limits apply to both longitudinal and transverse sample directions where applicable. Yield strength limits are 0.2% offset values.
(b) Elongation minimums are percent in 4D for Billets, Bars, and Forgings.
(c) T value equals bend radius divided by sheet thickness.
(d) Limits specified for annealed of 1 inch thickness or less. Bend minimums are not applicable to material over 0.187 inch in thickness.
(e) Elongation minimum on sheet and strip of less than 0.025 inch thickness may be negotiated.
(f) Material in the solution treated condition.
(g) Limits apply to longitudinal sections up to 3 inches in thickness with a section maximum of 10 square inches.
(h) Limits apply to forgings having a maximum cross section not greater than 3 square inches.
(i) Maximum hardness values (11B) are specified in lieu of maximum yield strength values. Elongation values are for 1 inch gage length.
(j) Hardness values.

### TABLE XXI. TYPICAL TENSILE REQUIREMENTS – AMS SPECIFICATIONS

| Nominal Composition, wt% | AMS No. | Tensile Strength, ksi | Yield Strength, ksi | Elongation % | Red. in. Area % |
|---|---|---|---|---|---|
| | | <u>Forgings, Bars, and Rings</u> | | | |
| Unalloyed Ti, ~99.0 | 4921B | 80 | 70 | 15 | 30 |
| Ti-5Al-2.5Sn | 4926D | 115 | 110 | 10 | 25 |
| | 4966D | 115 | 110 | 10 | 25 |
| Ti-5Al-2.5Sn ELI | 4924B | 100 | 90 | 10 | 20 |
| Ti-2.5Al-11Sn-5Zr-1Mo-0.2Si | 4974 | 145 | 130 | 10 | 20 |
| Ti-8Al-1Mo-1V | 4972A | 130 | 120 | 10 | 20 |
| | 4973A | 130 | 120 | 10 | 20 |
| Ti-6Al-4V | 4928G | 130 | 120 | 10 | 25 |
| | 4965B | 150 | 140 | 10 | 20 |
| | 4967D | 150 | 140 | 10 | 20 |
| Ti-6Al-4V ELI | 4930A | 120 | 110 | 10 | 20 |
| Ti-6Al-6V-1Sn | 4971A | 170 | 160 | 8 | 20 |
| | 4978A | 150 | 140 | 10 | 20 |
| | 4979 | 170 | 155 | 8 | 20 |
| Ti-6Al-2Sn-4Zr-2Mo | 4975B | 130 | 120 | 10 | 25 |
| | 4976 | 130 | 120 | 10 | 25 |
| Ti-6Al-2Sn-4Zr-6Mo | 4981 | 170 | 160 | 10 | 20 |
| Ti-7Al-4Mo | 4970C | 160 | 150 | 8 | 15 |
| Ti-11.5Mo-6Zr-4.5Sn | 4977A | 110 | 90 | 15 | 50 |
| | 4980A | 110 | 90 | 15 | 50 |
| | | <u>Extrusions</u> | | | |
| Ti-6Al-4V | 4935B | 130 | 120 | 10 | 20 |
| Ti-6Al-6V-2Sn | 4936 | 145 | 135 | 8 | 15 |
| | | <u>Plate, Sheet, and Strip</u> | | | |
| Unalloyed Ti, ~99.5 | 4902B | 50 | 40 | 20 | -- |
| Unalloyed Ti, ~99.2 | 4900D | 65 | 55 | 18 | -- |
| Unalloyed Ti, ~99.0 | 4901E | 80 | 70 | 15 | -- |
| Ti-5Al-2.5Sn | 4910F | 120 | 113 | 10 | -- |
| Ti-5Al-2.5Sn ELI | 4909B | 100 | 95 | 10 | -- |
| Ti-8Al-1Mo-1V | 4915B | 145 | 135 | 10 | -- |
| | 4916B | 135 | 120 | 10 | -- |
| Ti-8Mn | 4908B | 125 | 110 | 10 | -- |
| Ti-4Al-3Mo-1V | 4912A | 150 | 135 | 10 | -- |
| | 4913A | 180 | 155 | 4 | -- |
| Ti-6Al-4V | 4906 | 140 | 126 | 10 | -- |
| | 4911C | 134 | 126 | 8 | -- |
| Ti-6Al-4V ELI | 4907B | 130 | 120 | 10 | -- |
| Ti-6Al-6V-2Sn | 4918C | 150 | 145 | 8 | -- |
| Ti-13V-11Cr-3Al | 4917B | 130 | 120 | 10 | -- |
| | | <u>*Tubing*</u> | | | |
| Unalloyed Ti, ~99.5 | 4941 | 50 | 40 | 20 | -- |
| | 4942 | 50 | 40 | 20 | -- |
| Ti-3Al-2.5V | 4943 | 90-115 | 75 | 15 | -- |
| | | <u>Wire</u> | | | |
| Unalloyed Ti, ~99.5 | 4951C | 50-80 | -- | -- | -- |
| Ti-5Al-2.5Sn | 4953 | 115-150 | -- | -- | -- |
| Ti-8Al-1Mo-1V | 4955 | | No tensile requirements | | |
| Ti-6Al-4V | 4954B | | No tensile requirements | | |
| Ti-6Al-4V ELI | 4956 | | No tensile requirements | | |
| Ti-11.5Mo-6Zr-4.5Sn | 4977A | 110 | 90 | 15 | 50 |
| | 4980A | 110 | 90 | 15 | 50 |

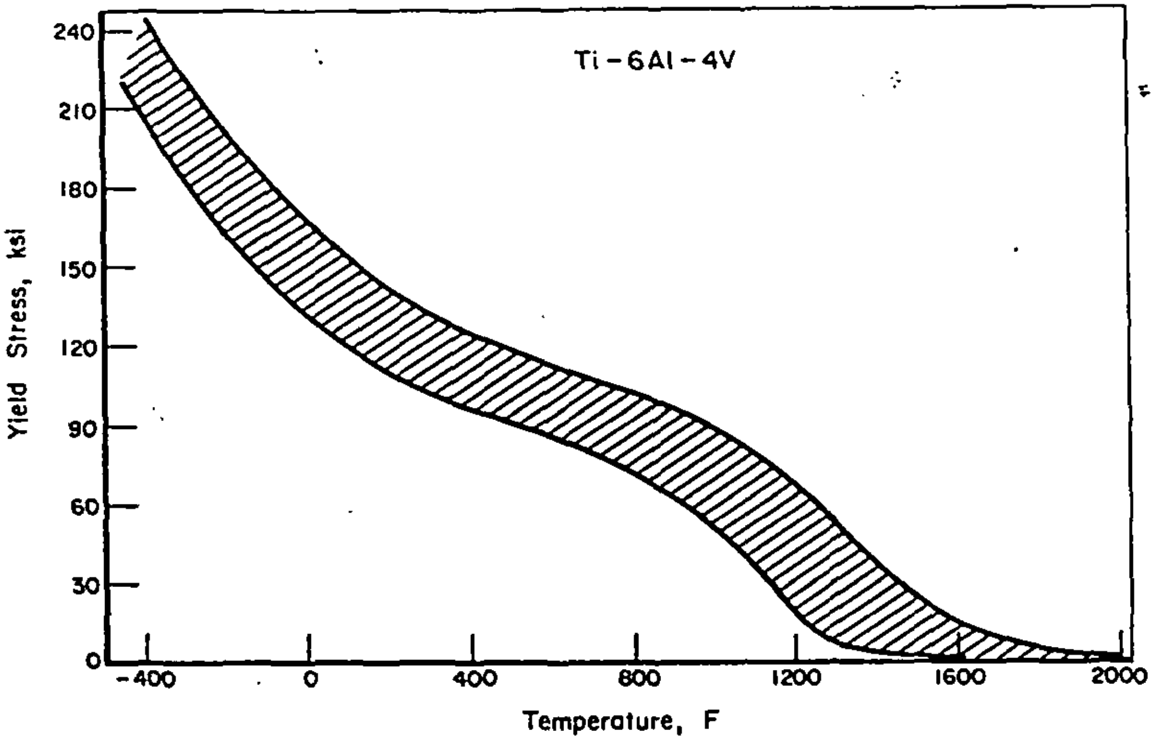


Figure 3. Typical Range in Tensile Yield Strength Found for Ti-6Al-4V Alloy Due to Variation in Chemistry, Structure, Mill Product Form, Heat Treatment, and Test Conditions

At cryogenic temperatures, titanium alloys are not so much service limited by strength as by ductility and toughness limitations. Nevertheless, several alloys are quite ductile at low temperature and Ti-6Al-4V and Ti-5Al-2.5Sn alloys (ELI grades), as well as unalloyed titanium, can be used to the low temperature of liquid helium (–453 F).

The rather broad range of yield strengths depicted in Figure 3 for the Ti-6Al-4V alloy at any particular temperature is a result of differences in material chemistry, structure, and test conditions. Major differences in yield strength can be observed for low to high alloy content (high aluminum structures have lower strength than structures altered by a precipitate phase, e.g. as-aged structures), and variations in the strain rate of the tensile test (high strain rates result in high yield strengths). These are not the only variables contributing to the variations in properties found for a given titanium composition, but they are major variables.

The typical tensile properties of unalloyed titanium and four common alloys over a broad use-temperature range are shown in Figure 4. The yield strength, ultimate strength separation shown for Ti-6Al-4V alloy is typical for the other materials shown. Note that tensile ductility generally decreases with decreasing temperature and is generally highest for the lowest strength materials. Note too, the very large difference in yield strength between unalloyed titanium (annealed) and that shown for one of the high strength beta titanium alloys, Ti-13V-11Cr-3Al (in the solution treated plus aged condition).

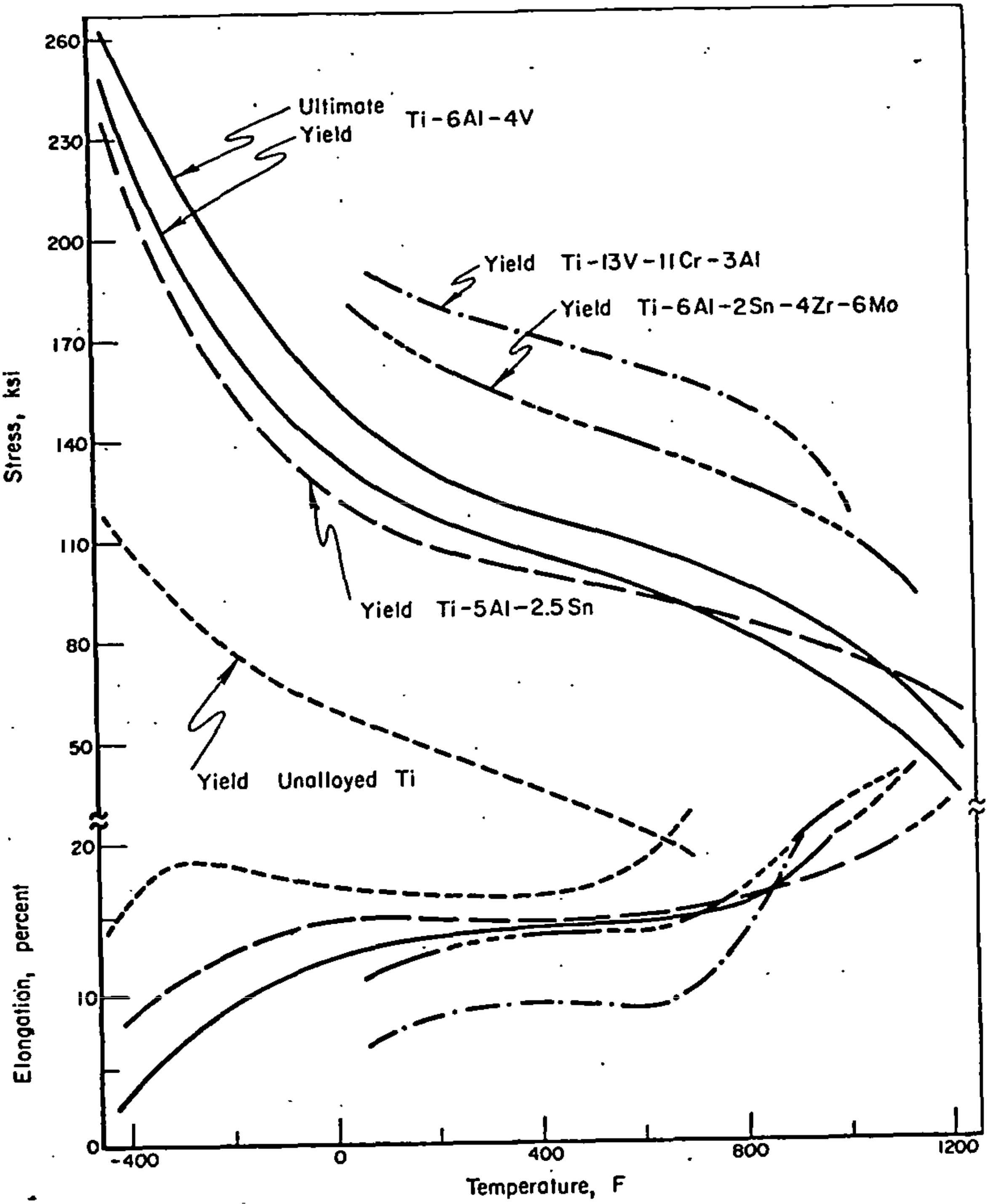
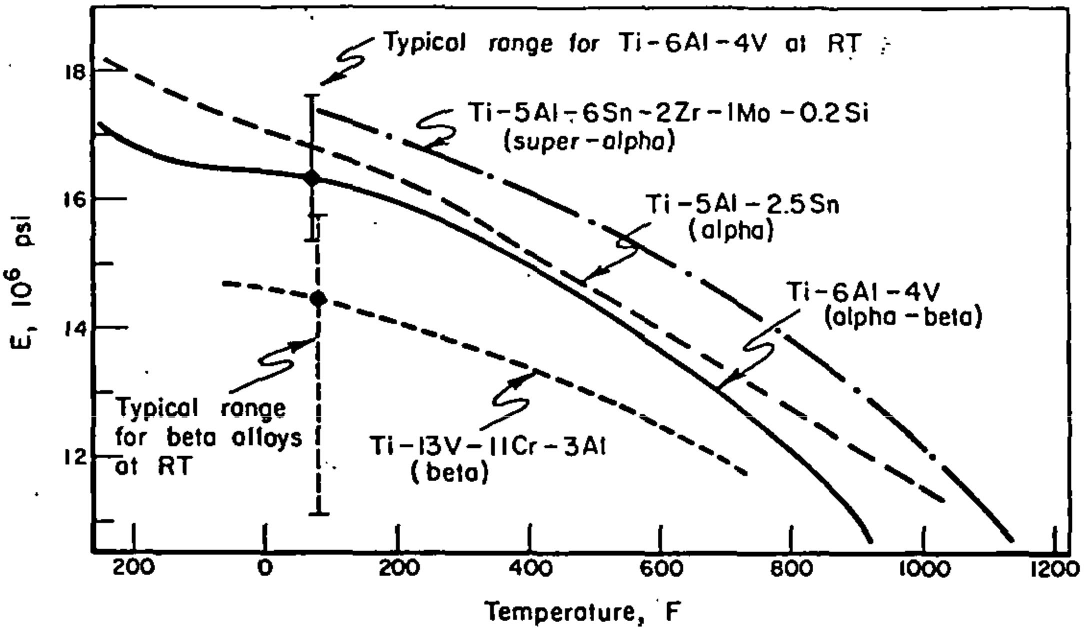
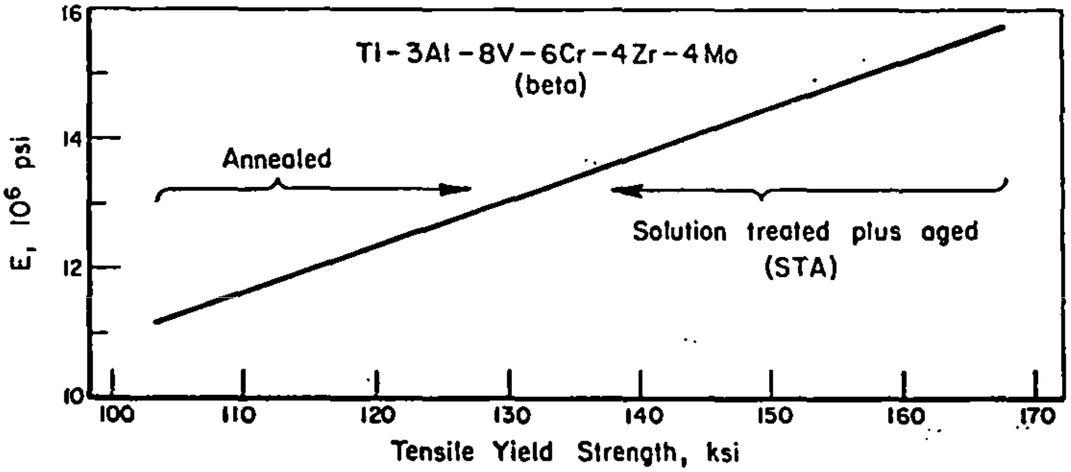


Figure 4. Effect of Temperature on the Typical Tensile Properties of Titanium Materials



a.



b.

Figure 5. Typical Variation in Elastic Modulus Values for Selected Titanium Alloys Due to (a) *Test Temperature, and* (b) Heat Treatment Condition and Strength Level

The effect of temperature on the tensile modulus of elasticity for selected titanium alloys is shown in Figure 5a. The rather large variation in modulus values that can be observed for many titanium materials at any given temperature is depicted for the Ti-6Al-4V and beta titanium alloys by the vertical lines drawn at room temperature. As is the case for tensile yield strength, modulus may vary due to chemistry, structure, texture, heat treatment, and test conditions and techniques. The variation of modulus with one of these variables, heat treatment (and the resulting strength variation), is illustrated in Figure 5b. The data for the Ti-3Al-8V-6Cr-4Zr-4Mo beta alloy reveal

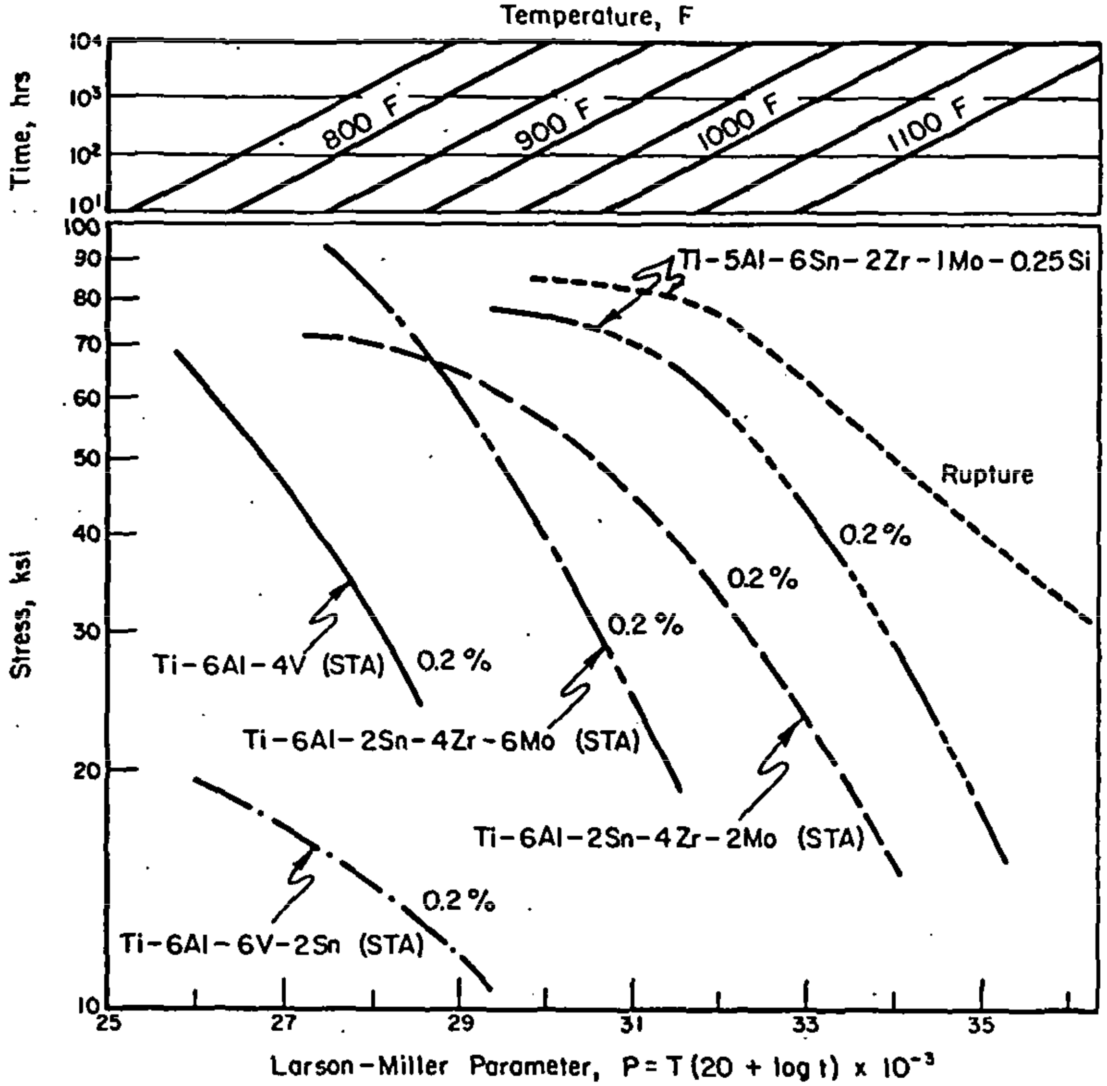


Figure 6. Typical Creep and Stress Rupture Behavior for Selected Titanium Alloys

that the trend is for higher modulus values to be found for higher strength material, in this case for beta microstructures that have been modified by alpha phase precipitate (STA treatments).

The compression properties of many materials are on a 1 to 1 equivalency with the measured tensile properties. Several titanium alloys have shown higher strengths in compression tests however, as for example, Ti-6Al-4V, Ti-6Al-2Cb-1Ta-0.8Mo, and Ti-8Al-1Mo-1V alloys. The Ti-8Al-1Mo-1V alloy has been shown to have 127 ksi $F_{cy}$ versus 120 ksi $F_{ty}$ in appropriate tests on material from a single heat. Typically, the Ti-6Al-4V alloy has higher compression strength than tensile strength as shown below:

| | $F_{cy}$, ksi | $F_{ty}$, ksi |
|---|---|---|
| Annealed plate, sheet, strip | 132 | 126 |
| Annealed bar and forgings | 126 | 120 |
| Heat treated (STA) plate and sheet | 154 | 145 |

Modulus values (and Poissons ratio) for Ti-6Al-4V have been reported as: $E_c$, 16.4; $E_t$, 16.0; G, 6.2; (and $\mu$, 0.31). On the other hand, some titanium alloys have been shown to behave opposite to the above. For example, the $F_{cy}$ for one heat of Ti-6Al-2Sn-4Zr-6Mo alloy was measured as 157 ksi versus an $F_{ty}$ of 170 ksi. Thus, it would appear appropriate to study reliable data to determine the relationship between compression and tensile properties for any titanium material of interest with respect to use under compression conditions.

13. Typical Creep and Stress-Rupture Behavior. The elevated-temperature utility of titanium alloys under creep conditions is of great importance in such applications as jet engine compressor components. The excellent creep properties of titanium alloys in the intermediate temperature range of about 350 to 1000 F have enabled them to become prime materials for this and other elevated temperature applications. The Ti-6Al-4V alloy has been used extensively in engines where creep was an important consideration, but the history of the titanium industry reveals the continuous development of alloys having improved creep strengths. Figure 6 shows three such materials compared on the basis of creep stress versus the Larson-Miller parameter where time and temperature (for elevated-temperature exposure) are combined. As shown in this plot, the Ti-6Al-6V-2Sn alloy is not as creep resistant as Ti-6Al-4V alloy which in turn is not as resistant as any of the alloys whose curves (depicting the creep conditions of time, temperature, and stress to result in 0.2 percent plastic strain) plot to the right of the curve for Ti-6Al-4V. These are typical curves for the alloys illustrated, and, like tensile and other properties, variations can occur with chemistry, microstructural, heat treatment, and testing technique variables. The rupture curve shown in Figure 6 for the Ti-5Al-6Sn-2Zr-1Mo-0.25Si alloy is displaced to the right of the 0.2 percent plastic creep curve since obviously, longer times, higher temperatures, or higher stress levels are required to produce the rupture end point of the deformation process defined as creep. Some additional alloys notable for their excellent creep resistance are the Ti-8Al-1Mo-1V, Ti-2.5Al-11Sn-5Zr-1Mo-0.2Si, and Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si compositions.

14. Stability Characteristics. The elevated-temperature tensile, creep, and other mechanical properties of titanium alloys are important items for consideration regarding a materials service limitations. Related to such limitations and of equal importance is the stability of properties during and/or after exposure to service conditions. The stability of properties for titanium alloys is quite good if exposures are confined within the limits determined for given compositions. The limits generally relate to conditions that promote oxidation, corrosion, stress-corrosion, metallurgical changes, and simple overstressing, and may be approached or exceeded to various degrees. In some cases, the degree of property change after a particular exposure may be so small that stability is unquestioned. In other cases, large property changes might occur so that an instability is not in doubt. However, arbitrary amounts of property change are typically assigned to define stability or instability and are often determined on the basis of what minimum properties can be tolerated during or after a service exposure.

Tensile yield strength and tensile ductility are the properties frequently used as guides in evaluating the stability of titanium alloys. For example, a 50 percent decrease in the tensile ductility of a titanium alloy due to an elevated temperature exposure may be used as the arbitrary stability-instability demarcation point. In other cases, a large change in yield strength, in either the positive or negative direction, resulting from an exposure, may be used to define the stability-instability limit. Others have cited stability as the ability to retain an adequate (some tolerable value) low temperature toughness after long-time thermal exposure. Whatever the stability criterion might be, it is important to understand that exposure conditions should be selected so that they do not promote property changes in excess of tolerable amounts. Generally speaking, the severity of exposures can be reduced by reducing either time, temperature, or stress, or combinations of these variables.

The data of Table XXII show typical stability data for selected alloys. Tensile properties before and after thermal or thermal-stress (creep) exposures show relative stability (e.g. Ti-6Al-4V alloy) or instability (e.g. Ti-5Al-6Sn-2Zr-1Mo-0.25Si alloy) for particular exposure conditions. While not illustrated by the data of this table, it is well known that some titanium alloys are more stable than others for a given exposure condition, and for particular alloys, some material conditions are more stable than others. For example, as shown in Figure 7, the Ti-13V-11Cr-3Al beta alloy is more stable in 600 F thermal exposure in the cold worked condition than as annealed. Similarly, as illustrated in Figure 8, the Ti-5Al-6Sn-2Zr-1Mo-0.25Si super-alpha alloy is more stable under conditions where surface embrittlement caused by oxidation is not a problem. The case shown eliminates the surface oxidation effects by metal removal but the same degree of stability might be obtained by eliminating oxygen during exposure, as for example, during exposure in vacuum or by use of protective coatings. The decrease in ductility of the surface machined samples with increasing exposure temperature, as shown in Figure 8, is undoubtedly due to metallurgical changes such as precipitation or ordering of structural phases. It is apparent that these changes become more pronounced with increasing exposure temperature. The degree of change might be reduced with a change in alloy processing, heat treatment, or perhaps with slight composition modification. Thus it may be readily seen that many variables enter a stability-instability consideration and that control over this characteristic may be exercised by proper selection of alloy and condition as well as by matching exposure conditions to the limitations of the material.

15. Toughness Parameters. There are several methods used to take the measure of toughness of titanium materials including impact toughness, notched and unnotched impact tensile, notched low strain rate tensile, dynamic tear, and static crack propagation tests. The various methods yield data indicating the relative resistance to cracking and fracture under overload conditions. Notched tensile testing (notched/unnotched strength ratio) and impact testing are methods that have long been used to afford a measure of toughness. Tough materials have a high impact energy absorption characteristic and are less sensitive to notches as in notch tensile testing. For example, notch insensitive materials commonly show a notch/unnotch tensile strength ration of > 1 whereas notch sensitive materials have ratios < 1. Sensitivity of a material to environmental (e.g. low temperatures) or to metallurgical (e.g. heat treatment or interstitial contamination) conditions can be determined using notch to unnotch tensile data comparisons.

Commonly the Charpy V-notch impact test is employed to afford a quick and inexpensive toughness determination. Specimens are used either at room or sub-room temperatures to determine the amount of energy absorbed at fracture. Typical Charpy impact data are shown in Figure 9 for unalloyed titanium and three alloys, all in the annealed condition. As might be expected, low strength unalloyed titanium is very tough to very low temperatures. The Ti-5Al-2.5Sn alpha alloy and the Ti-6Al-4V alpha-beta alloy also are quite tough whereas the Ti-8Mn alloy, being a richly beta stabilized alpha-beta alloy, does not show exceptional toughness at low temperatures. Its ductile to brittle transition temperature is somewhat higher than for the other alloys shown. Generally, titanium alloys that are richly beta stabilized, have moderately high ductile to brittle transition temperatures and are not noted for good toughness characteristics at low temperature.

As with many other properties of titanium, toughness is highly dependent upon a large number of variables which include alloy chemistry, structure, texture, and testing conditions.

TABLE XXII. TYPICAL TENSILE PROPERTY STABILITY OF SELECTED ALLOYS AFTER ELEVATED TEMPERATURE EXPOSURE

| Exposure Conditions | | | RT Tensile Properties | | | |
|---|---|---|---|---|---|---|
| Time, hours | Temp. F | Stress, ksi | Ultimate Strength, ksi | Yield Strength, ksi | Elongation % | Red. in Area, % |
| | | | **Ti-5Al-2.5Sn** | | | |
| | No exposure data | | 138 | 132 | 8 | 40 |
| 500 | 700 | None | 138 | 131 | 10 | 40 |
| | | | **Ti-6Al-4V (Case A, Sheet annealed 2 hours at 1300F)** | | | |
| | No exposure data | | 145 | 137 | 13 | 38 |
| 7000 | 550 | None | 143 | 135 | 14 | 41 |
| | | | **Ti-6Al-4V (Case B, Bar Annealed 15 hours at 1290 F)** | | | |
| | No exposure data | | 123 | 117 | 14 | 43 |
| 100 | 750 | 50 | 133 | 124 | 14 | 40 |
| 100 | 750 | 70 | 133 | 122 | 11 | 37 |
| | | | **Ti-6Al-2Sn-4Zr-2Mo** | | | |
| | No exposure data | | 153 | 140 | 20 | 41 |
| 3000 | 825 | 48 | 156 | 145 | 14 | 23 |
| 150 | 1000 | 25 | 146 | 136 | 15 | 42 |
| | | | **Ti-6Al-2Sn-4Zr-6Mo** | | | |
| | No exposure data | | 186 | 174 | 10 | 35 |
| 150 | 900 | 45 | 185 | 164 | 7 | 21 |
| | | | **Ti-8Mo-8V-2Fe-3Al** | | | |
| | No exposure data | | 149 | 139 | 14 | 32 |
| 500 | 600 | 94 | 156 | 144 | 16 | 29 |
| | | | **Ti-11.5Mo-6Zr-4.5Sn** | | | |
| | No exposure data | | 147 | 141 | 25 | 66 |
| 2000 | 550 | 70 | 148 | 146 | 24 | 70 |
| | | | **Ti-5Al-6Sn-2Zr-1Mo-0.25Si** | | | |
| | No exposure data | | 146 | 131 | 10 | 23 |
| 181 | 1000 | 35 | 144 | 134 | 5 | 9 |
| 376 | 1000 | 45 | 155 | 147 | 2 | 5 |

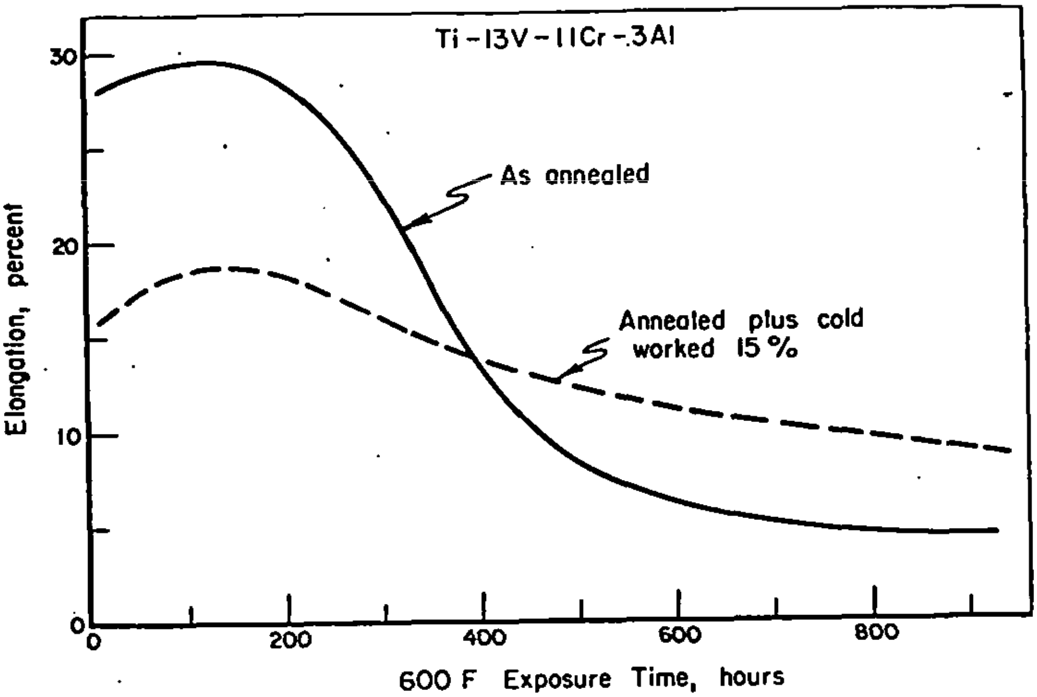


Figure 7. Effect of Thermal Exposure on the Post-Exposure Tensile Ductility of a Beta Titanium Alloy in Two Conditions

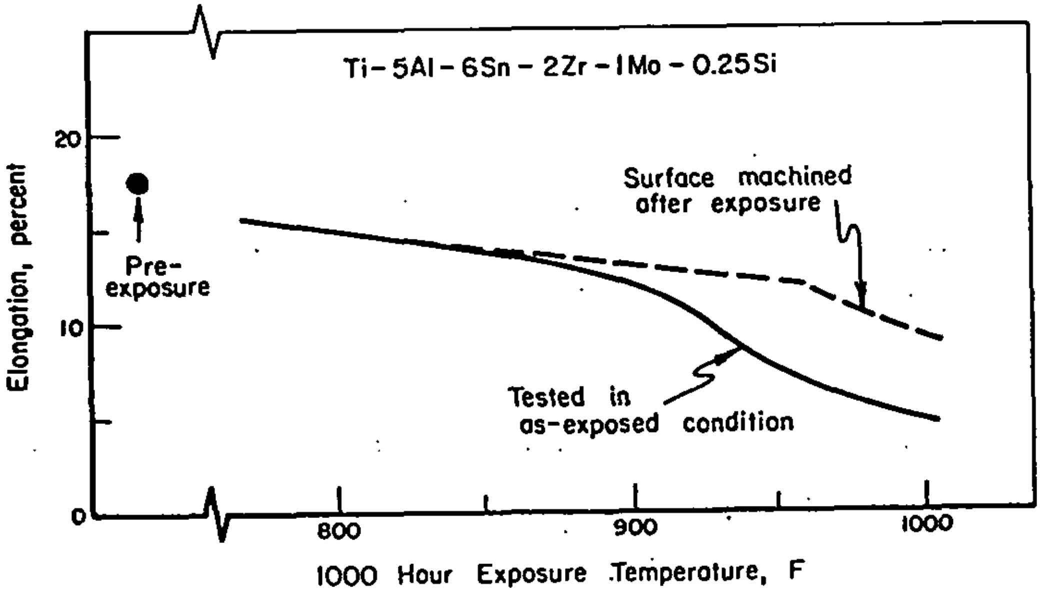


Figure 8. Effect of Creep Exposure on the Post-Exposure Tensile Ductility of a Super-Alpha Titanium Alloy with and without the Exposed and Oxidized Surface Layer Removed

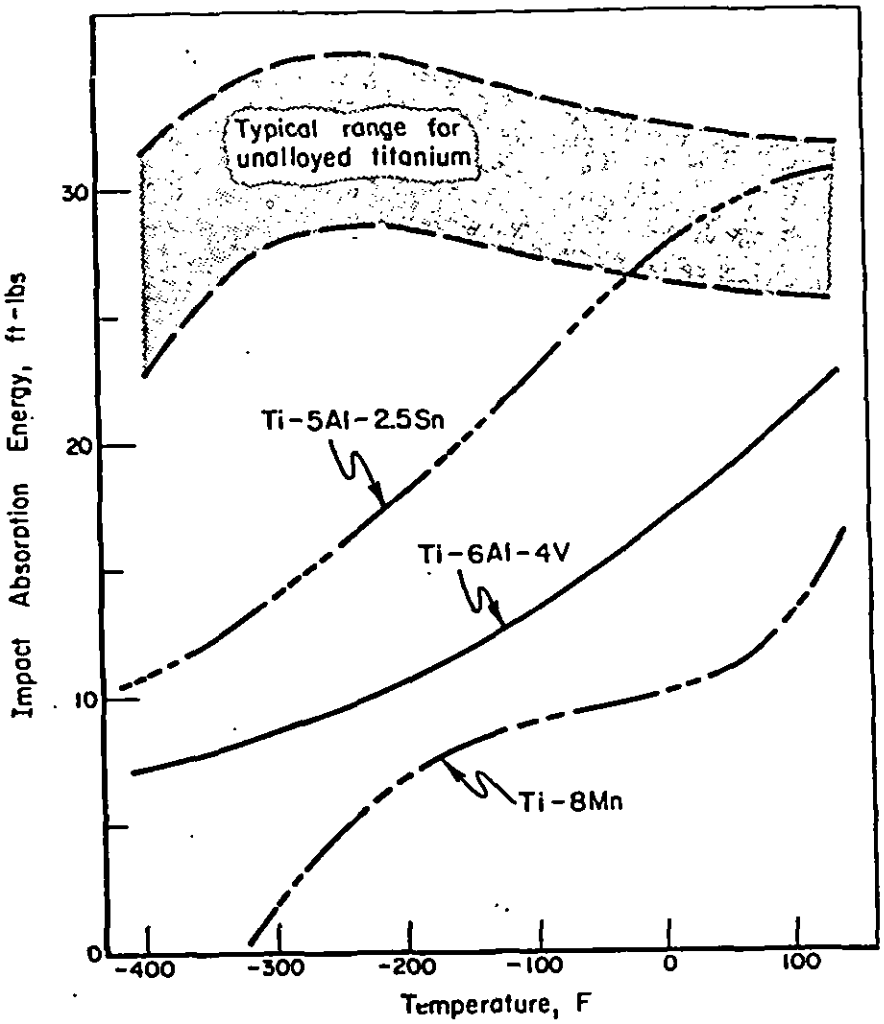


Figure 9. Effect of temperature on the Charpy V–Notch Toughness of Unalloyed Titanium (Various Grades) and Three Alloys in the Annealed Condition

not been possible to control all the variables to obtain entirely consistent results with some of the more sophisticated static crack propagation type fracture toughness tests. For example, a large number of specimens taken from numerous heats of annealed bars, plates, and forgings of Ti-6Al-4V alloy gave the fracture toughness-tensile yield strength data of Figure 10. Compact tension and four point bending tests were used in generating these data. The large spread in toughness at a single strength level and the range of strength levels measured for the annealed condition are both possible as a result of the aforementioned material variables which may exist within the confines of specification limitations. Generally, low alloy chemistry tends to result in low strength-high toughness combinations, acicular microstructures tend to give the same result, and anisotropic textured materials yield results directly related to test specimen orientation. The overriding generalization that has been observed most consistently is that toughness tends to be inversely related to strength as illustrated by the scatter band trend lines of Figure 10.

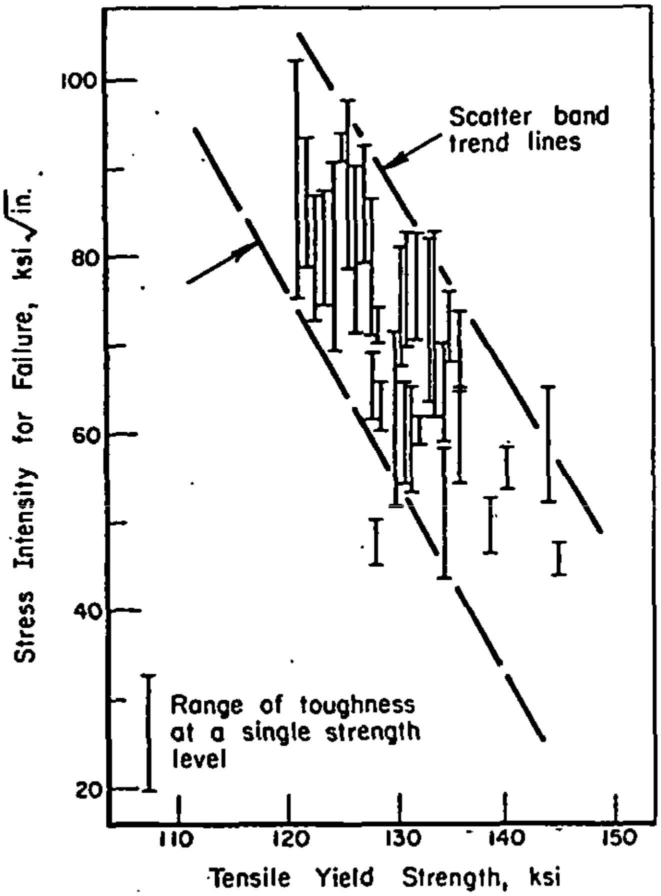


Figure 10. Fracture Toughness—Tensile Yield Strength Relationship Observed for Annealed Ti-6Al-4V Bars, Plates, and Forgings (within Specifications Limitations)

The typical fracture toughness-tensile yield strength trend lines for several alloys are shown in Figure 11. The data are for annealed Ti-5Al-2.5Sn, Ti-8Al-1Mo-1V, and Ti-5Al-6Sn-2Zr-1Mo-0.2Si, alloys and solution heat treated plus aged (STA) Ti-6Al-2Sn-4Zr-6Mo, Ti-6Al-6V-2Sn, and the beta alloys. Both annealed and STA conditions are included in the trend line shown for the Ti-6Al-4V alloy. The excellent fracture toughness characteristics of the annealed materials at low to moderately high strength levels are a feature of titanium alloys generally. The toughness advantage of the beta alloys in the range of high strengths commonly obtained in the STA condition is not a feature of all beta titanium alloys (the Ti-13V-11Cr-3Al alloy has low fracture toughness in the STA condition), but is a feature for some of the newer beta alloys including the indicated compositions and the Ti-3Al-8V-6Cr-4Mo-4Zr alloy. The trend for decreasing toughness with increasing strength is again apparent in the data of Figure 11.

16. Fatigue Characteristics. The fatigue properties of titanium and its alloys, while being of the most importance in many applications, are seldom if ever described in specifications. Possibly this is because there are so many variables associated with the fatigue performance of a material that it is difficult to predict the behavior except within rather broad limits. The material variables affecting fatigue performance include chemistry, microstructure, and texture, and of

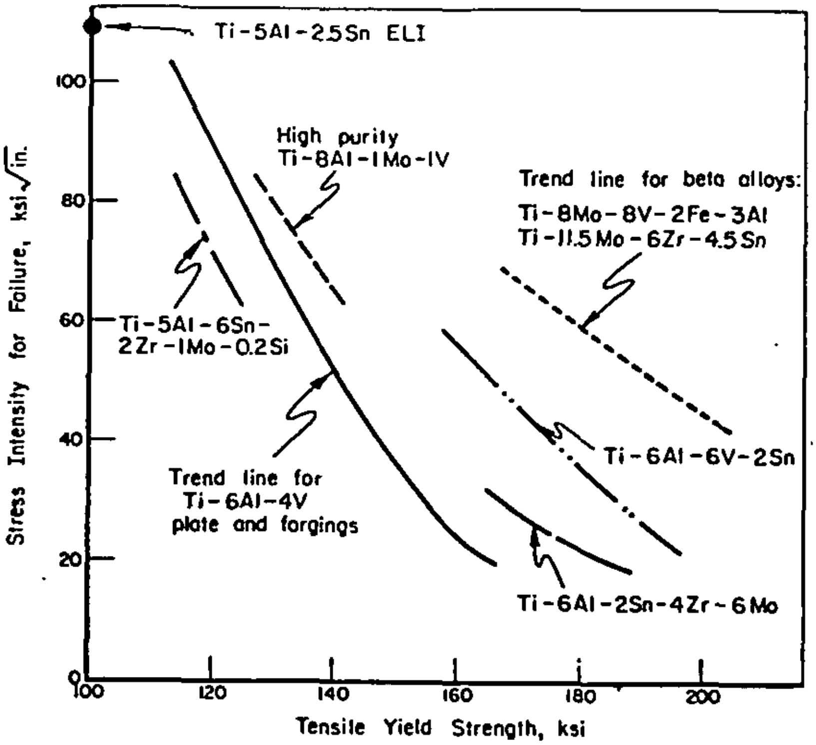


Figure 11. *Fracture Toughness—Tensile Yield Strength Trend Lines for Selected Titanium Alloys in the Annealed and Heat Treated (STA) Conditions.*

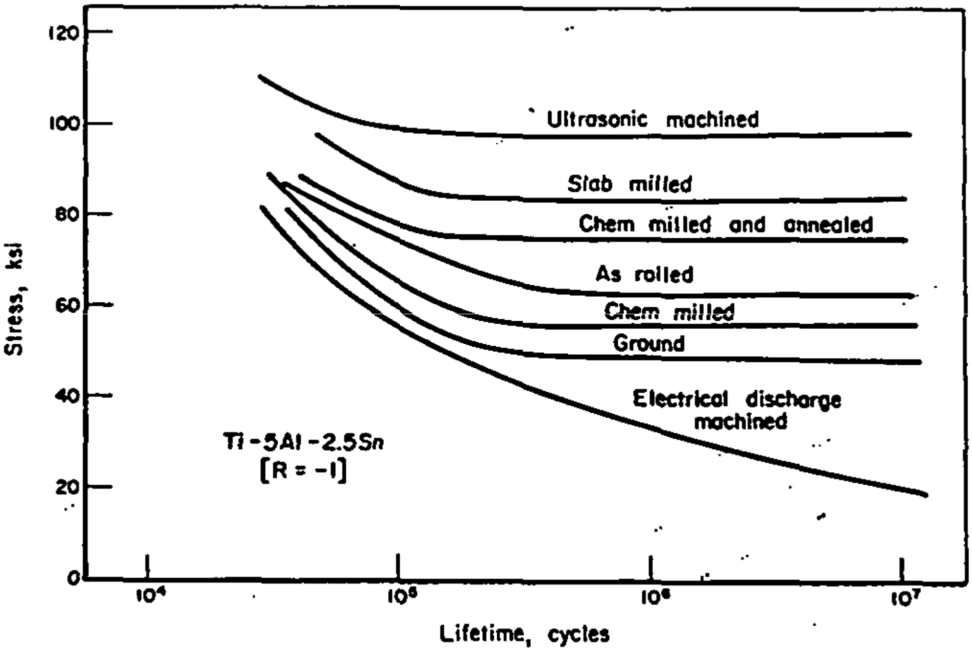


Figure 12. Effect of Surface Finish on the Room Temperature Rotating Beam Fatigue Behavior of Ti-5Al-2.5Sn Alloy

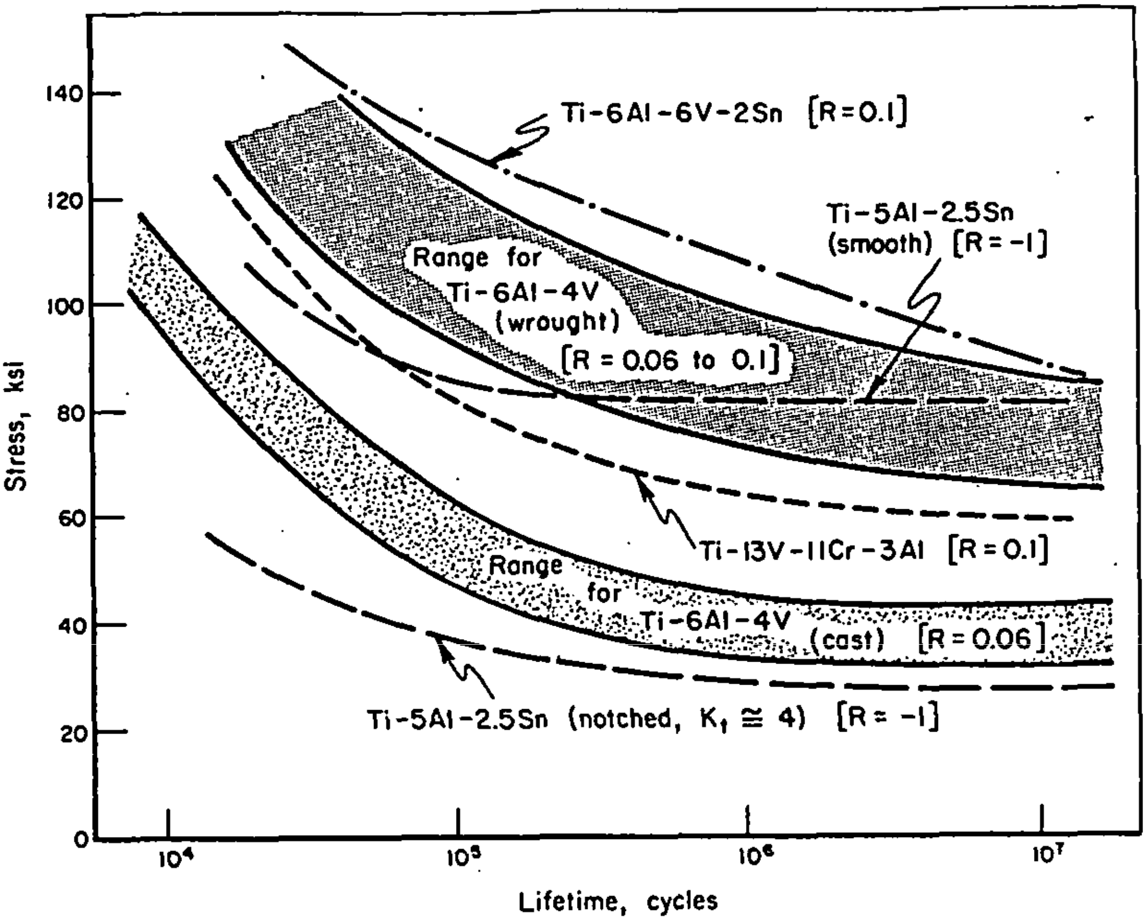


Figure 13. Typical Room Temperature Fatigue Characteristics of Selected Titanium Alloys

course, these are controlled during the make-up and processing of titanium alloys. In addition to the material factors, fatigue performance is determined by surface conditions of the material, environmental factors, and of course specimen geometry and the test variables. To afford some idea of the influence these factors bring to bear, the range in fatigue strength observed for Ti-5Al-2.5Sn alloy surface finished in a variety of ways is depicted in Figure 12. Shop peening or glass-bead peening to optimum surface conditions can be used to alleviate the bad effects induced by some of the surface conditions illustrated.

The typical fatigue behavior observed in tension-tension and rotating beam tests for selected titanium alloys is shown in Figure 13. Some of the stress-lifetime cycle curves are comparable (same kind of tests) and indicate relationships between alloys, notch-unnotch (smooth) test geometries, and product forms. For example, the superior fatigue strength of Ti-6Al-6V-2Sn and Ti-6Al-4V alloys over the Ti-13V-11Cr-3Al beta alloy is indicated. Note the range depicted for various mill product forms and annealed microstructures of Ti-6Al-4V alloy. The effect of a moderately sharp notch on reducing the fatigue strength of Ti-5Al-2.5Sn illustrates generally the degradation in strength induced by stress risers. The large difference between the fatigue strength of wrought forms and cast forms of Ti-6Al-4V alloy, both in the smooth condition, is readily apparent. The notched geometry for both wrought and cast forms of Ti-6Al-4V alloy result in

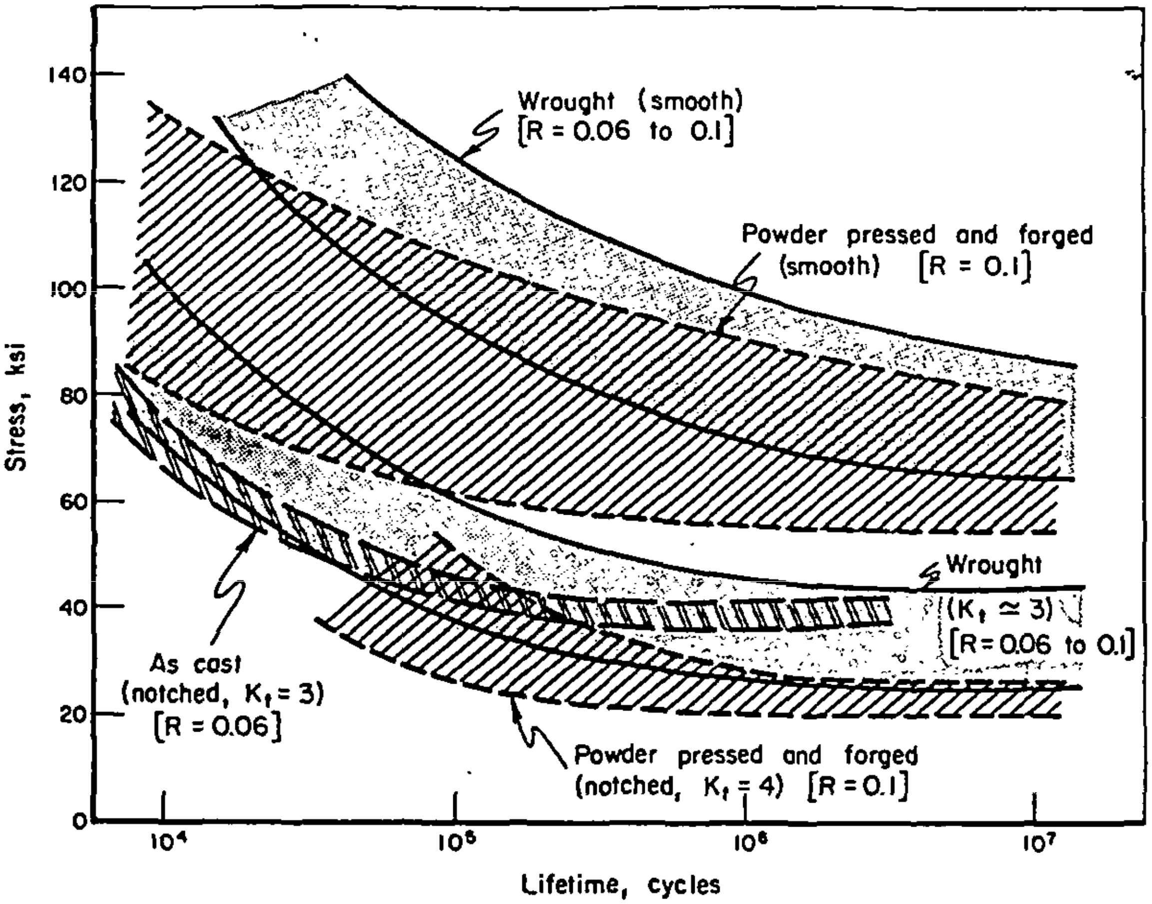


Figure 14. Ranges in Fatigue Behavior Observed for Various Forms of Ti-6Al-4V Alloy

essentially the same strength range as shown by the curves of Figure 14. In this figure, the notched and smooth fatigue strength ranges for alloy produced by powder metallurgy techniques are also shown. The range for the notched condition is basically comparable with the ranges for notched wrought and notched cast materials (the powder product specimens have a somewhat sharper notch to result in slightly lower fatigue strength). The range for smooth specimens produced by powder metallurgy is somewhat inferior to the range for wrought products although superior to the range for cast Ti-6Al-4V alloy. It should be understood that the data summarized are those for a powder metallurgy product that has been additionally forged to further densify and optimize the microstructure. Powder metallurgy products that are not densified by forging (or other metalworking techniques) do not have as good fatigue strength as the consolidated products.

17. Comparison of Properties of Various Products. The room temperature tensile properties and the —40 F Charpy impact properties of selected titanium alloys are given in Table XXIII. Typical data are given for wrought, cast, and powder metallurgy bars. As might be expected, the properties of the wrought material are superior to those of cast or powder forms in any of the alloys compared. Unalloyed titanium product prepared by any one of the techniques has quite good properties. The development of improved cast and powder metallurgy products and properties continues, so that the inferiority of such materials compared with wrought product becomes less pronounced. In many cases, the cost advantages available with cast or powder

TABLE XXIII. COMPARISON OF PROPERTIES REPORTED FOR POPULAR ALLOYS FROM WROUGHT, CAST, AND POWDER FORMS

| Nominal Composition wt % | Product Type | Remarks | Room Temperature Tensile Data: Ultimate Tensile Strength, ksi | Yield Strength, ksi | Elongation, % | Red. in Area, % | Charpy –40 F Impact Toughness, ft–lb |
|---|---|---|---|---|---|---|---|
| Unalloyed Ti | Wrought bar | Annealed | 80 | 70 | 18 | 33 | 26 |
| | Cast bar | As cast | 92 | 74 | 20 | 31 | 19 |
| | Pressed powder | Annealed[a] | 70 | 54 | 18 | 22 | –– |
| Ti-5Al-2.5Sn ELI | Wrought bar | Annealed | 118 | 103 | 19 | 34 | –– |
| | Cast bar | As cast | 115 | 105 | 10 | 17 | –– |
| | Pressed powder | Anneal and forge[b] | 115 | 104 | 16 | 27 | –– |
| Ti-6Al-4V | Wrought bar | Annealed | 145 | 134 | 16 | 34 | 16 |
| | Cast bar | As cast | 149 | 128 | 12 | 19 | 14 |
| | | Annealed | 147 | 129 | 10 | 16 | –– |
| | | STA[c] | 171 | 157 | 6 | 11 | –– |
| | Pressed powder | Annealed[c] | 120–127 | 107–114 | 5–8 | 8–14 | –– |
| | | Anneal and forge[b] | 134 | 122 | 12 | 27 | –– |
| | | STA[c] | 140 | 130 | 4 | 6 | –– |
| Ti-6Al-6V-2Sn | Wrought bar | Annealed | 163 | 153 | 16 | 38 | 15 |
| | Cast Bar | As cast | 160 | 140 | 6 | 11 | 10 |
| | Pressed powder | Annealed[a] | 140 | 122 | 5 | 5 | –– |

Note:
(a) About 94 percent dense.
(b) Almost 100 percent dense.
(c) Aging treatment not specified

TABLE XXIV. COMPARISON OF ROOM TEMPERATURE PROPERTIES REPORTED FOR SEVERAL FORMS OF Ti-11.5Mo-6Zr-4.5Sn ALLOY AS SOLUTION TREATED PLUS AGED
(8 Hour Aging at 950 F)

| Product Form | Thickness, inches | Ultimate Tensile Strength, ksi | Tensile Yield Strength, ksi | Tensile Elongation % | Fracture Toughness $K_{Ic}$ ksi$\sqrt{in.}$ | $10^7$–Cycle Fatigue Strength, ksi |
|---|---|---|---|---|---|---|
| Forging | 4.0 | 182 | 172 | 4 | 61 | — |
| | <1.0 | 193 | 185 | 5 | — | — |
| Plate | 2.0 | 186 | 182 | 4 | 57 | — |
| | 0.5 | 204 | 194 | 4 | 60 | 140 |
| Sheet | 0.063 | 205 | 195 | 5 | — | 82 |
| | 0.020 | 196 | 186 | 4 | — | 120 |
| | 0.010 | 201 | 192 | 3 | — | — |
| Foil | 0.002 | 227 | 213 | 2 | — | — |
| Extrusion | 0.27 | 186 | 169 | — | 48 | — |
| Tubing | 0.120 (wall) | 185 | 176 | 8 | — | — |
| | 0.050 (wall) | 180 | 169 | 6 | — | — |
| Bar | 1.188 | 210 | 201 | 8 | — | — |
| | 0.500 | 180 | 172 | 10 | — | 150 |
| | 0.196 | 185 | 170 | 18 | — | — |
| Wire | 0.063 | 195 | 184 | 15 | — | 150 |
| Casting | <1.0 | 173 | 160 | 7 | — | — |
| | <1.0 | 182 | 164 | 7 | — | — |

products are considerable so that potential applications should be carefully examined to determine if the slightly lower properties of these products might be profitably utilized.

The data of Table XXIV are for numerous wrought and cast forms of the Ti-11.5Mo-6Zr-4.5Sn (Beta III) alloy in the solution treated and aged condition. Tensile, fracture toughness, and fatigue data are given. Properties also are given for various product thicknesses where available. While the general uniformity of properties for various section sizes of any of the wrought products is apparent, the total range in properties for all wrought products is quite large as shown below.

180-227 ksi UTS, 169-213 ksi YS, 2-18% EL.

The range is broadened if the data for the cast products are included. A range in properties for various product forms is quite a common occurence for metals but is typically the case for titanium alloys. Thus, the user of titanium materials should be fully aware of the variations in properties that can pertain between product forms and examine the available data carefully prior to a material commitment.

TABLE XXV. DENSITY AND STRENGTH/DENSITY RATIOS TYPICALLY AVAILABLE IN TITANIUM ALLOYS

| Nominal Composition, wt % | Density lb/in.$^3$ | Typical Annealed/STA Yield Strengths, ksi | Typical Yield Strength to Density Ratios, inch x 10$^6$ |
|---|---|---|---|
| Unalloyed Ti (Medium Strength) | 0.163–0.164 | 60/— | 0.367/— |
| Ti-0.15 to 0.25Pd | 0.163 | 46/— | 0.282/— |
| Ti-2Cu | 0.165 | 90/115 | 0.545/0.697 |
| Ti-5Al-2.5Sn (also ELI) | 0.161 | 117/— | 0.726/— |
| Ti-2.25Al-11Sn-5Zr-1Mo-0.25Si | 0.174 | —/135 | —/0.776 |
| Ti-5Al-6Sn-2Zr-1Mo-0.25Si | 0.163 | 135/— | 0.828/— |
| Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si | 0.162 | 137/— | 0.846/— |
| Ti-6Al-2Cb-1Ta-0.8Mo | 0.162 | 120/— | 0.741/— |
| Ti-8Al-1Mo-1V | 0.159 | 142/— | 0.893/— |
| Ti-8Mn | 0.171 | 125/— | 0.731/— |
| Ti-3Al-2.5V | 0.162 | 85/110 | 0.525/0.679 |
| Ti-4Al-3Mo-1V | 0.163 | 120/167 | 0.736/1.024 |
| Ti-5Al-2Sn-2Zr-4Mo-4Cr | 0.168 | —/160 | —/0.952 |
| Ti-6Al-4V (also ELI) | 0.161 | 130/155 | 0.807/0.963 |
| Ti-6Al-6V-2Sn | 0.164 | 150/180 | 0.915/1.098 |
| Ti-6Al-2Sn-4Zr-2Mo | 0.164 | 135/— | 0.823/— |
| Ti-6Al-2Sn-4Zr-6Mo | 0.169 | 165/— | 0.976/— |
| Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si | 0.162 | —/160 | —/0.988 |
| Ti-7Al-4Mo | 0.162 | 150/175 | 0.926/1.080 |
| Ti-1Al-8V-5Fe | 0.168 | 165/215 | 0.982/1.280 |
| Ti-2Al-11V-2Sn-11Zr | 0.174 | —/180 | —/1.034 |
| Ti-3Al-8V-6Cr-4Mo-4Zr | 0.174 | 125/170 | 0.718/0.977 |
| Ti-11.5Mo-6Zr-4.5Sn | 0.183 | 115/185 | 0.628/1.011 |
| Ti-8Mo-8V-2Fe-3Al | 0.175 | 125/180 | 0.714/1.028 |
| Ti-13V-11Cr-3Al | 0.175 | 130/175 | 0.743/1.000 |

The density and strength-to-density ratio data presented in Table XXV represent an additional consideration when comparing the properties of titanium alloys. While densities for individual materials can vary slightly, for example with compositional differences from heat to heat, the values tabulated are the generally accepted values. The tensile yield strength values given (annealed and solution treated plus aged values) are representative for the materials and conditions shown and as previously described, can vary markedly due to a number of factors. Thus, the strength/density ratios given in Table XXV are merely representative. Nevertheless, the strength/density ratio affords a useful parameter for comparison purposes and in such terms density should always be one of the factors considered in selecting a titanium material for an application.

# SECTION III

# METALLURGY AND PROCESSING

## Metallurgical Information

18. Titanium Production Variables. The production of the basic titanium sponge metal from its primary ore (rutile) and the basic processing of sponge to finished mill products and castings was described earlier in Section I, Paragraph 3. While the previous description described the production of ingot and subsequent products in terms of the forms and dimensions available, it is appropriate at this point to describe in more detail the alloys available and the metallurgical factors of importance.

The alloys of titanium which are now commonly available to users are listed in Table II and additional tables. The compositions listed are nominal compositions and the actual compositions can vary over the ranges or below the maximum amounts of components given in specifications. Since titanium producers are subject to the external pressures of numerous company and public specifications, they find it frequently necessary to make several grades of some alloys to meet the many requirements of users including cost requirements. Thus, for many of the nominal compositions, several grades of the alloy are available, and in at least one case, that for the Ti-6Al-4V alloy, more than a dozen different grades can be found.

There are two primary factors controlling grades: ingot quality and alloy chemistry. Ingot quality has to do with such variables as input raw material and additional variables as described below.

- Input raw material (virgin sponge metal versus scrap)
- Kinds of scrap (laboratory control revert, massive scrap, turnings, etc).
- Ratio of scrap to virgin metal (in mixed material electrodes)
- Methods of making electrodes (pressed virgin metal versus welded scrap—welding of components in or out of vacuum)
- Melting controls (degree of vacuum, abnormalities in the melt cycle if any, double or triple melting of ingots)
- Degree of ingot testing (macro- and micrometallographic and chemical analyses from prescribed locations).

Surprisingly, there are only a few classifications for ingot quality resulting from all these variables. Those of interest to this description are: (1) Premium Grade, and (2) Standard Grade. As might be expected, both reliability and cost are higher with the premium grade of ingot. The ingot grades in turn may be subclassified in grade according to alloy chemistry.

Alloy chemistry is basic to grade control. In the case of the Ti-6Al-4V alloy where numerous grades are available, the variation of oxygen content is used as the primary control. For example, the ELI (for extra low interstitial content) grade of Ti-6Al-4V alloy has been mentioned. (ELI grades of alloy usually contain less than 0.13 percent oxygen). Other grades might have more oxygen (e.g. a standard grade or a high oxygen grade). Within the primary grades controlled by interstitial content, there are subgrades which differ from one another due to the control of the aluminum, vanadium, and iron contents. For example, Ti-6Al-4V alloy with high aluminum content (within specification range) might be prepared for thick section product or product to be solution treated plus aged to a high strength level. Thus by simply multiplying the variables of ingot quality and alloy chemistry, the availability of a large number of alloy grades for a given composition is apparent. The grade of an alloy is important with respect to particular properties and property combinations and these are further controlled by the mill processing and product form as well as by heat treatment procedures. It is therefore recommended, due to the foregoing, that users of titanium products should communicate with the producers to insure that the product supplied will meet the intended requirements.

## 19. Effects of Alloying Elements — Metallurgy and Microstructure.

a. General. An alloying element added to titanium has important effects upon the physical and mechanical characteristics of this metal. Each element that might be combined with titanium either intentionally or unintentionally, and in either small or large amounts, results in some degree of strengthening and in some change in the basic crystal structure. In this sense, even the commercial unalloyed grades of titanium are alloys, since each of the grades contain various quantities of the interstitial elements (carbon, oxygen, nitrogen, and hydrogen) and iron plus other metallic elements in measurable amounts. The iron and other metallic additions result in the solid solution strengthening of titanium. In addition, iron and selected other metallics can combine with titanium to form intermetallic compounds under thermal and saturation conditions when solid solution conditions are exceeded.

Another important alloying effect apart from the strengthening effect of additions to titanium, is the change induced in the polymorphous transformation temperature of the crystal structure. The transformation temperature from the hexagonal-close-packed form (hcp or alpha phase) to the body-centered-cubic form (bcc or beta phase) in pure titanium, occurs at about 1625 F (885C). The effect of alloying elements on titanium is to raise or lower the transformation temperature dependent upon the kind of alloying elements in solution. The amount of the element affects the degree of change. The interstitial soluble elements, carbon, oxygen, and nitrogen, and the metal aluminum, are examples of elements that raise the hcp to bcc transformation temperature. Iron, vanadium, chromium, molybdenum, and manganese, are examples of elements that markedly lower the transformation temperature. Tin and zirconium tend to lower the transformation temperature only slightly (e.g. tin lowers the hcp to bcc transus temperature 1F/1%) and such elements are often referred to as neutral stabilizers.

The ability of elements to distort the crystal structure of titanium to cause strengthening or to cause changes in the polymorphous behavior varies from element to element and is the basis of titanium alloy metallurgy. Metallurgists are continually experimenting with alloying elements to obtain improved titanium alloys with consistent and predictable properties. Elements that raise the hcp-bcc transus (alpha stabilizers), or those that lower the transus (beta stabilizers), and combinations of such elements have been used to develop alpha, beta, and alpha-beta alloys — so-called because their microstructures are predominantly of these phases at room temperature.

b. Alpha Alloys. The commercial unalloyed grades of titanium are technically alpha alloys as is the alloy of titanium containing small amounts of palladium added to improve corrosion resistance. The Ti-5Al-2.5Sn alloy is the best example of a high strength alpha alloy that has commercial status. The amount of tin included in the make-up of Ti-5Al-2.5Sn, as well as the small amounts of iron and other beta stabilizers that might be present as impurities, is insufficient to override the dominant effect of the aluminum alpha stabilizer alloyed at the 5 percent level. This alloy may be characterized as having a hcp alpha microstructure at ambient temperature and of course due to the alloying additions, moderately high strength compared to unalloyed titanium.

Two notable features of alpha alloys are: a good retention of strength at elevated temperature under low strain rate conditions, and good weldability. Also, alpha alloys show little strain rate sensitivity. There are numerous applications where these attributes are of great importance. The high strength at elevated temperature feature of the more highly aluminum alloyed alpha compositions can be somewhat disadvantageous from the viewpoint of a more limited fabricability compared with mixed two-phase alpha-beta alloys and beta compositions. This difficulty can be alleviated by additions of neutral stabilizers and small amounts of beta stabilizers to afford extremely useful compositions.

c. Near-Alpha Alloys. As previously mentioned, the commercial alpha titanium alloys contain some beta-stabilizing elements although these are frequently in alpha soluble quantities. The microstructures of such materials may or may not include small observable quantities of the beta phase. Additional but still small quantities of beta stabilizers to an alpha stabilized base result in the presence of larger quantities of the beta phase in the predominant alpha structure. Such additions not only promote a small amount of beta phase retention but alter the mechanical characteristics of the alloy as well. Depending upon the amount and kind of beta stabilizers used, strength, stability, and fabricability may be improved in comparison with all alpha compositions of the same alpha stabilized base. Alpha alloys modified with relatively small amounts of beta stabilizers are frequently referred to as near-alpha alloys.

A small but critical amount of an intermetallic-compound-forming addition to molybdenum-containing near-alpha alloys has been found to have a synergistic effect on creep strength. Boron, germanium, bismuth, and silicon behave similarly as the compound forming element in such alloys but the latter has been used most extensively in near-alpha compositions (also called super-alpha alloys). Since an intermetallic compound such as $Ti_5Si_3$, complex intermetallics, can form in these materials and can be observed in the microstructures as a dispersed precipitate phase, the term alpha-dispersoid alloy is also sometimes applied. Alloys of this class are almost exclusively for service in gas turbine engines having as their principal attribute significantly higher creep strength than an all-alpha or a near-alpha alloy of the same base composition. The alloys of this class also have been developed to maintain other useful features including high short-time elevated temperature strength, adequate ductility, and stability during and after thermal excursions.

The Ti-1 to 2 Ni and Ti-2Cu alloys are the commercial representatives of yet another type of alpha-dispersoid composition. The intermetallic compound forming elements, nickel and copper, are used in a titanium base that is not fortified with additions of aluminum, tin, or zirconium. The titanium-nickel alloy is made exclusively for its good corrosion resistance. The titanium copper alloy is made for uses requiring the formability and weldability of unalloyed titanium combined with an improved elevated-temperature strength requirement. The intermetallic compounds, $Ti_2Ni$ and $Ti_2Cu$, are usually observed as a fine precipitate phase randomly dispersed in an alpha microstructure. This is generally the form of occurrence of the intermetallic compounds that can precipitate under certain thermal conditions when the so-called beta-eutectoid stabilizers are alloyed with titanium. Elements of this type include bismuth, silicon, iron, manganese, and chromium, as well as nickel and copper. The alloying characteristics of these elements in titanium is the lowering of the hcp-bcc transformation temperature (called the beta transus temperature), limited solubility in the alpha phase, and propensity to form intermetallic compounds.

d. *Alpha-Beta Alloys.* As mentioned previously, one type of beta stabilizer is called beta-eutectoid stabilizers because they have eutectoid behavior when alloyed with titanium and are compound formers. Another type of beta stabilizers is called beta-isomorphous stabilizers because they are soluble in beta titanium over the full range of the alloy system. Elements of this type do not form compounds and include molybdenum, vanadium, columbium, and tantalum. Alpha-beta titanium alloys result when sufficient beta-stabilizers of either type are added to a base composition to cause quantities of the beta phase to persist to room temperature. The base composition may or may not contain alpha stabilizers although the commercial alpha-beta titanium alloys usually do—an exception is the Ti-8Mn composition. A two phase alpha plus beta microstructure is characteristic, although a large variation in the appearance of the structure, due to various deformation and thermal processing techniques, can make the interpretation of microstructures difficult.

The mechanical characteristics of alpha-beta titanium alloys are highly dependent upon the combination of alpha-stabilizers and beta stabilizers used in their make-up as well as upon processing history. Aluminum is frequently used as the alpha stabilizer which among other features contributes to the strength of the alloy over the full service temperature range. Commercial alpha-beta alloys usually contain considerable quantities of the beta isomorphous elements, molybdenum or vanadium, which impart stability as well as strength at high temperatures. The addition of beta-eutectoid stabilizers also imparts strength although their use in large quantities can result in instability due to the inappropriate precipitation of compound.

In general terms, the amount of alloy addition in alpha-beta alloys is relatable to strength level. For example, the Ti-6Al-4V alloy is considerably stronger than the Ti-3Al-2.5V alloy. Similarly, alpha-beta alloys with increasing amounts of beta stabilizing addition are inherently stronger in short-time tensile testing and due to the larger beta content, are heat treatable to higher strengths. For example, the short-time strength and the heat treatability of the Ti-6Al-6V-2Sn alloy is greater than Ti-6Al-4V. Also, Ti-6Al-2Sn-4Zr-6Mo is stronger and more responsive to heat treatment than Ti-6Al-2Sn-4Zr-2Mo. (The latter alloy is also frequently considered a near-alpha alloy and serves to show the relationship between near-alphas and weakly beta stabilized alpha-beta alloys.) However, if the low strain rate performances of these materials are compared, as in creep for example, the Ti-6Al-4V alloy is shown to be better than Ti-6Al-6V-2Sn and the Ti-6Al-2Sn-4Zr-2Mo outperforms Ti-6Al-2Sn-4Zr-6Mo.

In addition to the strength and heat treatability features characteristic of alpha-beta alloys, this class can be characterized as having good fabricability, good ductility and stability commensurate with preferred strength levels and exposure conditions, and marginal weldability except when the beta stabilizing content is low. For example, Ti-3Al-2.5V, Ti-6Al-4V, and Ti-6Al-2Sn-4Zr-2Mo alloys are weldable whereas weldability is not recommended for the Ti-6Al-6V-2Sn, Ti-6Al-2Sn-4Zr-6Mo, Ti-4Al-3Mo-1V, and Ti-8Mn alloys. The heat treatment of alpha-beta alloys is discussed further in a subsequent section.

e. Beta Alloys. Increasing quantities of the beta stabilizing elements added to a titanium base have been described to result in increasing amounts of the beta phase in the micro-structure and to afford alloys of the classes: alpha (trace to small amounts of beta stabilizers), near-alpha (small amounts of beta), and alpha-beta (weakly beta stabilized to strongly beta stabilized compositions). Larger amounts of beta stabilizing additions result in up to 100 percent beta phase retention to room temperature and the alloy class—beta. The commercial beta titanium alloys are so-called metastable beta compositions since the partial transformation of the beta phase to alpha phase, to an intermediate phase (omega), or to intermetallic compound phase, can occur during thermal exposure. In fact, the precipitation of these phases during the heat treatment of the betas is the reaction relied upon to result in the high strengths characteristic of metastable beta alloys. Metastable beta titanium alloys have been used in airframes (e.g. Ti-13V-11Cr-2Al sheet and forgings in the SR-71) and for such specialty items as springs and fasteners. Titanium alloys with larger amounts of beta stabilizers to result in stable beta microstructures are possible but are not currently utilized as commercial materials.

In addition to the heat treated high strength characteristic of beta alloys, the excellent ductility of the nonheat-treated beta phase is a notable feature. The highly ductile beta phase has great cold workability which permits excellent room temperature formability. The alloys also can be formed at elevated temperatures where their deformation resistance is very low when the strain rate is low but high when strain rate is high. In short, the beta alloys are strain rate sensitive. Thus, as with richly beta stabilized alpha-beta alloys, short-time elevated temperature strengths of betas are high, whereas creep strengths are low compared with alpha or near-alpha alloys.

The weldability of beta titanium alloys is not considered outstanding. The betas are quite weldable from the annealed condition and are very ductile as welded. However, the annealed condition is a low strength condition and attempts to strengthen welded material by heat treatment usually result in very low ductility of weldments. Combinations of post-weld heat treatment and deformation, if amenable to the welded part, can improve the weld ductility although it is not a commonly used procedure.

f. Synopsis. There are basically two classifications of the alloying elements that might be combined with titanium: (1) alpha stabilizing additions, and (2) beta stabilizing additions. The alpha stabilizing elements which promote the alpha phase are principally represented by aluminum and by the interstitially soluble elements, carbon, oxygen, and nitrogen. The beta stabilizing elements which promote retention of the beta phase are represented by the so-called beta isomorphous elements such as molybdenum and vanadium by the beta-eutectoid stabilizers (intermetallic compound formers) such as iron, manganese, chromium, and silicon, and the so-called neutral stabilizers, tin and zirconium that tend to lower the beta transus temperature only slightly. Singly or in any combination, these additions tend to strengthen titanium, to promote other mechanical, physical, and metallurgical characteristics, as well as to control basic microstructures. These effects are summarized in Figure 15 where the highly schematized microstructures of the various alloy classes are approximately correlated with exemplary commercial compositions and trend lines of major significance.

20. Effects of Processing and Heat Treatment Variables. Mill products of many types are produced by the hot fabrication of ingots or cast preforms using a wide variety of reduction schedules and methods. The variations in the reduction schedules and associated processing variables (e.g. cooling rate from processing temperatures and post-fabrication heat treatment) result in a wide variety of microstructural conditions which, as might be expected, are characterized by different mechanical properties. Processing variables are interrelated with alloy composition variables in determining microstructure and property differences.

To illustrate the typical fabrication schedules for titanium alloys in terms of thermal history and to show their correlation with resulting microstructures and properties, the case for the Ti-6Al-4V alloy is described. It should be understood that an idealized and highly simplified case

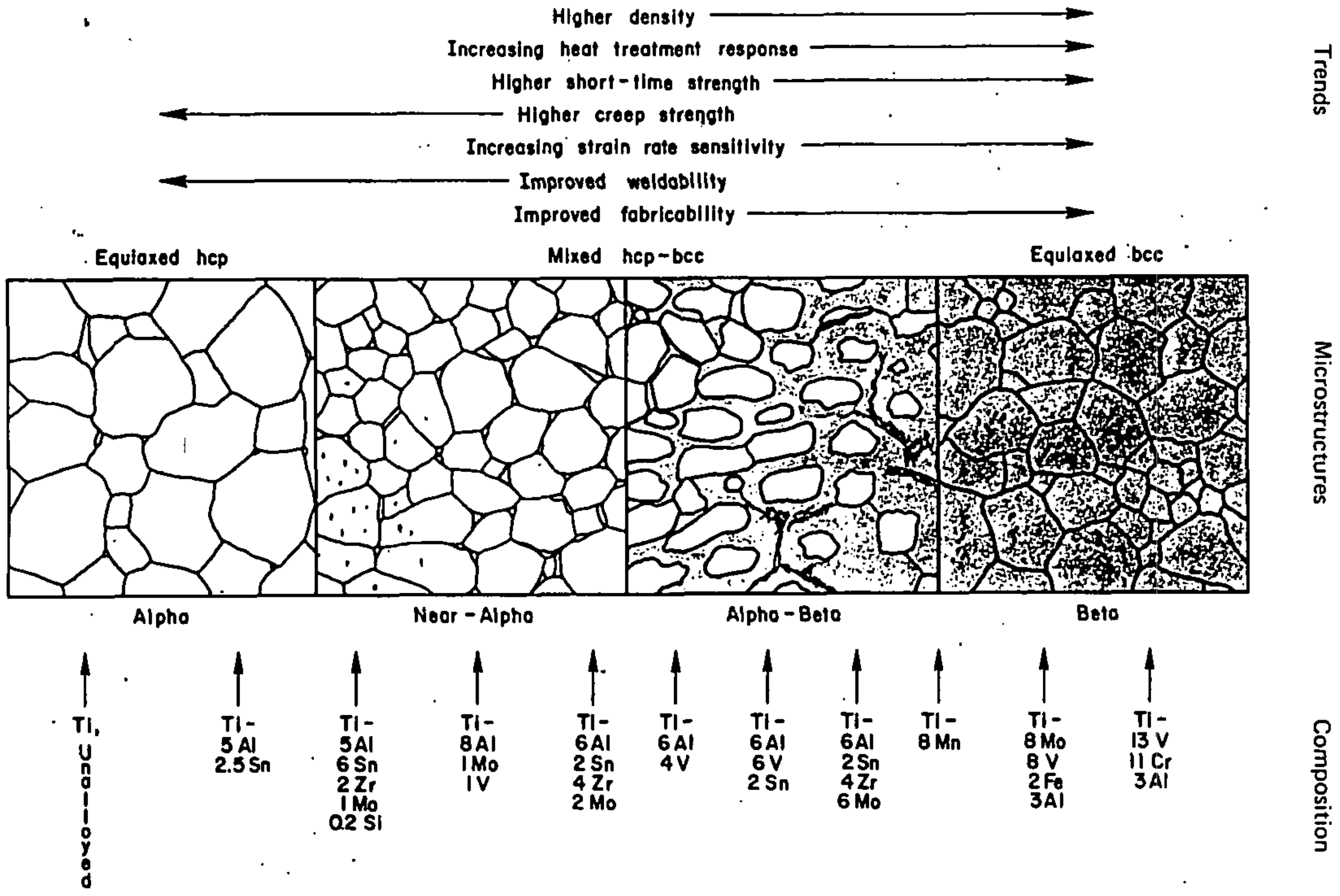


Figure 15. Correlation of Titanium Alloy Class with Schematic Equilibrium Microstructures, Major Property Trends and Compositions

is presented since it is impossible in a short space to depict all the variables and variations which actually occur. Also, the alloy variable should be apparent—the Ti-6Al-4V alloy would be processed differently and behave differently than dissimilar compositions.

The case for the Ti-6Al-4V alloy is shown schematically in Figure 16. The line drawing of this figure is a partial phase diagram of the Ti-6Al-V system wherein the points on the vertical through the 4 percent vanadium composition represent significant temperatures of processing and heat treatment. Representative microstructures are depicted from selected temperatures.

Normal breakdown fabrication operations for Ti-6Al-4V alloy usually are performed above the beta transus temperatures (e.g. point A in Figure 16) whereas finishing fabrication temperatures can be high in the alpha-beta field (point B) to low in the alpha-beta field (point C). Subsequent mill annealing (and sometimes fabrication) may be carried out at still lower temperatures (point D). Solution heat treatment of Ti-6Al-4V alloy may be accomplished in the alpha-beta field (ranging between points B and C) whereas subsequent aging is done at a much lower temperature (point E). The microstructures shown for various temperatures and cooling rates of processing are generalized and in practice can vary considerable from those depicted (e.g. variation with degree of deformation at the indicated temperature and/or prior processing history). Nevertheless, the illustrations show the major differences in structure resulting from beta processing versus alpha-beta processing versus alpha-beta processing and such differences in the alpha to beta phase ratio that might be obtained by fabrication at different temperatures within the alpha-beta field. Processing at increasing temperatures within the alpha-beta field gives rise to decreasing amounts of primary equiaxed alpha in the microstructures. Extensive processing moderately low in the alpha-beta field followed by simple annealing at still lower temperatures results in an equiaxed alpha plus grain-boundary beta microstructure as illustrated. The alpha phase is the continuous phase under these conditions. Heat treatments at still lower temperatures, that is at aging or overaging temperatures, result in microstructural transformations that may vary in extent with the thermal exposure conditions and are sometimes difficult to detect visually. Profound changes of a microscopic and submicroscopic nature do not occur however, that can be observed with magnification, and generally consist of precipitate phases emanating from preexisting phases. Classically, alpha phase precipitates from the metastable beta phase.

The acicularity of the transformed beta microstructure is an important feature of many titanium alloys and processing procedures. The platelets or needles of the alpha phase occur as the beta phase transforms to alpha with the lowering of temperature and the resulting acicularized structure may have quite different properties than equiaxed structures. Note in Figure 16 that in structures emanating from high in the alpha-beta field, a mixture of equiaxed alpha (called primary alpha) and acicular alpha (called alpha prime, $\alpha'$) is observed. The acicular alpha is also referred to as martensitic alpha and is the transformation product from the beta phase which existed at the solution temperature (point B of Figure 16).

The coarseness of acicular alpha that forms from either beta processing or alpha-beta processing is related to cooling rate. Decreased cooling rates result in coarse acicular structures. If the processing of Ti-6Al-4V and other similar alpha-beta alloys has included relatively little or no work in the alpha-beta field, and if it is subsequently annealed low in the two-phase region, the structure reflects the prior beta and transformed beta structures developed during the processing above, passing through, and just below the beta transus temperature. If extensive working of the alloy occurs in the alpha-beta field, the structure is altered from the predominant transformed beta structure to one consisting of a mixture of equiaxed primary alpha and either a transformed beta (working high in the alpha-beta field) or a metastable beta (working low in the alpha-beta field) microstructure.

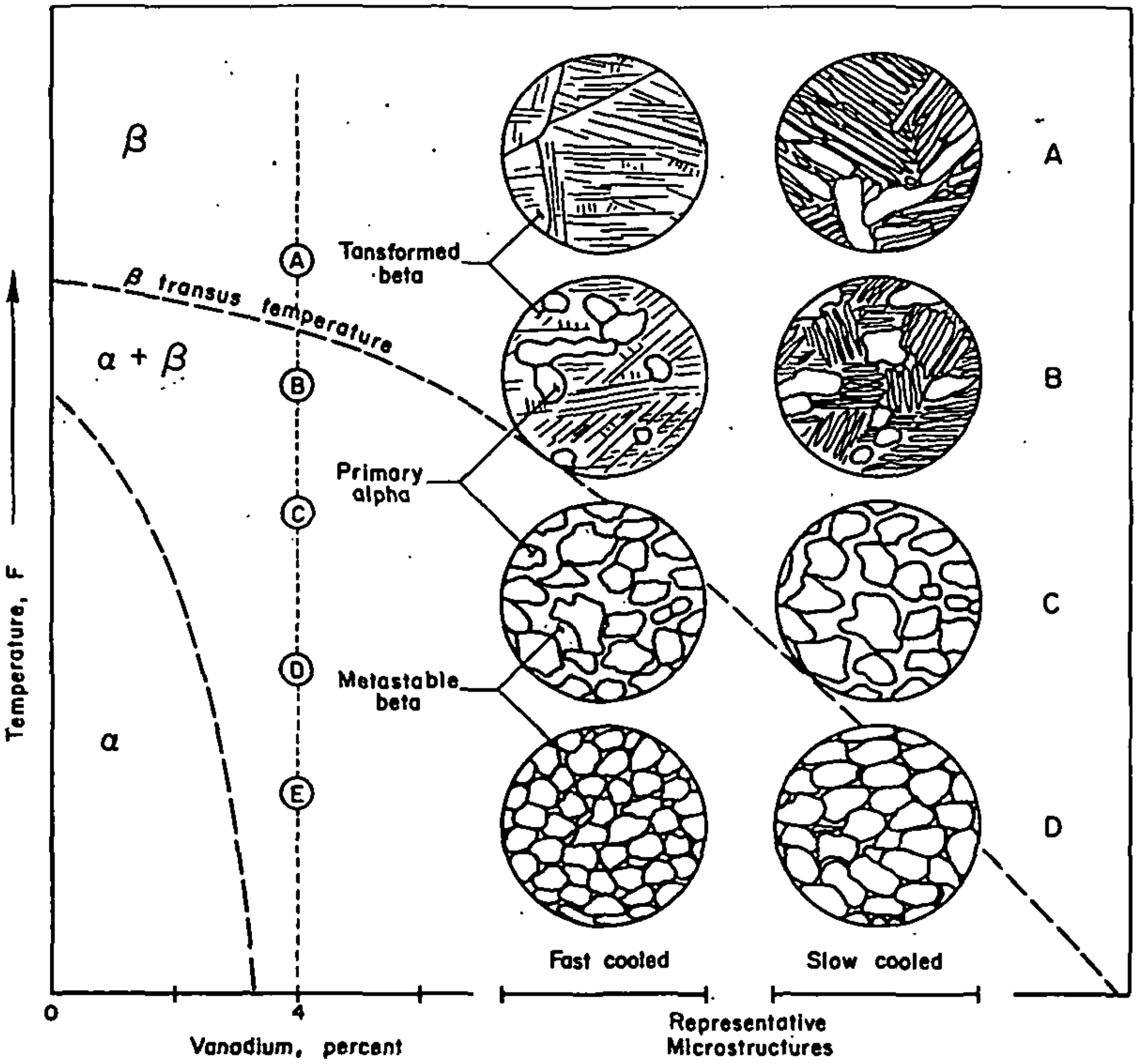


Figure 16. Partial Phase Diagram of the Ti-6Al-V System and the Schematic Representation of Microstructures Resulting from the Fabrication of Ti-6Al-4V Alloy at Various Temperatures

Currently, the fabrication of many alloys, principally near-alpha and alpha-beta types, is accomplished using either alpha-beta fabrication or beta fabrication schedules. As the names imply, the schedules differ principally in the fabrication temperatures used. Alpha-beta processing, while usually including beta temperatures for breakdown fabrication, features finish fabrication (preferably at least 50 percent reduction) in the alpha-beta field. Beta processing features extensive work in the beta field, resulting in a predominantly acicularized microstructure, with some limited fabrication at temperatures below the beta acicularized microstructure, with some limited fabrication at temperatures below the beta transus which is insufficient to cause the formation of much equiaxed primary alpha. The two main advantages of alpha-beta processing are: (1) oxidation rates are lower at alpha-beta temperatures than at beta temperatures, and (2) alpha-beta microstructures have long been equated with maximum tensile yield strength and ductility. The advantages of correct beta processing (*incorrect beta processing can be deleterious to properties*) include: (1) lower fabrication energy requirements for a given part size or production of larger part size with the same fabrication energy and equipment, (2) closer part dimension tolerances which may be related to substantial material savings, and (3) improvement of important mechanical properties. A summary of the properties observed for the Ti-6Al-4V alloy as beta processed (relative to alpha-beta processing) are shown below.

| Property | Beta Processing Effect |
|---|---|
| Tensile yield strength | Slightly lower |
| Ultimate tensile strength | Same |
| Tensile elongation | Slightly lower |
| Tensile reduction in area | Reduced |
| Notched tensile strength ($K_t = 10$) | Improved |
| Notched-time-fracture strength ($K_t = 3.8$) | Improved |
| Creep strength | Improved |
| Creep stability | Same |
| Fatigue strength (at $10^7$ cycles) | Same |
| Fracture toughness | Improved |

The amount of reduction during metalworking, the reduction temperatures, the temperature holding time, and the cooling rates are the important variables that control microstructures and subsequently mechanical properties. The processing steps may be distinctly categorized for the various mill product forms, i.e., forgings, bar, plate, sheet, strip, or extrustions. However, there are variables within these variables, such as: initial ingot size (relative to reductions achievable for a specific end-item thickness), planned or unplanned beta processing versus alpha-beta processing, final end-item section size, and variations in microstructure and texture associated with each processing history. The directionality effects stemming from various degrees of texturing are well known to be different in continuously rolled strip than in forgings, for example, and to be somewhat controllable through control of processing variables. The morphology of microstructure, beta grain size, and primary alpha grain size and shape (important with regard to fracture toughness and saltwater stress-corrosion susceptibility), are similarly controllable to a large extent through process control. Each variable, interacting with possibly one or more additional variables, can give rise to rather wide differences in mechanical properties. In addition to the above variables, the variables of secondary processing mill products to finished parts via bending, stretching, twisting, machining, and pickling operations must be considered with regard to their possible influence on final properties.

The variables of final heat treatment are imposed on the processing variables introduced earlier. Heat treatment procedures are the "last chance" for the titanium user to control mechanical properties and of course the extent of heat treatment property control is somewhat limited by the prior processing. While heat treatments have been developed to somewhat neutralize the effects of earlier occurring variables, some are more difficult to neutralize than others. Further, the variables *of the various heat treatment techniques and schedules are influential in themselves toward effecting* property variation. Thus, relative to the mechanical properties available for Ti-6Al-4V alloy as obtained in a specific condition of heat treatment, the entire gamut of possible variables may have influenced the properties observed (and in addition, the testing variables). Therefore, consideration for all variables and their effects should be given in the review and study of properties obtainable with selected heat treatments. A review of the heat treatments being used for Ti-6Al-4V alloy follows:

- Stress relief annealing
  (2 to 4 hours at 1100 F, air cool to room temperature)
- Full annealing (or mill annealing)
  (2 hours, 1350 ±25 F, air cool to room temperature)
- Annealing for continuously rolled sheet
  (5 minutes, 1600 F, Rapid furnace cool, plus 5 minutes 1100 F, air cool to room temperature)
- Recrystallization annealing
  [4 or more hours, 1700 F, furnace cool to 1400 F at 100 F/hour (no faster), cool to 900 F at 670 F/hour (no slower), air cool to room temperature]
- Duplex annealing
  (10 minutes 1725 F, air cool, plus 4 hours, 1250 F, air cool to room temperature)
- Beta annealing [or beta conditioning followed by other heat treatments]
  (30 minutes, 1900 F, air cool, plus 2 hours, 1350 F, air cool to room temperature)
  [30 minutes, 1900 F, air cool, followed by solution treating and overaging.]
- Solution heat treatment
  (10 minutes, 1725 F, water quench)
- Solution heat treatment and overaging
  (10 minutes, 1725 F, water quench, plus 4 hours, 1250 F, air cool to room temperature)
- Solution heat treatment and aging
  (10 minutes, 1725 F, water quench, plus 4 hours, 950-1000 F, air cool to room temperature)

The general effects of the various heat treatments are as follows: annealing heat treatments result in moderately low strength but ductile material; the specialized annealing heat treatments—i.e., recrystallization annealing, duplex annealing, and beta annealing—result in nearly the same strength and ductility combinations as from annealing but with improved fracture toughness characteristics; and the solution heat treatment plus aging heat treatments result in improved strength with some sacrifice in ductility and toughness. Overaging heat treatments result in less strength but in more ductility and toughness than aging heat treatments. The difference between overaging and aging heat treatments on the hardness of Ti-6Al-4V alloy (directly relatable to tensile strength) is illustrated in Figure 17. (Overaging treatments tend to produce more precipitate than aging treatments, and in different form and distribution, to account for differences in properties.) Beta heat treatments given as preliminary treatments tend to lower strength and ductility but to improve toughness. Solution heat treatment, per se, results in a ductile condition suitable for forming and/or subsequent aging but is usually not used as a final heat treatment for a serviceable part.

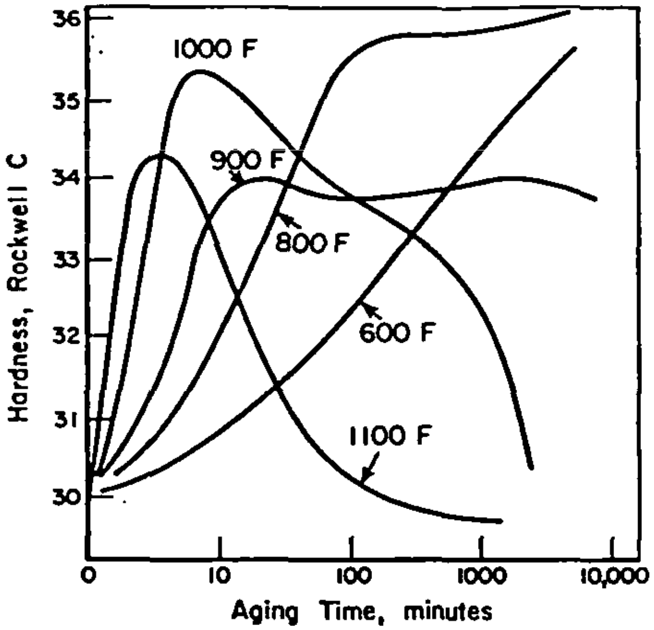


Figure 17. Effect of Aging Time and Temperature on the Hardness of Ti-6Al-4V Alloy Solution Annealed at 1562 F and Water Quenched

While it is not possible to describe the fabrication and heat treatment variables that exist for all commercial alloys, it is hoped that the features detailed for the Ti-6Al-4V alloy can be viewed as an exemplary case. Many of the principles described pertain to numerous other materials and can be directly applied. On the other hand, sufficient differences exist between Ti-6Al-4V alloy and alpha alloys (e.g. alpha alloys are not heat treatable) or beta alloys (e.g. beta alloys are routinely beta fabricated and seldom show primary alpha in structures) so that the careful review of the metallurgy of each grade to be used should be undertaken prior to using them.

## Heat Treatment Processes

21. Heat Treatment Requirements. Generally, heat treating procedures are used to obtain desired properties within the limitations of the respective titanium alloys, mill product forms, sizes, and prior metallurgical conditions imposed by prior processing. The requirements for control of heat treating processes, as applied to titanium and titanium alloys in manufacturing and maintenance facilities, are covered by Specification MIL-H-81200A, "Heat Treatment of Titanium and Titanium Alloys". This specification is currently being studied to determine the extent of revisions to be made, since it currently does not contain information on all titanium alloys listed in major materials specifications such as MIL-T-9046 and MIL-T-9047 and others such as some newer AMS specifications. In addition, MIL-H-81200A presently describes heat treatments for quite a few alloys that are no longer in production and/or used. Nevertheless, this specification describes the minimums acceptable for such items as temperature measuring equipment, furnaces, heating media, fixtures and racks, and heat treatment operations and procedures (time-temperature-and cooling details) as well as sampling, inspection, and testing procedures. As

described in previous subsections, temperatures and times for heat treatment are merely two of the variables that can influence final properties; other variables relate to alloy chemistry, fabricating schedules, part thickness, etc. For this reason, the temperature and time ranges recommended for heat treatment are adjustable to develop the desired properties for titanium alloys which are specified in the related procurement documents, or detailed in applicable drawings and purchase orders. Mandatory temperatures and soaking times specified for the various heat treatments (solution, aging, annealing, and stress-relief annealing) to cover all the variables for titanium materials as previously described, cannot be stated. On the other hand, the recommendations of specifications such as those in MIL-H-81200A, establish a minimum acceptance level for procedures and properties, and deviation from them must be substantiated by actual tests to prove that the deviation produces an equivalent or superior product.

22. Furnaces. Since titanium is such a reactive metal at elevated temperatures, vacuum furnaces are ideal for its heat treatment, However, while vacuum furnaces are commonly used to heat treat titanium and its alloys, the expense of vacuum heat treatment is not practical for many procedures and parts. Therefore, furnaces having inert gas, air, or combusted gases as the atmospheres are used more commonly. In all cases, the furnace should be of a suitable design and construction to permit the easy handling of the part, the uniform heating of the part, and any desired preferential cooling of the part.

In the case of inert atmosphere furnaces, the inert gas such as argon or helium, should be used at a dew point of -65 F or lower to prevent contamination of the titanium parts being heat treated. The inert gas should be circulated to insure the protection of all surfaces of the part(s). In the case of fuel-fired furnaces, where combusted gas is the atmosphere, the most important precaution to be observed is that the titanium work piece should not be exposed directly to the flame. The furnace atmosphere should be as free from water vapor as possible and should be slightly oxidizing. Both water vapor and incompletely burned fuel vapors can react with titanium to form atomic hydrogen which is readily absorbed by titanium. The only practical method for removing hydrogen from titanium is by vacuum annealing. The other contaminating interstitial elements, carbon, oxygen, and nitrogen, cannot be removed from titanium although contaminated outer metal layers can be removed from work pieces.

Air chamber furnaces are very flexible and economical for handling large volumes of titanium parts being heat treated, especially for moderately low-temperature heat treatments. On the other hand, at high temperatures, where surface oxidation becomes significant, a muffle furnace design using external heating offers more protection, particularly if the furnace is gas fired. Electric furnaces for small lots or special heat treatments are preferred, since heating can be accomplished either internally or externally with a minimum of contamination. Resistance and induction types of electric furnaces also have been used to minimize contamination through reduced heating times. Salt bath type furnaces have been used for the heat treatment of titanium also, although furnaces of this type do not appear to be preferred, probably due to the intergranular attack of titanium by certain salts, notably chlorides, which necessitate removal of the outer metal layers of work pieces so contaminated.

The effectiveness of certain heat treatments, notably solution heat treatment is largely dependent upon the effectiveness of the cold quenching termination of the thermal exposure. Quench delay time is critical with regard to obtaining optimum properties. For this reason, furnaces for solution heat treatment, for example, should be located in close proximity to the quenching equipment. In many cases, furnaces and quenching equipment are built together in such a way that the titanium part can be dropped or rolled from the hot zone into the quenching media in a very short time. Water is the most widely used quenching medium, although low-viscosity oils and water containing wetting agents (e.g. 3 percent NaOH) have been used also.

23. Stress-Relief Annealing Treatments. The manipulation of titanium during fabrication and/or welding operations in making end-use items can result in the build-up of residual stresses. Since the part may be in a penultimate finished condition when the stresses are built up, a final full annealing operation may not be feasible due to surface oxidation, fixturing to hold dimensions, or mechanical property considerations (e.g. if the penultimate finished part is in the aged condition). For the allevaition of such residual stress, the stress relief annealing of the part may be considered. This is generally a moderately low temperature, short-time thermal exposure designed to relieve the stresses by thermal activation but to not degrade properties by oxidation or undesirable phase transformations. As indicated in Table XXVI, temperatures in the range of 700 to 1450 F can be used (varies with alloy composition) although commonly temperatures around 1000 F are popular. To minimize oxidation, the time and temperature of the stress relief anneal should be kept low. Frequently only portions of the residual stresses are removed, but to a level not likely to be troublesome. A common practice in the stress relief of weldments in aged structures is to perform part of the aging heat treatment prior to welding and to complete the aging after welding, simultaneously relieving residual stresses. Aging heat treatment temperatures also can be used to relieve the stresses in nonwelded structures to be finished in the aged condition. Higher temperature, longer time, stress relief annealing treatments result in conditioning the metal to approach the full annealed state.

24. Annealing Treatments. A stress-free, equilibrium crystal structure in titanium materials achieved by full annealing is generally the most ductile and stable condition. The annealed structure varies with alloy type as might be expected; alpha alloys ideally are annealed to an "all-alpha" (trace of beta phase possible) equiaxed microstructure, near-alpha and alpha-beta alloys are annealed to equiaxed alpha plus residual beta phase microstructures (alpha/beta ratio depends on composition and annealing temperature), and beta alloys are annealed to an equiaxed beta microstructure. Since annealing temperatures for beta titanium alloys may be the same as solution heat treatment temperatures and beta phase may be retained with either slow or fast cooling from temperature, annealing and solution treatments for beta alloys are synonomous.

As described in Section III, Paragraph 20., there are several kinds of annealing variations for the Ti-6Al-4V alloy. The various thermal exposures are designed to promote modifications of microstructures, commensurate with various mill product forms, which yield somewhat different combinations of strength, ductility, and toughness, but characteristically the moderately strong and stable condition is promoted—not the highest strength condition. Typically the more highly alloyed near-alpha compositions and the alpha-beta alloys may be annealed in more than one manner. One of the common aims of all such heat treatments is to achieve a reproducible structure capable of resisting further change by phase transformation when exposed to the elevated temperatures of a service exposure. In general, the high temperature exposure in a modified annealing heat treatment fixes or determines the phase morphology and alpha/beta ratio (subject to a preferred prior fabrication schedule) and the final low temperature part of the treatment stabilizes the composition of the beta phase to resist transformation. In many ways, the low temperature exposure of modified annealing heat treatments are like overaging heat treatments which are discussed in Paragraph 26. The modified special purpose annealing treatments also are further discussed in a subsequent paragraph (Paragraph 27). The frequently used full annealing time and temperature ranges for titanium alloys are given in Table XXVII. These annealing treatments result in the moderately strong, ductile and tough properties commonly sought for structural materials.

25. Solution Heat Treatments. Thermal exposures that are designed to develop a preferred metastable composition of the beta phase in two-phase (alpha plus beta) or all-beta alloys are

## TABLE XXVI. STRESS–RELIEF ANNEALING SCHEDULES

| Nominal Composition, wt % | Stress-Relief Temperature, F | Stress-Relief Time, hours |
|---|---|---|
| Unalloyed Ti grades and Ti-0.15 to 0.20 Pd alloys | 780 to 825 | 7 to 8 |
| | 880 to 925 | 2 to 4 |
| | 975 to 1000 | 1/2 to 1 |
| | 1000 to 1100 | 1/4 to 2/3 |
| Ti-5Al-2.5Sn (and ELI) | 990 to 1200 | 1/4 to 6 |
| Ti-1 to 2 Ni | Not reported | |
| Ti-2Cu | 1075 to 1125 | 1 |
| Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si | Not reported | |
| Ti-5Al-6Sn-2Zr-1Mo-0.25Si | Not reported | |
| Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si | Not reported | |
| Ti-6Al-2Cb-1Ta-0.8Mo | 1000 to 1200 | 1/4 to 1 |
| Ti-8Al-1Mo-1V | 1075 to 1125 | 2 |
| | 1450 | 1/6 to 1/3 (a) |
| Ti-8Mn | 900 to 1100 | 1/2 to 2 |
| Ti-3Al-2.5V | 700 to 1200 | 1/2 to 3 |
| Ti-4Al-3Mo-1V | 900 to 1100 | 1/2 to 8 |
| Ti-5Al-2Sn-2Zr-4Mo-4Cr | Not reported | |
| Ti-6Al-4V (and ELI) | 900 to 1200 | 1/2 to 50 (b) |
| | 1000 to 1100 | 2 to 4 (c) |
| Ti-6Al-6V-2Sn | 1000 to 1200 | 1/2 to 4 |
| Ti-6Al-2Sn-4Zr-2Mo | 900 to 1200 | 1 to 4 |
| Ti-6Al-2Sn-4Zr-6Mo | Not reported | |
| Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si | Not reported | |
| Ti-7Al-4Mo | 900 to 1300 | 1/2 to 8 |
| Ti-1Al-8V-5Fe | 1000 to 1300 | 1/2 to 4 |
| Ti-2Al-11V-2Sn-11Zr | Not reported | |
| Ti-3Al-8V-6Cr-4Mo-4Zr | Not reported (d) | |
| Ti-11.5Mo-6Zr-4.5Sn | 900 to 1100 | 8 (e) |
| | 1325 to 1350 | [1 to 5 minutes] (f) |
| Ti-8Mo-8V-2Fe-3Al | 950 to 1100 | 1 to 4 (e) |
| Ti-13V-11Cr-3Al | 900 to 1000 | 1/2 to 60 (e) |
| | 1400 to 1450 | 1/4 (f) |

Notes:

(a) A short exposure at full annealing temperature may be used. Air cooling from this exposure results in stimulating the duplex annealed condition; slow cooling; stimulates the mill annealed condition.

(b) For 100 percent relief; 50 hr – 1000 F or 5 hr – 1200 F. For 50 percent relief; 5 hr – 1000 F or 1/2 hr – 1100 F.

(c) Commonly used ranges.

(d) Full annealing or above the beta transus temperature ( ~ 1460 F) may be used to relieve residual stresses or stress relief may be achieved simultaneously with aging heat treatment.

(e) Stress relief may be achieved simultaneously with aging heat treatment.

(f) Stress relief may be achieved using short-time exposure at the solution annealing temperature.

## TABLE XXVII. ANNEALING SCHEDULES

| Nominal Composition, wt % | Annealing Temperature, F | Annealing Time, hours(a) | |
|---|---|---|---|
| Unalloyed Ti grades | 1300 | 2(b) | (AC) |
| and Ti-0.15 to 0.20 Pd alloys | 1000 to 1500 | 1/4 to 4 | (AC) |
| Ti-5Al-2.5Sn (And ELI) | 1300 to 1675 | 1/4 to 4 | (AC) |
| Ti-1 to 2Ni | | Not reported | |
| Ti-2Cu | 1250 to 1450 | 1/2 to 2 | (AC) |
| Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si | 1650 + | 1 | (AC) |
| Duplex (2 step) anneal(c) | 930 | 24 | (AC) |
| Ti-5Al-6Sn-2Zr-1Mo-0.25Si | 1800 + | 1/2 | (AC) |
| Duplex (2 step) anneal(c) | 1100 | 2 | (AC) |
| Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si | 1300 | 1 | (AC) |
| Duplex (2 step) anneal(c) | 1950 + | 1/4 | (AC) |
| | 1300 | 1 | (AC) |
| Ti-6Al-2Cb-1Ta-0.8Mo | 1300 to 1700 | 1/4 to 2 | (AC) |
| Ti-8Al-1Mo-1V | 1400 to 1450 | 1/4 to 8 | (AC)(FC)(d) |
| Duplex (2 step) anneal(c) | 1650 to 1850 + | 1/3 to 1 | (AC) |
| | 1100 to 1375 | 8 | (AC) |
| Ti-8Mn | 1250 to 1350 | 1/2 to 1-1/2 | (FC)(e) |
| Ti-3Al-2.5V | 1200 to 1400 | 1 to 3 | (AC) |
| Ti-4Al-3Mo-1V | 1225 to 1350 | 1 to 4 | (FC)(e) |
| Ti-5Al-2Sn-2Zr-4Mo-4Cr | | Not reported | |
| Ti-6Al-4V (And ELI) | 1275 to 1600 | 1/4 to 8 | (AC) |
| | 1350 to 1400 | 2(b) | (AC) |
| Ti-6Al-6V-2Sn | 1300 to 1500. | 1 to 8 | (AC)(FC)(f) |
| Ti-6Al-2Sn-4Zr-2Mo | 1300 to 1550 | 1 to 8 | (FC)(e) |
| Duplex (2 step) anneal(c) | 1650 to 1750 + | 1/2 to 1 | (AC) |
| | 1100 to 1450 | 1/4 to 8 | (AC) |
| Triplex (3 step) anneal(c) | 1650 + | 1/2 | (AC) |
| | 1450 + | 1/4 | (AC) |
| | 1100 | 2 | (AC) |
| Ti-6Al-2Sn-4Zr-6Mo | 1500 to 1600 + | 1/2 to 1 | (AC) |
| Duplex (2 step) anneal(c) | 1100 to 1300 | 1/4 to 8 | (AC)(g) |
| Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si | | Not reported | |
| Ti-7Al-4Mo | 1425 to 1475 | 1 to 8 | (FC)(e) |
| Ti-1Al-8V-5Fe | 1250 to 1400 | 1 to 4 | (AC)(FC)(f) |
| Ti-2Al-11V-2Sn-11Zr | 1400 to 1600 | 1/2 to 1 | (AC)(FC)(h) |
| Ti-3Al-8V-6Cr-4Mo-4Zr | 1500 to 1700 | 1/4 to 1/2 | (AC)(WQ)(i) |
| Ti-11.5Mo-6Zr-4.5Sn | 1275 to 1600 | 1/10 to 2/3 | (AC)(WQ)(i) |
| Ti-8Mo-8V-2Fe-3Al | 1450 | 1/10 to 1/4 | (AC)(WQ)(i) |
| Ti-13V-11Cr-3Al | 1400 to 1500 | 1/10 to 1 | (AC)(WQ)(i) |

Notes:

(a) Cooling rates in parentheses: AC=air cooling, FC=furnace cooling, WQ=water quench.
(b) Commonly used annealing treatment.
(c) Both the high and the low temperature steps are required. Three steps are required in triplex annealing.
(d) Slow cooling results in the mill annealed condition. Air cooling results in the duplex annealed condition.
(e) Slow cooling to 1000-1050 F, not exceeding 300 F/hour, improves stability.
(f) Either air cooling or slow cooling as in (e).
(g) Short-time, high temperature second step for sheet and up to 8 hours at 1100 F for thick-section products.
(h) Either air cooling or slow cooling to 1000 F, followed by WQ.
(i) Either air cooling or water quenching from solution annealing temperature.

designated solution heat treatments. A feature of solution heat treatment technique is to rapidly cool from the elevated temperature to ambient temperature to retain the composition of the beta phase as it existed at temperature. This beta phase may retain a metastability or it may transform to various degrees upon cooling, depending upon its composition, but in either case it is cooled to a condition which will transform upon subsequent aging heat treatment. The transformation of the phases fixed during solution heat treatment by subsequent aging heat treatments is the mechanism responsible for the high strength in heat treatable titanium alloys. Table XXVIII gives the commonly used time and temperature solution heat treatment schedules for titanium compositions amenable to strengthening by solution heat treatment and aging (STA) procedures.

The solution temperature required to bring about a preferred solid solution depends upon alloy composition and degree of heat treatment response desired. Generally, for alpha-beta alloys, temperatures high in the two-phase field promote a high aging (strengthening) response and vice versa. Soaking times at temperature relate to temperature uniformity within sections of various thickness and solid solubility equilibrium conditions. Soaking time requirements increase with increasing section thickness. The minimum soaking period may be determined by testing samples to make sure that the required mechanical properties can be developed from the solution treatment used. Minimum soaking times are sought for production reasons and in order to minimize the contamination that can occur at solution temperatures. The oxygen surface contamination which commonly occurs during solution treatment in air is frequently removed prior to further processing such as by forming or aging treatments.

A rapid cooling (e.g. water quenching) from the solution temperature is necessary to obtain the maximum heat treatment response (strengthening or hardenability) in alpha-beta alloys. Quick cooling also aids in avoiding the formation of grain boundary alpha (which can occur upon slow cooling) that can result in poor ductility. Richly beta stabilized alloys such as beta alloys can be cooled less quickly (e.g. air cooling) from solution temperatures and still retain a good aging response because the beta phase, being more highly alloyed than in alpha-beta alloys, is more sluggish. For the above reasons, beta alloys have deeper hardenability than alpha-beta alloys. That is, thicker sections may be strengthened more uniformly through the thickness than comparable thicknesses of alpha-beta alloys. In thick sections of weakly beta stabilized alpha-beta alloys, center sections cannot be cooled rapidly enough to promote much subsequent aging response and for such alloys, their depth of hardenability is limited. Alloys that are strongly beta stabilized have a deep hardenability which is generally proportional to the degree of beta stabilization. The following tabulation shows the relationship between compositions in terms of beta stabilization and depth of hardenability (section thickness that can be strengthened by STA treatment although not necessarily to a uniform strength level throughout the thickness.)

Ti-6Al-4V, weakly beta stabilized : up to 1 inch
Ti-6Al-6V-2Sn, greater beta stabilization : up to 2 inches
Ti-6Al-2Zr-2Sn-2Mo-2Cr-0.25Si and
  Ti-6Al-2Sn-4Zr-6Mo, richly beta stabilized : up to 6 inches
Ti-8Mo-8V-2Fe-3Al and
  Ti-13V-11Cr-3Al, beta alloys : up to 8 inches

Relative to rapid cooling and the attainment of acceptable STA mechanical properties in alpha-beta alloys, is the quench delay time—the time delay between solution temperature and the actual start of the quenching operation. Obviously, if the delay time is long, the part will be essentially slow cooled between the solution temperature and whatever temperature the part reaches just prior to quenching. That situation can lead to poor heat treatment response and therefore quench delay time should be minimized especially for the weakly beta stabilized alpha-beta alloys.

## TABLE XXVIII. SOLUTION HEAT TREATING SCHEDULES(a)

| Nominal Composition, wt % | Solution Temperature, F | | Soaking Time, hours | |
|---|---|---|---|---|
| | Flat-Rolled Products | Bars and Forgings | Flat-Rolled Products | Bars and Forgings |
| Ti-3Al-2.5V | 1600 to 1700 | 1600 to 1700 | 1/4 to 1/3 | 1/4 to 1/3 |
| Ti-4Al-3Mo-1V | 1620 to 1700 | 1700 to 1775 | 1/10 to 1/2 | 1/6 to 2 |
| Ti-5Al-2Sn-2Zr-4Mo-4Cr | — | 1475(b) | — | 4(b) |
| Duplex solution treatment (d) | — | 1500 to 1575 + | — | 4(c) |
| | — | 1475 | — | 4 |
| Ti-6Al-4V | 1650 to 1775 | 1650 to 1775 | 1/10 to 1 | 1/6 to 1 |
| Ti-6Al-6V-2Sn | 1550 to 1650 | 1550 to 1650 | 1/6 to 1/2 | 1/6 to 1 |
| Ti-6Al-2Sn-4Zr-6Mo | 1550 to 1700 | 1550 to 1700 | 1/6 to 1/2 | 1/4 to 1 |
| Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si | 1725 to 1750 | 1725 to 1750 | 1/4 to 1(e) | 1/2 to 1(e) |
| Ti-7Al-4Mo | 1675 to 1775 | 1675 to 1775 | 1/6 to 1-1/2 | 1/6 to 2 |
| Ti-1Al-8V-5Fe | — | 1350 to 1450 | — | 1/6 to 2 |
| Ti-2Al-11V-2Sn-11Zr(f) | 1350 to 1450 | 1400 to 1700 | 1/6 to 1/2(e) | 1/3 to 1(e) |
| Ti-3Al-8V-6Cr-4Mo-4Zr(g) | 1500 to 1700 | 1500 to 1700 | 1/10 to 1/2(e) | 1/4 to 1(e) |
| Ti-11.5Mo-6Zr-4.5Sn(g) | 1275 to 1500 | 1275 to 1600 | 1/10 to 1/2(e) | 1/10 to 1(e) |
| Ti-8Mo-8V-2Fe-3Al(g) | 1450 to 1475 | 1450 to 1475 | 1/10 to 1/3(e) | 1/4 to 1(e) |
| Ti-13V-11Cr-3Al | 1400 to 1500 | 1400 to 1500 | 1/6 to 1/2(e) | 1/6 to 1(e) |

Notes:

(a) Only alloys recommended for use in the solution treated plus aged condition are tabulated. Solution treatments terminated by water quenching (WQ) unless otherwise indicated.

(b) Solution treatment for beta fabricated material.

(c) Air cooled from high solution temperature to low solution temperature.

(d) Solution treatment for alpha-beta fabricated material.

(e) Solution treatments terminated by either water quenching (WQ) or air cooling (AC).

(f) Typical solution treatments indicated.

(g) The longer-time, higher temperature solution treatments are favored for thick-section products (e.g., plate and forgings) while short-time, lower temperature treatments are used for items such as sheet and wire.

## TABLE XXIX. MAXIMUM QUENCH DELAY, WROUGHT ALLOYS

(For Immersion—Type Quenching)(a)

| Nominal Thickness, inches | Maximum Time, seconds (b) |
|---|---|
| Up to 0.091 incl | 4 |
| Over 0.91 | 7 |

Notes:

(a) Quench delay time should begin when the furnace door begins to open, and end when the last corner of the load is immersed in the water quench tank. The maximum quench delay time may be exceeded, with extremely large loads or long length, if performance tests indicate that all parts comply with all other requirements.

(b) Shorter times than those shown may be necessary to ensure that the minimum requirements are complied with when quenched

The maximum quench delay times suggested for various product thicknesses are given in Table XXIX.

26. Aging Heat Treatments. The heat treatments recommended to achieve the commonly expected high strength levels for titanium alloys are given in Table XXX. Aging heat treatments cause the transformation of the metastable phases produced by the solution heat treatment to other phases. Classically, alpha phase precipitates from the beta phase during aging resulting in a residual enriched beta phase and alpha precipitate.

Metastable $\beta \rightarrow \alpha$ ppt. + enriched $\beta$.

However, other reactions are commonplace. For example, the omega phase also may precipitate from the beta phase and intermetallic compounds can form upon aging. Further, in the case of certain alloys, the beta phase existing at the solution temperature transforms upon quenching to an alpha form that is supersaturated with beta stabilizer (alpha prime). During subsequent aging, the supersaturated alpha transforms to beta and alpha phases.

Supersaturated $\alpha' \rightarrow \beta + \alpha$ ppt.

It is not unusual for several of these reactions to occur simultaneously during the aging heat treatment to contribute to the total strengthening process.

As indicated by the curves of Figure 17, the time and temperature of the aging exposure has much to do with the strength level achieved. Classically, the low aging temperatures result in the formation of much omega phase which characteristically imparts high strength and low ductility to the material being aged. Higher aging temperatures tend to precipitate alpha from the beta phase by a nucleation and growth process, and with longer aging times, alpha particle size may become large, the residual beta phase may be softened, and a net reduction in strength may occur. This condition is called the overaged condition. It is characterized as a moderately high strength condition combined with better ductility and toughness than an aged condition for the same alloy with the same prior processing history. Overaging may be carried out to an extreme degree to render the properties of a material similar to the properties of a fully annealed structure.

27. Special Purpose Heat Treatments. The demand for higher strength and better ductility in titanium materials which existed since their first use has recently been accompanied by a demand for additional characteristics such as improved toughness, improved thermal stability, and improved resistance to stress-corrosion. To meet this demand, the development of new titanium alloys has been pursued, and in addition, heat treatment techniques have been modified to afford property improvements. For example, several of the annealing heat treatments described for the Ti-6Al-4V alloy in Section III, Paragraph 20, are relatively new and have led to the availability of mechanical property combinations that were not available with simple mill annealing or with the solution treating plus aging procedures.

Recrystallization Annealing, for example, affords a maximum toughness and resistance to stress-corrosion cracking at an annealed strength level. The recrystallization anneal is achieved by furnace cooling from a moderately high solution temperature in the alpha-beta field. Such a treatment tends to enrich the residual beta phase at a low volume percent of the structure and to otherwise produce an equilibrium microstructure composed of equiaxed alpha and residual beta phases—very stable and tough.

Duplex annealing is similar to solution treating plus overaging for Ti-6Al-4V alloy with the important difference of a low cooling rate from the solution temperature. Due to the difference

TABLE XXX. AGING HEAT TREATMENT SCHEDULES[a]

| Nominal Composition, wt % | Aging Temperature, F | Aging Time, hours[b] |
|---|---|---|
| Ti-3Al-2.5V | 900 to 950 | 2 to 8 |
| Ti-4Al-3Mo-1V | 900 to 975 | 2 to 12 |
| | 1050 to 1150[c] | 1/6 to 6 |
| Ti-5Al-2Sn-2Zr-4Mo-4Cr | 1100 to 1200 | 8 |
| Ti-6Al-4V | 900 to 1050 | 4 to 12 |
| | 1050 to 1300[c] | 2 to 4 |
| Ti-6Al-6V-2Sn | 875 to 1150 | 2 to 8 |
| | 1100 to 1200[c] | 2 to 8 |
| Ti-6Al-2Sn-4Zr-6Mo | 1050 to 1150 | 2 to 8 |
| | 1200 to 1300[c] | 1 to 4 |
| Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.2Si | 1000 | 4 |
| Ti-7Al-4Mo | 950 to 1200[d] | 4 to 24 |
| Ti-1Al-8V-5Fe | 900 to 1100 | 2 to 4 |
| Ti-2Al-11V-2Sn-11Zr[e] | 850 to 1250 | 1 to 48 |
| Ti-3Al-8V-6Cr-4Mo-4Zr | 800 to 1050 | 6 to 24 |
| | 1050 to 1250[c] | 6 to 12 |
| Ti-11.5Mo-6Zr-4.5Sn | 900 | 8 |
| | 1100[c] | 8 |
| Ti-8Mo-8V-2Fe-3Al | 900 to 950 | 8 |
| | 1100 to 1200[c] | 8 to 16 |
| Ti-13V-11Cr-3Al | 825 to 1000 | 2 to 60 |

Notes:
(a) Only alloys recommended for use in the solution treated plus aged condition are tabulated.
(b) Aging and overaging treatments are terminated by air cooling.
(c) Overaging heat treatment schedules.
(d) The overaged condition may be achieved with the higher temperatures of the range indicated.
(e) Aging treatments, including double aging treatments within the time and temperature ranges shown have been evaluated. A standard aging treatment has not been selected.

in cooling rate, the beta phase residual from the solution treatment is not subject to profound transformation since it is already partially stabilized during slow cooling. The subsequent overaging treatment further stabilizes the two-phase microstructure and affords a material with moderately high strength (intermediate to annealed and STA strengths) and good ductility and toughness. Also, the elimination of the quenching operation offers a production advantage for this heat treatment.

Beta annealing of alpha-beta alloys as the name implies, is accomplished using an annealing temperature above the beta transus temperature and relatively slow cooling from this high temperature, followed by an overaging treatment. The high solution annealing temperature results in a 100 percent beta microstructure (at temperature) which transforms to an acicular alpha structure upon cooling (see Structure A of Figure 16). Transformed beta microstructures are associated with excellent toughness and desirable combinations of other properties as described previously.

While the above special heat treatments have been described using the case for Ti-6Al-4V alloy, other alpha-beta compositions can be similarly heat treated with similar results. In addition to these treatments, some compositions have preferred heat treatment schedules that were developed along with the development of the alloy or of a particular alloy form, to optimize properties. For example, continuously rolled Ti-6Al-4V strip is annealed according to a special schedule. Further, the Ti-8Al-1Mo-1V alloy has simple and duplex annealing treatments applicable to various product forms and to the degree of stability and other properties desired. The Ti-6Al-2Sn-4Zr-2Mo alloy has duplex and triplex annealing treatments, and variations in the heat treatment schedules appropriate to various product forms. Thus it becomes apparent that while broad descriptions of the various heat treatments for titanium can be summarized, it is recommended that users of any particular titanium material should seek detailed heat treatment instructions for the development of combinations of properties desired.

28. Heat Treatment Precautions. There are two fundamental requirements for successful titanium heat treatment: (1) minimizing contamination, and (2) maximizing the accuracy of the time, temperature, and cooling rate prescribed for heat treating a given material. The importance of the latter point and the related metallurgical effects have been reviewed in the foregoing sections. Additional points related to precautions in avoiding contamination are summarized.

The oxidation of titanium at elevated temperatures can occur in air at quite low temperatures including aging temperatures and can lead to the degradation of properties if aging times are prolonged or if aging temperatures are high. The actual scaling of titanium can occur at about 1100 F, and above this temperature, scaling and contamination of subscale metal layers increases with increasing temperature and time of exposure. Oxygen diffusion results in a hard, brittle surface (subscale) layer. This layer should be removed by mechanical or chemical means prior to forming parts, further heat treatment steps, or application in components.

In addition to oxygen contamination (and to a small extent nitrogen) precautions that should be observed during heat treatment, hydrogen contamination precautions should be followed. Hydrogen may be readily absorbed from uncontrolled atmospheres of heat treating furnaces (e.g. high dew point in inert gas atmospheres, fuel vapors in fuel-fired furnaces, or atmospheric water vapor), and from pickling and scale removal baths. Absorbed hydrogen can be embrittling in titanium under various conditions related to alloy type. Therefore if a hydrogen contamination is suspected, it should be eliminated by vacuum annealing.

The above interstitial contamination problems are not the only ones of concern. For example, iron oxide in contact with very high temperature titanium can result in a thermite type reaction. In addition, the presence of chlorides during heat treatment (even from finger prints) can lead to a stress-corrosion problem. Other metals can react vigorously with titanium at elevated temperatures, and so can ceramic, other inorganic and organic materials. The necessity for the cleanliness of the heat treatment operation becomes apparent when the reactivity of titanium with practically everything it is in contact with is fully realized.

Distortion due to heat treatment has been a problem among some titanium users. Generally no problem exists if the work piece being heat treated is not finished to final dimensions, since a final dimensional control can be imposed on a heat distorted part. However, the heat treatment of dimensionally finished parts can be a problem due to distortion and should be avoided. In some cases, fixturing can be quite helpful in avoiding gross distortion, and in fact is frequently used even on undimensioned work pieces. However fixturing cannot be relied upon to prevent distortion and warpage completely, so the preferred technique is to perform heat treatment prior to dimensional finishing.

## Forming Processes

29. General. Titanium is more difficult to form than the more familiar steels and aluminum alloys. Titanium alloys generally have less predictable forming characteristics, and being quite strong materials, require higher forming pressures which must be controlled over a smaller workability range. That is, the spread between yield and ultimate strength, expressed as a percentage of the ultimate strength, is smaller. Other characteristics adversely affecting titanium formability include tendencies toward nonuniformities in sheet, notch sensitivity, galling sensitivity, low shrink capabilities, and potential embrittlement by interstitial contamination (as in hot forming). Substantial improvements have been made in forming machines, dies and techniques during the last several years that have led to practices for forming titanium that have had a high degree of success. Nevertheless, the successful forming of titanium still relies on a good deal of experience.

Some companies prefer hot forming to improve the formability and dimensional tolerance control of titanium. Others use the cold forming, hot-sizing approach to accomplish the fabrication of parts having close tolerances and acceptable mechanical properties.

When formed at room temperature, unalloyed titanium and its alloys behave like cold-rolled stainless steel. For example, in stretch forming, titanium seems to behave like full-hard stainless steel, while in press forming, unalloyed titanium can be produced to shapes achieved in one-quarter-hard stainless. Further, the formability of most titanium alloys at 1200 F is comparable to that of annealed stainless steel at room temperature. The commercial unalloyed titanium grades, being more ductile than the titanium alloys (generally), present fewer problems and can be fabricated to simple shapes at room temperature.

Springback in titanium is often unpredictable but always to a degree that can be a problem if not taken into forming considerations. Springback angles commonly range between 20 and 40 degrees for sheets of Ti-6Al-4V alloy formed in bending at room temperature. The wide variations in yield strength among different heats, magnified by a low modulus of elasticity, can give a wide spread in springback angle, especially if the bend angle of the part is fixed by the forming tool and the bend radius to thickness ratio is large. Of course, springback and springback nonuniformity, tend to diminish with increasing forming temperature.

All titanium alloys resist sudden movement; hence, stretching and pressing operations are usually recommended where a controlled rate of load application can be maintained. The slower the forming speed, the better the formability at room temperature. At elevated temperatures, some titanium alloys, like Ti-6Al-4V, have better formabilities at higher forming temperatures. Faster speeds may be necessary from an economic viewpoint, and can be tolerated if large radii can be accommodated in the part design. The formability of titanium is poor in operations characterized by shrink flanges such as found in rubber press forming. Consequently areas that require gathering of material should be minimized when designing parts.

Hot forming improves the forming characteristics of titanium mainly by increasing its ductility; major improvements normally occur above 1000 F for most titanium alloys. The yield strength normally starts to decrease significantly at about the same temperature and this leads to lower forming pressure requirements. Parts formed at elevated temperatures exhibit greater contour uniformity since smaller property variations exist between various lots of material at the higher temperatures.

It is apparent from the foregoing discussion that titanium and its alloys may be formed both at room temperature and at elevated temperatures with formability being improved using the higher

## TABLE XXXI. RELATIVE FORMABILITY OF ANNEALED TITANIUM ALLOYS FOR SIX SHEET–FORMING OPERATIONS AT ROOM AND ELEVATED TEMPERATURES[a]

| Brake Press (Minimum Bend Radius) at Room Temperature | Drop Hammer (Maximum Stretch) at 850 to 950 F | Hydropress (Trapped Rubber) |  | Joggle (Runout Joggle-Depth Ratio) |  | Stretch Wrap (Maximum) at Room Temperature | Skin Stretch (Maximum at 850 to 950 F |
|---|---|---|---|---|---|---|---|
|  |  | Stretch (Maximum) at 600 to 700 F | Shrink (Maximum) at 600 to 700 F | At Room Temperature | At 600 to 700 F |  |  |
| 13V-11Cr-3Al[b] (1.5T) | 13V-11Cr-3Al[b] (16%) | 13V-11Cr-3Al[b] (10%) | 13V-11Cr-3Al[b] (6%) | 13V-11Cr-3Al[b] (1.25) | 13V-11Cr-3Al[b] (1) | 8Mn (8%) | 8Mn (18%) |
| 8Mn (3T) | 8Mn (16%) | 8Mn (7.5%) | 8Mn (5%) | 8Mn (4) | 8Mn (3) | 5Al-2.5Sn (8%) | 6Al-4V (17%) |
| 5Al-2.5Sn (3.5T) | 5Al-2.5Sn (13%) | 6Al-4V (5%) | 6Al-1V (4%) | 5Al-2.5Sn (4) | 6Al-4V (3) | 13V-11Cr-3Al[b] (5.5%) | 13V-11Cr-3Al[b] (13.5%) |
| 6Al-4V (4.5T) | 6Al-4V(13%) | 5Al-2.5Sn (5%) | 5Al-2.5Sn (3%) | 6Al-4V (4.5) | 5Al-2.5Sn (4.5) | 6Al-4V (3.5%) | 5Al-2.5Sn (12.5%) |

Notes:

(a) Alloys are listed in order of forming ease, the most formable alloy being at the top of the list.
Numbers in parentheses following alloy designations are laboratory test values for the indexes of formability shown in parentheses at the top of each list.
Laboratory index values shown should be related at least 25 percent when designing for production.

(b) Solution-treated condition.

temperatures. The disadvantages of hot forming, the possibility of work-piece contamination and the requirement for heated tooling, are not formidable and hot forming is today more widely used than cold forming. Table XXXI gives a comparison of the relative formability of representative titanium alloys in various hot and cold forming operations.

30. Material Preparation. Conventional cleaning, etching, and descaling procedures can be used to remove dirt, surface oxidized layers, and/or scales from titanium materials before forming. Scales and surface oxides can increase the notch sensitivity during forming. Grease, oil, and all residues from solvents or fingerprinting that might be a source of chlorides must be removed before any heating operation associated with forming to avoid a possible stress-corrosion reaction. Parts requiring removal of oxides by etching or pickling operations must be of sufficient gage to allow for this metal removal treatment. The pickling operation must be carefully controlled to minimize local attack and undue dimensional changes.

Blanks and parts prepared for forming by one or more of several possible cutting operations such as sawing, nibbling, or shearing should have the worked edges deburred. The scratches resulting from the deburring operation should be parallel to the material surface. The edges of shrink and stretch flanges should be polished prior to forming. Sharp edges should be removed and chamferred edges should be avoided. Cracks in sheared edges are undesirable, but may be tolerated if they are in an area that can be removed by trimming after forming. Scratches on the surface of a blank to be formed are detrimental to the formability of titanium. Consequently, all necessary steps should be taken to reduce the occurrence of scratches before or between forming operations. Interleafing with paper is often used as an aid in minimizing surface scratching.

When titanium is to be heated in air for a long period of time, scale-inhibiting coatings may be used to minimize surface contamination. The application of such coatings are usually covered by company specifications and should be carefully followed. Inspection procedures, both on incoming material and on material processed for forming, cannot be overemphasized.

31. Tooling. The choice of tooling materials for titanium forming depends on the forming operation, the forming temperature, the number of parts to be produced, and cost considerations. Cold forming operations, which stress the tooling in compression, can be conducted with tools made from epoxy-faced aluminum or zinc alloys. The latter can be cast close to the desired dimensions and are easy and cheap to machine. Because machining is expensive, the cost of tool materials is usually a small part of the total tooling costs.

The ability of tooling to withstand wear and distortion at the forming temperature controls the number of parts that can be made on a set of hot-forming dies. The selection of tooling materials for hot forming is often a compromise based on expectations of tool performance and the number of parts to be produced before changes in design or order completion occur. Ceramic materials, cast iron, die steels, nickel-base alloys, and stainless steels have been used successfully for hot-forming tools. Good tooling is expensive and is only justified when close tolerances or large production quantities of parts are required. The following materials are examples of some used for hot-forming operations.

| Operation | Materials |
|---|---|
| Stretch forming | Cast ceramic (Glasrock), H-11, H-15, Hi Si cast iron, AISI 4130, and type 310 stainless steel |
| Brake forming | H-11, H-13, and Incoloy 802. |
| Yoder roll forming | H-11, H-13 tool steels |

| | |
|---|---|
| Draw forming | High Si cast iron and Incoloy 802. |
| Hammer and hydropress forming | High Si cast iron, RA330 stainless steel, Inconel X, and Incoloy 802. |
| Hot sizing operations | Mild steel, High Si cast iron, High Si nodular cast iron, H-13, Types 310 and RA330 stainless steels, Inconel X, Hastelloy X, and Incoloy 802. |

Hot forming may be accomplished using heating of the blank alone or combined blank-die heating. The latter, of course, is preferred. Integral heating of tooling for hot forming is common since temperature control is easier and more precise. Die temperatures of 400 to 1500 F have been used and depend on the titanium alloy to be formed, the shape of the part, and the forming method. Dies and platens are frequently heated with electricity because of its flexibility, ease of control, and cleanliness. Insulating blankets of various types are frequently used in conjunction with hot-forming operations.

32. Lubricants. Lubricants perform three main functions in titanium forming operations: (1) they minimize the energy of pressure required to overcome friction between the blank and the tooling, (2) they reduce galling and seizing between blank and tooling, and (3) they control the rate of heat transfer between blank and tooling as in hot forming. Friction is generally undesirable since it accentuates the difficulty of securing uniform blank movement over the tooling.

Organic, nonchlorinated oils, greases, and waxes may be used in cold forming operations as well as the solid dry film lubricants such as the graphites and molybdenum disulfide types. Colloidal graphite is commonly used in both hot and cold forming operations. At elevated temperatures, boundary type lubrication seems to be best. Consequently it is common practice to use the solid dry film lubricants in conjunction with oils and greases for hot forming. Many satisfactory lubricants have been used in forming titanium that typically result in reducing the coefficient of friction to 0.20 or less and in turn this results in low tool wear.

33. Forming Methods. The many kinds of forming operations commonly used in making end items from the better known metals of commerce, are also used in making parts from titanium and its alloys. Basically each of the operations involves deformation by bending or stretching or combinations of these and as earlier described might be done hot or cold. Hot forming generally affords greater ductility and therefore greater formability. The operations include: brake forming, stretch forming, deep draw forming, trapped rubber and drop hammer forging, spinning and shear forming, dimpling, joggling, roll bending and roll forming, tube bulging, and tube bending. As mentioned previously, titanium work pieces under deformation in these various operations behave much like the various grades of stainless steel. Generally, the titanium alloys have a more limited formability than the steels so that while all of the various forming methods can be used in making titanium parts, cautious approaches to the forming method selected should be employed.

34. Forming Process Precautions. There are several specific precautions to be observed in forming titanium and its alloys. These relate to contamination, notch sensitivity, anisotropy, strain rate sensitivity, the Bauschinger effect, and simple overstraining.

The contamination of titanium during forming may be avoided or eliminated as a problem quite easily when it is realized how readily it can occur. In the handling of as-received titanium stock, for example, the mere act of fingerprinting to any extent is considered poor form since the chlorides of the prints might lead to a stress-corrosion problem in some further processing step. Similarly the ink printing on some stock and any accumulation of layout marking, dirt, grease, etc., should be eliminated early in the processing sequence. Cleaning procedures, the use of solvents and pickling operations for example, should be controlled so as not to introduce further contamination. These precautions are especially important when hot forming is planned. During hot forming, the oxidation of titanium surfaces is certain to occur to some degree, depending on any coatings used, and severity of the exposure—temperature and dwell time. Thus, the elimination of contamination picked up during the hot-forming operation must be carefully controlled too, by descaling, pickling, or machining operations. To insure the attainment of desired mechanical properties, contamination should be minimized throughout the entire sequence of forming operations.

Titanium alloys are perhaps as sensitive to surface defects as any of the high strength materials with respect to effects on formability. The scratch marks on surfaces that can appear during handling and the tool marks on cut surfaces, edges in particular, can be the stress risers that result in poor formability. Such notches must be minimized or eliminated to achieve a good formability, and in critical operations, such as stretch forming, the polishing of edges is not a too extreme precautionary measure. Generally, scratches, notches, or defects oriented parallel to the major strain axis of the workpiece are less a problem than those otherwise oriented.

Because titanium mill products are often anisotropic, sections that are to be formed should be oriented in such a way that the major deformation occurs in a direction of maximum ductility. For example, in stretch forming, blank layout should be performed so that maximum stretch will be accomplished in the rolling or longitudinal direction—parallel to the grain. In bending, the bend axis would preferable be perpendicular to the grain to take advantage of the maximum tensile elongation in the longitudinal direction. While it is realized that preferred material orientations cannot be achieved in some forming operations or in some parts, the limitations of ductility in anisotropic products should be understood and accommodated. Similarly, the strain rate sensitivity and the variation of this sensitivity among various titanium alloys should be understood in selecting a forming process that is the most closely matched to the materials capability.

Cold forming can result in a loss of compressive yield strength via the Bauschinger effect. This is a phenomenon wherein the compressive yield strength can be appreciably lowered upon plastically deforming a metal in tension. (Tensile yield strength also may be decreased by plastically deforming in compression.) Titanium alloys are subject to this phenomenon to various degrees and serious degradation of properties can be experienced in cold formed parts where the problem has not been anticipated. Figure 18 shows the decreases in compressive yield strengths for representative alloys deformed by various amounts in tension. In spite of the extent of these strength decreases under certain conditions, the yield strengths may be restored by stress relief annealing or, of course, by full annealing or solution treating and aging if those are steps in part making subsequent to forming. Stress relief annealing, a hot sizing operation, or a full heat treatment of some type following a cold forming operation not only eliminates the problem of the Bauschinger effect but minimizes or eliminates problems of delayed cracking and stress corrosion. Thus where cold forming is selected in lieu of a hot forming operation, it is well to consider an appropriate thermal exposure to recondition the workpiece to insure optimum properties.

## Machining Processes

35. General. Several years ago, titanium had the reputation of being very difficult to machine compared with common construction materials. However, years of experience and research on various problems have progressively improved the situation. Today, tools and techniques are available for machining titanium efficiently. In fact, some machining operations give more consistent results on titanium than they do for some steels. A bonus factor is the ease of attaining good surface finishes. Roughness values as low as 20 to 30 microinches can be obtained on some parts.

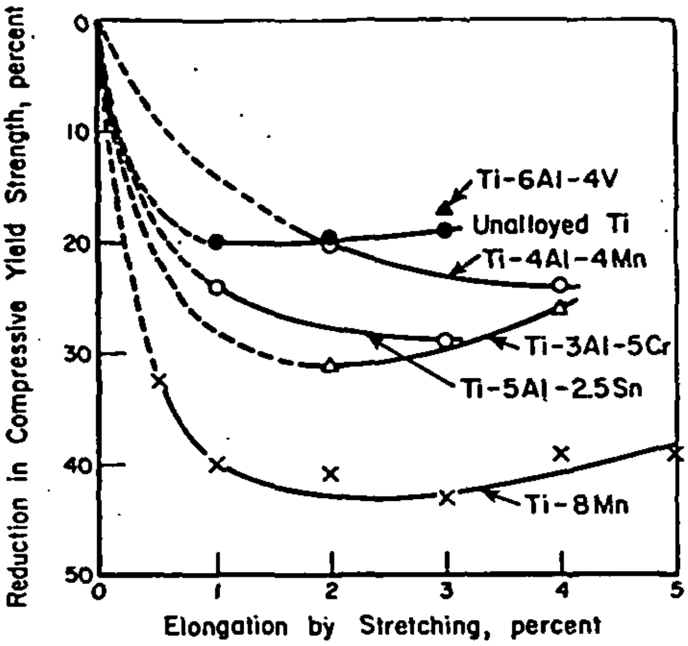


Figure 18. Effect of Cold Stretch Forming on the Compressive Yield Strengths of Various Titanium Alloys

Generally, machining problems for titanium can originate from four sources: high cutting temperatures, chemical reactivity and abrasiveness with tools, and a relatively low modulus of elasticity. A built-up edge, however, does not form on tools used to machine titanium. Although this phenomenon accounts for the characteristically good finish on machined surfaces, it also leaves the cutting edge naked to the abrading action of the chip peeling off the work. In addition, titanium produces a thin chip, which flows at high velocity over the tool face on a small tool-chip contact area. This, plus the high strength of titanium produces high contact pressures at the tool-chip interface. This combination of events and the poor heat conductivity of titanium results in unusually high tool-tip temperatures.

The cutting temperature achieved at the tool point depends partly on the rate at which heat is generated, from the tool forces involved, and partly on the rate at which it is removed by the chip, the cutting fluid, and by conduction through the tool. The heat-transfer characteristics of the chip and work material depend on thermal diffusivity, which is a function of density, specific heat, and thermal conductivity. Since titanium exhibits poor thermal diffusivity, tool-chip interface temperatures are higher than they would be when machining other metals at equal tool stresses. The higher temperatures in the cutting zone lead to rapid tool failure unless efficient cooling is provided by suitable cutting fluids.

The strong chemical reactivity of titanium with tool materials at high cutting temperatures and pressures induces galling, welding, and smearing, since an alloy is continuously formed between the titanium chip and the tool material. This alloy passes off with the chip, producing tool wear. Titanium reactivity also shows up when the tool dwells in the cut, even momentarily as in drilling.

The surface of titanium usually contains a high content of oxygen, especially if it has been exposed to air at high temperatures. This oxygen-enriched layer is hard and abrasive, and can cause dulling of tools. Therefore, it is often desirable to clean the surface, prior to machining, by sand blasting or by chemical descaling. When this is not possible, the first cut taken is usually a heavy one, to cause the tool to penetrate under the hard "skin" of oxygen-enriched titanium. Abrasion by surface contamination or scale can notch cutting tools at the depth-of-cut line. Consequently, this is another reason to remove oxygen enriched surface layers, if possible, prior to machining operations.

The stiffness of a part, determined by the shape and the elastic modulus of the alloy workpiece is an important consideration in designing fixtures and selecting machining conditions for titanium. Since the elastic modulus for titanium is only about half that of steel, a titanium part may deflect several times as much as a similar steel part during machining, creating tolerance, tool rubbing and other tool miscutting problems.

36. Machining Requirements. Successful machining of titanium and its alloys requires the use of high-quality machine tools and cutting tools; an absolute minimum of vibration; rigid setups; and observance of recommended machining practices.

Machine tool selection is a primary factor; just any machine will not do. In fact, machine tools used for machining titanium must be in excellent condition and possess certain basic attributes that insure vibration-free operations. These include dynamic balance of rotating elements; true running spindles; snug bearings, slides, and screws; sturdy frames; wide speed/feed ranges; and ample power to maintain speed throughout cutting. Undersized or under-powered machines should be avoided. Certain locations of machines near or adjacent to heavy traffic also can induce unwanted vibration and chatter during machining.

Rigidity of operation is a very important consideration. Generally, it is obtained through the use of adequate clamping and by minimizing deflection of work and tool during machining. In milling, this means strong, short tools, machining close to the table, rigid fixturing, frequent clamping of long parts, and the use of backup support for thin walls and delicate workpieces. Rigidity in turning is achieved by machining close to the spindle, gripping the work firmly in the collet, and providing steady or follow rests for slender parts. Drilling requires short drills, positive clamping of sheet, and backup plates on through holes.

Cutting speed is important in all machining operations and is a very critical variable for titanium. Cutting speed has a pronounced effect on tool-chip temperature: excessive speeds can cause overheating and short tool life. Consequently, speeds are limited to relatively low values, unless adequate cooling can be supplied at the cutting site. However, all machining variables should be carefully selected to effect optimum machining rates.

All machining operations require a positive uniform feed achieved mechanically. The cutting tool should never dwell or ride in the cut without removing metal. As an added precaution, all cutters should be retracted when they are returned across the work. The cutter should be up to speed and should maintain this speed as the cutter takes the load.

In summary, correct machining setups for titanium require strong, sharp cutting tools; positive feeds; relatively low cutting speeds; and certain types of cutting fluids. Improper cutter rigidity and/or geometry can contribute to vibration. Spindle speeds and feeds should be verified on each machine to ensure correct cutting conditions, since small changes in cutting conditions can produce large changes in tool life. All machining variables should be carefully selected to effect optimum machining rates.

37. Tooling. When machining titanium, it is necessary to select a tool that retains its hardness at high temperatures. Sintered-carbide tools are a good choice because of their "red hardness". Excellent results are usually obtained with these but, because of their brittleness, carbide tools may chip and spall when titanium chips weld to them. Machining of titanium with carbide tools requires rigid machines and a rigid setup. "Throwaway" carbide inserts are the most economical cutters because of their high productivity. With the use of inserts, higher-rotational speeds and heavier feeds can be used; and no time is lost picking up cuts. Another reason why the "throwaway" inserts are more economical than cemented types, is that the cost of new or multi-point inserts is lower than the cost of retipping or regrinding. Grade 883 or equivalent carbide tips have performed best on titanium alloys, both for roughing cuts and finishing operations. Cast-alloy steels, which fill the gap between carbides and high-speed steels, are used when conditions do not permit the use of carbides.

Titanium can be cut using high-speed steel tools; however, production rate is lowered. Nevertheless, for interrupted cuts, high-speed tools may be the best choice. Live centers are always used to support the work because of seizing when fixed centers are employed.

38. Coolants. Titanium can be machined dry with good results; however, much better results will be obtained when proper coolants are used. The coolant should be directed as close as possible to the point of tool contact. Mist coolant or "through-the-wheel" coolant has proven excellent for grinding or drilling titanium.

Cutting fluids are used on titanium to increase tool life, to improve surface finish, to minimize welding, and to reduce residual stresses in the part. Soluble oil-water emulsions, water-soluble waxes, and chemical coolants are usually used at the higher cutting speeds (75 to 100 fpm and up). Low-viscosity sulfurized oils, chlorinated oils, and sulfochlorinated oils are used at lower cutting speeds to reduce tool-chip friction and to minimize welding of chip to tool. Cutting oils may have either mineral oil or mineral oil-lard oil bases. Many fluids that improve machinability are complex, often proprietary, and sometimes contain unidentified active compounds. (Chlorinated oil cutting fluids pose a danger of stress corrosion from chlorine residues. These residues should be promptly removed with a nonchlorinated degreaser.) Machining handbooks frequently identify specific coolants for use in specific titanium machining operations.

39. Metal Removal Techniques. Both conventional and unconventional metal removal techniques can be used in machining titanium. Conventional methods including milling, turning, boring, drilling, tapping, reaming, sawing, broaching, and various abrasive cutting operations have been developed for titanium. Unconventional methods such as electrochemical machining and grinding, chemical milling, and electric-discharge machining have been advanced to a high state of efficiency in working titanium. Each method has connected with it a multitude of procedural details which should be followed to obtain the best results. Due to the large number of instructions and recommendations for each process it is impossible to cover them thoroughly in this handbook. However, highlights concerning several of the commonly used metal removal techniques are cited.

a. Milling. Breaking or chipping of milling cutters remains a problem. A partial solution is to use "climb milling", rigid machines, and a rigid setup. Progressive tool chipping and wear produces a surface-finish deterioration and loss of tolerance. Other problems found in milling include heat, deflection, and abrasion. In addition to using "climb milling" and rigid setups, milling may be done more successfully when cutting speed is low, tool angles promote unhampered chip flow, and tools are used that are of relatively small diameter but with the largest number of teeth.

b. Drilling. Success in drilling titanium is obtained by adopting a "keep drilling" concept, using mechanical feeds. The drill should not be allowed to ride, and low speeds and heavy feeds should be maintained. The drill should be sharp and as short as possible. When feeding the work by hand, galling and seizing will occur if the rate of feed is not constant. The coolant should consist of a sulfurized- or chlorinated-type mixed with mineral oils, or soluble oils and water and should be supplied to the cutting zone in a positive manner. The galling action of titanium during drilling, which may be accentuated by high cutting temperatures and pressures, results in rapid tool wear, out-of-round holes, tapered holes, or smeared holes, with tap breakage a likely consequence if the holes are to be threaded.

c. Tapping. Tapping screw-holes can be troublesome, particularly in tapping blind-holes where chips can build up. The largest possible tap drill should be used; those with spiral points are the best. A rigid power setup is better than hand tapping. Very slow tapping speeds with highly active cutting fluids are most effective.

d. Sawing. Titanium can be sawed by using a coarse pitch blade having two to six teeth per inch. Blades whose analysis is high in molybdenum content outperform general-purpose blades. Blade tension should be high. Heavy feeds and slow speeds are best, and a coolant should be used. Some difficulty is encountered in sawing large billets. Due to the relatively heavy feed pressures required to keep the blade cutting the material, and because the blade is subject to wear, it is difficult to maintain a straight cut. In cutting billet diameters over 8 inches, grooving the material 1/8-inch wide to a 1-inch depth on the circumference helps to alleviate this problem, as this reduces the diameter and helps to guide the saw blade. Maximum rigidity is needed when sawing titanium and is favored by using the widest and thickest cutting band permitted by the band wheel and any radii of cut that might be desired.

e. Turning and Boring. These operations and facing are essentially the same and offer no unusual difficulties: They give less trouble than milling, especially when cutting is continuous rather than intermittent. However, the problems of high tool-tip temperatures, galling and abrasive reaction with tool materials, and lack of set-up rigidity can be serious if the general rules for titanium machining are not followed. Low cutting speeds, feeds to result in constant metal removal, and adequate coolant directed positively to the work zone are recommended for best results.

f. Abrasive Cutting. Another means of cutting titanium is to use abrasive cutting belts, discs, or cutoff wheels. Overheating and contamination of the work is prevented by generous use of coolants. Titanium and its alloys can be cut abrasively at about the same rate as hardened high-speed steels. Moderately light cuts are recommended. Smearing of ground titanium surfaces can result from abrasive tool loading, and inadequacies of the set-up rigidity, cutting speed inadequacies and poor tool characteristics. These problems can be minimized by choosing the right abrasive tool and conditions. Aluminum oxide and silicon carbide abrasive tools are available in a variety of grit sizes, hardnesses and bond materials. Optimum speeds and feeds (generally light) are recommended for each type. As in other machining operations, cutting fluids and their proper application to the workpiece are very important for the successful abrasive cutting of titanium.

g. Chemical Milling. This unconventional method for metal removal refers to shaping, fabricating, machining, or blanking of metal parts to specific configurations by controlled chemical dissolution with suitable etchants or reagents. Chemical milling is particularly useful for removing metal from the surface of formed or complex-shaped parts, or from thin sections. The method provides an increased capability and flexibility in the fabrication of parts and offers savings in labor time, and materials. The chief drawback is the very careful control required in maintaining the desired dimensional tolerances and the composition of the acid etchant to prevent excessive hydrogen pickup.

The acid etchants used for the chemical milling of titanium are proprietary aqueous solutions containing hydrofluoric acid (HF) plus other oxidizing acids and additives to inhibit hydrogen pickup and to enhance etching characteristics. Etch rates range from about 0.5 to 5.0 mils per minute (1 to 1.5 usually). Time of immersion in the acid solution of course determines the depth of cut. Depth of cut limitations are about 0.5 inch for titanium and minimum widths of cuts that can be machined are about three times the etch depths (due to the sideways etching at about the same rate as down). Dimensional tolerances can be held to about ±2 mils and typical surface-roughness values produced range between 15 to 50 microinches. Etchants are usually circulated in the etch tanks and parts are moved and turned to promote uniform metal removal. Etchants also may be sprayed against the work piece where, for example, the piercing of thin parts is desired.

Metal can be removed from an entire part with chemical milling or else selective machining can be accomplished by using masking. Simultaneous etching of a part from both sides is possible. No elaborate holding fixtures are required. Many parts can be machined at the same time with of course tank size and solution volume limitations. Masking materials such as vinyl polymers and neoprene elastomers are often applied in multiple coats and baked on (200 to 300 F) and patterns desired may be subsequently scribed. The manual peeling of the mask to expose the area to be etched follows. Patterns also may be developed by silk screen and photographic techniques. After machining, the maskants can be easily removed by manual peeling or by immersion in solvents.

## Joining Technology

40. General. Many individual joining processes may be used in assembling a titanium structure. The processes include welding of several types, brazing, soldering (rarely), solid state adhesive bonding, and mechanical fastening. Of these joining types, only welding is markedly sensitive to the choice of titanium alloy. The remaining processes can be applied to any of the alloys with about the same degree of success. There are many factors affecting the choice of a joining process and these include consideration of the metallurgical compatibility, strength requirements, cost requirements, and permanency of the joint. Each process has its advantages and disadvantages and few fixed rules are applicable in selecting a joining method. Since joint requirements are quite varied, this handbook does not attempt to compare advantages associated with the various methods. Instead, brief descriptions of the processes are offered which emphasize the major requirements and precautions.

Before discussing the several individual methods for joining titanium, some of the various characteristics of titanium, which strongly affect joining techniques are reviewed.

a. Titanium and its alloys have a high affinity for oxygen, hydrogen and nitrogen at elevated temperatures, and can become severely embrittled by them at relatively low levels of concentration. There are several possible sources for the contaminants.

b. Titanium alloys are susceptible to stress corrosion by sodium chloride (e.g., from fingerprints) at temperatures above 600 F.

c. Molten titanium is highly reactive with most materials, including all the common refractories.

d. Excessive alloying with other structural metals (e.g., steel and aluminum) greatly reduces the impact strength of titanium due to the formation of brittle intermetallic compounds and excessive solid-solution hardening.

e. Titanium exhibits a high coefficient of friction, and has poor wear and galling characteristics.

f. Titanium is noble in most galvanic couples.

41. Welding Technology. Important factors for welding titanium concern material and process suitabilities. Titanium materials suitability involves two distinct criteria: (1) The ability to physically produce a welded joint, and (2) satisfactory performance of the joint in service. Very few titanium alloys fail to meet the first while the second may be satisfied by proper alloy selection. Commercially-pure titanium and the alpha-type alloys do not respond to heat treatment, and their mechanical properties are affected only slightly by variations in microstructure. These alloys are readily adapted to all types of welding operations. Depending on alloy content, the mechanical properties of alpha-beta alloys may be greatly affected by heat treatment and variations in microstructure. Special consideration is required in selecting alpha-beta alloys for welding applications, because some alloys are embrittled by welding operations. Generally, increased beta stabilizer content in alpha-beta type alloys decreases the suitability of the alloy for welding. Welded joints in beta alloys are ductile in the as-welded condition, but their strengths are low. When heat-treated to increase strength, weld ductility decreases. Thus, where a choice is available, alpha titanium alloys are preferred for welded assemblies, with alpha-beta and beta alloys being less desirable depending upon the ultimate properties required in the joint.

Titanium welding process suitability is related to cost, requirements for joint strength and leaktightness, and considerations for mill product form, component configuration, and joint design and location. The welding processes that may be used on titanium assemblies include fusion welding, resistance welding and explosive welding, though less popular than these other methods is used in the clodding of sheet and plate and the interior or exterior of cylinders. In the first category, the processes of inter-gas-shielded tungsten arc (GTA for gas-tungsten-arc), inert gas-shielded metal arc (GMA), inter-gas-shielded arc spot (arc-spot), and electron beam (EB) welding are popular. Laser welding is being developed. In the second category, spot, roll-spot, and seam welding are the classic processes. In addition, upset-welding processes may be used to assemble special configurations. For example, flash welding, a form of resistance welding, is used to produce joints in bars, forgings, rolled rings, and tubing. Induction pressure welding, gas pressure welding, and high frequency (ultrasonic) welding also are common processes.

42. Fusion Welding. This is a general term often used to categorize welding processes in which joining is accomplished by heating to the melting point using an external heat source. Titanium fusion welding is accomplished using an electric arc, plasma arc, or an electron beam to melt the metal. GTA, GMA, Arc-Spot, and EB fusion welding processes for titanium have much in common and the points discussed in this section relate to all of them. Factors to be considered in fusion welding include: composition of base metal, cleaning of the parts to be joined, joint design, filler wire, inert gas and its application, tooling, heat input, distortion (shrinkage and residual stress), residual stress (property values), weld defects, inspection, and subsequent joint performance. Obviously a welding handbook would be required to describe all these variables and their interrelationships. Here, only the highlights are mentioned.

a. Base metal composition and condition. Alloy selection for titanium welding has been previously discussed. Points to be added include concerns regarding compatibility with the heat-treated condition of the base metal before and after welding and contamination that might be incorporated in the base metal prior to welding. Since any fusion-welding cycle results in a weld zone of as-cast metal, any preexisting microstructural condition in the joint area will be changed during welding. In addition to the weld zone, the heat-affected zone of the weld area goes through a cycle of heating high into the solid solution phase range. While this heating cycle has no harmful effect on the mechanical properties of unalloyed titanium, it can adversely affect the properties of highly heat-treatable titanium alloys to the extent that they become unsuitable for many applications. Heat treatment subsequent to welding must be designed for compatibility to the modified structures of the joint. Contamination of the base metal surface layers in operations preceding welding should be removed prior to welding because this source of contamination is sure to result in nonoptimum weld joints.

Since excessive alloying of titanium with other common structural metals has a deleterious effect, titanium has never been satisfactorily directly welded to other metals. However, methods have been advanced which use compatible metals (e.g., silver and vanadium) as an interlayer between steel and titanium to afford serviceable joints between these dissimilar metals.

b. Cleaning. Careful preweld cleaning is essential to successful fusion welding of titanium. Poor cleaning can result in weld contamination and defects, particularly porosity. Edges to be joined are often etched*, draw filed, wire brushed, or abraded and wiped with acetone or alcohol just prior to welding. One commonly followed rule is: if the areas to be welded cannot be cleaned, do not try to make the weld.

c. Joint Design. Square abutting edges of titanium parts to be joined are satisfactory for the thinner sections. Thick sections may require a machined bevel or some other contour on the abutting edges. Designs are usually based on geometries that are suitable from the viewpoints of amenability to proper shielding and of allowing sufficient clearance for filling with molten metal. The fusion welding process to be used is also a factor. For example, EB weld joint configuration has a much narrower gap than GTA or GMA configurations. Close dimensional tolerances are always preferred with any of the welding processes.

d. Filler Wire. Some fusion welding processes involve the addition of metal from sources other than the base metal. Wire is most commonly used, since it is easy to add at a controlled rate. Wire added during GTA (formerly referred to as TIG) welding is called "cold wire". Wire used in GMA (formerly referred to as MIG) welding may be called "electrode wire". Filler wire is the common term and is available in both unalloyed and alloy grades. Titanium wire for welding must meet stringent quality standards since the high surface-area-to-volume ratios of common wire sizes used in welding represent a sizeable contamination source for weldments. Wire defects, such as seams, laps, cracks, or center bursts, are strictly undesirable for filler wire since the defect areas are a possible repository for contaminants.

e. Inert Gas. Special procedures have been developed to ensure against weld contamination in adopting fusion-welding processes to titanium assemblies. Only high purity welding grade gases should be used. The special procedures include the use of large gas nozzles and trailing shields to protect the face of the welds from air, and backing bars that provide means for introducing inert gas to shield the back of the welds from air. Also, inert-gas-filled welding chambers are often used

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* Recommended etchant is a 30% $HNO_3$—3% HF—balance $H_2O$ solution, used with caution to avoid hydrogen pickup.

with these processes. The dew point of the shielding gas serves as a measure of the gas purity with respect to water vapor. Argon and helium are used for shielding with all fusion welding processes except EB (EB welding in vacuum). In addition to making sure of the purity of the basic gas, another concern is that the inert gas is not degraded during flow through the welding equipment due to leaky joints, etc.

f. Tooling. Conventional GTA and GMA welding power supplies, torches, and control systems are used effectively in welding titanium. Of course, the conventional welding equipment selected for use must be supplemented with auxiliary shielding tooling for welding to be done outside of chambers. Shielding devices are available that provide an adequate inert gas flow at the fusion zone, behind the fusion zone (trailing shield) and on the side opposite the fusion zone (backup shielding). Hold down tooling is commonly of the "chill" type (e.g. copper) to afford rapid cooling of the heated metal and may in fact be designed integrally with the shielding arrangement.

g. Heat Input. With titanium fusion welding, it is the preferred practice to use heat inputs that are just above the minimum energy required to melt sufficient metal to form a weld. High level heat inputs contribute to various bad effects. The lowest heat inputs are obtained with EB welding.

h. Distortion. Fusion welding processes are characterized by thermal cycles that cause localized shrinkage. Shrinkage must be planned for—it cannot be avoided. Shrinkage, in turn, can result in part distortion. Shrinkage can be controlled to some extent by tooling restraints and both shrinkage and distortion are minimized by low heat inputs. The residual stresses in fusion weldments caused by shrinkage and other aspects of the thermal cycle are often high when distortion is low and vice versa. Such locked-in stresses are best alleviated by stress-relief annealing or full heat treatment cycles if those are appropriate after welding. If the residual stresses are not relieved, it is quite possible that in addition to distortion problems, the stresses can contribute to general mechanical property degradation.

i. Defects. Fusion weldments can exhibit defects related to irregularities of the weld zone geometry such as underfilling, overlaps, undercuts, porosity, lack of fusion (e.g. at abutting surfaces), inclusions, and cracks. The production of defect-free welds is highly dependent on the quality requirements of applicable specifications and inspection methods used. For example, cracks are easily inspected for visually and are cause for weld rejection. Similarly, underfill, undercuts, and overlaps, are easily detected and such defects may be alleviated by weld repairing (rewelding). Inclusions, internal cracks, and porosity are much more difficult to detect however, requiring, for example, radiography for identification. Some factors suspected of causing porosity in titanium welds are: high hydrogen content, oxygen, nitrogen, and carbon contamination (joint area improperly cleaned or dirty filler wire), and insufficiencies in technique related to improper heat input, welding speed, gas flow, and cooling rate. Thorough inspection techniques are capable of detecting most of the defects that are known to result in degradation of weld properties.

j. Joint Performance. The only reliable way to determine what weld features are truly defects is to evaluate the effects of such features in a test program. Evaluations must include tests that are representative of the service conditions expected. Many defect-like weld anomolies have no effect on the static-tension properties although these same features may be found to degrade performance in a fatigue test. Thus, under the best of circumstances regarding both weld preparation, inspection, and evaluation short of actual service, a conservative engineering approach is called for in the use of weldments. Under these conditions, fusion welding can be an extremely advantageous technique for assembling components.

43. Electron Beam Welding. Because EB welding is quite a different form of fusion welding than GTA or GMA processes, a general description of some of the features of EB welding is offered. The EB welding process is carried out in a high vacuum — at, or less than, 0.1 micron of mercury pressure — and uses a stream of electrons accelerated from a cathode by a high electrical potential to produce the required heat. The electrons give up their energy as heat upon striking the material to be welded. Two types of equipment are generally available: low voltage, rated up to 60 kilivolts accelerating potention, and high voltage, rated at 60 to 150 kilovolts. With either type, the low-vacuum system assures that contamination of the weld and heat-affected zone is less than that caused by any other welding technique. The lower-voltage equipment gives a weld fusion zone with a width-to-penetration ratio of from two-to-one (2:1) to unity; the high-voltage equipment gives a ratio of one-to-five (1:5) or greater. This penetration is often quite large because the electron beam drills a fine hole through the work which is then filled in by capillary action. The main disadvantages of the high-voltage equipment are the generation of X-rays, which require lead shielding, and the excessive drop-through and spatter at the root of the weld. The disadvantages can be managed quite efficiently however so that EB welding has become a highly valued process for the joining of titanium.

44. Resistance Welding. This category of joining technology is characterized by methods wherein the metals to be joined are heated to the melting point or very close to it, using heat generated by the resistance of the parts to the flow of electric current. Titanium and all ofiits weldable grades can be successfully resistance-welded with techniques similar to those used for ferrous alloys; these techniques are somewhat simpler than those often used for aluminum alloys. The most pertinent processes of this type are spot, roll-spot, and seam welding. As mentioned previously, flash welding is sometimes considered a resistance welding method although it also can be classified along with pressure welding.

In the most common form of spot and seam welding, electric current is passed through a localized area of overlapping sheets until sufficient heat is generated to melt a portion of the interfacing metals to form a weld nugget. The nugget is entirely contained within the remaining solid portions of the sheet. Joints can also be made in which no melting is involved. These have been called diffusion bonded or solid-state bonded joints. They are similar to conventional resistance welds except that no molten nugget area is formed. Both kinds of joints have heat affected zones in the joint area. As might be expected, the weld nugget and the heat affected zones can be controlled by selection of current size and application time which in turn controls the elevated temperature cycle experienced at the joint. Electrode tool size and pressure applied through the electrodes as well as the composition and geometry of the parts being joined are also factors in determining the size and quality of the joint.

As in fusion welding, titanium alloy composition, condition, and cleanliness contribute to the success or failure of resistance welds. Thus, these factors of pertinency to fusion welding as previously discussed apply to resistance welding. Joint design is of course different; resistance welding involves joining of overlapping material layers. Such factors as edge distance and interspot spacing are of importance. Access to both sides of the joint is mandatory. There are further differences. For example, filler wire is never used in spot or seam welding. Also, some of the defects found in resistance welds, e.g. insufficient penetration, excessive sheet separation or surface indentation, are of a different character than defects in fusion welds. On the other hand, some of the problems encountered are common to both forms of welding, e.g. porosity, inclusions, contamination, cracks, distortion, requirements for stress relief annealing, inspection, and post-weld joint performance. Some of the features of spot and seam welding are as follows:

a. Spot Welding. Titanium is spot welded in much the same manner as other metals. Special shielding (i.e., inert-gas shielding), such as used for fusion welding, is not necessary because of the close proximity of the adjacent surfaces at the weld zone, and the very short duration of the weld cycle. Titanium is often considered to be more readily spot welded than aluminum and many of the carbon and low alloy steels, because of its relatively low electrical and thermal conductivity. Also, since titanium and stainless steels are similar in electrical and thermal conductivity, and strength at elevated temperatures, it is convenient and simple to adapt stainless steel spot-welding techniques for use with titanium. Therefore, a titanium alloy of a given thickness can be spot welded with the same welding machine settings that are satisfactory for a similar gage stainless steel. The recommended machine settings developed for titanium by various investigators substantiate this to a degree, and is generally considered as accurate as the ability to incorporate any recommended data into the settings from one production machine to another. Various auxiliary controls, such as up-slope or down-slope or post-weld heat controls, do not seem to offer any exceptional advantages when used in welding titanium. Roll-spot welding is the same as spot welding except that a wheel-shaped electrode is used instead of the cylindrical type. Rotation of the wheel is intermittent with the wheel electrodes in a fixed position during the actual weld cycle. The apparatus is indexed to provide programmed spacing between the parts joined.

b. Seam Welding. Since seam welding is essentially a series of overlapping spot welds made progressively along a joint by rotating the electrodes, the same criteria for the spot welding of titanium would apply to seam welding techniques for titanium.

45. Upset Welding Processes. This method of making joints not only involves the generation of heat within the parts to be joined but in addition features sufficient pressures to upset the heated metal, bringing the surfaces to be joined in intimate contact. Further, there may be an actual extrusion of the metal which formed the original contact surface to a position removed from the axis of the ultimate joint. Thus, a feature of some pressure weldments is that original surfaces which may become contaminated during heating, are removed from the critical portion of the final joint. In this kind of joint, heat generation may be from gas torches, induction coils, electric resistance between parts to be joined (flash welding), or high frequency generators (ultrasonic welding). Contamination from the heat source is relatively unimportant due to the above described upset feature in making the joint. Other methods are used too. For example, entire parts may be heated in vacuum or inert gas and pressure joined with a minimum of localized upset at the joint. Such methods are akin to diffusion bonding as well as to upset welding.

Conventional pressure welding equipment is satisfactory for upset welding titanium and its alloys. The welds are made in the same manner as for steel using similar upset pressures of about 2500 psi. The pressure may be applied throughout the heating cycle which, as previously mentioned, may be generated using gas torch welding equipment, induction heating, or resistance heating techniques. The pieces to be joined are machined so that they are in a good fit up in the welding machine prior to the application of heat. Butt joints are satisfactory for thin sections whereas beveled edges are sometimes used on thicker sections. For joints with solid cross sections, inert-gas shielding is not required but may be used. Enclosures can be placed around the joints and in the case of hollow cross sections, inert gas can be introduced inside of the assembly so that all surfaces are protected from contamination.

Upset welding is better adapted to the high-strength heat treatable titanium alloys than fusion welding in two respects. (1) molten metal is not retained in the joint, so cast structures are not present and (2) the hot metal of the ultimate joint is worked in the joining process which tends to improve ductility. Upset welds that have mechanical properties approaching those of the base metals can be made on conventional machines.

While ultrasonic welding is not truly an upset welding technique, it is described within this category as a convenience and due to the fact that small amounts of metal can be displaced in producing the joint. Ultrasonic welding may be considered a form of pressure welding in which two sheet surfaces to be joined are brought together and clamped between two electrodes. One electrode oscillates at ultrasonic frequency with respect to the other, parallel to the plane of the interface. This causes the faying surfaces to rub across each other to form a solid-phase weld where a galling action takes place. The vibrational energy not only causes relative motion of the two surfaces, but generates some heat in the joint area which softens the metal and promotes welding. As in other upset welding processes, the mechanical properties of the joint can be nearly equivalent to those of the base metal under optimum welding conditions.

46. Quality Assurance for Weldments. Quality control for welding should start with incoming material. Weld tests made on material to be used in welded assemblies will ensure that the base metal and filler rods are satisfactory for the intended application.

One of the better and quicker means of evaluating weldments is visual appearance. Generally, welds with dull white, gray, or yellow scale are excessively contaminated. With more adequate shielding, the weld surface may have a bright metallic blue or gold appearance or a combination thereof. Colors such as these indicate surface contamination only, and the welds generally are satisfactory. If the welds have the appearance of newly polished silver, this is an indication of nearly perfect shielding. However, contaminated welds with this appearance can be produced if the shielding around the molten puddle is insufficient, but shielding over the solidified weld is good. Also, good weld surface appearance does not provide an indication that the base or filler metals were not excessively contaminated before the welding operation began. Even slight surface contamination should be removed from titanium weldments if post weld heat treatment is to be used. If not removed it can diffuse into the material during the heat treatment causing property deterioration. Of course, before surface appearance is used to evaluate weld contamination, welds with varying surface appearances should be made under routine welding conditions, and then should be tested for ductility.

Other quality-control procedures used for titanium weldments include dye penetrant, ultrasonics and radiography for locating cracks, porosity, and other defects such as incomplete weld penetration, tungsten inclusions, visual examination for undercut, penetration, and weld reinforcement. Metallographic examination, mechanical tests, and hardness measurements are also usual specification requirements.

47. Diffusion and Deformation Bonding. These techniques for joining metals including titanium are important subcategories of the technique referred to as solid state bonding. Within this class, joints are produced with all components of the joining system being maintained as solids. Roll bonding, gas-pressure bonding, and solid-state welding are other names used for the general technique. Properly prepared—metallurgically clean—surfaces are essential for achieving a successful joint using this joining method.

In diffusion bonding, deformation is limited to that amount required to bring the surfaces to be joined into intimate contact. Once the surfaces are in contact, a joint is formed by diffusion of some element or elements across the previously existing interface. Diffusion bonding is primarily a time- and temperature-controlled process. The steps involved in diffusion bonding are:

(1) Preparation of the surfaces to be bonded by cleaning or other special treatments

(2) Assembly of the components to be bonded

(3) Application of the required bonding pressure and temperature in the selected bonding environment

(4) Holding under the conditions prescribed in Step 3 for the required bonding time

(5) Removal from the bonding equipment for inspection and/or test.

Diffusion-bonded joints have been made in titanium and several of its alloys at selected conditions encompassing the following ranges:

| | |
|---|---|
| Temperature | 1500 to 1900 F |
| Time | 30 minutes to 6 hours |
| Pressure | 5 to 10 ksi. |

The methods used to apply pressure include simple presses containing a fixed and movable die, evacuation of sealed assemblies so that the pressure differential applies a given load, and placing the assembly in autoclaves so that high gas pressures can be applied. A variety of heating methods also can be used in diffusion bonding, but generally the temperature is raised by heating with some type of radiation heater. With titanium, a vacuum environment is most practical, although it is possible to bond in an inert gas.

Deformation bonding differs from diffusion bonding primarily in that a measurable reduction in the thickness of the parts being joined occurs with deformation bonding. The large amount of deformation involved makes it possible to produce a bond in much shorter times and frequently at lower temperatures than with diffusion bonding. The desired pressure in deformation bonding may be applied by suitable mechanical devices such as presses, as in the joining of built-up structures from layered components, or rolling mills, as in roll-welded sandwich structures. Considerable effort has been expended in the development of these processes since the joint mechanical properties that are attainable are the same as base metal properties. Correctly produced, a bonded joint may be indistinguishable from the base metal.

48. Brazing. This method of joining titanium can be used to advantage in many applications where welded joints are undesirable or difficult to achieve such as in the joining of dissimilar metals to titanium or of sandwich structures. Most of the common brazing techniques are used including induction, furnace, resistance, torch; and dip brazing. Most of the problems encountered in brazing titanium are related to titanium's high affinity for other elements. That is, contamination problems, as described in previous sections, and compatibility problems related to the difficulty in finding braze filler metals that do not react disadvantageously with the base metal (i.e. producing embrittlement or erosion problems). Another problem area has been one of finding braze filler metals suitable for use in the thermal cycles that are compatible with the heat treatments used for titanium alloys. Since the preparation of surfaces to be brazed involves the same general precautions as are applicable to other joining processes for titanium, discussion will be confined to the topics of filler metals, fluxes and atmospheres, and brazing methods.

a. Filler Metals. To be useful as a brazing filler metal for titanium, an alloy must melt within a desired temperature range which is generally between a temperature much above the use temperature (on the low side) and below the beta transus temperature of the titanium alloy (on the high side). Also, a brazing filler metal should readily wet but not alloy with titanium at brazing temperatures to prevent degradation of the joint by formation of brittle intermetallic compounds.

Practically all metals readily wet titanium but because of titanium's high reactivity, they also readily alloy with titanium. Because titanium-silver compounds are relatively ductile, silver and silver-base alloys are used as brazing filler metals to produce brazed joints. Although alloying and consequent formation of brittle intermetallics are not eliminated, ductile joints are possible when the copper content of the silver is low. Silver and silver-base brazing filler metals form strong joints with usable strengths up to 600-800 F. The most useful alloys are silver-lithium, silver-aluminum-manganese, and silver-copper-lithium. The silver-lithium alloys are used in a composition range of 0.5 to 3.0 percent lithium. The typical composition for the silver-aluminum-manganese alloy is Ag-5Al-1Mn. The brazing temperature for this alloy is between 1450 and 1650 F.

Among other brazing alloys of interest are the silver-cadmium-zinc filler metals developed for oxyacetylene torch-brazing applications (Ag-5Cd-25Zn is typical), palladium-base alloys which are quite strong and are resistent to nitric acid (also impermeable to helium leakage), aluminum base alloys such as 3003 alloy, and a family of titanium-zirconium-beryllium alloys. A preferred palladium-base alloy is Pd-15.4 Ag-3.5 Si with a liquidus temperature of 1280 F. Titanium-zirconium-base filler metal alloys include: Ti-43Zr-12Ni-2Be, Ti-48Zr-5Be, and Ti-45Zr-5Al-5Be. The latter alloys have improved crevice corrosion resistance, good strength and peel characteristics and flow at temperatures below the beta transus temperatures of the titanium foil alloys.

b. Fluxes and Atmospheres. Special fluxes, either in combination with, or without, inert-gas atmospheres or vacuums, may be used for successful brazing of titanium. However it is not a common practice to use fluxes in brazing titanium. All fluxes for titanium contain chloride compounds. Thus there is a strong possibility that stress-corrosion cracking as a result of flux entrapment may occur when brazing with these compounds. Consequently, tests should be made with brazed joints, prior to use of these materials, to determine adequacy and acceptability.

Vacuums of from $10^{-5}$ to $10^{-6}$ Torr are often used to prevent contamination of titanium by oxygen and nitrogen from the air during furnace and induction brazing. Inert-gas atmospheres of helium or argon are also employed. The argon gas technique, however, is more commonly used than either the helium-gas or vacuum techniques. Some fluxes have been developed for use where the titanium member(s) of the joint is protected against high-temperature oxidation by first electrochemically depositing a metal-protecting film on the titanium. However, as previously stated, fluxes are not commonly used in conjunction with any of the brazing methods.

c. Brazing Methods. The effect of the brazing thermal cycle on base-metal properties is important in selecting brazing method and filler metal for any particular application. The brazing temperature may affect the ultimate and yield strengths of heat-treatable alloys unless it is possible to fully heat treat the assembly after brazing. If the brazing operation is part of the heat treatment schedule, it must be at the solution temperature since brazing alloys are not available that melt and flow at aging temperatures. Some overaging heat treatments are compatible with brazing temperatures however if the lower strengths of an overaged condition are satisfactory. If the brazing is to be done at the solution temperature, cooling rate from the thermal exposure must be compatible with the recommended cooling rate for the alloy being brazed in order to develop the preferred properties. Of course, if the material to be brazed is intended for use in the annealed condition, the brazing cycle can usually be adjusted to conform with a preferred annealing heat treatment schedule.

The various brazing techniques used for titanium and its alloys, together with their relative advantages and disadvantages, are as follows:

Induction brazing technique is used when the filler metals being used alloy readily with titanium; the object of this technique is to obtain the shortest brazing time to minimize alloying in the joints. The assembly to be brazed or the assembly and induction coil, together with filler metal preplaced, are enclosed in a nonmetallic container filled with an inert gas; then, they are brazed using a predetermined heating cycle. Design of both joint and induction coil are important. Some drawbacks to this technique are the type and size of joint that can be heated by an induction coil, and the need for protection against atmospheric contamination.

Furnace brazing is more easily adapted to various joint configurations and larger-sized assemblies than the induction brazing method. However, filler metals are usually held in the molten state for longer periods of time than in the induction method, which can result in excessive alloying. To minimize brittle intermetallics formation, filler metals that do not alloy readily with titanium should be used. The joints produced by this method are usually of lower strengths than those from either induction or torch-brazed techniques. Also, preplaced filler metal and protective-atmosphere or vacuum techniques are required.

Torch brazing uses a standard oxyacetylene torch. Short brazing times, with consequent minimizing of alloying, are possible. A slightly reducing flame is used. The equipment cost is low when using this technique. The flux is preplaced in the joint, and the filler metal either preplaced or fed into the joint. This method generally requires special fluxes and skilled operators. Also, the removal of fluxes, contaminated surfaces after brazing, and possibility of stress-corrosion from entrapped flux pose certain problems.

The resistance brazing technique uses spot-welding equipment to make lap joints. Filler metal in the form of foil, is placed between the sheets with or without flux. Protection against atmospheric contamination is not generally required.

Chemical-bath dip brazing can be used, but this method is not generally recommended because the titanium surface can be contaminated rather easily by the salt bath.

49. *Soldering.* Solder joining of titanium can be accomplished by first depositing a thin film of silver, copper, or tin on titanium using a metal plating technique applicable to titanium. These films can be wetted by 60Sn-40Pb or 50Sn-50Pb solder-alloys heated with a soldering iron using commercial soldering flux. The deposited films are thin and soluble in the liquid solders. If the soldering temperatures become too high or soldering time too long, the film will completely dissolve in the liquid solder. The soldering of titanium is not a much used joining process.

50. Adhesive Bonding. This method of joining titanium shares many factors in common with other joining techniques. Reproduction of good adhesive-bonded joints requires consideration of the materials, processing conditions, equipment, and subsequent service conditions. The principal material involved in adhesive bonding is the adhesive itself—the titanium composition being bonded is of little importance. A wide variety of chemical compounds have been used for adhesives. They may be classified as thermoplastic, thermosetting, elastomeric, ceramic, and blends of the first three types. Suitable adhesives for a given application must fulfill the requirements of being amenable to a reliable processing technique that will insure reproducible joint properties, and of performing satisfactorily under service exposures particularly if elevated temperature exposures are involved.

Equipment for adhesive bonding of titanium is of the same general types used in bonding other materials. A major factor in the bonding process is the surface preparation. Books have been written on the subject. Significant differences in joint properties may occur because of surface preparation variations. Degreasing and acid etching or alkaline cleaning as well as abrasive cleaning (e.g. grit blasting) have been used. The chief aim is to remove foreign matter from the surface and to activate it to receive the adhesive. Chlorinated solvents are avoided as are pickling solutions which promote hydrogen pickup. Activation films typically used for titanium can be complex mixtures of phosphates, fluorides, chromates, sulfates, and nitrates. Film thickness as well as composition is important and prepared adherend surfaces should be bonded no later than 8 hours after preparation.

Assembly of an adhesive-bonded joint after surface preparation involves applying the adhesive, positioning and holding the adherends in the desired relationship, and curing. Adhesive application depends on the type of adhesive used and can involve roller coating, brushing, troweling, dipping, spraying, or laying on since thick or thin liquids, viscous plastics, tapes or sheets may be the adhesive form used. Positioning and holding pressures and devices are quite variable depending upon the configuration being assembled and other factors. For example, dead-weight loading may be satisfactory for simple shapes whereas elaborate vacuum chucking arrangements might be required in the assembly of complex parts. Riveting has been used to hold assemblies together too. Up to several hundred psi pressures are required for some adhesives. Curing may be possible at room temperature but the higher strength adhesives are cured at elevated temperatures. Curing time is quite important and joints properly processed and cured can be very satisfactory from a mechanical properties viewpoint.

51. Mechanical Fastening. There are many methods available to produce a mechanically fastened joint including shrink fitting, keys, spring retainers, nails, screws, rivets, and bolts. The type of fastening used is determined on the basis of expected loads and type of loading to be encountered in service. Titanium and its alloys may be joined by any of the mechanical fastening methods. Further, titanium fastening devices such as rivets and bolts are manufactured to be used in the joining of titanium and other materials. Mechanically fastened joints differ so widely from each other in joint design, type fastener, and means of assembly, that it is impossible in a short space to fully describe any of the variables involved. Instead, this section limits discussion to a few features of the mechanical fastening of and with titanium.

Titanium and its alloys are mechanically joined with the same kind of fasteners used for more conventional structural metals. Fasteners are available in a large number of sizes and shapes. Fastener types for both shear and tension loading are available and may be made of titanium (and alloys), aluminum, Monel, H11 or SAE 4340 steels, or A286 high temperature alloy. Almost any fastener design can be applied to titanium so long as the factors of cost, application equipment, fastener availability, shop experience, and joint performance are considered. Two compatibility considerations also should be given attention: coefficient of thermal expansion and galvanic corrosion potential. For example, in high temperature service, mechanically fastened joints between titanium and other metals can be subject to loosening and tightening of the fastener due to thermal expansion differences. Fastening with dissimilar metals also raises the possibility of galvanic corrosion in the presence of aqueous electrolytes unless the fasteners are electrically isolated as with sealants.

Fastening devices have been manufactured from a wide variety of titanium materials including unalloyed grades (principally rivets), Ti-8Al-1Mo-1V, the beta alloys, Ti-6Al-6V-2Sn, but chiefly the Ti-6Al-4V alloy. Galling and seizing are problems encountered with fasteners made of titanium-between fastener and hole in interference fit joints and between screw and thread in threaded type fasteners. To ameliorate these difficulties, various coatings have been used, some of which (e.g. cadmium) have led to fastener failure problems. Coatings on titanium fasteners also have been used to alleviate galvanic corrosion problems, for example on titanium fasteners used to join aluminum components. As more and more experience is gained, solutions to the problems are more readily available and an increased use of titanium fasteners has been observed. They offer a reliable high strength means of securing a joint with a considerable weight saving potential.

## Coatings and Surface Treatments

52. General. Surface preparations of numerous types may be applied to titanium and its alloys for a variety of protection, property improvement, and decoration purposes. The preparations include metallic and nonmetallic coatings of numerous types and chemical and mechanical treatments. These may be categorized in several different ways, the usual method being classification by type of processing. However, since only a brief presentation of the subject will be included in this handbook, the various surface treatments available for titanium are included under the categories of protective coatings, coatings for property improvement, and surface treatments other than coatings.

Surface treatments for titanium may be applied to improve the oxidation and/or the corrosion resistance, the erosion and the wear and galling characteristics, the dynamic mechanical properties, other physical properties such as radiation characteristics, and the cosmetics. Some surface treatments require an elaborate process for application while others may be quite simply applied. Most surface treatments require precleaning of the titanium surface. The usefulness of surface treatments strongly depends upon the type and severity of service requirements. For example, service requirements range from the simple need to color-code equipment, achievable by painting, to the complex needs of wear resistant gear teeth, obtainable for lightly loaded gears by combinations of electrochemical metal plating, shot blasting, and lubricants. Generally, surface treatments for titanium are quite useful and serviceable in the less severe applications whereas some of the more severe potential applications cannot be satisfied with existing surface treatments.

53. Protective Coatings. The reactivity of titanium increases markedly with increasing temperature which results in scaling and surface contamination. At temperatures of about 1200 F and above, oxygen contamination can be a problem if workpieces are not in some way protected (e.g. by inert atmosphere, vacuum, or coatings). At 1500 F and above, scale formation on titanium can be quite rapid and metal loss to the scale can be significant. Further, the metal layers beneath the scale can be severely contaminated. Thus, the need for protective coatings in such operations as the primary fabrication of mill products and heat treatment is apparent. The titanium producers use protective coatings to minimize the problem. Ceramic coatings of several types are used which are generally composition controlled for selected temperature usage. Compositions are usually proprietary but products are readily available with full instructions for application and use temperature limits. A principal feature of these coatings is that they inhibit hydrogen pickup as well as oxygen pickup. Both nonfusing nonself-descaling and fusable self-descaling types are available and coatings of both types may be used in certain heat treatment processes as well as in metalworking operations.

Titanium and its alloys are quite resistant to many corrosive media and conditions but the useful range of alloys may be extended in certain environments by the use of coatings. For example, the degradation of titanium (by cracking) by the so-called hot-salt-stress-corrosion reaction (in chloride containing environments at temperatures of 450 F and higher) may be alleviated by anodized coatings or by metallic coatings. Since anodized coatings vary in hardness, density, crystallinity, and thickness depending upon anodizing conditions and electrolytes, different results have been reported. Generally however, thin, dense anodized coatings formed in NaOh, $H_2SO_4$ or $NaNH_4HPO_4$, afford some protection from hot-salt stress-corrosion and such coatings have been found to minimally degrade conjunctive properties such as post-creep tensile ductility and fatigue. Aluminum coatings applied by hot dipping or flame spraying to thicknesses of about 1 mil and electroplated nickel coatings also have been found to afford some protection against the hot-salt stress-corrosion reaction. Aluminum coatings also are useful for the protection against oxidation and contamination of titanium in elevated-temperature exposures. Incorrectly applied coatings, or coatings which can interact with the basis metal in the service environment, are likely to have deleterious effects to the basis metal. It is highly improbable that coatings which are classified as protective for titanium apply optimally for all conditions of use designated for the protective coating. On the other hand, judicial selection of coating systems will do much to enhance protection of titanium in many specific and unique applications.

54. Coatings for Property Improvement. The most widely researched type of coating for titanium is one for the improvement of titanium's wear and galling resistance. The relative softness of titanium even in heat treated hardened conditions, combined with its high reactivity with other materials, leads to the wear and galling problem. The hard oxides and the oxygen enriched surface layers that form on titanium are of no help in alleviating galling and wear since they tend to be brittle as well as hard and readily spall. Therefore, in service conditions where a rubbing together of surfaces is likely to be encountered, the necessity exists for coatings which can improve upon the galling and wear characteristics of titanium.

Metallic and nonmetallic coatings of many types have been used to improve wear properties. Metallic coatings can be applied by dipping, electroplating, flame spraying, plasma-spraying, vapor deposition, painting and baking, and other methods. Numerous metals can be used, including aluminum, nickel, chromium, molybdenum, and others. Nonmetallic coatings can be applied by a number of methods also, including gaseous diffusion, salt bath reaction, painting, electrochemical reaction, flame spraying, and chemical conversion reactions. The nonmetallics researched have included nitrogen, oxygen, carbon, metal oxides, ceramics, and complex organic and inorganic compounds. Each coating appears to have advantages, such as relative ease of application and improved wear characteristics, and disadvantages, such as degradation of fatigue properties, associated with it. There is no such thing as the best coating for the improvement of wear and galling: each need for coating must be carefully studied to determine the best coating for a particular application. The following descriptions are for typical coatings which have been found to be beneficial in the prior experience.

a. Aluminum. This metal has been applied by painting, flame spraying, roll cladding, and hot dipping methods for example, wherein various thicknesses of coatings can be built up. Although aluminum has no better galling and wear resistance than titanium, it can be anodized by conventional means. The anodized aluminum coating in combination with a lubricant, organics or resin bonded dry-film lubricants for example, offer some improvement in the wear of titanium. As previously mentioned, aluminum coatings are more commonly applied to afford some protection against oxidation.

b. Nickel. Both electroless nickel plating and electroplating from conventional baths have been used to apply nickel to titanium surfaces. Nickel plating has been used by itself in conjunction with lubricants and as a primary undercoating for overplates with chromium, iron, and other metals, to achieve improvements in wear and galling properties. The metal can be used as plated, or as plated plus diffusion heat treated to achieve better adherency. Titanium-nickel intermetallic compound can form at elevated temperatures and this compound has been shown to be deleterious to mechanical properties as well as to contribute to surface spalling. Nevertheless, nickel plates can be used advantageously to improve the surface properties of titanium in some applications.

c. Chromium. Electroplating of chromium on titanium, with or without an underplate of nickel or copper, has been examined extensively with the purpose of improving wear and galling properties. Various electroplating procedures have given different degrees of adherency which is one of the problems in using electroplate for this purpose. Diffusion heat treatments can be used to improve adherency but this can lead to the formation of titanium-chromium intermetallic compound and problems of surface embrittlement. Lubricants used in conjunction with electroplates afford meaningful benefits in titanium applications where the wear problem does not involve heavy contact stresses.

d. Molybdenum. This metal is usually flame-sprayed onto the titanium substrate and can be built up to desirable thicknesses. Since titanium and molybdenum do not form intermetallic compounds, surface embrittlement is not a problem. However, oxygen enriched molybdenum coatings and thick coatings are inherently brittle. Used with organic or inorganic lubricants, molybdenum is used satisfactorily in applications involving sliding contact (e.g. shafts), whereas it is unsuitable for resisting severe abrasion and high-shock loads.

e. Nitrogen. The surface of titanium may be hardened significantly with nitrogen via a gas diffusion reaction or from cyanide salt baths. Carbonitriding also may be accomplished from cyanide type baths. Quite high reaction temperatures are involved in nitriding titanium which may be undesirable from a substrate properties viewpoint. However, the high hardness of nitrided surfaces may be successfully used in conjunction with lubricants to resist wear.

f. Oxygen. Titanium surfaces may be hardened by simply exposing work pieces to air or oxygen at elevated temperatures. However, a more satisfactory coating from the viewpoint of coating durability is obtained by using one of the numerous anodizing procedures. Titanium can be anodized in nearly any electrolyte to give coatings ranging between hard, thin, crystalline coats and soft, thick, amorphous coats depending on electrolyte and electrical conditions. Direct current exposure of the work piece in the anodizing solution should only be attempted after thorough pre-cleaning and exposures should be carefully controlled to yield the coating characteristics desired. Anodized coatings used in conjunction with either wet or dry-film lubricants are widely used to improve the wear and galling resistance of titanium.

g. Ceramics. As an example of this type coating for titanium, flame sprayed aluminum oxide may be considered. The $Al_2O_3$ coatings, applied either on the bare titanium or with a nickel-chromium intermediate coating, can be used effectively in conjunction with lubricants to provide hard coatings that are resistant to abrasion and wear. Ceramic coatings also may be used to improve erosion resistance.

h. Chemical Conversion Coatings. Coatings of this type act as a base for lubricants promoting their retention and thereby aiding the lack of lubricity and associated wear problems. Conversion coatings may be applied by spraying, brushing, or immersion in salt baths, the latter being the commonly used method. Sodium and potassium salts of phosphates and fluorides in carefully controlled acidic solutions give a useful coating in from 2 to 10 minute exposure. The resultant coatings are comprisedoof titanium-potassium-phosphate-fluoride compounds which are quite stable and hold lubricants well. The conversion coatings can be used to facilitate metal-working as well as to improve wear in service exposures.

i. Lubricants. The list of lubricants that have been applied to titanium is seemingly without end. Liquid and solid lubricants used on bare titanium afford some improvement for the wear problem but are much more effective when used with a hard coating of some type, e.g. anodized coatings. Synthetic long-chain compounds, halogenated hydrocarbons, reactive inorganic solutions (e.g. iodine in alcohol or hydrogen sulfide in water), colloidal graphite, and molybdenum disulfide in either resin or lacquer have been used with variable results. When used on bare titanium, no strong natural bonding takes place between lubricant and titanium. Lubricants alone may perform satisfactorily at low loads but heavy loads quickly cause a breakthrough and metal to metal contact. The liquid lubricants which have shown a great deal of promise on bare titanium are methylene iodide and polyethylene glycol. Molybdenum disulfide in a heat cured resin base appears to be one of the most beneficial dry-film lubricants. It cannot be overemphasized, however, that lubricants alone do not offer much improvement in the wear and galling of titanium and are better used in conjunction with one of the coatings for titanium such as a metal electroplate or anodized coating.

In addition to the coatings applied to titanium for the improvement of the wear problem, coatings of various kinds can be used to improve other surface properties. For example, metallic plating (thin) followed by diffusion annealing was found to alter surface stress relaxation characteristics and thereby improve creep and fatigue properties of the basis metal. Aluminum, copper, and chromium were effective in this regard. Aluminum coatings and gold castings, the latter painted on and subsequently fired (at 950 to 1400 F) have been used to improve the heat-reflection characteristics of titanium. High emissivity paints for titanium also have been developed although paints are usually used more for appearance and identification purposes than for such functional purposes as an aid to thermal radiation. Anodized titanium has relatively low reflectance at short wave-lengths and high reflectance at longer wavelengths to afford improved solar energy collecting surfaces. The corrosion resistance coatings and the oxidation resistant coatings were previously described and are rementioned here to point out the fact that there are coatings for titanium of many types, apparently a coating for nearly every need.

55. Surface Treatments Other Than Coatings. Both mechanical and chemical surface treatments are available for titanium that can impart desirable surface characteristics. Processes such as shot peening, vapor blasting, grit blasting, surface rolling, or barrel tumbling can be used, for example, to introduce surface residual stress for the purpose of improving fatigue properties or reducing stress-corrosion sensitivity. Such treatments work harden the surface and alter surface roughness, both factors that can affect bulk mechanical properties. For example, a fatigue life improvement may be obtained in properly glass-bead peened surfaces (glass shot preferred to steel shot to avoid iron contamination of surfaces in certain corrosive or reactive environments). Glass bead peening of the interior surfaces of titanium spacecraft tankage also was used to reduce stress-corrosion susceptibility. Peening intensity is quite an important factor in achieving a beneficial result. In addition to the mechanical working of surfaces, mechanical finishing of titanium surfaces achieved by machining, grinding, or polishing operations, is equally important in affecting such properties as fatigue life. Smooth finishes also can be important where reflectivity, fluid flow resistance, corrosion, coating adherency, friction, or appearance might be the property of interest.

Electrochemical and chemical polishing of titanium surfaces are important processes for some applications. A jewelry finish can be obtained on titanium in an alcohol-chloride electrolyte using titanium as anode and 30- to 60-volt direct current. A current of 1 to 5 amp/sq. in. is maintained in the room temperature solution for 1 to 6 minutes to achieve a polished surface quite pleasing in appearance and beneficial to such surface sensitive properties as fatigue life and bend ductility. Chemical polishing also is possible, usually in aqueous solutions containing the fluoride ion (e.g. $NH_4FHF$ to $H_2SiF_6$ solutions) and an oxidizing acid (e.g. $HNO_3$). The rate of chemical dissolution and the degree of polishing are related to the solution temperature, the titanium alloy, and the condition of the initial surface. Polished surfaces can be beneficial in many applications.

## Corrosion Characteristics

56. General. Titanium is inherently a reactive metal, so that whenever it is exposed to air or other environments containing available oxygen a thin surface film of oxide is formed. It is to

this film that titanium owes its excellent corrosion resistance. Titanium is equal to, or better than, most metals in resistance to direct chemical corrosion by a wide variety of chemicals and is generally resistant to stress corrosion, erosion-corrosion, galvanic corrosion, and oxidation. Compared to many other structural metals, titanium generally is more resistant to corrosion in a wide variety of chemical environments, and generally is less prone to failure from stress-, erosion-, and galvanic-corrosion, and from oxidation.

The most protective films on titanium are usually developed when water, even in trace amounts, is present in the environment. 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 in nature, may take place. Examples of such reactions that may be initiated at room temperature or slightly above are (1) titanium and dry chlorine and (2) titanium and dry fuming nitric acid.

The corrosion resistance of the various titanium alloys has not been investigated as extensively as that of the commercially pure grades; however, available data indicates that the general corrosion-resistance characteristics of titanium are not impaired by alloying. In fact, some of the beta alloys are highly resistant to some very hostile environments (e.g. $H_2SO_4$). When exposed to various types of atmospheres for extended periods, commercially pure alloy titanium retains the luster obtained in the finishing operation.

57. Chemical Environments. Titanium and its alloys corrode rapidly in environments that cause breakdown of the protective films. Of most importance are such reagents as hydrofluoric, hydrochloric, sulfuric, phosphoric, oxalic, and formic acids. However, attack by all these media except hydrofluoric acid can be reduced in many instances by the addition of acid salts, oxidizing acids, and other suitable inhibitors. Dry chlorine also attacks titanium, but it is quite resistant in wet chlorine (1% moisture) and other oxidizing gases, such as $SO_2$ and $CO_2$.

Titanium has excellent corrosion resistance to all concentrations of nitric acid up to 350 F. However in nitric acid above 20 percent concentration and at 375 F, the corrosion rate may be as high as 100 mils/year. Even at 550 F the rate of attack in 20% $HNO_3$ is only 12 mils/year. An anomaly exists, however, at 375 F, in that corrosion rates as high as 100 mils/year are reported at concentrations above 20 percent $HNO_3$. Caution should be exercised, however, when titanium alloys are used in anhydrous fuming $HNO_3$ because the reaction can by pyrophoric. The resistance of titanium to chromic acid is good, as is its resistance to aqua regia ($3HCl \cdot 1HNO_3$). For mixtures of sulfuric and nitric acids, corrosion rates increase with increasing $H_2SO_4$ concentration.

Titanium, like many other metals, has good resistance to dilute solutions of alkali. Hot, strong, caustic solutions will attack unalloyed titanium and titanium alloys. On the other hand, there is no evidence to suggest that titanium alloys are susceptible to caustic embrittlement as are carbon steels and stainless steels.

Titanium is superior to stainless steels in its resistance 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 will cause pitting of titanium alloys. In addition, at temperatures above about 200 F, titanium may evince crevice corrosion in seawater or in promine. On the other hand, titanium is not attacked by the highly corrosive ferric chloride and sodium hypochlorite solutions, which are corrosive to stainless steel.

Long-term studies indicate that titanium in seawater and marine environments is resistant to pitting, stress corrosion, galvanic corrosion, crevice corrosion (below about 200 F), erosion-corrosion, and corrosion fatigue. Titanium tested for effect of flowing seawater showed a thinning rate corresponding to 0.00003 inch per year. No thinning could be detected in similar tests conducted in slowly moving seawater. Even after severe testing for 60 days in rapidly moving seawater, titanium showed negligible attack. Conditions which usually accelerate attack (stagnation in crevices; under fouling organisms; under moist salt crystals) failed to damage the metal. In salt spray tests, titanium alloys were not attacked after exposure for 1000 hours.

The tensile properties of titanium alloys are generally unaffected by prolonged exposure to a marine environment. Tensile test specimens with yield strengths of 105 ksi have withstood static loads of up to 80 ksi in sea air for over four years without sign of failure. Specimens tested in seawater and in marine air maintained a fatigue endurance limit of 60 ksi.

Pure hydrocarbons are not considered corrosive to most metals, including titanium. In addition, titanium exhibits good corrosion behavior in most chlorinated and fluorinated hydrocarbons, and other similar compounds used as hydraulic and/or heat-exchange fluids. It should be pointed out, however, that 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, a portion of which may be absorbed by the titanium, resulting in loss of ductility, or chlorides may be released that can initiate elevated-temperature stress-corrosion cracking.

Titanium is not recommended for use in gaseous or liquid oxygen since a violent reaction can occur. When a fresh titanium surface such as a crack or fracture is exposed to gaseous oxygen, even at -250 F and at a pressure of about 50 to 100 psi, burning can begin. Once the reaction starts, the oxide formed is not protective, as it is, for example, with stainless steel. In liquid oxygen, titanium is impact sensitive at levels below those of many organics. Titanium and its alloys also exhibit pyrophoric reactions under impact in chlorine trifluoride, liquid fluorine, and nitrogen tetroxide. However, only in the case of liquid and gaseous oxygen has the reaction been found to propagate once it was initiated.

58. Stress-Corrosion. "Stress-corrosion is a form of localized corrosion which results in cracking from the simultaneous action of a corrosive environment and sustained tensile stress on a metal." It is characterized by a brittle-type fracture occurring in an otherwise ductile material. The surface direction of the cracks is perpendicular to the direction of the stress load. Cracking may be either intergranular or transgranular, depending on the alloy, the structure, and the environment. In general, stress-corrosion cracking of titanium alloys is intergranular.

Commercially pure titanium has not been found to fail by stress-corrosion cracking in any media except fuming $HNO_3$ or methanol containing HCl, $H_2SO_4$, or $Br_2$. However, under "plane strain" conditions, in the presence of a preexisting crack, unalloyed titanium containing high oxygen levels will exhibit rapid crack propagation in seawater at low stress levels. This phenomenon is thought by many to be akin to stress corrosion cracking. The common aqueous stress-corrosion test solutions do not have any effect on titanium alloys under normal conditions. However recent tests have disclosed that titanium alloys under exposure conditions of ambient temperature, aqueous media, and in a state of stress that produces a virgin metal surface (a fresh crack) will undergo stress corrosion. In particular, it has been found that some common aqueous stress-corrosion solutions (distilled water, tap water, 3.5% NaCl solution) affect the fatigue life of sharp-notch test specimens at high stress levels. Figure 19 illustrates the increased fatigue crack growth rate in water and salt water compared with cracking in air. Such environments cause reduced stress

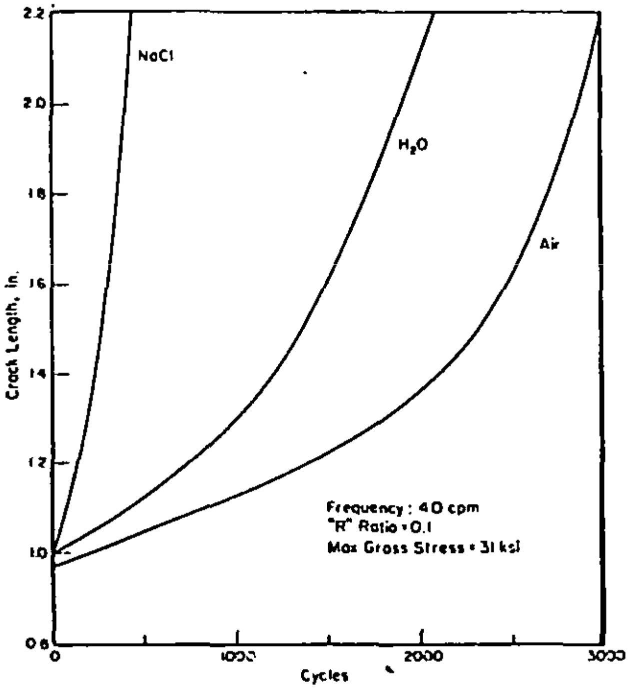

Figure 19. Crack Length Increase As a Function of Fatigue Cycles in Duplex Annealed Ti-8Al-1V Sheet in Various Environments

rupture life in fatigue-cracked tension and bend specimens. In the latter case, cracking propagates very rapidly from the infinitely sharp fatigue-induced notch in a direction normal to the direction of the tension stress. A fresh titanium surface is continually being exposed to the test medium in this type of test. Under these conditions, it appears that the titanium materials, as well as some other structural materials tested, undergo a stress-corrosion type of deterioration. The same effect was observed in steels and was commonly used to speed up crack development in the preparation of fatigue-precracked fracture-toughness specimens. While the practical limitations imposed by this ambient-temperature reaction are presently unknown, it is entirely clear that titanium alloys are not immune from such reactions, as was previously believed.

The susceptibility of precracked titanium alloys to stress corrosion cracking in salt water appears to be affected by the aluminum, oxygen, and tin content and isomorphous beta stabilizers. The data indicate that the susceptibility occurs with higher oxygen, aluminum, or aluminum-tin contents. Figure 20 shows the effect of increasing aluminum content on the environmental toughness of a Ti-Al-Mo-V alloy series. Tensile yield strength and air toughness are not much affected by a high aluminum content whereas the high aluminum content alloys have a degraded toughness in salt water. The presence of isomorphous beta-stabilizers—molybdenum, vanadium, and columbium—tends to reduce sensitivity of titanium alloys. The addition of molybdenum to Ti-7Al-2Cb-1Ta or Ti-7Al-3Cb tended to reduce their susceptibility to cracking, and the addition

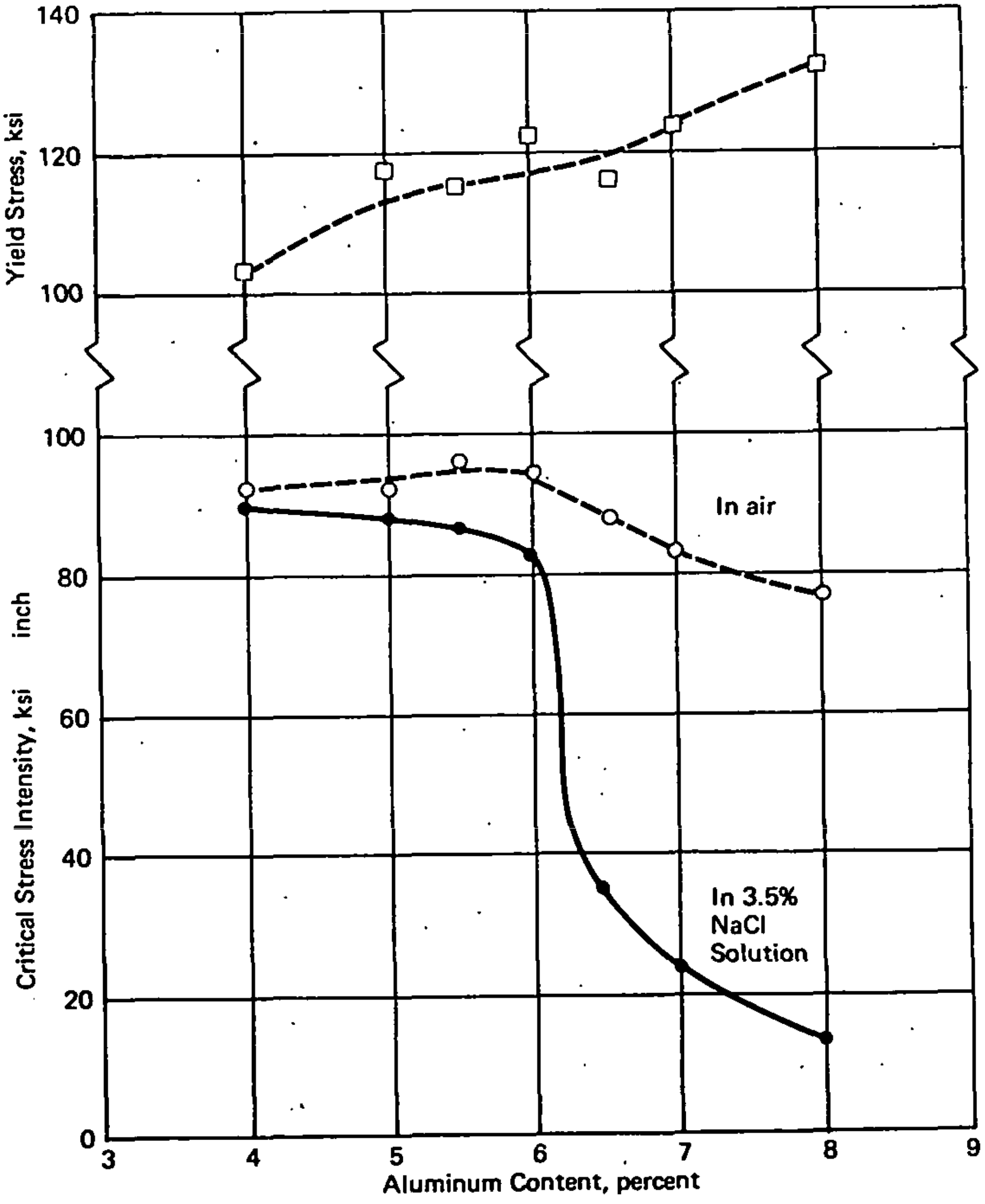

Figure 20. Effect of Aluminum Content on the Strength, Toughness, and Stress-Corrosion Susceptibility of Ti-1.5Mo-0.5V—Base Alloys (Nominally 1000 PPM Oxygen)

of molybdenum is currently being considered as a compositional improvement for certain alloys in order to reduce their cracking potential in salt water. The Ti-6Al-2Cb-1Ta-0.8Mo alloy was developed on this basis.

Alloys that have shown some degree of susceptibility to rapid crack propagation in salt water are listed below, but not necessarily in order of susceptibility:

Unalloyed Ti with 0.32 percent oxygen content
Ti-5Al-2.5Sn
Ti-6Al-4V
Ti-6Al-6V-2Sn
Ti-7Al-3Mo
Ti-8Al-1Mo-1V
Ti-8Mn
Ti-13V-11Cr-3Al

There probably is no such thing as a titanium alloy which is completely immune to the salt-water stress-corrosion reaction although some materials are highly resistant to it. These include:

Unalloyed Ti with low oxygen content
Ti-4Al-3Mo-1V
Ti-6Al-2Mo
Ti-6Al-2Cb-1Ta-0.8Mo
Ti-2Al-4Mo-4Zr (experimental)
Ti-5Al-2Sn-2Mo-2V (experimental)
Ti-11.5Mo-6Zr-4.5Sn (as solution treated)

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

Alloys of titanium can also suffer stress-corrosion cracking at ambient temperatures under certain other specific conditions. Failures have been encountered in red fuming $HNO_3$ (as mentioned above), in $N_2O_4$, and in HCl. In addition, certain alloys have shown 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.

In the case of red fuming $HNO_3$, cracking is limited to environments containing less than 1.5% water or more than 6% $NO_2$. The cracking is thought to be related to the selective attack of small amounts of beta-phase and/or an enriched-alloy zone along the grain boundaries. In addition, this attack leaves finely divided, highly reactive particles of titanium which will detonate under slight shock. Adding water above 1.5% to the anhydrous acid greatly reduces the chance for stress-corrosion cracking and pyrophoric reactions.

Failure of the Ti-6Al-4V alloy in tankage applications has occured in $N_2O_4$ containing oxygen and chlorides as impurities. With the oxygen replaced by greater than 0.06 percent NO as an inhibitor, failures are prevented. This attack may be the result of incomplete oxide formation at the metal-surface slip planes, or by preferential absorption of the chloride ion. Current specifications for propellant-grade $N_2O_4$ require the NO content to be between 0.4 and 0.8 percent.

Methyl alcohol is another medium that initiates stress-corrosion cracking of titanium and its alloys. With small additions of bromine, HCl, or $H_2SO_4$ 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 level. For example, solution-treated-and-aged

Ti-6Al-4V evinces some failures at about 70 percent of its yield strength, while annealed Ti-6Al-4V cracks only on stressing near its yield point. The Ti-6Al-1Mo-1V alloy appears more susceptible.

Stress-corrosion cracking also occurs at elevated temperatures. Late in 1955, surface cracking was observed on Ti-6Al-4V alloys undergoing creep testing at 700 F. The cracking was attributed at that time to surface embrittlement induced by oxidation. Later, it was established that cracks were often associated with fingerprints. Follow-up testing of specimens under stress in contact with pure NaCl produced cracking at elevated temperatures. This phenomenon has become known as hot-salt stress-corrosion cracking.

While cracking of titanium alloys in contact with hot sodium chloride has been obtained in laboratory studies at temperatures as low as 450 F, this phenomenon has not been officially reported as the cause of failure of a titanium part in service. It should be pointed out, however, that, with the possible exception of jet-engine components, titanium parts in service are not usually subjected to combinations of stress and temperature in the range found to induce cracking in the laboratory.

Studies to date have indicated that several types of chloride salts will initiate failure. However, NaCl now appears to be most reactive. Oxygen or a reducible oxide ($TiO_2$) must also apparently be present for cracking to occur, although the critical concentration of oxygen is low (1 to 10 microns Hg pressure). Water may also enter into the reaction and appears to be necessary, although its critical concentration is low (on the order of 10 ppm).

Recent studies on the mechanism have shown that a gas-phase reaction can occur, whereas previously a liquid-phase reaction seemed to be required. The mechanism apparently involves NaCl, $O_2$, $H_2O$, and reaction products of $TiCl_2$, NaOH and $TiO_2$. A more recent theory proposes that NaCl and water react to form NaOH and HCl. The HCl reacts with the protective oxides on the surface, forming unprotective chlorides. The hydrogen released by the attack of the exposed titanium is then believed to diffuse into the metal to cause subsequent hydrogen embrittlement.

It appears that most titanium alloys are susceptible to some degree to hot-salt stress-corrosion cracking. The alpha-phase alloys, such as Ti-5Al-2.5Sn, are apparently most susceptible to attack. The alpha-beta alloys are less susceptible but the degree of susceptibility may increase with increases in aluminum content. For example, the Ti-8Al-1Mo-1V alloy (both as mill annealed and duplex annealed) is very susceptible. However, the Ti-8Mn alloy, which contains no aluminum, is also susceptible.

Alloys with intermediate resistance are Ti-6Al-4V, Ti-6Al-6V-2Sn, and Ti-3Al-11Cr-13V. Among the most resistant alloys are Ti-4Al-3Mo-1V, Ti-2.5Al-11Sn-5Zr-1Mo-9.2Si, and an experimental Ti-2Al-4Mo-4Zr alloy. Variations in heat treatment have been found to affect the reactivity of many alloys also. Table XXXII lists approximate stress-temperature thresholds for several titanium alloys.

The use of certain coatings on a titanium surface shows promise of protection. Surface coatings of nickel plate, aluminum plate, and zinc plate show promise of delaying attack when the coating is nonporous. In one study, flame-sprayed aluminum and nickel and electroless nickel were porous and not very effective, while hot-dipped aluminum gave good protection. In other work, promising results were obtained with a duplex nickel coating. In view of the role of oxygen (even as $TiO_2$) on the hot-salt cracking, it is not believed that anodized films will offer satisfactory protection.

TABLE XXXII. APPROXIMATE THRESHOLDS FOR STRESS—CORROSION CRACKING OF TITANIUM ALLOYS IN HOT SALT

| Nominal Composition, wt % | Condition | 100—Hr Threshold Stress, ksi | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 550 | 600 | 650 | 700 | 750 | 800 | 850 | 900 | 950 |
| Ti-5Al-2.5Sn | Annealed | 28 | 30 | — | 15 | — | 10-20 | — | — | — |
| Ti-8Al-1Mo-1V | Aged | — | — | — | — | 25 | — | 20 | — | 15 |
| | Annealed | 25 | 55 | — | 23 | — | 18 | — | — | — |
| Ti-2.5Al-1Mo-10Sn-5Zr | Aged | — | — | — | 70 | — | 40 | — | 35 | — |
| Ti-4Al-3Mo-1V | Aged | — | 95 | — | 25 | — | 25 | — | — | — |
| | Annealed | 84 | 78 | — | 28 | — | 15-49 | — | — | — |
| Ti-6Al-4V | Aged | — | 95 | 65 | 25 | 30 | 12 | 15 | — | — |
| | Annealed | 50 | 50 | — | 22 | — | 18-24 | — | — | — |

Another phenomenon that is closely related to stress-corrosion cracking is that of liquid-metal embrittlement. Many alloy systems, including titanium, have been found to exhibit brittle failure when in contact with specific low-melting-point metals. In the case of titanium alloys, molten cadmium will cause cracking (e.g. when used as a coating on titanium fasteners). Mercury and mercury amalgams also initiate cracking. However, in this case, plastic rather than elastic deformation is required to induce cracking. Further, it has been found that silver will cause cracking of stressed Ti-7Al-4Mo and Ti-5Al-2.5Sn alloys at temperatures of 650 F and above.

59. Crevice Corrosion. Crevice corrosion of titanium and its alloys has been shown to occur in chloride-salt solutions at elevated temperature. This attack occurs above 200 F, 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. The titanium alloy with about 0.2 percent palladium provides increased resistance to crevice attack, but it too is attacked after long-term exposure at elevated temperature. A comparatively new alloy, Ti-(1-2) Ni, also is resistant to crevice corrosion. While the mechanism is not completely understood, microcrevices, lack of oxygen, and hydride formation may be involved.

60. Galvanic Corrosion. In most environments, the electromotive potential of passive titanium is quite similar to that for Monel and stainless steels. Therefore, galvanic effects are not likely to occur when titanium alloys are coupled to these materials. On the other hand, less noble materials, such as aluminum alloys, carbon steels, and magnesium alloys, may suffer accelerated attack when coupled with titanium. The extent and degree of galvanic attack of a dissimilar metal couple depends on the environment to which the couple is exposed, and on the respective areas of each metal involved, e.g., if titanium is the cathodic member of a couple, and if the area of the anodic member is smaller in relation to the titanium, then in a corrosive environment severe corrosion of the anodic member could be expected. On the other hand, less attack will be evident if the areas of the two metals are reversed. Such attack can be prevented or minimized in most cases by protective paints and other treatments, which include modifying the environment or insulating the dissimilar metals from direct contact with each other.

# SECTION IV

# BIBLIOGRAPHY

Pertinent references to the various subjects described in this handbook are listed according to the topical paragraph numbering system used. The Table of Contents may be used as a guide to the subjects covered. Insofar as possible, the readily available references are listed, although in several cases, references that fully describe the subjects of interest are difficult to obtain. Governmental libraries and the various information services may be of assistance in locating some of the references cited.

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