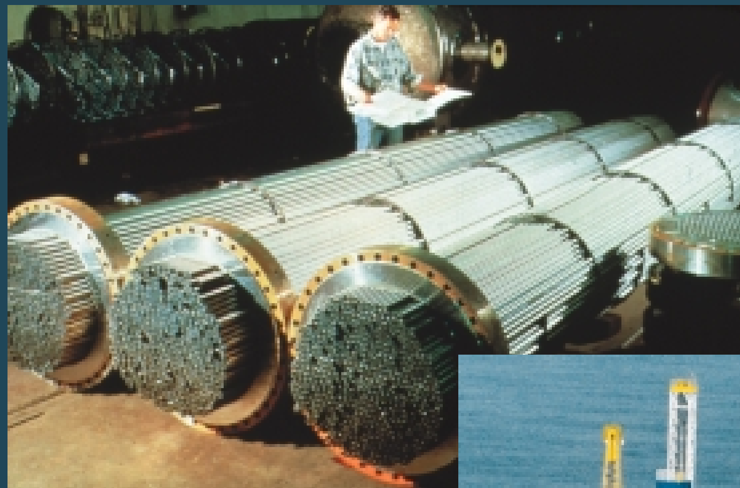

TITANIUM ALLOY GUIDE

RMI TITANIUM Company®

An RTI International Metals, Inc. Company

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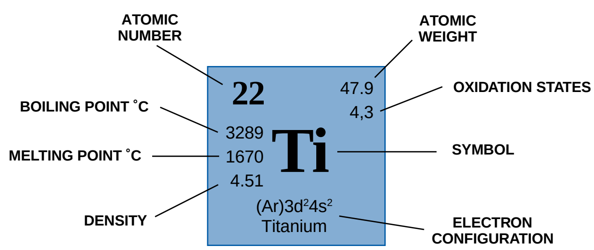
PROPERTIES OF PURE ELEMENTAL TITANIUM AT ROOM TEMPERATURE



hcp Crystal Structure		Heat of Vaporization	9.83 MJ/kg
Lattice Parameters	c=0.468 nm	Specific Heat	518 J/kg ˚K
	a=0.295 nm	Magnetic Susceptibility	3.17×10^{-6} cm³/g
Atomic Volume	10.64 cm³/mol	Magnetic Permeability	1.00005
Covalent Radius	1.32Å	Modulus of Elasticity	100 GPa
Color	Dark Grey	Poisson's Ratio	0.32
Hardness	70 to 74 BHN	Solidus/Liquidus Temp.	1725˚C
Coefficient of Thermal		Beta Transus Temp.	882˚C
Expansion	8.4×10^{-6}/˚C	Thermal Neutron Absorption	
Electrical Resistivity	42 µohm-cm	Cross Section	5.6 Barnes
Thermal Conductivity	20 W/m-˚K	Electronegativity	1.5 Pauling's
Heat of Fusion	292 kJ/kg		

Cover and Back Photo Descriptions

1.– Heat Exchangers
2.– Offshore Drilling Platform
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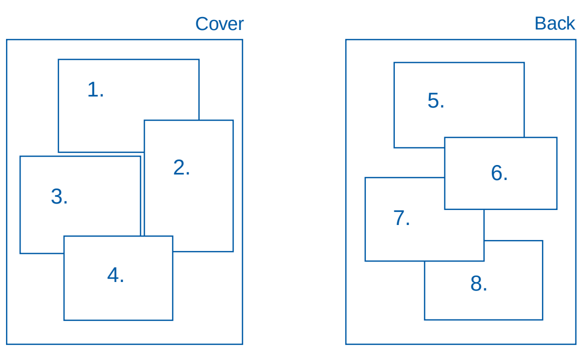


INTRODUCTION

Titanium has been recognized as an element (Symbol Ti; atomic number 22; and atomic weight 47.9) for at least 200 years. However, commercial production of titanium did not begin until the 1950's. At that time, titanium was recognized for its strategic importance as a unique lightweight, high strength alloyed, structurally efficient metal for critical, high-performance aircraft, such as jet engine and airframe components. The worldwide production of this originally exotic, "Space Age" metal and its alloys has since grown to more than 50 million pounds annually. Increased metal sponge and mill product production capacity and efficiency, improved manufacturing technologies, a vastly expanded market base and demand have dramatically lowered the price of titanium products. Today, titanium alloys are common, readily available engineered metals that compete directly with stainless and specialty steels, copper alloys, nickel-based alloys and composites.

As the ninth most abundant element in the Earth's Crust and fourth most abundant structural metal, the current worldwide supply of feedstock ore for producing titanium metal is virtually unlimited. Significant unused worldwide sponge, melting and processing capacity for titanium can accommodate continued growth into new, high-volume applications. In addition to its attractive high strength-to-density characteristics for aerospace use, titanium's exceptional corrosion resistance derived from its protective oxide film has motivated extensive application in seawater, marine, brine and aggressive industrial chemical service over the past fifty years. Today, titanium and its alloys are extensively used for aerospace, industrial and consumer applications. In addition to aircraft engines and airframes, titanium is also used in the following applications: missiles; spacecraft; chemical and petrochemical production; hydrocarbon production and processing; power generation; desalination; nuclear waste storage; pollution control; ore leaching and metal recovery; offshore, marine deep-sea applications, and Navy ship components; armor plate applications; anodes, automotive components, food and pharmaceutical processing; recreation and sports equipment; medical implants and surgical devices; as well as many other areas.

This booklet presents an overview of commercial titanium alloys offered by RMI Titanium Company. The purpose of this publication is to provide fundamental mechanical and physical property data, incentives for their selection, and basic guidelines for successful fabrication and use. Additional technical information can be found in the sources referenced in the back of this booklet. Further information, assistance, analysis and application support for titanium and its alloys, can be readily obtained by contacting RMI Titanium Company headquartered in Niles, Ohio, USA, or any of its facilities and offices worldwide listed in this booklet.

PERIODIC TABLE

22 Ti

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc		V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun								

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

The information provided on the following pages is intended for reference only. Additional details can be obtained by contacting the Technical staff of RMI Titanium Company through its Sales Department or through the website at www.RMITitanium.com.

WHY SELECT TITANIUM ALLOYS?

Attractive Mechanical Properties

Titanium and its alloys exhibit a unique combination of mechanical and physical properties and corrosion resistance which have made them desirable for critical, demanding aerospace, industrial, chemical and energy industry service. Of the primary attributes of these alloys listed in Table 1, titanium's elevated strength-to-density represents the traditional primary incentive for selection and design into aerospace engines and airframe structures and components. Its exceptional corrosion/erosion resistance provides the prime motivation for chemical process, marine and industrial use. Figure 1 reveals the superior structural efficiency of high strength titanium alloys compared to structural steels and aluminum alloys, especially as service temperatures increase. Titanium alloys also offer attractive elevated temperature properties for application in hot gas turbine and auto engine components, where more creep-resistant alloys can be selected for temperatures as high as 600˚C (1100˚F) [see Figure 2].

Table 1. Primary Attributes of Titanium Alloys

- Elevated Strength-to-Density Ratio (high structural efficiency)
- Low Density (roughly half the weight of steel, nickel and copper alloys)
- Exceptional Corrosion Resistance (superior resistance to chlorides, seawater and sour and oxidizing acidic media)
- Excellent Elevated Temperature Properties (up to 600˚C (1100˚F))

The family of titanium alloys offers a wide spectrum of strength and combinations of strength and fracture toughness as shown in Figure 3. This permits optimized alloy selection which can be tailored for a critical component based on whether it is controlled by strength and S-N fatigue, or toughness and crack growth (i.e., critical flaw size) in service. Titanium alloys also exhibit excellent S-N fatigue strength and life in air, which remains relatively unaffected by seawater (Figure 4) and other environments. Most titanium alloys can be processed to provide high fracture toughness with minimal environmental degradation (i.e., good SCC resistance) if required. In fact, the

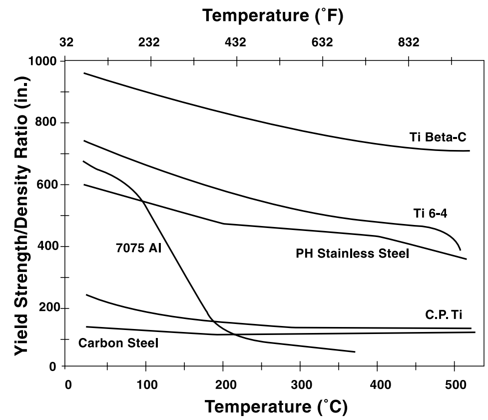


Figure 1

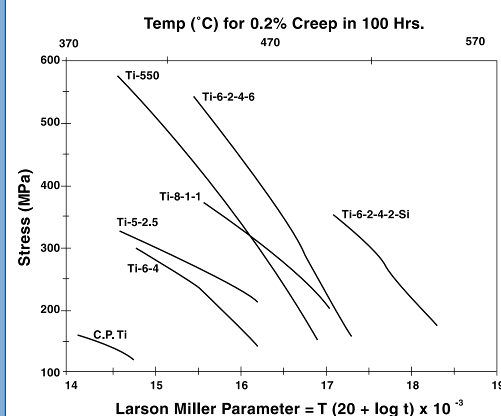


Figure 2

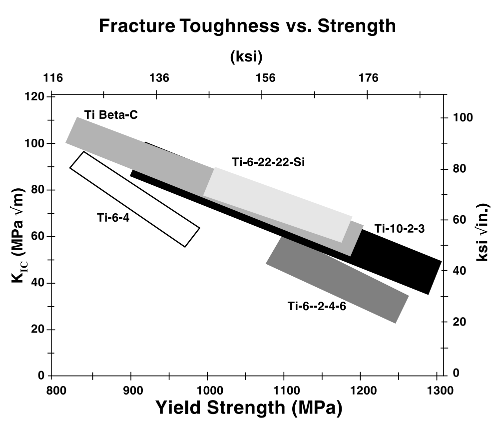


Figure 3

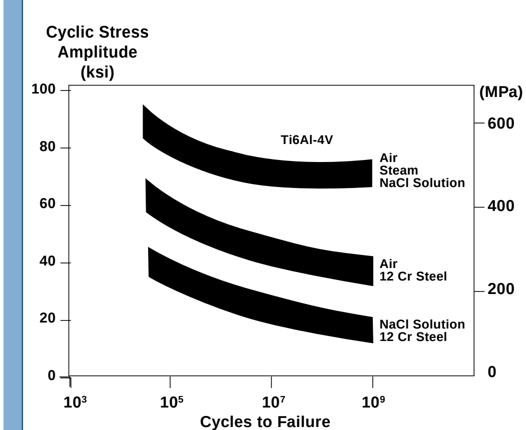
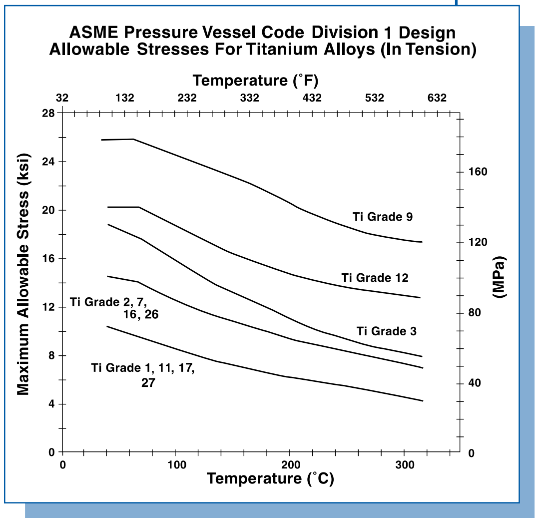


Figure 4

lower strength titanium alloys are generally resistant to stress corrosion cracking and corrosion-fatigue in aqueous chloride media.

For pressure-critical components and vessels for industrial applications, titanium alloys are qualified under numerous design codes and offer attractive design allowables up to 315˚C (600˚F) as shown in Figure 5. Some common pressure design codes include the ASME Boiler and Pressure Vessel Code (Sections I, III, and VIII), the ANSI (ASME) B31.3 Pressure Code, the BS-5500, CODAP, Stoomwezen and Merkblatt European Codes, and the Australian AS 1210 and Japanese JIS codes.

Figure 5



Corrosion and Erosion Resistance

Titanium alloys exhibit exceptional resistance to a vast range of chemical environments and conditions provided by a thin, invisible but extremely protective surface oxide film. This film, which is primarily TiO_2, is highly tenacious, adherent, and chemically stable, and can spontaneously and instantaneously reheal itself if mechanically damaged if the least traces of oxygen or water (moisture) are present in the environment. This metal protection extends from mildly reducing to severely oxidizing, and from highly acidic to moderately alkaline environmental conditions; even at high temperatures. Titanium is especially known for its elevated resistance to localized attack and stress corrosion in aqueous chlorides (e.g., brines, seawater) and other halides and wet halogens (e.g., wet Cl_2 or Cl_2-sat. brines), and to hot, highly-oxidizing, acidic solutions (e.g., $FeCl_3$ and nitric acid solutions) where most steels, stainless steels and copper- and nickel-based alloys can experience severe attack. Titanium alloys are also recognized for their superior resistance to erosion, erosion-corrosion, cavitation, and impingement in flowing, turbulent fluids. This exceptional wrought metal corrosion and erosion resistance can be expected in corresponding weldments, heat-affected zones and castings for most titanium alloys, since the same protective oxide surface film is formed.

The useful resistance of titanium alloys is limited in strong, highly-reducing acid media, such as moderately or highly concentrated solutions of HCl, HBr, H_2SO_4, and H_3PO_4, and in HF solutions at all concentrations, particularly as temperature increases. However, the presence of common background or contaminating oxidizing species (e.g., air, oxygen, ferrous alloy metallic corrosion products and other metallic ions and/or oxidizing compounds), even in concentrations as low as 20-100 ppm, can often maintain or dramatically extend the useful performance limits of titanium in dilute-to-moderate strength reducing acid media.

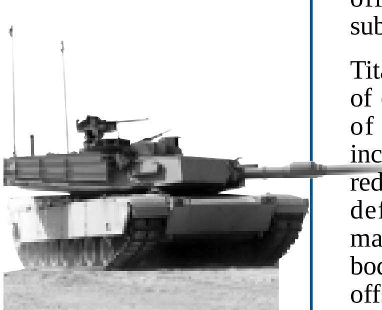
Where enhanced resistance to dilute reducing acids and/or crevice corrosion in hot (≥75˚C) chloride/halide solutions is required, titanium alloys containing minor levels of palladium (Pd), ruthenium (Ru), nickel (Ni), and/or higher molybdenum (>3.5 wt.% Mo) should be considered. Some examples of these more corrosion-resistant titanium alloys include ASTM Grades 7, 11, 12, 16, 17, 18, 19, 20, 26, 27, 28, and 29. These minor alloy additions also inhibit susceptibility to stress corrosion cracking in high strength titanium alloys exposed to hot, sweet or sour brines.

Therefore, titanium alloys generally offer useful resistance to significantly larger ranges of chemical environments (i.e., pH and redox potential) and temperatures compared to steels, stainless steels and aluminum-, copper- and nickel-based alloys. Table 3 (see page 5) provides an overview of a myriad of chemical environments where titanium alloys have been successfully utilized in the chemical process and energy industries. More detailed corrosion data and application guidelines for utilizing and testing titanium alloys in these and other environments can be found in the reference section in the back of this booklet.

Other Attractive Properties

Table 2. Other Attractive Properties of Titanium Alloys

- Exceptional erosion and erosion-corrosion resistance
- High fatigue strength in air and chloride environments
- High fracture toughness in air and chloride environments
- Low modulus of elasticity
- Low thermal expansion coefficient
- High melting point
- Essentially nonmagnetic
- High intrinsic shock resistance
- High ballistic resistance-to-density ratio
- Nontoxic, nonallergenic and fully biocompatible
- Very short radioactive half-life
- Excellent cryogenic properties



Titanium's relatively low density, which is 56% that of steel and half that of nickel and copper alloys, means twice as much metal volume per weight and much more attractive mill product costs when viewed against other metals on a dimensional basis. Together with higher strength, this obviously translates into much lighter and/or smaller components for both static and dynamic structures (aerospace engines and airframes, transportable military equipment), and lower stresses for lighter rotating and reciprocating components (e.g., centrifuges, shafts, impellers, agitators, moving engine parts, fans). Reduced component weight and hang-off loads achieved with Ti alloys are also key for hydrocarbon production tubular strings and dynamic offshore risers and Navy ship and submersible structures/components.

Titanium alloys exhibit a low modulus of elasticity which is roughly half that of steels and nickel alloys. This increased elasticity (flexibility) means reduced bending and cyclic stresses in deflection-controlled applications, making it ideal for springs, bellows, body implants, dental fixtures, dynamic offshore risers, drill pipe and various sports equipment. Titanium's inherent nonreactivity (nontoxic, nonallergenic and fully biocompatible) with the body and tissue has driven its wide use in body implants, prosthetic devices and jewelry, and in food processing. Stemming from the unique combination of high strength, low modulus and low density, titanium alloys are intrinsically more resistant to shock and explosion damage (e.g., military applications) than most other engineering materials. These alloys possess coefficients of thermal expansion which are significantly less than those of aluminum, ferrous, nickel and copper alloys. This low expansivity allows for improved interface compatibility with ceramic and glass materials and minimizes warpage and fatigue effects during thermal cycling.

Titanium is essentially nonmagnetic (very slightly paramagnetic) and is ideal where electromagnetic interference must be minimized (e.g., electronic equipment housings, well logging tools). When irradiated, titanium and its isotopes exhibit extremely short radioactive half-lives, and will not remain "hot" for more than several hours. Its rather high melting point is responsible for its good resistance to ignition and burning in air, while its inherent ballistic resistance reduces susceptibility to melting and burning during ballistic impact, making it a choice lightweight armor material for military equipment. Alpha and alpha-beta titanium alloys possess very low ductile-to-brittle transition temperatures and have, therefore, been attractive materials for cryogenic vessels and components.

Heat Transfer Characteristics

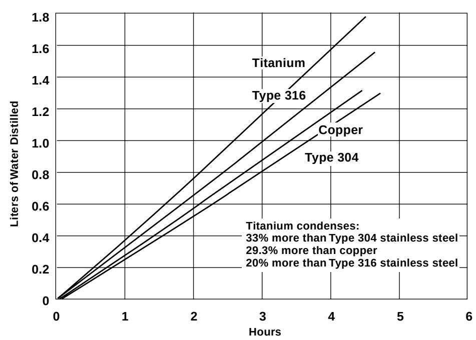
Titanium has been a very attractive and well-established heat transfer material in shell/tube, plate/frame, and other types of heat exchangers for process fluid heating or cooling, especially in seawater coolers. Exchanger heat transfer efficiency can be optimized because of the following beneficial attributes of titanium:

- Exceptional resistance to corrosion and fluid erosion
- An extremely thin, conductive oxide surface film
- A hard, smooth, difficult-to-adhere-to surface
- A surface that promotes condensation
- Reasonably good thermal conductivity
- Good strength

Although unalloyed titanium possesses an inherent thermal conductivity below that of copper or aluminum, its conductivity is still approximately 10-20% higher than typical stainless steel alloys. With its good strength and ability to fully withstand corrosion and erosion from flowing, turbulent fluids (i.e., zero corrosion allowance), titanium walls can be thinned down dramatically to minimize heat transfer resistance (and cost). Titanium's smooth, noncorroding, hard-to-adhere to surfaces maintains high cleanliness factors over time. This surface promotes drop-wise condensation from aqueous vapors, thereby enhancing condensation rates in cooler/condensers compared to other metals as indicated in Figure 6. The ability to design and operate with high process or cooling water side flow rates and/or turbulence further enhances overall heat transfer efficiency.

All of these attributes permit titanium heat exchanger size, material requirements and overall initial life cycle costs to be reduced, making titanium heat exchangers more efficient and cost-effective than those designed with other common engineering alloys.

Figure 6



Relative rates of water distilled from a 3.5% sodium chloride solution.
Rates of distillation and condensation are high for titanium compared to other metal exchanger surfaces.

Table 3. Chemical Environments Where Titanium Alloys Are Highly Resistant and Have Been Successfully Applied

GENERIC MEDIA	TYPICAL EXAMPLES	GUIDELINE FOR SUCCESSFUL USE
Acids (oxidizing)	HNO_3, H_2CrO_4, $HClO_4$	—
Acids (reducing)	HCl, HBr, HI, H_2SO_4, H_3PO_4, sulfamic, oxalic, trichloroacetic acids	Observe acid conc./temp. limits, avoid HF solns., (1)
Alcohols	Methanol, ethanol, propanol, glycols	Avoid **dry** (anhydrous) methanol, can cause SCC.
Alkaline solutions (strong)	NaOH, KOH, LiOH	Excessive hydrogen pickup and/or corrosion rates at higher temps. (>75-80˚C).
Alkaline solutions (mild)	$Mg(OH)_2$, $Ca(OH)_2$, NH_4OH, amines	—
Bleachants	ClO_2, chlorate, hypochlorites, wet Cl_2, perchlorates, wet Br_2, bromates	(1)
Chloride brines	NaCl, KCl, LiCl	(1)
Gases	O_2, Cl_2, Br_2, I_2, NO_2, N_2O_4	Ignition/burning possible in pure or enriched O_2 gas, or **dry** halogen gases or red-fuming NO_2(N_2O_4).
Gases (other)	H_2, N_2, CO_2, CO, SO_2, H_2S, NH_3, NO	Excessive hydrogen absorption in **dry** H_2 gas at higher temps. and pressures.
Halogens	Cl_2, Br_2, I_2, F_2	Avoid **dry** halogens, need to be moist (wet) for good resistance. Avoid F_2 and HF gases.
Hydrocarbons	Alkanes, alkenes, aromatics, etc. sweet and sour crude oil and gas	—
Halogenated hydrocarbons	Chloro-, chloro-fluoro-, or brominated alkanes, alkenes, or aromatics	Need at least traces of water (>10-100 ppm) for passivity, (1)
Liquid metals	Na, K, Mg, Al, Pb, Sn, Hg	Observe temp. limitations. Avoid molten Zn, Li, Ga, or Cd.
Hydrolyzable metal halide solutions	$MgCl_2$, $CaCl_2$, $AlCl_3$, $ZnCl_2$	Observe temp./conc. guidelines, (1)
Oxidizing metallic halide solns.	$FeCl_3$, $CuCl_2$, $CuSO_4$, $NiCl_2$, $Fe_2(SO_4)_3$	(1)
Organic acids	TPA, acetic, stearic, adipic, formic, tartaric, tannic acids	Observe temp./conc. guidelines for formic acid, and select Pd- or Ru-enhanced alloys if necessary.
Other organic compounds	Aldehydes, ketones, ethers, esters, glycols	—
Salt solutions	Sulfates, phosphates, nitrates, sulfites, carbonates, cyanates, etc.	—
Seawater	Aerated, deaerated, contaminated, or slightly acidified condition	(1)

(1) Select Pd- or Ru-enhanced, Ni-containing, and/or Mo-rich titanium alloys to prevent localized (crevice) corrosion when temperatures exceed 75-80˚C.

A Guide to Commercial Titanium Alloys and Their Mill Product Forms

Alloy Composition (ASTM Grade) [Common Name]	Alloy Description	Available Product Forms	Typical Applications
COMMERCIALLY PURE (UNALLOYED) TI GRADES			
Ti Grade 1	Lower strength, softest, unalloyed Ti grade with highest ductility, cold formability, and impact toughness, with excellent resistance to mildly reducing to highly oxidizing media with or without chlorides and high weldability.	Ingot/Bloom, Bar*, Billet, Plate, Strip, Welded Tubing, Welded Pipe, Wire*	AC, CG, CP, DS, HE, HR, FP, MI, PB, NS
Ti Grade 2	Moderate strength unalloyed Ti with excellent weldability, cold formability, and fabricability; "workhorse" and "garden variety" Ti grade for industrial service with excellent resistance to mildly reducing to highly oxidizing media with or without chlorides. Approved for sour service use under the NACE MR-01-75 Standard.	Ingot/Bloom, Bar*, Billet, Plate, Strip, Welded Tubing, Welded Pipe, Seamless Tubing*, Wire*, Foil*	AC, AD, AP, AR, CG, CP, DS, FP, HE HR, MI, NS, PB, PP, OP, SR
Ti Grade 3	Slightly stronger version of Gr. 2 Ti with similar corrosion resistance with good weldability and reasonable cold formability/ductility.	Ingot/Bloom, Bar*, Billet, Plate, Strip, Welded Tubing, Welded Pipe	CP, NS, PP
Ti Grade 4	Much stronger, high interstitial version of Grades 2 and 3 Ti with reasonable weldability, and reduced ductility and cold-formability.	Ingot/Bloom, Bar*, Billet, Plate, Strip	AC, AD, CP
COMMERCIALLY PURE GRADES MODIFIED WITH Pd OR Ru			
Ti-0.15Pd (Grade 7) [Ti-Pd]	Most resistant Ti alloy to corrosion in reducing acids and localized attack in hot halide media, with physical/mechanical properties equivalent to Gr. 2 Ti, and excellent weldability/fabricability.	Ingot/Bloom, Bar*, Billet, Plate, Strip, Welded Tubing, Welded Pipe, Wire*	AC, AP, CP, DS, HE, PB
Ti-0.15Pd (Grade 11)	Most resistant Ti alloy to corrosion in reducing acids and localized attack in hot halide media, with physical, mechanical, formability properties equivalent to Gr. 1 Ti (soft grade) and excellent weldability.	Ingot/Bloom, Bar*, Billet, Plate, Strip, Welded Tubing, Welded Pipe, Wire*	AC, CP, DS, HE, HR, PB
Ti-0.05Pd (Grade 16)	Lower cost, leaner Pd version of Ti Gr. 7 with equivalent physical/mechanical properties, and similar corrosion resistance. Tubing, Welded Pipe	Ingot/Bloom, Bar*, Billet, Plate, Strip, Welded Tubing, Welded Pipe, Wire*	AC, AP, CP, DS, HE, HR, PB
Ti-0.05Pd (Grade 17)	Lower cost, leaner Pd version of Ti Gr. 11 with equivalent physical/mechanical properties and fabricability (soft grade) and similar corrosion resistance. Tubing, Welded Pipe	Ingot/Bloom, Bar*, Billet, Plate, Strip, Welded Tubing, Welded Pipe, Wire*	AC, CP, DS, HE, HR, PB
Ti-0.1Ru (Grade 26) [TiRu-26®]	Lower cost, Ru-containing alternative for Ti Gr. 7 with equivalent physical/mechanical properties and fabricability and similar corrosion resistance. Tubing, Welded Pipe	Ingot/Bloom, Bar*, Billet, Plate, Strip, Welded Tubing, Welded Pipe, Wire*	AC, AP, CP, DS, HE, HR, PB
Ti-0.1Ru (Grade 27) [TiRu-27®]	Lower cost, Ru-containing alternative for Ti Gr. 11 with equivalent physical/mechanical properties (soft grade) and fabricability and similar corrosion resistance.	Ingot/Bloom, Bar*, Billet, Plate, Strip, Welded Tubing, Welded Pipe	AC, CP, DS, HE, HR, PB
ALPHA AND NEAR-ALPHA ALLOYS			
Ti-0.3Mo-0.8Ni(Grade 12) [Ti-12]	Highly weldable and fabricable Ti alloy offering improved strength and pressure code design allowables, hot brine crevice corrosion, and reducing acid resistance compared to Ti Grades 1, 2, and 3. Approved for sour service use under the NACE MR-01-75 Standard.	Ingot/Bloom, Billet, Welded Pipe, Plate, Strip, Welded Tubing, Seamless Pipe, Wire*	CP, DS, GB, HE, HR, OP
Ti-3Al-2.5V (Grade 9) [Ti-3-2.5]	Medium strength, non-ageable Ti alloy offering highest strength and design allowables under the pressure vessel code, with good weldability and cold fabricability for mildly reducing to mildly oxidizing media.	Ingot/Bloom, Billet, Welded Pipe, Plate, Strip, Welded Tubing, Foil* SeamlessTubing*, Wire*	AD, CG, NS, SR
Ti-3Al-2.5V-Pd(Grade 18) [Ti-3-2.5-Pd]	Pd-enhanced version of Ti-3Al-2.5V with equivalent physical and mechanical properties and fabricability, offering elevated resistance to dilute reducing acids and crevice corrosion in hot halide (brine) media.	Ingot/Bloom, Billet, Welded Pipe, Plate, Strip, Welded Tubing, Seamless Pipe	CP, GB, HE, OP, PD
Ti-3Al-2.5V-Ru(Grade 28) [Ti-3-2.5-Ru]	Ru-enhanced version of Ti-3Al-2.5V with equivalent physical and mechanical properties and fabricability, offering elevated resistance to dilute reducing acids and crevice corrosion in hot halide (brine) media. Approved for sour service use under the NACE MR-01-75 Standard.	Ingot/Bloom, Billet, Welded Pipe, Plate, Strip, Welded Tubing, Seamless Pipe, Wire*	CP, GB, HE, OP, PD
Ti-5Al-2.5Sn (Grade 6) [Ti-5-2.5]	Weldable, non-ageable, high-strength alloy offering good high temperature stability, strength, oxidation and creep resistance.	Ingot/Bloom, Bar*, Billet, Sheet	GT
Ti-5Al-2.5Sn ELI [Ti-5-2.5 ELI]	Extra low interstitial version of Ti-5Al-2.5Sn exhibiting an excellent combination of toughness and strength at cryogenic temperatures; suited for cryogenic vessels for service as low as -255˚C.	Ingot/Bloom, Bar*, Billet	SS
Ti-8Al-1Mo-1V [Ti-8-1-1]	Highly creep-resistant, non-ageable, weldable, high-strength Ti alloy for use up to 455˚C; exhibiting the lowest density and highest modulus of all commercial Ti alloys.	Ingot/Bloom, Bar*, Billet, Sheet	GT
Ti-6Al-2Sn-4Zr-2Mo-0.1Si [Ti-6-2-4-2-S]	Weldable, high strength Ti alloy offering excellent strength, stability, and creep resistance to temperatures as high as 550˚C.	Ingot/Bloom, Bar*, Billet, Sheet	AF, AU, GT

Size capabilities listed on back inside cover.

A Guide to Commercial Titanium Alloys and Their Mill Product Forms

Alloy Composition (ASTM Grade) [Common Name]	Alloy Description	Available Product Forms	Typical Applications
ALPHA-BETA ALLOYS			
Ti-6Al-4V (Grade 5) [Ti-6-4]	Heat treatable, high-strength, most commercially available Ti alloy ("workhorse" alloy for aerospace applications), for use up to 400˚C offering an excellent combination of high strength, toughness, and ductility along with good weldability and fabricability.	Ingot/Bloom, Bar*, Billet, Plate, Sheet, Seamless Pipe, Wire*, Seamless Tubing*, Foil*	AD, AF, AU, BA, CG, GT, HE, LG, NS, PD, SR, SS
Ti-6Al-4V ELI (Grade 23) [Ti-6-4 ELI]	Extra low interstitial version of Ti-6Al-4V offering improved ductility and fracture toughness in air and saltwater environments, along with excellent toughness, strength, and ductility in cryogenic service as low as -255˚C. Typically used in a non-aged condition for maximum toughness.	Ingot/Bloom, Bar*, Billet, Plate, Sheet, Wire*, Seamless Tubing*, Foil*	AF, MI, BA, NS, OP, SS
Ti-6Al-4V-0.1Ru (Grade 29) [Ti-6-4-Ru]	Extra low interstitial, Ru-containing version of Ti-6Al-4V offering improved fracture toughness in air, seawater, and brines, along with resistance to localized corrosion in sweet and sour acidic brines as high as 330˚C. Approved for sour service use under the NACE MR-01-75 Standard.	Ingot/Bloom, Bar*, Billet, Plate, Sheet, Seamless Pipe, Wire*	CP, DS, GB, OP, PD
Ti-6Al-7Nb	High strength Ti alloy with good toughness and ductility, used primarily for medical implants stemming from its excellent biocompatibility.	Ingot/Bloom, Bar*, Billet, Wire*	MI
Ti-6Al-6V-2Sn [Ti-6-6-2]	Heat-treatable, high-strength Ti alloy with higher strength and section hardenability than Ti-6Al-4V, but with lower toughness and ductility, and limited weldability. Can be used in mill annealed or in the aged (very high strength) condition.	Ingot/Bloom, Bar*, Billet, Plate, Sheet	AF
Ti-6Al-2Sn-4Zr-6Mo [Ti-6-2-4-6]	Heat-treatable, deep-hardenable, very high strength Ti alloy with improved strength to temperatures as high as 450˚C, with limited weldability. Approved for sour service under the NACE MR-01-75 Standard.	Ingot/Bloom, Bar*, Billet	GT
Ti-4Al-4Mo-2Sn-0.5Si [Ti-550]	Heat-treatable, high strength forging alloy with good strength and creep resistance to temperature as high as 400˚C.	Ingot/Bloom, Bar*, Billet	GT
Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.15Si [Ti-6-22-22]	Heat-treatable, high strength Ti alloy with strength and fracture toughness-to-strength properties superior to those of Ti-6Al-4V, with excellent superplastic formability and thermal stability.	Ingot/Bloom, Bar*, Billet, Plate, Sheet, Wire*	AF, SS
Ti-4.5Al-3V-2Mo-2Fe [SP-700]	Heat-treatable, high strength Ti alloy with superior strength and exceptional hot and superplastic formability compared to Ti-6Al-4V, combined with good ductility and fatigue resistance.	Ingot/Bloom, Bar*, Billet, Plate, Sheet	AF, CG, GT, SR, SS
Ti-5Al-4Cr-4Mo-2Sn-2Zr [Ti-17]	Heat-treatable, deep section hardenable, very high strength Ti alloy with superior strength and creep resistance over Ti-6Al-4V to temperatures as high as 400˚C, and limited weldability.	Ingot/Bloom, Bar*, Billet	GT
NEAR-BETA AND BETA ALLOYS			
Ti-10V-2Fe-3Al [Ti-10-2-3]	Heat-treatable, deep hardenable, very high strength Ti alloy possessing superior fatigue and strength/toughness combinations, with exceptional hot-die forgeability, but limited weldability.	Ingot/Bloom, Bar*, Billet	AF, LG
Ti-3Al-8V-6Cr-4Zr-4Mo [Ti Beta-C™] (Grade 19)	A heat-treatable, deep section hardenable, very high strength Ti alloy possessing good toughness/strength properties, low elastic modulus and elevated resistance to stress and localized corrosion in high temperature sweet and sour brines. Approved for sour service under the NACE MR-01-75 Standard.	Ingot/Bloom, Bar*, Billet, Seamless Pipe, Wire*	GB, LG, NS, PD, SS
Ti-3Al-8V-6Cr-4Zr-4Mo-0.05Pd [Ti Beta-C/Pd] (Grade 20)	A Pd-containing version of the Ti-38644 alloy (Beta-C/Pd) possessing equivalent physical/mechanical properties, but with significantly enhanced resistance to stress and localized corrosion in high temperature brines.	Ingot/Bloom, Bar*, Billet, Seamless Pipe	GB, NS, PD

*Signifies products not currently produced by RMI, but commercially available.

Legend for Typical Applications

AC	Anode/cathode/cell components
AD	Aircraft ducting, hydraulic, tubing, misc.
AF	Airframe components
AP	Air pollution control equipment
AR	Architectural, roofing
AU	Automotive components
BA	Ballistic armor
CG	Consumer products (watches, eye glass frames, etc.)
CP	Chemical processing equipment
DS	Desalination, brine concentration/evaporation
FP	Food processing/pharmaceutical
GB	Geothermal brine energy extraction
GT	Gas turbine engine components
HE	Hydrometallurgical extraction/electrowinning
HR	Hydrocarbon refining/processing
LG	Landing gear components
MI	Medical implants/devices, surgical instruments
NS	Navy ship components
OP	Offshore hydrocarbon production/drilling
PB	Pulp/paper bleaching/washing equipment
PD	Hydrocarbon production/drilling
PP	Power plant cooling system components
SR	Sports/recreational equipment
SS	Space vehicles/structures, missile components

Size capabilities listed on back inside cover.

BASIC TITANIUM METALLURGY

RMI titanium mill products, available in both commercially pure and alloy grades, can be grouped into three categories according to the predominant phase or phases in their microstructure … alpha, alpha-beta, and beta. Although each of these three general alloy types requires specific and different mill processing methodologies, each offers a unique suite of properties which may be advantageous for a given application.

In pure titanium, the alpha phase … characterized by a hexagonal close-packed crystalline structure … is stable from room temperature to approximately 882˚C (1620˚F). The beta phase in pure titanium has a body-centered cubic structure and is stable from approximately 882˚C (1620˚F) to the melting point of about 1688˚C (3040˚F).

Effects of Alloying Elements

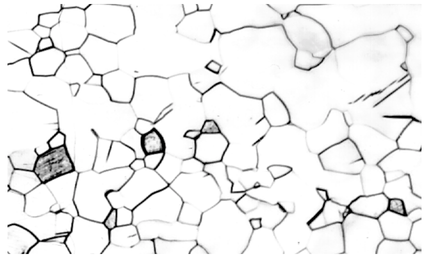
The selective addition of alloying elements to titanium enables a wide range of physical and mechanical properties to be obtained. Basic effects of a number of alloying elements are as follows:

1. Certain alloying additions, notably aluminum and interstitials (O, N,C), tend to stabilize the alpha phase, i.e., raise the temperature at which the alloy will be transformed completely to the beta phase. This temperature is known as the beta transus temperature.
2. Most alloying additions … such as chromium, niobium, copper, iron, manganese, molybdenum, tantalum, vanadium … stabilize the beta phase by lowering the temperature of transformation (from alpha to beta).
3. Some elements … notably tin and zirconium … behave as neutral solutes in titanium and have little effect on the transformation temperature, acting as strengtheners of the alpha phase.

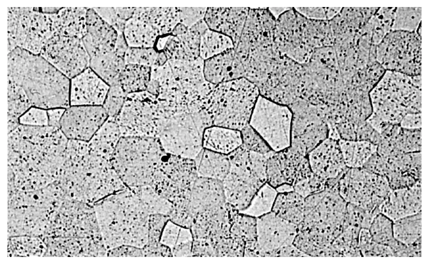
Titanium alloy microstructures are characterized by the various alloy additions and processing. A description of the various types of alloys and typical photomicrographs of various mill products manufactured are illustrated.

Alpha Alloys

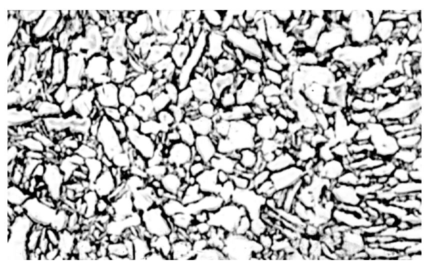
The single-phase and near single-phase alpha alloys of titanium exhibit good weldability. The generally high aluminum content of this group of alloys assures excellent strength characteristics and oxidation resistance at elevated temperatures (in the range of 316-593˚C (600 - 1100˚F)). Alpha alloys cannot be heat-treated to develop higher strength since they are single-phase alloys.



Unalloyed Ti 200X
Commercially pure plate, 0.03% iron
732˚C (1350˚F)/30 Min.; Air Cool
(Mill-annealed condition)



Ti-Pd 100X
ASTM Grade 7
Sheet
704˚C (1300˚F)/20 Min.; Air Cool
(Mill-annealed condition)



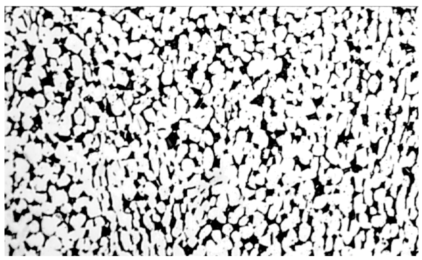
Ti 5Al-2.5Sn 200X
Alpha Alloy
Hot roll 51mm (2 in.) round bar
816˚C (1500˚F)/2 Hr.; Air Cool
(Mill-annealed condition)

Alpha-Beta Alloys

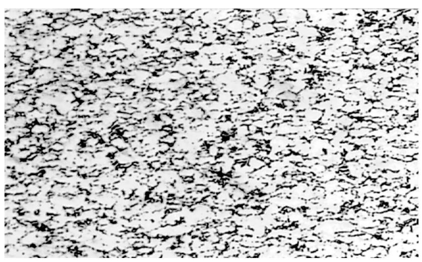
The addition of controlled amounts of beta-stabilizing alloying elements causes some beta phase to persist below the beta transus temperature, down to room temperature … resulting in a two-phase system. Even small amounts of beta stabilizers will stabilize the beta phase at room temperature. A group of alloys designed with high amounts of alpha stabilizers and with a small amount of beta stabilizers are alpha-beta alloys, usually called high alpha or near alpha alloys.

As larger amounts of beta stabilizers are added, a higher percentage of the beta phase is retained at room temperature. Such two-phase titanium alloys can be significantly strengthened by heat treatment … quenching from a temperature high in the alpha-beta range, followed by an aging cycle at a somewhat lower temperature.

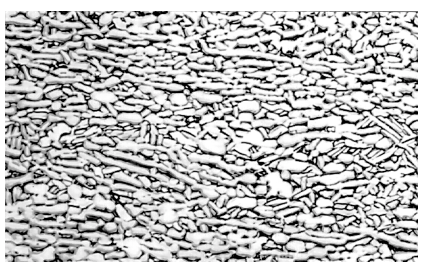
The transformation of the beta phase … which would normally occur on slow cooling … is suppressed by the quenching. The aging cycle causes the precipitation of fine alpha particles from the metastable beta, imparting a structure that is stronger than the annealed alpha-beta structure.



Ti-6Al-2Sn-4Zr-2Mo-Si 200X
Near alpha alloy 230mm (9 in.) round billet
(As forged condition)

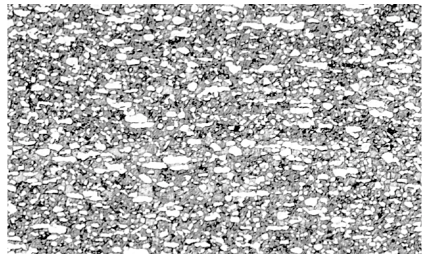


Ti-6Al-4V 100X
Alpha-beta alloy 8mm (0.031 in.) sheet
788˚C (1450˚F)/15 Min.; Air Cool
(Mill-annealed condition)

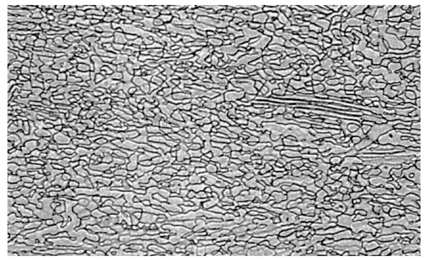


Ti-6Al-4V 200X
Alpha-beta alloy 38mm (1.5 in.) plate
788˚C (1450˚F)/15 Min.; Air Cool
(Mill-annealed condition)

Ti-6Al-4V 100X
Alpha-beta alloy 38mm (1.5 in.) bar
1016˚C (1860˚F)/20 Min.; Air Cool
(Transformed-beta condition)



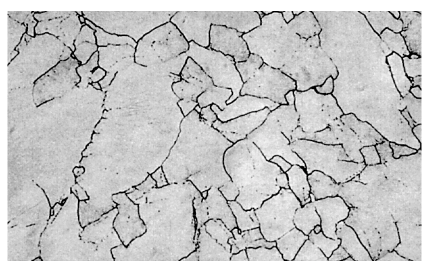
Ti-6Al-2Sn-2Zr-2Mo-2Cr-Si 200X
Alpha-beta alloy 1.6mm (.063 in.) sheet
900˚C (1650˚F)/30 Min.; Air Cool +
510˚C (950˚F)/10 Hr.; Air Cool
(Solution treated and aged)



Ti-4.5Al-3V-2Mo-2Fe (SP700) 500X
Alpha-beta alloy 46mm (1.8 in.) plate
788˚C (1450˚F)/2 Hr.; Air Cool
(Mill-annealed condition)

Beta Alloys

The high percentage of beta-stabilizing elements in this group of titanium alloys results in a microstructure that is metastable beta after solution annealing. Extensive strengthening can occur by the precipitation of alpha during aging.



Ti-3Al-8V-6Cr-4Zr-4Mo 100X
Beta alloy 16mm (0.625 in.) dia. bar
816˚C (1500˚F)/30 Min.; Air Cool
(Solution treated condition)

Ti-3Al-8V-6Cr-4Zr-4Mo 250X
Beta alloy 16mm (0.625 in.) dia. bar
816˚C (1500˚F)/15 Min.; Air Cool +
566˚C (1050˚F) /6 Hr.; Air Cool
(Solution treated and aged condition)

MACHINING TITANIUM

Titanium can be economically machined on a routine production basis if shop procedures are set up to allow for the physical characteristics common to the metal. The factors which must be given consideration are not complex, but they are vital to successfully machining titanium.

The different grades of titanium, i.e., commercially pure and various alloys, do not have identical machining characteristics, any more than all steels, or all aluminum grades have identical characteristics. Like stainless steel, the low thermal conductivity of titanium inhibits dissipation of heat within the workpiece itself, thus requiring proper application of coolants.

Good tool life and successful machining of titanium alloys can be assured if the following guidelines are observed:

- Maintain sharp tools to minimize heat buildup and galling
- Use rigid setups between tool and workpiece to counter workpiece flexure
- Use a generous quantity of cutting fluids to maximize heat removal
- Utilize lower cutting speeds
- Maintain high feed rates
- Avoid interruptions in feed (positive feed)
- Regularly remove turnings from machines

The machinability of commercially pure grades of titanium has been compared by veteran shop men to that of 18-8 stainless steel, with the alloy grades of titanium being somewhat harder to machine.

Specific information on machining, grinding and cutting titanium and its alloys can be found in RMI's comprehensive booklet "MACHINING."

Turning

Commercially pure and alloyed titanium can be turned with little difficulty. Carbide tools should be used wherever possible for turning and boring since they offer higher production rates and longer tool life. Where high speed steels are used, the super high speeds are recommended. Tool deflection should be avoided and a heavy and constant stream of cutting fluid applied at the cutting surface. Live centers must be used since titanium will seize on a dead center.

Milling

The milling of titanium is a more difficult operation than that of turning. The cutter mills only part of each revolution, and chips tend to adhere to the teeth during that portion of the revolution that each tooth does not cut. On the next contact, when the chip is knocked off, the tooth may be damaged.

This problem can be alleviated to a great extent by employing climb milling, instead of conventional milling. In this type of milling, the cutter is in contact with the thinnest portion of the chip as it leaves the cut, minimizing chip "welding".

For slab milling, the work should move in the same direction as the cutting teeth; and for face milling, the teeth should emerge from the cut in the same direction as the work is fed.

In milling titanium, when the cutting edge fails, it is usually because of chipping. Thus, the results with carbide tools are often less satisfactory than with high speed steel. The increase in cutting speeds of 20-30% which is possible with carbide tools compared with high speed steel tools does not always compensate for the additional tool grinding costs. Consequently, it is advisable to try both high speed steel and carbide tools to determine the better of the two for each milling job. The use of a water-base coolant is recommended.

Drilling

Successful drilling is accomplished by using sharp drills of proper geometry and by maintaining maximum drilling force to ensure continuous cutting. It is important to avoid having the drill ride the titanium surface since the resultant work hardening makes it difficult to reestablish the cut.

Another important factor in drilling titanium is the length of the unsupported section of the drill. This portion of the drill should be no longer than necessary to drill the required depth of hole and still allow the chips to flow unhampered through the flutes and out of the hole. This permits application of maximum cutting pressure, as well as rapid drill removal to clear chips and drill re-engagement without breakage. An adequate supply of cutting fluid to the cutting zone is also important.

High speed steel drills are satisfactory for lower hardness alloys and for commercially pure titanium but carbide drills are best for most titanium alloys and for deep hole drilling.

Tapping

Percentage depth of thread has a definite influence on success in tapping titanium and best results in terms of tool life have been obtained with a 65% thread. Chip removal is a problem which makes tapping one of the more difficult machining operations. However, in tapping through-holes, this problem can be simplified by using a gun-type tap with which chips are pushed ahead of the tap. Another problem is the smear of titanium on the land of the tap, which can result in the tap freezing, or binding in the hole. An activated cutting oil such as a sulfurized and chlorinated oil is helpful in avoiding this problem.

Grinding

Titanium is successfully ground by selecting the proper combination of grinding fluid, abrasive wheel, and wheel speeds. Both aluminum oxide and silicon carbide wheels are used. Considerably lower wheel speeds than in conventional grinding of steels are recommended. Feeds should be light and particular attention paid to the coolant. A water-sodium nitrite coolant mixture gives good results with aluminum oxide wheels. Silicon carbide wheels operate best with sulfo-chlorinated oils, but these can present a fire hazard, and it is important to flood the work when using these oil-base coolants.

Sawing

Two common methods of sawing titanium are band sawing and power hacksawing. As with titanium machining operations, standard practices for sawing titanium are established. Rigid, high quality equipment should be used incorporating automatic, positive feeding. High speed steel blades are effective but for specific blade recommendations and cutting practices the blade manufacturers should be consulted. Cutting fluids are required.

Abrasive sawing is also commonly employed with titanium. Rubber bonded silicon carbide cutoff wheels are successfully used with water-base coolants flooding the cutting area.

Water Jet

Water jet cutting is a recent innovation in cutting titanium. A high speed jet containing entrained abrasive is very effective for high cutting speeds and for producing smooth burr-free edges. Sections up to three inches have been cut and the process is relatively unaffected by differences in hardness of the titanium workpiece.

Electric Discharge Machining

Though not common, complex titanium components with fine detail can be produced via EDM. The dielectric fluid often consists of various hydrocarbons (various oils) and even polar compounds, such as deionized water. Care must be taken to avoid or remove any subtle surface contamination in fatigue sensitive components.

Chem Milling

Chem milling has been used extensively to shape, machine or blank fairly complex titanium components, especially for aerospace applications (e.g., jet engine housings). These aqueous etching solutions typically consist of HNO_3-HF or dilute HF acids, with the HNO_3 content adjusted to minimize hydrogen absorption depending on the specific alloy.

FORMING TITANIUM

Titanium and its alloys can be cold and hot formed on standard equipment using techniques similar to those of stainless steels. However, titanium possesses certain unique characteristics that affect formability, and these must be considered when undertaking titanium forming operations.

The room temperature ductility of titanium and its alloys is generally less than that of the common structural metals including stainless steels. This necessitates more generous bend radii and less allowance for stretch formability when cold forming.

Titanium has a relatively low modulus of elasticity, about half that of stainless steel. This results in greater springback during forming and requires compensation either during bending or in post-bend treatment.

Titanium in contact with itself or other metals exhibits a greater tendency to gall than does stainless steel. Thus, sliding contact with tooling surfaces during forming calls for the use of lubricants. Effective lubricants generally include grease, heavy oil and/or waxy types, which may contain graphite or moly disulfide additives for cold forming; and solid film lubricants (graphite, moly disulfide) or glassy coatings for higher temperature forming.

The following is basic information on forming titanium. A great deal of published information exists on titanium forming practices in the common commercial forming processes. The reader is urged to consult the references in the back of this booklet and other qualified sources before undertaking a titanium forming operation for the first time.

Surface Preparation

Before titanium sheet is formed it should be clean and free of surface defects such as nicks, scratches or grinding marks. All scratches deeper than the finish produced by 180-grit emery should be removed by sanding. To prevent edge cracking, burred and sharp edges should be radiused. Surface oxides can lead to cracking during cold forming and should be removed by mechanical or chemical methods.

Plate products should be free of gross stress raisers, very rough, irregular surface finishes, visible oxide scale and brittle alpha case (diffused-in oxygen layers) to achieve reasonable cold or warm formability. Experience has shown that pickled plate often exhibits enhanced formability (e.g., in brake bending and dish forming) compared to plate with as-grit blasted and/or as-ground surface finishes.

Cold Versus Hot Forming

Commercially pure titanium, the ductile, low-alloy alpha and unaged beta titanium alloys can be cold formed within certain limits. The amount of cold forming either in bending or stretching is a function of the tensile elongation of the material. Tensile elongation and bend data for the various grades of titanium sheet and plate can be found in ASTM Specification B265.

Heating titanium increases its formability, reduces springback, and permits maximum deformation with minimum annealing between forming operations. Mild warm forming of most grades of titanium is carried out at 204-316˚C (400-600˚F) while more severe forming is done at 482-788˚C (900-1450˚F). Heated forming dies or radiant heaters are occasionally used for low temperature forming while electric furnaces with air atmospheres are the most suitable for heating to higher temperatures. Gas fired furnaces are acceptable if flame impingement is avoided and the atmosphere is slightly oxidizing.

Any hot forming and/or annealing of titanium products in air at temperatures above approximately 590-620˚C (1100-1150˚F) produces a visible surface oxide scale and diffused-in oxygen layer (alpha case) that may require removal on fatigue- and/or fracture-critical components. Oxide scale removal can be achieved mechanically (i.e., grit-blasting or grinding) or by chemical descale treatment (i.e., molten hot alkaline salt descale). This is generally followed by pickling in HF-HNO_3 acid solutions, machining or grinding to ensure total alpha case removal, where required. These acid pickle solutions are typically maintained in the 5:1 to 10:1 volume % HNO_3 to HF ratio (as stock acids) to minimize hydrogen pickup depending on alloy type.

Stress Relief and Hot Sizing

Cold forming and straightening operations produce residual stresses in titanium that sometimes require removal for reasons of dimensional stability and restoration of properties.

Stress relieving can also serve as an intermediate heat treatment between stages of cold forming. The temperatures employed lie below the annealing ranges for titanium alloys. They generally fall within 482-649˚C (900-1200˚F) with times ranging from 30 to 60 minutes depending on the workpiece configuration and degree of stress relief desired.

Hot sizing is often used for correcting springback and inaccuracies in shape and dimensions of preformed parts. The part is suitably fixtured such that controlled pressure is applied to certain areas of the part during heating. This fixtured unit is placed in a furnace and heated at temperatures and times sufficient to cause the metal to creep until it conforms to the desired shape. Creep forming is used in a variety of ways with titanium, often in conjunction with compression forming using heated dies.

Typical Forming Operations

Following are descriptions of several typical forming operations performed on titanium. They are representative of operations in which bending and stretching of titanium occur. The forming can be done cold, warm or hot. The choice is governed by a number of factors among which are workpiece section thickness, the intended degree of bending or stretching, the speed of forming (metal strain rate), and alloy/ product type.

Brake Forming

In this operation, bending is employed to form angles, z-sections, channels and circular cross sections including pipe. The tooling consists of unheated dies or heated female and male dies.

Stretch Forming

Stretch forming has been used on titanium sheet primarily to form contoured angles, hat sections, Z-sections and channels, and to form skins to special contours. This type of forming is accomplished by gripping the sheet blank in knurled jaws, loading it until plastic deformation begins, then wrapping the part around a male die. Stretch forming can be done cold using inexpensive tooling or, more often, it is done warm by using heated tooling and preheating the sheet blank by the tooling.

Spinning and Shear-Forming

These cold, warm or hot processes shape titanium sheet or plate metal into seamless hollow parts (e.g., cylinders, cones, hemispheres) using pressure on a rotating workpiece. Spinning produces only minor thickness changes in the sheet, whereas shear-forming involves significant plastic deformation and wall thinning.

Superplastic Forming (SPF)

SPF of titanium alloys is commonly used in aircraft part fabrication, allowing production of complex structural efficient, lightweight and cost-effective component configurations. This high temperature sheet forming process (typically 870-925C˚(1660-1700˚F)) is often performed simultaneously with diffusion bonding (solid-state joining) in argon gas-pressurized chambers, eliminating the need for welding, brazing, sizing or stress relief in complex parts. Titanium sheet alloys that are commonly superplastically-formed include the Ti-6Al-4V and Ti SP-700 alpha-beta alloys.

Other Forming Processes

Titanium alloy sheet and plate products are often formed cold, warm or hot in gravity hammer and pneumatic drop hammer presses involving progressive deformation with repeated blows in matched dies. Drop hammer forming is best suited to the less high strain rate-sensitive alpha and leaner alpha-beta titanium alloys. Hot closed-die and even isothermal press forging is commonly used to produce near-net shape components from titanium alloys. Trapped-rubber forming of titanium sheet in cold or warm (540˚C (1000˚F) max.) pressing operations can be less expensive than that utilizing conventional mating "hard die" tooling. Even explosive forming has been successfully employed to form complex titanium alloy sheet/plate components.

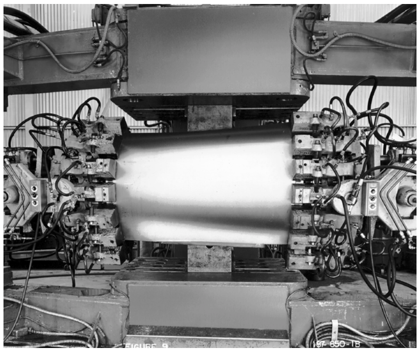
The lower strength, more ductile titanium alloys can be roll-formed cold as sheet strip to produce long lengths of shaped products, including welded tubing and pipe. Welded or seamless tubing can be bent cold on conventional mandrel tube benders. Seam-welded unalloyed titanium piping can also be bent cold or warm on standard equipment utilizing internal mandrels to minimize buckling, whereas higher strength alloy seamless piping can be successfully bent in steps via hot induction bending.

Deep Drawing

This is a process involving titanium bending and stretching in which deep recessed parts, often closed cylindrical pieces or flanged hat-sections, are made by pulling a sheet blank over a radius and into a die. During this operation buckling and tensile tearing must be avoided. It is therefore necessary to consider the compressive and tensile yield strengths of the titanium when designing the part and the tooling. The sheet blank is often preheated as is the tooling.

The softer, highly ductile grades of unalloyed titanium are often cold pressed or stamped in sheet strip form to produce heat exchanger plates, anodes or other complex components for industrial service.

Corrugated titanium section formed with heated dies on a brake press.
The Boeing Company



Hot-forming a titanium contoured hat stringer in a drop hammer.
The Boeing Company

WELDING TITANIUM

Commercially pure titanium and most titanium alloys are readily welded by a number of welding processes being used today. The most common method of joining titanium is the gas tungsten-arc (GTAW) process and, secondarily, the gas metal-arc (GMAW) process. Others include electron beam and more recently laser welding as well as solid state processes such as friction welding and diffusion bonding. Titanium and its alloys also can be joined by resistance welding and by brazing.

The techniques for welding titanium resemble those employed with nickel alloys and stainless steels. To achieve sound welds with titanium, primary emphasis is placed on surface cleanliness and the correct use of inert gas shielding. Molten titanium reacts readily with oxygen, nitrogen and hydrogen and exposure to these elements in air or in surface contaminants during welding can adversely affect titanium weld metal properties. As a consequence, certain welding processes such as shielded metal arc, flux cored arc and submerged arc are unsuitable for welding titanium. In addition, titanium cannot be welded to most other metals because of formation of embrittling metallic compounds that lead to weld cracking.

Welding Environment

While chamber or glove box welding of titanium is still in use today, the vast majority of welding is done in air using inert gas shielding. Argon is the preferred shielding gas although argon-helium mixtures occasionally are used if more heat and greater weld penetration are desired. Conventional welding power supplies are used both for gas tungsten arc and for gas metal arc welding. Tungsten arc welding is done using DC straight polarity (DCSP) while reverse polarity (DCRP) is used with the metallic arc.

Inert Gas Shielding

An essential requirement for successfully arc welding titanium is proper gas shielding. Care must be taken to ensure that inert atmosphere protection is maintained until the weld metal temperature cools below 426˚C (800˚F). This is accomplished by maintaining three separate gas streams during welding. The first or primary shield gas stream issues from the torch and shields the molten puddle and adjacent surfaces. The secondary or trailing gas shield protects the solidified weld metal and heat-affected zone during cooling. The third or backup shield protects the weld underside during welding and cooling. Various techniques are used to provide these trailing and backup shields and one example of a typical torch trailing shield construction is shown below. The backup shield can take many forms. One commonly used for straight seam welds is a copper backing bar with gas ports serving as a heat sink and shielding gas source. Complex workpiece configurations and certain shop and field circumstances call for some resourcefulness in creating the means for backup shielding. This often takes the form of plastic or aluminum foil enclosures or "tents" taped to the backside of the weld and flooded with inert gas.

Weld Joint Preparation

Titanium weld joint designs are similar to those for other metals, and the edge preparation is commonly done by machining or grinding. Before welding, it is essential that the weld joint surfaces be free of any contamination and that they remain clean during the entire welding operation. The same requirements apply to welding wire used as filler metal. Contaminants such as oil, grease and fingerprints should be removed with detergent cleaners or non-chlorinated solvents. Light surface oxides can be removed by acid pickling while heavier oxides may require grit blasting followed by pickling.

TIG torch with trailing shield

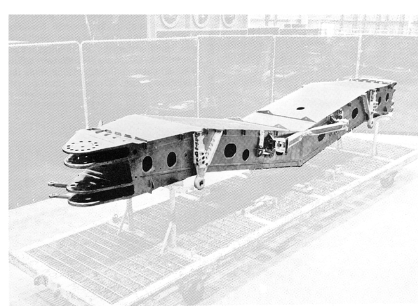
Weld Quality Evaluation

A good measure of weld quality is weld color. Bright silver welds are an indication that the weld shielding is satisfactory and that proper weld interpass temperatures have been observed. Any weld discoloration should be cause for stopping the welding operation and correcting the problem. Light straw-colored weld discoloration can be removed by wire brushing with a clean stainless steel brush, and the welding can be continued. Dark blue oxide or white powdery oxide on the weld is an indication of a seriously deficient purge. The welding should be stopped, the cause determined and the oxide covered weld should be completely removed and rewelded.

For the finished weld, non-destructive examination by liquid penetrant, radiography and/or ultrasound are normally employed in accordance with a suitable welding specification. At the outset of welding it is advisable to evaluate weld quality by mechanical testing. This often takes the form of weld bend testing, sometimes accompanied by tensile tests.

Resistance Welding

Spot and seam welding procedures for titanium are similar to those used for other metals. The inert-gas shielding required in arc welding is generally not required here. Satisfactory welds are possible with a number of combinations of current, weld time and electrode force. A good rule to follow is to start with the welding conditions that have been established for similar thicknesses of stainless steels and adjust the current, time or force as needed. As with arc welding, the surfaces to be joined must be clean. Before beginning a production run of spot or seam welding, weld quality should be evaluated by tension shear testing of the first welds.



F-14 welded wing carry-through assembly

TITANIUM ALLOY	COMMERCIALLY PURE/UNALLOYED
ASTM GRADE (UNS NO.)	**GRADE 1 (R50250)**
Chemical Composition (wt. %) (Max. values unless range is shown)	0.08C; 0.03N; 0.18O; 0.20Fe; 0.015H

TENSILE PROPERTIES		Guar.R.T. Min.	Typical Elevated Temperature Properties 93°C (200°F)	204°C (400°F)	315°C (600°F)
Ultimate Strength	MPa (ksi)	241 (35)	262 (38)	200 (29)	159 (23)
Yield Strength, 0.2% offset	MPa (ksi)	172 (25)	138 (20)	97 (14)	83 (12)
Elongation in 51 mm (2") gage length	(%)	24	40	38	48
Reduction in Area - Bar, Billet & Forging only	(%)	30			

OTHER MECHANICAL PROPERTIES			Guar.R.T. Min.	93°C (200°F)	204°C (400°F)	315°C (600°F)
Stress to Rupture in Time Shown	Stress	MPa (ksi)		195 (28)	152 (22)	97 (14)
	Time-Hrs. at Temp. (°C)			10,000 (100)	10,000 (200)	1,000 (250)
Stress & Time to Produce Elongation Shown (creep)	Stress	MPa (ksi)				90 (13)
	Time-Hrs. at Temp. (°C)					1,000 (250)
	Creep	(%)				1.0

Charpy V-Notch Impact @ R.T.		Joules (ft-lbs)	95 - 162 (70 - 120)
Bend Radius	Under 1.78 mm (0.070") thick		1.5 x Thickness
	1.78 mm (0.070") and over		2.0 x Thickness
Welded Bend Radius			1.5 - 2.0 x Thickness
Nominal Hardness			70 HRB
PHYSICAL PROPERTIES			
Nominal Beta Transus		°C (°F)	890 (1630)
Coefficient of Thermal Expansion 10^{-6}/°C (10^{-6}/°F)	0-100°C (32 -212°F)		8.6 (4.8)
	0-315°C (32-600°F)		9.2 (5.1)
	0-538°C (32-1000°F)		9.5 (5.3)
	0-648°C (32-1200°F)		9.9 (5.5)
	0-816°C (32-1500°F)		9.9 (5.5)
Density		g/cm^3 (lbs/in^3)	4.51 (0.163)
Melting Point, Approx.		°C (°F)	1670 (3040)
Electrical Resistivity @ R.T.		10^{-6} ohm•cm (10^{-6} ohm•in)	54 (21)
Modulus of Elasticity – Tension		GPa (10^3 ksi)	103 (14.9)
Modulus of Elasticity – Torsion		GPa (10^3 ksi)	41 (6.0)
Thermal Conductivity		W/m•°C (BTU/hr•ft•°F)	20.8 (12.0)
Specific Heat		J/Kg•°C (BTU/lb•°F)	520 (0.124)
Weldability			Excellent
Industry Specifications			ASTM - B265, B337, B338, B348, B363, B381, B861, B862, F67

COMMERCIALLY PURE/UNALLOYED

GRADE 2 (R50400)

0.08C; 0.03N; 0.25O; 0.30Fe; 0.015H

Guar.R.T. Min.	Typical Elevated Temperature Properties		
	93°C (200°F)	204°C (400°F)	315°C (600°F)
345 (50)	393 (57)	283 (41)	221 (32)
276 (40)	276 (40)	166 (24)	103 (15)
20	28	41	38
30*	40	55	75
	276 (40)	240 (35)	117 (17)
	10,000 (100)	10,000 (150)	1,000 (250)
	209 (30)	179 (26)	103 (15)
	1,000 (25)	1,000 (150)	1,000 (250)
	1.0	1.0	1.0
40 - 82 (30 - 60)			
2.0 x Thickness			
2.5 x Thickness			
2.5 - 3.0 x Thickness			
82 HRB			
913 (1675)			
8.6 (4.8)			
9.2 (5.1)			
9.7 (5.4)			
10.1 (5.6)			
10.1 (5.6)			
4.51 (0.163)			
1660 (3020)			
56 (22)			
103 (15)			
41 (6.0)			
20.8 (12.0)			
520 (0.124)			
Excellent			
ASTM - B265, B337, B338, B348, B363, B381, B861, B862, F67 and AMS 4902			

COMMERCIALLY PURE/UNALLOYED

GRADE 3 (R50550)

0.08C; 0.05N; 0.35O; 0.30Fe; 0.015H

Guar.R.T. Min.	Typical Elevated Temperature Properties			
	93°C (200°F)	204°C (400°F)	315°C (600°F)	426°C (800°F)
448 (65)	469 (68)	310 (45)	262 (38)	207 (30)
379 (55)	338 (49)	207 (30)	138 (20)	117 (17)
18	24	35	33	22
30*				
	400 (58)	300 (43)	228 (33)	138 (20)
	1,000 (25)	10,000 (100)	10,000 (200)	1,000 (250)
	283 (41)	241 (35)	83 (12)	131 (19)
	100 (25)	1,000 (25)	1,000 (315)	1,000 (250)
	1.0	1.0	1.0	1.0
24 - 48 (18 - 35)				
2.0 - 2.5 x Thickness				
2.5 x Thickness				
2.5 - 3.0 x Thickness				
90 HRB				
920 (1690)				
8.6 (4.8)				
9.2 (5.1)				
9.7 (5.4)				
10.1 (5.6)				
10.1 (5.6)				
4.51 (0.163)				
1660 (3020)				
56 (22)				
103 (15)				
43 (6.2)				
19.7 (11.4)				
520 (0.124)				
Very Good				
ASTM - B265, B337, B338, B348, B363, B381, B861, B862, F67; and AMS 4900				

TITANIUM ALLOY			COMMERCIALLY PURE/UNALLOYED				
ASTM GRADE (UNS NO.)			GRADE 4 (R50700)				
Chemical Composition (Max. values unless range is shown)		(wt. %)	0.08C; 0.05N; 0.40O; 0.50Fe; 0.015H				
TENSILE PROPERTIES			Guar.R.T. Min.	Typical Elevated Temperature Properties 93˚C (200˚F)	204˚C (400˚F)	315˚C (600˚F)	426˚C (800˚F)
Ultimate Strength		MPa (ksi)	552 (80)	538 (78)	365 (53)	283 (41)	214 (31)
Yield Strength, 0.2% offset		MPa (ksi)	483 (70)	421 (61)	255 (37)	172 (25)	145 (21)
Elongation in 51 mm (2") gage length		(%)	15	23	25	28	26
Reduction in Area - Bar, Billet & Forging only		(%)	25				
OTHER MECHANICAL PROPERTIES							
Stress to Rupture in Time Shown	Stress	MPa (ksi)		462 (67)	330 (48)	200 (29)	241 (35)
	Time-Hrs. at Temp. (˚C)			1,000 (25)	10,000 (100)	1,000 (315)	10,000 (250)
Stress & Time to Produce Elongation Shown (creep)	Stress	MPa (ksi)		283 (41)	188 (27)	116 (17)	200 (29)
	Time-Hrs. at Temp. (˚C)			1,000 (25)	1,000 (100)	1,000 (200)	1,000 (315)
	Creep	(%)		1.0	0.1	0.1	1.0
Charpy V-Notch Impact @ R.T.		Joules (ft-lbs)	13 - 27 (10 - 20)				
Bend Radius	Under 1.78 mm (0.070") thick		2.5 x Thickness				
	1.78 mm (0.070") and over		3.0 x Thickness				
Welded Bend Radius			3.0 - 5.0 x Thickness				
Nominal Hardness			100 HRB				
PHYSICAL PROPERTIES							
Nominal Beta Transus		˚C (˚F)	949 (1740)				
Coefficient of Thermal Expansion 10^{-6}/˚C (10^{-6}/˚F)	0-100˚C (32 -212˚F)		8.6 (4.8)				
	0-315˚C (32-600˚F)		9.2 (5.1)				
	0-538˚C (32-1000˚F)		9.7 (5.4)				
	0-648˚C (32-1200˚F)		10.1 (5.6)				
	0-816˚C (32-1500˚F)		10.1 (5.6)				
Density		g/cm³ (lbs/in³)	4.51 (0.163)				
Melting Point, Approx.		˚C (˚F)	1660 (3020)				
Electrical Resistivity @ R.T.		10^{-6} ohm•cm (10^{-6} ohm•in)	60 (24)				
Modulus of Elasticity – Tension		GPa (10^3 ksi)	105 (15.2)				
Modulus of Elasticity – Torsion		GPa (10^3 ksi)	45 (6.5)				
Thermal Conductivity		W/m•˚C (BTU/hr•ft•˚F)	17.3 (10.0)				
Specific Heat		J/Kg•˚C (BTU/lb•˚F)	540 (0.129)				
Weldability			Good				
Industry Specifications			ASTM - B265, B348, B381, F67; AMS 4901 and 4921				

Ti - 0.15Pd

GRADE 7 (R52400)			
0.08C; 0.03N; 0.25O; 0.30Fe; 0.12-0.25Pd; 0.015H			
Guar.R.T. Min.	Typical Elevated Temperature Properties		
	93˚C (200˚F)	204˚C (400˚F)	315˚C (600˚F)
345 (50)	393 (57)	283 (41)	221 (32)
276 (40)	276 (40)	166 (24)	103 (15)
20	28	41	38
30	40	55	75
	276 (40)	240 (35)	117 (17)
	10,000 (100)	10,000 (150)	1,000 (250)
	209 (30)	179 (26)	103 (15)
	1,000 (25)	1,000 (150)	1,000 (250)
	1.0	1.0	1.0
40 - 82 (30 - 60)			
2.0 x Thickness			
2.5 x Thickness			
2.5 - 3.0 x Thickness			
82 HRB			
913 (1675)			
8.6 (4.8)			
9.2 (5.1)			
9.7 (5.4)			
10.1 (5.6)			
10.1 (5.6)			
4.51 (0.163)			
1660 (3020)			
56 (22)			
103 (15)			
41 (6.0)			
20.8 (12.0)			
520 (0.124)			
Excellent			
ASTM - B265, B337, B338, B348, B363, B381, B861 and B862			

Ti - 0.15Pd

GRADE 11 (R52250)			
0.08C; 0.03N; 0.18O; 0.20Fe; 0.12-0.25Pd; 0.015H			
Guar.R.T. Min.	Typical Elevated Temperature Proproperties		
	93˚C (200˚F)	204˚C (400˚F)	315˚C (600˚F)
241 (35)	262 (38)	200 (29)	159 (23)
172 (25)	138 (20)	97 (14)	83 (12)
24	40	38	48
30			
	195 (28)	152 (22)	97 (14)
	10,000 (100)	10,000 (200)	1,000 (250)
			90 (13)
			1,000 (250)
			1.0
95 - 162 (70 - 120)			
1.5 x Thickness			
2.0 x Thickness			
1.5 - 2.0 x Thickness			
70 HRB			
890 (1630)			
8.6 (4.8)			
9.2 (5.1)			
9.5 (5.3)			
9.9 (5.5)			
9.9 (5.5)			
4.51 (0.163)			
1670 (3040)			
54 (21)			
103 (14.9)			
41 (6.0)			
20.8 (12.0)			
520 (0.124)			
Excellent			
ASTM - B265, B337, B338, B348, B363, B381, B861 and B862			

TITANIUM ALLOY					Ti - 0.05Pd			
ASTM GRADE (UNS NO.)					**GRADE 16 (R52402)**			
Chemical Composition (Max. values unless range is shown)		(wt. %)			0.08C; 0.03N; 0.25O; 0.30Fe; 0.04-0.08Pd; 0.015H			
TENSILE PROPERTIES					**Guar.R.T. Min.**	**Typical Elevated Temperature Properties**		
						93˚C (200˚F)	**204˚C (400˚F)**	**315˚C (600˚F)**
Ultimate Strength		MPa (ksi)			345 (50)	393 (57)	283 (41)	221 (32)
Yield Strength, 0.2% offset		MPa (ksi)			276 (40)	276 (40)	166 (24)	103 (15)
Elongation in 51 mm (2") gage length		(%)			20	28	41	38
Reduction in Area - Bar, Billet & Forging only		(%)			30*	40	55	75
OTHER MECHANICAL PROPERTIES					*Bar, billet, forgings only			
Stress to Rupture in Time Shown	Stress	MPa (ksi)				276 (40)	240 (35)	117 (17)
	Time-Hrs. at Temp. (˚C)					10,000 (100)	10,000 (150)	1,000 (250)
Stress & Time to Produce Elongation Shown (creep)	Stress	MPa (ksi)				209 (30)	179 (26)	103 (15)
	Time-Hrs. at Temp. (˚C)					1,000 (25)	1,000 (150)	1,000 (250)
	Creep	(%)				1.0	1.0	1.0
Charpy V-Notch Impact @ R.T.		Joules (ft-lbs)			40 - 82 (30 - 60)			
Bend Radius	Under 1.78 mm (0.070") thick				2.0 x Thickness			
	1.78 mm (0.070") and over				2.5 x Thickness			
Welded Bend Radius					2.5 - 3.0 x Thickness			
Nominal Hardness					82 HRB			
PHYSICAL PROPERTIES								
Nominal Beta Transus		˚C (˚F)			913 (1675)			
Coefficient of Thermal Expansion 10^{-6}/˚C (10^{-6}/˚F)	0-100˚C (32 -212˚F)				8.6 (4.8)			
	0-315˚C (32-600˚F)				9.2 (5.1)			
	0-538˚C (32-1000˚F)				9.7 (5.4)			
	0-648˚C (32-1200˚F)				10.1 (5.6)			
	0-816˚C (32-1500˚F)				10.1 (5.6)			
Density		g/cm³ (lbs/in³)			4.51 (0.163)			
Melting Point, Approx.		˚C (˚F)			1660 (3020)			
Electrical Resistivity @ R.T.		10^{-6} ohm•cm (10^{-6} ohm•in)			56 (22)			
Modulus of Elasticity – Tension		GPa (10^3 ksi)			103 (15)			
Modulus of Elasticity – Torsion		GPa (10^3 ksi)			41 (6.0)			
Thermal Conductivity		W/m•˚C (BTU/hr•ft•˚F)			20.8 (12.0)			
Specific Heat		J/Kg•˚C (BTU/lb•˚F)			520 (0.124)			
Weldability					Excellent			
Industry Specifications					ASTM - B265, B337, B338, B348, B363, B381, B861 and B862			

Ti - 0.05Pd

GRADE 17 (R52252)

0.08C; 0.03N; 0.18O; 0.20Fe; 0.04-0.08Pd; 0.015H

Guar.R.T. Min.	Typical Elevated Temperature Properties 93°C (200°F)	204°C (400°F)	315°C (600°F)
241 (35)	262 (38)	200 (29)	159 (23)
172 (25)	138 (20)	97 (14)	83 (12)
24	40	38	48
30*			
	195 (28)	152 (22)	97 (14)
	10,000 (100)	10,000 (200)	1,000 (250)
			90 (13)
			1,000 (250)
			1.0
95 - 162 (70 - 120)			
1.5 x Thickness			
2.0 x Thickness			
1.5 - 2.0 x Thickness			
70 HRB			
890 (1630)			
8.6 (4.8)			
9.2 (5.1)			
9.5 (5.3)			
9.9 (5.5)			
9.9 (5.5)			
4.51 (0.163)			
1670 (3040)			
54 (21)			
103 (14.9)			
41 (6.0)			
20.8 (12.0)			
520 (0.124)			
Excellent			
ASTM - B265, B337, B338, B348, B363, B381, B861 and B862			

Ti - 0.1Ru (TiRu - 26®)

GRADE 26 (R52404)

0.08C; 0.03N; 0.25O; 0.30Fe; 0.08-0.14Ru; 0.015H

Guar.R.T. Min.	Typical Elevated Temperature Properties 93°C (200°F)	204°C (400°F)	315°C (600°F)
345 (50)	393 (57)	283 (41)	221 (32)
276 (40)	276 (40)	166 (24)	103 (15)
20	28	41	38
30*	40	55	75
	276 (40)	240 (35)	117 (17)
	10,000 (100)	10,000 (150)	1,000 (250)
	209 (30)	179 (26)	103 (15)
	1,000 (25)	1,000 (150)	1,000 (250)
	1.0	1.0	1.0
40 - 82 (30 - 60)			
2.0 x Thickness			
2.5 x Thickness			
2.5 - 3.0 x Thickness			
82 HRB			
913 (1675)			
8.6 (4.8)			
9.2 (5.1)			
9.7 (5.4)			
10.1 (5.6)			
10.1 (5.6)			
4.51 (0.163)			
1660 (3020)			
56 (22)			
103 (15)			
41 (6.0)			
20.8 (12.0)			
520 (0.124)			
Excellent			
ASTM - B265, B337, B338, B348, B363, B381, B861 and B862			

TITANIUM ALLOY			Ti - 0.1Ru (TiRu - 27®)			
ASTM GRADE (UNS NO.)			GRADE 27 (R52254)			
Chemical Composition (Max. values unless range is shown)		(wt. %)	0.08C; 0.03N; 0.18O; 0.20Fe; 0.08-0.14Ru; 0.015H			
TENSILE PROPERTIES			Guar.R.T. Min.	Typical Elevated Temperature Properties 93˚C (200˚F)	204˚C (400˚F)	315˚C (600˚F)
Ultimate Strength		MPa (ksi)	241 (35)	262 (38)	200 (29)	159 (23)
Yield Strength, 0.2% offset		MPa (ksi)	172 (25)	138 (20)	97 (14)	83 (12)
Elongation in 51 mm (2") gage length		(%)	24	40	38	48
Reduction in Area - Bar, Billet & Forging only		(%)	30			
OTHER MECHANICAL PROPERTIES						
Stress to Rupture in Time Shown	Stress	MPa (ksi)		195 (28)	152 (22)	97 (14)
	Time-Hrs. at Temp. (˚C)			10,000 (100)	10,000 (200)	1,000 (250)
Stress & Time to Produce Elongation Shown (creep)	Stress	MPa (ksi)				90 (13)
	Time-Hrs. at Temp. (˚C)					1,000 (250)
	Creep	(%)				1.0
Charpy V-Notch Impact @ R.T.		Joules (ft-lbs)	95 - 162 (70 - 120)			
Bend Radius	Under 1.78 mm (0.070") thick		1.5 x Thickness			
	1.78 mm (0.070") and over		2.0 x Thickness			
Welded Bend Radius			1.5 - 2.0 x Thickness			
Nominal Hardness			70 HRB			
PHYSICAL PROPERTIES						
Nominal Beta Transus		˚C (˚F)	890 (1630)			
Coefficient of Thermal Expansion 10^{-6}/˚C (10^{-6}/˚F)	0-100˚C (32 -212˚F)		8.6 (4.8)			
	0-315˚C (32-600˚F)		9.2 (5.1)			
	0-538˚C (32-1000˚F)		9.5 (5.3)			
	0-648˚C (32-1200˚F)		9.9 (5.5)			
	0-816˚C (32-1500˚F)		9.9 (5.5)			
Density		g/cm³ (lbs/in³)	4.51 (0.163)			
Melting Point, Approx.		˚C (˚F)	1670 (3040)			
Electrical Resistivity @ R.T.		10^{-6} ohm•cm (10^{-6} ohm•in)	54 (21)			
Modulus of Elasticity – Tension		GPa (10^3 ksi)	103 (14.9)			
Modulus of Elasticity – Torsion		GPa (10^3 ksi)	41 (6.0)			
Thermal Conductivity		W/m•˚C (BTU/hr•ft•˚F)	20.8 (12.0)			
Specific Heat		J/Kg•˚C (BTU/lb•˚F)	520 (0.124)			
Weldability			Excellent			
Industry Specifications			ASTM - B265, B337, B338, B348, B363, B381, B861 and B862			

Ti - 0.3Mo - 0.8Ni

GRADE 12 (R53400)

0.08C; 0.03N; 0.25O; 0.30Fe; 0.2-0.4Mo; 0.6-0.9Ni; 0.015H

Guar. R.T. Min.	Typical R.T.	Typical Elevated Temperature Properties		
		93°C (200°F)	149°C (300°F)	204°C (400°F)
483 (70)	565 (82)	483 (70)	424 (61)	359 (52)
345 (50)	448 (65)	414 (60)	365 (53)	303 (44)
18	23	25	27	30
25				
			379 (55)	
			100,000	
	290 (42)	221 (32)	221 (32)	103 (15)
	10,000 (25)	1,000 (250)	10,000 (150)	10,000 (315)
	0.36	1.0	0.05	0.14

16 - 27 (12 - 20)
2.0 x Thickness
2.5 - 3.0 x Thickness
3.0 x Thickness
88 HRB
890 (1634)
—
9.6 (5.3)
—
—
—
4.51 (0.163)
1660 (3020)
52 (21)
103 (15)
43 (6.2)
19 (11.0)
544 (0.13)
Excellent
ASTM - B265, B337, B338, B348, B381, B861, B862 specs.; AMS 4902

Ti - 3Al - 2.5V

GRADE 9 (R56320)

0.08C; 0.03N; 0.15O; 0.25Fe; 2.5-3.5Al; 2.0-3.0V; 0.015H

Guar. R.T. Min.		Typical Elevated Temp. Prop. (Mill Ann.)		
Mill Ann.	C.W.S.R.*	R.T.	149°C (300°F)	204°C (400°F)
620 (90)	860 (125)	662 (96)	534 (77)	510 (74)
483 (70)	725 (105)	552 (80)	448 (65)	428 (62)
15 (12)**	10	23	26	—
25 (20)**	—	50	55	—
			421 (61)	
			1,000 (250)	
	379 (55)	262 (38)	400 (58)	207 (30)
	100,000 (93)	100,000 (177)	1,000 (250)	100,000 (315)
	1.0	1.0	1.0	1.0

*Cold-worked + stress relieved, only for tubing
**Transformed-beta condition only, red. in area min only for bar, billets and forgings

48 - 102 (35 - 75)
2.5 x Thickness
3.0 x Thickness
3.5 x Thickness
25 HRC
935 (1715)
9.5 (5.3)
9.9 (5.5)
9.9 (5.5)
—
—
4.48 (0.162)
1700 (3100)
126 (50)
107 (15.5)
44 (6.3)
8.3 (4.8)
544 (0.13)
Very Good
ASTM - B265, B337, B338, B348, B381, B861, B862 and; AMS 4943 and 4944

TITANIUM ALLOY			Ti - 3Al - 2.5V - 0.05Pd				
ASTM GRADE (UNS NO.)			**GRADE 18 (R56322)**				
Chemical Composition (Max. values unless range is shown)		(wt. %)	0.08C; 0.03N; 0.15O; 0.25Fe; 2.5-3.5Al; 2.0-3.0V; 0.04-0.08Pd; 0.015H				
TENSILE PROPERTIES			Guar. R.T. Min.		Typical Elevated Temp. Prop. (Mill Ann.)		
			Mill Ann.	C.W.S.R.*	R.T.	149°C (300°F)	204°C (400°F)
Ultimate Strength		MPa (ksi)	620 (90)	860 (125)	662 (96)	534 (77)	510 (74)
Yield Strength, 0.2% offset		MPa (ksi)	483 (70)	725 (105)	552 (80)	448 (65)	428 (62)
Elongation in 51 mm (2") gage length		(%)	15 (12)**	10	23	26	—
Reduction in Area - Bar, Billet & Forging only		(%)	25 (20)**	—	50	55	—
OTHER MECHANICAL PROPERTIES			*Cold-worked + stress relieved, only for tubing		** Transformed-beta condition only, red. in area min. only for bar, billets and forgings		
Stress to Rupture in Time Shown	Stress	MPa (ksi)				421 (61)	
	Time-Hrs. at Temp. (°C)					1,000 (250)	
Stress & Time to Produce Elongation Shown (creep)	Stress	MPa (ksi)		379 (55)	262 (38)	400 (58)	207 (30)
	Time-Hrs. at Temp. (°C)			100,000 (93)	100,000 (177)	1,000 (250)	100,000 (315)
	Creep	(%)		1.0	1.0	1.0	1.0
Charpy V-Notch Impact @ R.T.		Joules (ft-lbs)	48 - 102 (35 - 75)				
Bend Radius	Under 1.78 mm (0.070") thick		2.5 x Thickness				
	1.78 mm (0.070") and over		3.0 x Thickness				
Welded Bend Radius			3.5 x Thickness				
Nominal Hardness			25 HRC				
PHYSICAL PROPERTIES							
Nominal Beta Transus		°C (°F)	935 (1715)				
Coefficient of Thermal Expansion 10^{-6}/°C (10^{-6}/°F)	0-100°C (32 -212°F)		9.5 (5.3)				
	0-315°C (32-600°F)		9.9 (5.5)				
	0-538°C (32-1000°F)		9.9 (5.5)				
	0-648°C (32-1200°F)		—				
	0-816°C (32-1500°F)		—				
Density		g/cm³ (lbs/in³)	4.48 (0.162)				
Melting Point, Approx.		°C (°F)	1700 (3100)				
Electrical Resistivity @ R.T.		10^{-6} ohm•cm (10^{-6} ohm•in)	126 (50)				
Modulus of Elasticity – Tension		GPa (10^3 ksi)	107 (15.5)				
Modulus of Elasticity – Torsion		GPa (10^3 ksi)	44 (6.3)				
Thermal Conductivity		W/m•°C (BTU/hr•ft•°F)	8.3 (4.8)				
Specific Heat		J/Kg•°C (BTU/lb•°F)	544 (0.13)				
Weldability			Very Good				
Industry Specifications			ASTM - B265, B337, B338, B348, B363, B381, B861 and B862				

Ti - 3Al - 2.5V - 0.1Ru

GRADE 28 (R56323)

0.08C; 0.03N; 0.15O; 0.25Fe; 2.5-3.5Al; 2.0-3.0V; 0.08-0.14Ru; 0.015H

Guar. R.T. Min.		Typical Elev. Temp. Prop. (Mill Ann.)		
Mill Ann.	C.W.S.R.*	R.T.	149°C (300°F)	204°C (400°F)
620 (90)	860 (125)	662 (96)	534 (77)	510 (74)
483 (70)	725 (105)	552 (80)	448 (65)	428 (62)
15 (12)**	10	23	26	—
25 (20)**	—	50	55	—
*Cold-worked + stress relieved, only for tubing		**Transformed-beta condition only, red. in area min. only for bar, billets and forgings		
			421 (61)	
			1,000 (250)	
	379 (55)	262 (38)	400 (58)	207 (30)
	100,000 (93)	100,000 (177)	1,000 (250)	100,000 (315)
	1.0	1.0	1.0	1.0
48 - 102 (35 - 75)				
2.5 x Thickness				
3.0 x Thickness				
3.5 x Thickness				
25 HRC				
935 (1715)				
9.5 (5.3)				
9.9 (5.5)				
9.9 (5.5)				
—				
—				
4.48 (0.162)				
1700 (3100)				
126 (50)				
107 (15.5)				
44 (6.3)				
8.3 (4.8)				
544 (0.13)				
Very Good				
ASTM - B265, B337, B338, B348, B381, B861 and B862				

Ti - 5Al - 2.5Sn

GRADE 6 (R54520)

0.08C; 0.50Fe; 0.05N; 4.0-6.0Al; 2.0-3.0Sn; 0.20O .0175H (billet); 0.020H (bar); 0.020H (sheet)

Guar. R.T. Min.	Typical Elevated Temperature Properties		
	315°C (600°F)	427°C (800°F)	538°C (1000°F)
827 (120)	565 (82)	538 (78)	462 (67)
793 (115)	448 (65)	407 (59)	379 (55)
10	18	18	19
25	45	45	45
	435 (63)	415 (60)	140 (20)
	1,000	1,000	1,000
		330 (48)	62 (9)
		100	100
		0.1	0.1
14 (10)			
4.0 x Thickness			
4.5 x Thickness			
5.0 - 6.0 x Thickness			
34 HRC			
1038 (1900)			
9.4 (5.2)			
9.5 (5.3)			
9.5 (5.3)			
9.7 (5.4)			
10.1 (5.6)			
4.48 (.162)			
1600 (2910)			
160 (406)			
110 (16) -124 (18)			
48 (7.0)			
7.8 (4.5)			
530 (0.127)			
Good			
ASTM - B265, B348, B381; AMS - 4910, 4926, 4953, 4966; MIL-T - 9046 and - 9047			

TITANIUM ALLOY			Ti - 5Al - 2.5Sn - ELI			
ASTM GRADE (UNS NO.)			(R54521)			
Chemical Composition (Max. values unless range is shown)		(wt. %)	0.08C; 0.25Fe; 0.03N; 0.13O; 4.7-5.75Al; 2.0-3.0Sn; 0.0125H (billet & bar); 0.0150H (sheet)			
TENSILE PROPERTIES			Guar. R.T. Min.	Typical Cryogenic Properties		
				-196˚C (-320˚F)	-253˚C (-423˚F)	
Ultimate Strength		MPa (ksi)	724 (105)	1310 (190)	1580 (229)	
Yield Strength, 0.2% offset		MPa (ksi)	690 (100)	1210 (175)	1420 (206)	
Elongation in 51 mm (2") gage length		(%)	10	16	15	
Reduction in Area - Bar, Billet & Forging only		(%)	25			
OTHER MECHANICAL PROPERTIES						
Stress to Rupture in Time Shown	Stress	MPa (ksi)				
	Time-Hrs. at Temp. (˚C)					
Stress & Time to Produce Elongation Shown (creep)	Stress	MPa (ksi)				
	Time-Hrs. at Temp. (˚C)					
	Creep	(%)				
Charpy V-Notch Impact @ R.T.		Joules (ft-lbs)	20 (15)			
Bend Radius	Under 1.78 mm (0.070") thick		4.0 x Thickness			
	1.78 mm (0.070") and over		4.5 x Thickness			
Welded Bend Radius			4.0 – 5.0 x Thickness			
Nominal Hardness			33 HRC			
PHYSICAL PROPERTIES						
Nominal Beta Transus		˚C (˚F)	1038 (1900)			
Coefficient of Thermal Expansion 10^{-6}/˚C (10^{-6}/˚F)	0-100˚C (32 -212˚F)		9.4 (5.2)			
	0-315˚C (32-600˚F)		9.5 (5.3)			
	0-538˚C (32-1000˚F)		9.7 (5.4)			
	0-648˚C (32-1200˚F)		9.7 (5.5)			
	0-816˚C (32-1500˚F)		10.1 (5.6)			
Density		g/cm³ (lbs/in³)	4.48 (0.162)			
Melting Point, Approx.		˚C (˚F)	1600 (2910)			
Electrical Resistivity @ R.T.		10^{-6} ohm•cm (10^{-6} ohm•in)	160 (406)			
Modulus of Elasticity – Tension		GPa (10^3 ksi)	110 (16) -124 (18)			
Modulus of Elasticity – Torsion		GPa (10^3 ksi)	48 (7.0)			
Thermal Conductivity		W/m•˚C (BTU/hr•ft•˚F)	7.8 (4.5)			
Specific Heat		J/Kg•˚C (BTU/lb•˚F)	530 (0.127)			
Weldability			Very Good			
Industry Specifications			AMS 4909, 4924; MIL-T - 9046 and - 9047			

Ti - 8Al - 1Mo - 1V

(R54810)

0.08C; 0.05N; 0.12O, 7.5-8.5Al; 0.75-1.75Mo; 0.75-1.75V; 0.0125H (billet); 0.0125H (bar); 0.015H (sheet)

Guar.R.T.Min. Dup.Ann.	Typical Elevated Temperature Properties		
	316˚C (600˚F)	427˚C (800˚F)	538˚C (1000˚F)
931 (135)	745 (108)	100 (690)	595 (86)
827 (120)	550 (80)	520 (75)	450 (65)
10	20	20	28
	52	55	70
			396 (57.5)
			8
	683 (99)	414 (60)	124 (18)
	100	100	100
	0.2	0.2	0.2
20 - 34 (15 - 25)			
4.0 x Thickness			
4.5 x Thickness			
6.0 – 10.0 x Thickness			
36 HRC			
1038 (1900)			
8.5 (4.7)			
9.0 (5.0)			
10.1 (5.6)			
(10.3) (5.7)			
—			
4.37 (.158)			
1538 (2800)			
197 (500)			
128 (18.5)			
46 (6.7)			
6 (3.5)			
502 (0.120)			
Fair			

AMS - 4915, 4916, 4972, 4973;
MIL-T - 9046 and - 9047

*See Ti-8-1-1 heat treatment information in back of booklet
Note: STA in thin sections only. Not widely used.

Ti - 6Al - 2Sn - 4Zr - 2Mo - 0.1Si

(R54620)

0.08C; 0.05N; 0.12O; .25 Fe; 5.5-6.5Al; 1.75-2.25Sn; 3.5-4.5Zr; 1.75-2.25Mo; 0.10Si max.; 0.010H(billet); 0.0125H(bar)

Guar.R.T. Min.	Typical Elevated Temperature Properties		
	315˚C (600˚F)	427˚C (800˚F)	538˚C (1000˚F)
996 (130)	655 (95)	588 (85)	517 (75)
827 (120)	517 (75)	483 (70)	414 (60)
10	15	20	25
25	40	55	65
			345 (50)
			50
		400 (58)	83 (12)
		1000	1000
		0.1	0.1
4.5 x Thickness			
5.0 x Thickness			
—			
34 HRC			
999 (1830)			
7.7 (4.3)			
8.1 (4.5)			
8.1 (4.5)			
—			
—			
4.54 (0.164)			
1704 (3100)			
185 (470)			
114 (16.5)			
—			
7.7 (4.3)			
460 (0.11)			
Fair			

AMS - 4975, 4976, 4919;
MIL-T - 9046 and - 9047

*See Ti-6-2-4-2-S heat treatment information in back of booklet

TITANIUM ALLOY			Ti - 6Al - 4V			
ASTM GRADE (UNS NO.)			GRADE 5 (R56400)			
Chemical Composition (Max. values unless range is shown)		(wt. %)	0.08C; 0.25Fe; 0.05N; 0.20O; 5.50-6.75Al; 3.5-4.5V; 0.0100H (billet); 0.0125H (bar); 0.0150H (sheet)			
TENSILE PROPERTIES			Guar.R.T. Min.*	Typical Elevated Temperature Properties		
				150°C (300°F)	260°C (500°F)	370°C (700°F)
Ultimate Strength		MPa (ksi)	896 (130)	845 (121)	758 (110)	690 (100)
Yield Strength, 0.2% offset		MPa (ksi)	827 (120)	724 (105)	641 (93)	565 (82)
Elongation in 51 mm (2") gage length		(%)	10	16	17	18
Reduction in Area - Bar, Billet & Forging only		(%)	25	35	40	45
OTHER MECHANICAL PROPERTIES			* Mill-Annealed Condition (MA)			
Stress to Rupture in Time Shown	Stress	MPa (ksi)			724 (105)	620 (90)
	Time-Hrs. at Temp. (°C)				1000 (315)	1000 (400)
Stress & Time to Produce Elongation Shown (creep)	Stress	MPa (ksi)			483 (70)	296 (43)
	Time-Hrs. at Temp. (°C)				100 (315)	100 (371)
	Creep	(%)			0.1	0.1
Charpy V-Notch Impact @ R.T.		Joules (ft-lbs)	20 - 27 (15 - 20)			
Bend Radius	Under 1.78 mm (0.070") thick		4.5 x Thickness			
	1.78 mm (0.070") and over		5.0 x Thickness			
Welded Bend Radius			6.0 -10.0 x Thickness			
Nominal Hardness			33 HRC			
PHYSICAL PROPERTIES						
Nominal Beta Transus		°C (°F)	996 (1825)			
Coefficient of Thermal Expansion 10^{-6}/°C (10^{-6}/°F)	0-100°C (32 -212°F)		9.0 (5.0)			
	0-315°C (32-600°F)		9.5 (5.3)			
	0-538°C (32-1000°F)		10.1 (5.6)			
	0-648°C (32-1200°F)		10.6 (5.9)			
	0-816°C (32-1500°F)		11.0 (6.1)			
Density		g/cm³ (lbs/in³)	4.43 (.160)			
Melting Point, Approx.		°C (°F)	1650 (3000)			
Electrical Resistivity @ R.T.		10^{-6} ohm•cm (10^{-6} ohm•in)	171 (434)			
Modulus of Elasticity – Tension		GPa (10^3 ksi)	114 (16.5)			
Modulus of Elasticity – Torsion		GPa (10^3 ksi)	42 (6.1)			
Thermal Conductivity		W/m•°C (BTU/hr•ft•°F)	6.6 (3.8)			
Specific Heat		J/Kg•°C (BTU/lb•°F)	565 (0.135)			
Weldability			Very Good			
Industry Specifications			ASTM - B265, B348, B381, B861, F467 and F468; AMS - 4911, 4928, 4935, 4965 and 4967; MIL-T - 9046 and - 9047 *See Ti-6-4 heat treatment information in back of booklet			

Ti - 6Al - 4V ELI*					
GRADE 23 (R56407)					
0.08C; 0.03N; 0.13O; 0.25Fe; 5.5-6.5Al; 3.5-4.5V; 0.0125H					
Guar. R.T. Min.**	Guar. R.T. Min.***	Typical Elevated Temperature Properties ****			
		93˚C(200˚F)	149˚C(300˚F)	204˚C(400˚F)	260˚C(500˚F)
862 (125)	827 (120)	833 (121)	770 (112)	723 (105)	678 (98)
793 (115)	759 (110)	712 (103)	640 (93)	587 (85)	532 (77)
10	[7.5(6.0)]****	13	15	16	16
25	15				
*Extra low interstitials ** Per ASTM F136 specification			*** Per ASTM "B" product specifications **** Transformed-beta condition		
24- 40 (18 - 30)					
4.5 x Thickness					
5.0 x Thickness					
6 - 10 x Thickness					
32 HRC					
982 (1800)					
9.2 (5.1)					
9.5 (5.3)					
10.1 (5.6)					
10.4 (5.8)					
10.8 (6.0)					
4.43 (0.160)					
1650 (3000)					
165 (65)					
114 (16.5)					
42.8 (6.2)					
7.3 (4.2)					
565 (0.135)					
Very Good					
ASTM - B265, B348, B363, B381, B861, B862 andF136; AMS - 4907, 4930 and 4956					

Ti - 6Al - 4V - 0.1Ru****					
GRADE 29 (R56404)					
0.08C; 0.03N; 0.13O; 0.25Fe; 5.5-6.5Al; 3.5-4.5V; 0.08-0.14Ru; 0.015H					
Guar. R.T. Min.*	Guar. R.T. Min.**	Typical Elevated Temperature Properties **			
		93˚C(200˚F)	149˚C(300˚F)	204˚C(400˚F)	260˚C(500˚F)
827 (120)	827 (120)	833 (121)	770 (112)	723 (105)	678 (98)
759 (110)	759 (110)	712 (103)	640 (93)	587 (85)	532 (77)
10	[7.5(6.0)***]	13	15	16	16
25	15				
*Mill-annealed condition ** Transformed-beta condition			*** For sections ≥ 25.4mm **** ELI grade		
24- 40 (18 - 30)					
4.5 x Thickness					
5.0 x Thickness					
6 - 10 x Thickness					
32 HRC					
982 (1800)					
9.2 (5.1)					
9.5 (5.3)					
10.1 (5.6)					
10.4 (5.8)					
10.8 (6.0)					
4.43 (0.160)					
1650 (3000)					
165 (65)					
114 (16.5)					
42.8 (6.2)					
7.3 (4.2)					
565 (0.135)					
Very Good					
ASTM - B265, B337, B348, B381, B861 and B862					

TITANIUM ALLOY			Ti - 6Al - 6V - 2Sn			
ASTM GRADE (UNS NO.)			**(R56620)**			
Chemical Composition (Max. values unless range is shown)		(wt. %)	0.08C; 0.04N; 0.20O; 5.0-6.0Al; 5.0-6.0V; 1.5-2.5Sn; 0.35-1.0Fe; 0.35-1.0 Cu; 0.0125H (billet); 0.015H (bar, sheet, plate)			
TENSILE PROPERTIES			**Guar.R.T. Min.***	**Typical Elevated Temperature Prop. (Ann.)**		
				204˚C (400˚F)	**315˚C (600˚F)**	**427˚C (800˚F)**
Ultimate Strength		MPa (ksi)	1034 (150)	1070 (155)	1000 (145)	930 (135)
Yield Strength, 0.2% offset		MPa (ksi)	965 (140)	930 (135)	827 (120)	793 (115)
Elongation in 51 mm (2") gage length		(%)	10L, 8T			
Reduction in Area - Bar, Billet & Forging only		(%)	20L, 15T			
OTHER MECHANICAL PROPERTIES			* For sections ≤ 51mm, Annealed Condition			
Stress to Rupture in Time Shown	Stress	MPa (ksi)				
	Time-Hrs. at Temp. (˚C)					
Stress & Time to Produce Elongation Shown (creep)	Stress	MPa (ksi)		655 (95)	276 (40)	124 (18)
	Time-Hrs. at Temp. (˚C)			100 (315)	100 (370)	100 (427)
	Creep	(%)		0.2	0.2	0.2
Charpy V-Notch Impact @ R.T.		Joules (ft-lbs)	16 - 19 (12 - 14)			
Bend Radius	Under 1.78 mm (0.070") thick		4.0 x Thickness			
	1.78 mm (0.070") and over		4.5 x Thickness			
Welded Bend Radius			—			
Nominal Hardness			38 HRC (Ann. condition)			
PHYSICAL PROPERTIES						
Nominal Beta Transus		˚C (˚F)	946 (1735)			
Coefficient of Thermal Expansion 10^{-6}/˚C (10^{-6}/˚F)	0-100˚C (32 -212˚F)		9.0 (5.0)			
	0-315˚C (32-600˚F)		9.3 (5.2)			
	0-538˚C (32-1000˚F)		9.5 (5.3)			
	0-648˚C (32-1200˚F)		10.7 (6.0)			
	0-816˚C (32-1500˚F)		10.9 (6.1)			
Density		g/cm³ (lbs/in³)	4.54 (0.164)			
Melting Point, Approx.		˚C (˚F)	1650 (3000) - 1704 (3100)			
Electrical Resistivity @ R.T.		10^{-6} ohm•cm (10^{-6} ohm•in)	157 (398)			
Modulus of Elasticity – Tension		GPa (10^3 ksi)	114 (16.5)			
Modulus of Elasticity – Torsion		GPa (10^3 ksi)	—			
Thermal Conductivity		W/m•˚C (BTU/hr•ft•˚F)	5.5 (3.2)			
Specific Heat		J/Kg•˚C (BTU/lb•˚F)	635 (0.155)			
Weldability			Limited			
Industry Specifications			AMS 4918, 4936, 4971, 4978 and 4979; MIL-T - 9046 and - 9047 * See Ti-6-6-2 heat treatment information in back of booklet			

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

(R56260)

0.04C; 0.04N; 0.15Fe; 0.5O; 5.5-6.5Al; 1.75-2.25Sn; 3.5-4.5Zr; 5.5-6.5Mo; 0.0125H

Guar.R.T. Min.(Dplx)	Typical Elevated Temp. Prop. (Duplex Ann.) 315˚C (600˚F)	427˚C (800˚F)	538˚C (1000˚F)
1172 (170)	1103 (160)	1069 (155)	931 (135)
1103 (160)	896 (130)	862 (125)	724 (105)
10L, 8T	10	10	15
20L, 15T	30	30	50
			758 (110)
			100 (482)
	690 (100)	483 (70)	276 (40)
	70 (315)	100 (427)	100 (482)
	0.1	0.2	0.2
39 HRC			
946 (1735)			
9.4 (5.2)			
10.3 (5.7)			
10.4 (5.8)			
10.4 (5.8)			
10.6 (5.9)			
4.65 (0.168)			
1593 (2900) - 1677 (3050)			
200 (508)			
114 (16.5) Duplex Ann.			
—			
7.7 (4.4)			
500 (0.12)			
Limited			
AMS 4981B, MIL F - 83142A Comp 11 Frg Amin, MIL F - 8314 Comp 11 Frg Ht, MIL T - 9047G			

Ti - 6Al - 2Sn - 2Zr - 2Mo - 2Cr - 0.15Si

(UNASSIGNED)

0.05C; 0.03N; 0.25Fe; 0.14O; 5.25-6.25Al; 1.75-2.25Sn; 1.75-2.25Zr; 1.75-2.25Mo; 1.75-2.25Cr; 0.12-0.20Si; 0.0125H

Typ. R.T. Prop. (STA)	Typical Elevated Temperature Properties 204˚C (400˚F)	315˚C (600˚F)	427˚C (800˚F)
1172 (170)	100 (145)	965 (140)	896 (130)
1103 (160)	807 (117)	738 (107)	690 (100)
12	19	20	21
20	33	35	40
	979 (142)	910 (132)	841 (122)
	100 (204)	100 (315)	100 (427)
	841 (122)	827 (120)	572 (83)
	100 (204)	100 (315)	100 (427)
	0.2	0.2	0.2
16 (12)			
4.5			
5.0			
960 (1760)			
—			
9.2 (5.1)			
—			
—			
—			
4.65 (0.164)			
N/A			
N/A			
117 (17.0) STA			
46 (6.7)			
N/A			
N/A			
Limited			
AMS 4898			

TITANIUM ALLOY Ti - 5Al - 2Zr - 2Sn - 4Mo - 4Cr (Ti - 17)

ASTM GRADE (UNS NO.)		(R58650)			
Chemical Composition (wt. %) (Max. values unless range is shown)		4.5-5.5Al; 3.5-4.5Cr; 3.5-4.5Mo; 1.5-2.5Sn; 1.5-2.5Zr; 0.3Fe; 0.04N; 0.0125H; 0.08-0.13O			
TENSILE PROPERTIES		Guar. R.T. Min.*	Typical Elevated Temperature Properties (STA) 204°C (400°F)	315°C (600°F)	371°C (700°F)
Ultimate Strength MPa (ksi)		1165 (169)	993 (144)	965 (140)	917 (133)
Yield Strength, 0.2% offset MPa (ksi)		1110 (161)	841 (122)	807 (117)	745 (108)
Elongation in 51 mm (2") gage length (%)		10	14	12	13
Reduction in Area - Bar, Billet & Forging only (%)		32	46	48	47
OTHER MECHANICAL PROPERTIES		* Alpha-Beta processed			
Stress to Rupture in Time Shown	Stress MPa (ksi)		965 (140)	896 (130)	690 (100)
	Time-Hrs. at Temp. (°C)		800 (204)	1000 (315)	7500 (427)
Stress & Time to Produce Elongation Shown (creep)	Stress MPa (ksi)		793 (115)	690 (100)	241 (35)
	Time-Hrs. at Temp. (°C)		2200 (204)	1000 (315)	150 (427)
	Creep (%)		0.2	0.2	0.2
Charpy V-Notch Impact @ R.T. Joules (ft-lbs)		—			
Bend Radius	Under 1.78 mm (0.070") thick	—			
	1.78 mm (0.070") and over	—			
Welded Bend Radius		—			
Nominal Hardness		40 HRC			
PHYSICAL PROPERTIES					
Nominal Beta Transus °C (°F)		890 (1635)			
Coefficient of Thermal Expansion 10^{-6}/°C (10^{-6}/°F)	0-100°C (32 -212°F)	—			
	0-315°C (32-600°F)	9.7 (5.4)			
	0-538°C (32-1000°F)	—			
	0-648°C (32-1200°F)	—			
	0-816°C (32-1500°F)	—			
Density g/cm³ (lbs/in³)		4.65 (0.168)			
Melting Point, Approx. °C (°F)		N/A			
Electrical Resistivity @ R.T. 10^{-6} ohm•cm (10^{-6} ohm•in)		N/A			
Modulus of Elasticity – Tension GPa (10³ ksi)		114 (16.5) Dynamic			
Modulus of Elasticity – Torsion GPa (10³ ksi)		—			
Thermal Conductivity W/m•°C (BTU/hr•ft•°F)		N/A			
Specific Heat J/Kg•°C (BTU/lb•°F)		N/A			
Weldability		—			
Industry Specifications		AMS 4995			

Ti - 4.5Al - 3V - 2Mo - 2Fe (SP - 700)

(UNASSIGNED)

4.0-5.0Al; 2.5-3.5V; 1.8-2.2Mo; 1.7-2.3Fe; 0.15O; 0.08C; 0.05N;0.01H; 0.005Y

Guar. R.T.Min. (Ann.)	Typical R.T. Properties (Ann.)	Typical R.T. Properties (STA)
(130)	1023 (148)	1295 (188)
(120)	972 (141)	1177 (171)
10	19	13
25	60	30

14 - 27 (10 - 20) ft. - lbs.
4.5 x Thickness
5.0 x Thickness
—
34 HRC
900 (1650)
7.7 (4.3)
—
8.5 (4.7)
—
9.0 (5.0)
4.54 (0.164)
1593 (2900)
164 (65)
110 (15.9)
—
6.9 (4.0)
502 (0.12)
Good

AMS 4899

Ti - 4Al - 4Mo - 2Sn - 0.5Si (Ti-550)

(UNASSIGNED)

3.0-5.0Al; 1.5-2.5Sn; 0.12Fe; 3.0-5.0Mo; 0.3-0.7Si; 0.03N; 0.05C; 0.16-0.20O; 0.015H

Guar. R.T. Min.	Typical R.T.	Typical Elevated Temperature Properties 93˚C (200˚F)	204˚C (400˚F)	315˚C (600˚F)
1103(160)	1145(166)	1096(159)	979(142)	876(127)
958(139)	1021(148)	938(136)	800(116)	683(99)
9	12	15	16	17
20	36	—	—	—

	—		841 (122)
	—		100 (399)
752 (109)	710 (103)	703 (102)	517 (75)
1000 (100)	100 (300)	1000 (300)	100 (399)
0.05	0.10	0.10	0.10
23 (17)			
Hot formable only			
Hot formable only			
—			
37 HRC			
975 (1787)			
8.8 (4.9)			
9.2 (5.1)			
10.1 (5.6)			
—			
—			
4.6 (0.166)			
—			
159 (63)			
114 (16.5)			
—			
7.5 (4.35)			
—			
Limited			

TA-46, -47 and -48;

TITANIUM ALLOY			Ti - 10V - 2Fe - 3Al				
ASTM GRADE (UNS NO.)			**(UNASSIGNED)**				
Chemical Composition (Max. values unless range is shown)		(wt. %)	9.0-11.0V; 2.6-3.4Al; 1.6-2.2Fe; 0.13O; 0.05N; 0.05C; 0.015H				
TENSILE PROPERTIES			R.T. Min.			Typical Elevated Temp. Prop. (STA)*	
			(STA)[1]	(STA)	(STA)[2]	204°C (400°F)	315°C (600°F)
Ultimate Strength		MPa (ksi)	1193 (173)	1103(160)	965 (140)	827 (120)	738 (107)
Yield Strength, 0.2% offset		MPa (ksi)	1103 (160)	1000 (145)	896 (130)	724 (105)	600 (87)
Elongation in 51 mm (2") gage length		(%)	4	6	8	22	22
Reduction in Area - Bar, Billet & Forging only		(%)	6	10	20	65	63
OTHER MECHANICAL PROPERTIES			[1]High Strength [2]High Toughness				
Stress to Rupture in Time Shown	Stress	MPa (ksi)				620 (90)	69 (10)
	Time-Hrs. at Temp. (°C)					170 (370)	2300 (480)
Stress & Time to Produce Elongation Shown (creep)	Stress	MPa (ksi)	690 (100)			172 (25)	124 (18)
	Time-Hrs. at Temp. (°C)		10 (316)			100 (370)	100 (480)
	Creep	(%)	0.26			0.2	0.2
Charpy V-Notch Impact @ R.T.		Joules (ft-lbs)	—				
Bend Radius	Under 1.78 mm (0.070") thick		—				
	1.78 mm (0.070") and over		—				
Welded Bend Radius			—				
Nominal Hardness			32 - 41 HRC				
PHYSICAL PROPERTIES							
Nominal Beta Transus		°C (°F)	812 (1495)				
Coefficient of Thermal Expansion 10^{-6}/°C (10^{-6}/°F)	0-100°C (32 -212°F)		9.7 (5.4)				
	0-315°C (32-600°F)		—				
	0-538°C (32-1000°F)		—				
	0-648°C (32-1200°F)		—				
	0-816°C (32-1500°F)		—				
Density		g/cm^3 (lbs/in^3)	4.65 (0.168)				
Melting Point, Approx.		°C (°F)	N/A				
Electrical Resistivity @ R.T.		10^{-6} ohm•cm (10^{-6} ohm•in)	N/A				
Modulus of Elasticity – Tension		GPa (10^3 ksi)	83 - 110 (12 - 16) STA				
Modulus of Elasticity – Torsion		GPa (10^3 ksi)	41 (6)				
Thermal Conductivity		W/m•°C (BTU/hr•ft•°F)	N/A				
Specific Heat		J/Kg•°C (BTU/lb•°F)	N/A				
Weldability			Fair				
Industry Specifications			AMS 4986, 4983A, 4984, 4987				

Ti - 3Al - 8V - 6Cr - 4Mo - 4Zr (Ti Beta-C™)

GRADE 19 (R58640)

3.0-4.0Al; 7.5-8.5V; 5.5-6.5Cr; 3.5-4.5Zr; 3.5-4.5Mo; 0.3Fe; 0.12O; 0.05C; 0.03N; 0.02H

Guar. R.T.Min.*		Typical Elevated Temperature Properties (STA)			
(S.T.)	(STA)	R.T.	93°C(200°F)	204°C(400°F)	315°C (600°F)
793(115)	1172(170)	1227(178)	1172(170)	1117(162)	1069(155)
759(110)	1103(160)	1138(165)	1069(155)	1007(146)	972(141)
15	6	9	9	9	9
—	—	30	35	32	30

		1020 (148)	965 (140)
		500 (260)	100 (315)
	952 (138)	670 (100)	517 (75)
	750 (260)	100 (315)	170 (370)
	0.2	0.2	0.2

10.8 - 16.3 (8 - 12)
3.5 (ST)
4.0 (ST)
—
30 - 45 HRC
730 (1350)
8.3 (4.6)
9.5 (5.3)
9.7 (5.4)
—
—
4.82 (0.174)
1650 (3000)
160 (63)
ST: 93-96 (13.5-14.0); STA: 102 (14.8)
41.4 (6.0)
6.2 (3.6)
515 (0.123)
Fair

AMS 4957 and 4958;
MIL-T - 9046 and - 9047;
ASTM B265, B337, B348, B363, B381 and B861
* See Ti Beta-C™ heat treatment information in back of booklet

Ti - 3Al - 8V - 6Cr - 4Mo - 4Zr - 0.05Pd (Ti Beta-C™/Pd)

GRADE 20 (R58645)

3.0-4.0Al; 7.5-8.5V; 5.5-6.5Cr; 3.5-4.5Zr; 3.5-4.5Mo; 0.3Fe; 0.12O; 0.05C; 0.04-0.08Pd; 0.03N; 0.02H

Guar. R.T.Min.		Typical Elevated Temperature Properties (STA)			
(S.T.)	(STA)	R.T.	93°C(200°F)	204°C(400°F)	315°C (600°F)
793(115)	1172(170)	1227(178)	1172(170)	1117(162)	1069(155)
759(110)	1103(160)	1138(165)	1069(155)	1007(146)	972(141)
15	6	9	9	9	9
—	—	30	35	32	30

		1020 (148)	965 (140)
		500 (260)	100 (315)
	952 (138)	670 (100)	517 (75)
	750 (260)	100 (315)	170 (370)
	0.2	0.2	0.2

10.8 - 16.3 (8 - 12)
3.5 (ST)
4.0 (ST)
—
30 - 45 HRC
730 (1350)
8.3 (4.6)
9.5 (5.3)
9.7 (5.4)
—
—
4.82 (0.174)
1650 (3000)
160 (63)
ST: 93-96 (13.5-14.0); STA: 102 (14.8)
41.4 (6.0)
6.2 (3.6)
515 (0.123)
Fair

ASTM B265, B337, B348, B363, B381 and B861

TITANIUM ALLOY			Ti - 6Al - 7Nb		
ASTM GRADE (UNS NO.)					
Chemical Composition (Max. values unless range is shown)		(wt. %)	0.08C; 0.05N; 0.20O;0.25Fe; 5.5-6.5Al; 6.5-7.5Nb; 0.50Ta; 0.009H		
TENSILE PROPERTIES			Guar. R.T.Min.* (Ann.)	Typical R.T. Annealed Properties* 6.3-19 mm dia.	Typical R.T. Annealed Properties* 19-71 mm dia.
Ultimate Strength		MPa (ksi)	900 (130.5)	1021 (148)	979 (142)
Yield Strength, 0.2% offset		MPa (ksi)	800 (116)	910 (132)	883 (128)
Elongation in 51 mm (2") gage length		(%)	10	15	14
Reduction in Area		(%)	25	42	41
OTHER MECHANICAL PROPERTIES			* Bar Product Only		
Stress to Rupture in Time Shown	Stress	MPa (ksi)	—		
	Time-Hrs. at Temp. (˚C)		—		
Stress & Time to Produce Elongation Shown (creep)	Stress	MPa (ksi)	—		
	Time-Hrs. at Temp. (˚C)		—		
	Creep	(%)	—		
Charpy V-Notch Impact @ R.T.		Joules (ft-lbs)	—		
Bend Radius	Under 1.78 mm (0.070") thick		—		
	1.78 mm (0.070") and over		—		
Welded Bend Radius			—		
Nominal Hardness			—		
PHYSICAL PROPERTIES					
Nominal Beta Transus		˚C (˚F)	1010 (1850)		
Coefficient of Thermal Expansion 10^{-6}/˚C (10^{-6}/˚F)	0-100˚C (32 -212˚F)		N/A		
	0-315˚C (32-600˚F)		—		
	0-538˚C (32-1000˚F)		—		
	0-648˚C (32-1200˚F)		—		
	0-816˚C (32-1500˚F)		—		
Density		g/cm³ (lbs/in³)	4.52 (0.163)		
Melting Point, Approx.		˚C (˚F)	N/A		
Electrical Resistivity @ R.T.		10^{-6} ohm•cm (10^{-6} ohm•in)	—		
Modulus of Elasticity – Tension		GPa (10^3 ksi)	105 (15.2)		
Modulus of Elasticity – Torsion		GPa (10^3 ksi)	N/A		
Thermal Conductivity		W/m•˚C (BTU/hr•ft•˚F)	—		
Specific Heat		J/Kg•˚C (BTU/lb•˚F)	—		
Weldability			Good		
Industry Specifications			Medical Implant Alloy ASTM - F1295		

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Guaranteed Minimum Properties RMI 6Al - 4V**

MILL ANNEALED Ti 6Al - 4V BAR AND BILLET

Thickness or Diameter mm (inches)	Ultimate Tensile Strength MPa (ksi)	Yield Strength 0.2% Offset MPa (ksi)	Elong in 4D%		Reduction in Area%	
			Long.	Trans.	Long.	Trans.
47.6-101.6 (0.1875-4.000) incl.①	896 (130)	827 (120)	10	10	25	25
Over 101.6 (4.000) ②	896 (130)	827 (120)	8	8	20	15

① 103cm² (16 sq. inch) maximum
② 413cm² (64 sq. inch) maximum

MILL ANNEALED Ti 6Al - 4V SHEET, STRIP AND PLATE

Thickness mm (inches)	Ultimate Tensile Strength MPa (ksi)	Yield Strength 0.2% Offset MPa (ksi)	Elong in 50.8mm (2 in.)%	Min. Bend Radius
.20 (0.008) to .43 (0.017) excl.	924 (134)	869 (126)	6	4.5 T
.43 (0.017) to .81 (0.032) excl.	924 (134)	869 (126)	8	4.5 T
.81 (0.032) to 1.78 (0.070) excl.	924 (134)	869 (126)	10	4.5 T
1.78 (0.070) to 4.76 (0.1875) excl.	924 (134)	869 (126)	10	5.0 T
4.76 (0.1875) to 101.6 (4.000) incl.	896 (130)	827 (120)	10	—

SOLUTION TREATED AND AGED (STA) Ti 6Al - 4V BAR

Heat-Treat Cycle
954˚C (1750˚F)/1Hr.; Water Quench*
482-593˚C (900-1100˚F)/4 to 8 Hrs.; Air Cool

Diameter or Thickness as Rolled or Forged mm (inches)	Diameter or Thickness as Heat-Treated mm (inches)	Max Cross Sect. mm² (sq.in.)	Ultimate Tensile Strength MPa (ksi)	Yield Strength 0.2% Offset MPa (ksi)	Elong in 4D %		Reduction in in Area %	
					Long.	Tran.	Long.	Tran.
25.4 (1) and Under	12.7 (.5) and Under	101.6 (4)	1138 (165)	1069 (155)	10	8	25	20
	Over 12.7 to 25.4 (.5 to 1)	101.6 (4)	1103 (160)	1034 (150)	10	8	25	20
Over 25.4 to 50.8 (1 to 2)	25.4 (1) and Under	406.4(16)	1069 (155)	1000 (145)	8	6	20	15
	Over 25.4 to 50.8 (1 to 2)	101.6 (4)	1034 (150)	965 (140)	8	6	20	15
	Over 25.4 to 50.8 (1 to 2)	406.4(16)	965 (140)	896 (130)	8	6	20	15
Over 50.8 to 76.2 (2 to 3)	25.4 (1) and Under	406.4(16)	1034 (150)	965 (140)	8	6	20	15
	Over 25.4 to 50.8 (1 to 2)	152.4 (6)	1000 (145)	931 (135)	8	6	20	15
	Over 50.8 to 76.2 (2 to 3)	304.8(12)	965 (140)	896 (130)	8	6	20	15
Over 76.2 to 101.6 (3 to 4)	1 (25.4) and Under	406.4(16)	1034 (150)	965 (140)	6	4	15	10
	Over 25.4 to 50.8 (1 to 2)	406.4(16)	965 (140)	896 (130)	6	4	15	10
	Over 50.8 to 101.6 (2 to 4)	406.4(16)	896 (130)	827 (120)	6	4	15	10

SOLUTION TREATED AND AGED (STA) Ti 6Al-4V SHEET, STRIP AND PLATE

Heat-Treat Cycle
899-954˚C (1650-1750˚F)/5 Min. to 1Hr.; Water Quench*
482-593˚C (900-1100˚F)/4 to 8 Hrs.; Air Cool

Thickness mm (inches)	Ultimate Tensile Strength ksi (MPa)	Yield Strength 0.2% Offset MPa (ksi)	Elong in 50.8mm (2 in.)%
.41 to .84 (0.016 to 0.033) excl.	1103 (160)	1000 (145)	3
.84 to 1.3 (0.033 to 0.050) excl.	1103 (160)	1000 (145)	4
1.3 to 4.8 (0.050 to 0.1875) excl.	1103 (160)	1000 (145)	5
4.8 to 12.7 (0.1875 to 0.500) incl.	1103 (160)	1000 (145)	8
Over 12.7 to 19.0 (0.500 to 0.750) incl.	1103 (160)	1000 (145)	8
Over 19.0 to 25.4 (0.750 to 1.000) incl.	1034 (150)	965 (140)	6
Over 25.4 to 50.8 (1.000 to 2.000) incl.	1000 (145)	931 (135)	6

* Time from furnace to water should be less than 6 seconds

** For comprehensive details of this alloy see RMI Titanium Co. brochure entitled "RMI 6Al-4V."

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Properties After Heat Treatment

Type of Treatment	Desired Characteristics	Heat-Treat Cycle	Tensile Properties: Guaranteed Minimum	
Ti 8Al-1Mo-1V PROPERTIES AFTER HEAT TREATMENT: SHEET				
Single Anneal	For maximum room temp.properties and low creep to 317˚C (700˚F)	788˚C (1450F)/1-8 Hrs. Furnace-Cool	Ultimate strength .... Yield Strength 0.2% offset .... Elong. in 50.8mm (2 in.) (%) ·	1000MPa (145ksi) 931MPa (135ksi) 8 to (.64mm (0.025) incl.) 10 (Over .64mm (0.025) in.)
Duplex Anneal	For high fracture toughness	Single Anneal Plus 788˚C (1450˚F)/15 Min.; Air Cool	Ultimate strength .... Yield Strength 0.2% offset .... Elong. in 50.8mm (2 in.) (%) ·	931MPa (135ksi) 827MPa (120ksi) 8 to (.64mm (0.025) incl.) 10 (Over .64mm (0.025) in.)
Ti 8Al-1Mo-1V PROPERTIES AFTER HEAT TREATMENT: BAR to 63.5mm (2.5 in.) incl. dia. or thickness				
Duplex Anneal	For maximum room temp. properties and good creep resistance to 538˚C (1000˚F)	566-593˚C(1800-1850F)/1 Hr.; Air Cool (or Quench) Reheat at 982-1010˚C (1050-1100˚F)/8 Hrs.; Air Cool	Ultimate strength .... Yield Strength 0.2% offset .... Elong. in 50.8mm (2 in.) (%) · Reduction in Area (%)...........	896MPa (130ksi) 827MPa (120ksi) 10 20
Ti 8Al-1Mo-1V PROPERTIES AFTER HEAT TREATMENT: BAR over 63.5mm (2.5 in.) to 101.6 (4.0 in.) incl. thickness or dia.				
Duplex Anneal	For maximum room temp. properties and good creep resistance to 538˚C (1000˚F)	566-593˚C(1800-1850˚F)/1 Hr.; Air Cool (or Quench) Reheat at 982-1010˚C (1050-1100 ˚F)/8 Hrs.; Air Cool	Ultimate strength .... Yield Strength 0.2% offset .... Elong. in 50.8mm (2 in.) (%) · Reduction in Area (%)...........	827MPa (120ksi) 758MPa (110ksi) 10 20

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Properties After Heat Treatment

Ti 6Al - 6V - 2Sn SHEET AND PLATE PROPERTIES (ANNEALED)

Thickness mm (inches)	Ultimate Tensile Strength MPa (ksi)	Yield Strength 0.2% Offset MPa (ksi)	Elongation in 50.8mm (2 in.) or 4D(%)		Min. Bend Radius
			Long.	Trans.	
Up to .64 (0.025) excl.	1069 (155)	1000 (145)	8	6	4.0 T
.64 (0.025) to 1.8 (0.070) excl.	1069 (155)	1000 (145)	10	8	4.0 T
Over 1.8 (0.070) to 4.8 (0.1875) excl.	1069 (155)	1000 (145)	10	8	4.5 T
4.8 (0.1875) to 50.8 (2.00) incl.	1034 (150)	965 (140)	10	8	—
Over 50.8 (2.00) to 101.6 (4.00) incl.	1000 (145)	931 (135)	8	6	—

Ti 6Al - 6V - 2Sn BAR AND BILLET PROPERTIES (ANNEALED)

Thickness or Diameter inches	Ultimate Tensile Strength MPa (ksi)	Yield Strength 0.2% Offset MPa (ksi)	Elongation in 4D%		Reduction in Area%	
			Long.	Trans.	Long.	Trans.
Up to 50.8 (2.00) incl.	1034 (150)	965 (140)	10	8	20	20
Over 50.8 (2.00) to 101.6 (4.00) incl.①	1000 (145)	931 (135)	8	6	20	15
Over 101.6 (4.00) ②	965 (140)	896 (130)	8	6	15	15

① 103cm² (16 sq. inches) maximum

② 413cm² (64 sq. inches) maximum

Ti 6Al - 6V - 2Sn PROPERTIES (STA CONDITION)

Heat-Treat Cycle
857-913˚C (1575-1675˚F)/1Hr.; Water Quench
482-593˚C (900-1100˚F)/4 to 8 Hrs.; Air Cool

Thickness as Rolled or Forged mm (inches)	Thickness as Heat-Treated mm (inches)	Tensile Properties: Guaranteed Minimum						
		Ultimate Strength MPa (ksi)	Yield Strength MPa (ksi) 0.2% Offset	Elongation in 50.8mm (2 in.) (%)		Reduction in Area (%)		
				Long.	Tran.	Long.	Tran.	
25.4 (1) and Under	25.4 (1) and Under	1241 (180)	1172 (170)	8	6	20	15	
Over 25.4 (1) to 50.8 (2)	25.4 (1) and Under Over 25.4 (1) to 50.8 (2)	1241 (180) 1172 (170)	1172 (170) 1103 (160)	8 8	6 6	20 20	15 15	
Over 50.8 (2) to 76.2 (3)	25.4 (1) and Under Over 25.4 (1) to 50.8 (2) Over 50.8 (2) to 76.2 (3)	1172 (170) 1138 (165) 1069 (155)	1103 (160) 1069 (155) 1000 (145)	8 8 8	6 6 6	20 20 20	15 15 15	
Over 76.2 (3) to 101.6 (4)	25.4 (1) and Under Over 25.4 (1) to 50.8 (2) Over 50.8 (2) to 76.2 (3) Over 76.2 (3) to 101.6 (4)	1138 (165) 1103 (160) 1069 (155) 1034 (150)	1069 (155) 1034 (150) 1000 (145) 965 (140)	8 8 8 8	6 6 6 6	20 20 20 20	15 15 15 15	
Plate Thickness Over 4.7 (0.187) to 38.1 (1.5)	Over 4.7 (0.187) to 38.1 (1.5)	1172 (170)	1103 (160)	6		15		
Over 38.1 (1.5) to 63.5 (2.5)	Over 38.1 (1.5) to 63.5 (2.5)	1103 (160)	1034 (150)	6		15		

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Properties After Heat Treatment

Ti 6Al - 6V - 2Sn PROPERTIES (STA CONDITION)

Heat-Treat Cycle ①: 843-899˚C (1550-1650˚F)/1Hr.; Fast Air Cool 593˚C (1100˚F)/4 to 8 Hrs.; Air Cool

Product	Diameter or Distance Between Parallel Sides mm (inches)	Tensile Properties: Guaranteed Minimum					
		Ultimate Strength MPa (ksi)	Yield Strength MPa (ksi) 0.2% Offset	Elongation in 50.8mm (2 in.) (%)		Reduction in area (%)	
				Long.	Tran.	Long.	Tran.
Forgings	Up to 76.2 (3) incl.	1172 (170)	1103 (160)	10	8	20	15
Bar and Wire	Up to 63.5 (2.5) incl.	1172 (170)	1103 (160)	10	8	20	15
Bar	Over 63.5 (2.5) to 76.2 (3) incl.	1138 (165)	1069 (155)	8	6	15	12
Bar and Forgings	Over 76.2 (3) to 101.6 (4) incl.	1138 (165)	1069 (155)	8	6	15	12

① Alternate cycle sections over 25.4mm (1 in). heat to 14˚C (25 ˚F) below Beta Transus Temperature — 1-2 Hrs.; Fast Air Cool plus 802-857˚C (1475-1575˚F)/1-4 Hrs.; Air Cool or faster plus 593˚C (1100˚F)/4-8 Hrs.; Air Cool

Ti 6Al - 2Sn 4Zr - 2Mo - .01 Si SHEET AND PLATE (DUPLEX ANNEALED)②

Thickness mm (inches)	Ultimate Tensile Strength MPa (ksi)	Yield Strength 0.2% Offset MPa (ksi)	Elongation in 50.8mm (2 in.) or 4D%	Minimum Bend Radius
.51 (.020) to 1.78 (.070) excl.	931 (135)	862 (125)	8③	4.5 T
1.78 (.070) to 4.76 (.1875) excl.	931 (135)	862 (125)	10	5.0 T
4.76 (.1875) to 25.4 (1.00) incl.	931 (135)	862 (125)	10	—
Over 25.4 (1.00) to 76.2 (3.00) incl.	896 (130)	827 (120)	10	—

① Duplex Anneal 899˚C (1650˚F)/30 Min.; Air Cool plus 788˚C (1450˚F)/15 Min.; Air Cool
② Duplex Anneal 899˚C (1650˚F)/1 Hr.; Air Cool plus 593˚C (1100˚F)/8 Hrs.; Air Cool
③ 1.6mm (0.063in.) and heavier 10% minimum
④ Triplex Anneal minimum properties — Sheet only — Duplex Anneal plus 593˚C (1100˚F)/2 Hrs.; Air Cool 965 MPa (140 ksi) ilt., 896 MPa (130 ksi) yield, 8% elongation

Ti 6Al - 2Sn - 4Zr - 2Mo BAR AND BILLET (DUPLEX ANNEALED)

Thickness or Diameter mm (inches)	Ultimate Tensile Strength MPa (ksi)	Yield Strength 0.2% Offset MPa (ksi)	Elongation in 4D%		Reduction in Area%	
			Long.	Trans.	Long.	Trans.
To 50.8 (2.00) incl.	896 (130)	827 (120)	10	10	25	20
Over 50.8 (2.00) to 101.6 (4.00) incl.②	896 (130)	827 (120)	10	8	20	20
Over 101.6 (4.00) ③	896 (130)	827 (120)	8	8	20	15

① Duplex or solution treatment plus stabilization treatment 954˚C (1750˚F) (or Beta Transus minus 28˚C (50˚F)) 1 Hr.; Air Cool plus 593˚C (1100˚F)/8Hrs.; Air Cool
② 103cm² (16 square inches) maximum
③ 206cm² (32 square inches) maximum

Data provided for informational purposes only. Not all products listed and/or heat treat conditions are offered by RMI.

Properties After Heat Treatment

Ti 6Al - 2Sn - 2Zr - 2Mo - 2Cr - 0.15Si (ALPHA - BETA PROCESSED + STA CONDITION)

Product	Ultimate Tensile Strength MPa (ksi)	Yield Strength MPa (ksi)	Elongation %	Reduction in Area %	K_{IC} (ksi $\sqrt{in.}$) MPa$\sqrt{m}$
Sheet	1331 (193)	1193 (173)	7.5	—	—
Plate	1207 (175)	1131 (164)	12.0	35	67.0 (61)
Billet	1207 (175)	1089 (158)	14.0	30	71.5 (65)

Ti 6Al - 2Sn - 2Zr - 2Mo - 2Cr - 0.15Si (BETA PROCESSED + STA CONDITION)

Product	Ultimate Tensile Strength MPa (ksi)	Yield Strength MPa (ksi)	Elongation %	Reduction in Area %	K_{IC} (ksi $\sqrt{in.}$) MPa$\sqrt{m}$
50.8mm (2 in.) Plate	1158 (168)	1020 (148)	10	16	84.6 (77)
101.6mm (4 in.) Plate	1103 (160)	979 (142)	10	14	89.1 (81)
152.4mm (6 in.) Billet	1131 (164)	1014 (147)	9	13	97.9 (89)

Ti 3Al - 8V - 6Cr - 4Mo - 4Zr PRODUCT PROPERTIES (STA CONDITION)

Heat-Treat Cycle: 816-927˚C (1500-1700˚F)/1Hr.; Air or Water Quench, plus 427-538˚C (800-1000˚F)/8 Hrs. minimum; Air Cool

Product	Thickness as Heat-Treated mm (inches)	Minimum Tensile Properties					
		Ultimate Strength MPa (ksi)	Yield Strength 0.2% Offset MPa (ksi)	Elongation in 50.8mm (2 in.) (%)		Reduction in area (%)	
				Long.	Tran.	Long.	Tran.
Sheet ①	Up to 4.8 (0.1875) excl.	1241 (180)	1172 (170)	6	6	—	—
Plate	4.8 (0.1875) to 50.8 (2) incl. Over 50.8 (2) to 101.6 (4) incl.	1241 (180) 1241 (180)	1172 (170) 1172 (170)	8 8	8 6	— —	— —
Bar and Billet	12.7 (.5) to 38.1 (1.5) incl. Over 38.1 (1.5) to 76.2 (3) incl. Over 76.2 (3) to 152.4 (6) incl. Over 76.2 (3) to 228.6 (9) incl.*	1310 (190) 1241 (180) 1172 (170) 1241 (180)	1241 (180) 1172 (170) 1103 (160) 1172 (170)	8 8 6 10	— 6 3 10	15 15 15 20	— 15 5 20

*Test forged samples 3:1 minimum upset.

① Higher strength levels with reduced ductility may be achievable using solution treat and cold work + age processing.

Ti 3Al - 8V - 6Cr - 4Mo - 4Zr WIRE PROPERTIES (VARIOUS CONDITIONS)

Size mm (inches)	Condition	Typical Room Temperature Tensile Properties				
		Ultimate Strength MPa (ksi)	Yield Strength 2% Offset MPa (ksi)	Elongation in 50.8mm (2 in.) (%)	Reduction in Area (%)	Double Shear MPa (ksi)
7.9 (0.312)	Solution Annealed - 816˚C (1500˚F)/15 Min.; Air Cool S.A. + Age 427˚C (800˚F)/6 Hrs.; Air Cool S.A. + Age 482˚C (900˚F)/6 Hrs.; Air Cool	 896 (130) 1503 (218) 1448 (210)	 876 (127) 1413 (205) 1289 (187)	 16.0 8.0 6.7	 49.0 17.0 20.0	 634 (92) 862 (125) 848 (123)
12.7 (0.500)	① S.A. + 30% Cold Drawn + Age 482˚C (900˚F)/6 Hrs.; Air Cool	1641 (238)	1532 (222)	5.0	6.0	834 (121)
12.7 (0.500)	S.A. + 30% Cold Drawn + Age 510˚C (950˚F)/6 Hrs.; Air Cool	1572 (228)	1448 (210)	5.0	6.0	862 (125)
12.7 (0.500)	S.A. + 30% Cold Drawn + Age 538˚C (1000˚F)/4 Hrs.; Air Cool	1386 (201)	1276 (185)	10.0	24.0	834 (121)
7.6 (0.300)	S.A. + 39% Cold Drawn + Age 482˚C (900˚F)/6 Hrs.; Air Cool	1606 (233)	1510 (219)	8.0	15.0	952 (138)
6.0 (0.238)	S.A. + 59% Cold Drawn + Age 482˚C (900˚F)/6 Hrs.; Air Cool	1675 (243)	1613 (234)	7.0	21.0	924 (134)

① S.A. - Solution Anneal - 816˚C (1500˚F)/15 Min.; Air Cool

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Properties After Heat Treatment

TITANIUM ALLOY SP-700 15mm PLATE

Heat Treatment		0.2%YS MPa (ksi)	UTS MPa (ksi)	El (%)	RA (%)
Mill Anneal	720˚C (1328˚F)/1 hr./A.C.	972 (141)	1023 (148)	19.0	61.9
Recry. Anneal	800˚C (1470˚F)/1 hr/A.C.	917 (133)	966 (140)	20.8	61.6
STA	850˚C (1560˚F)/1 hr/A.C. +510˚C (950˚F)/6 hr/A.C.	1114 (162)	1213 (176)	14.4	39.6
STA	850˚C (1560˚F)/1 hr/W.Q +560˚C (1040˚F)/6 hr/A.C.	1240 (180)	1377 (200)	11.6	28.0

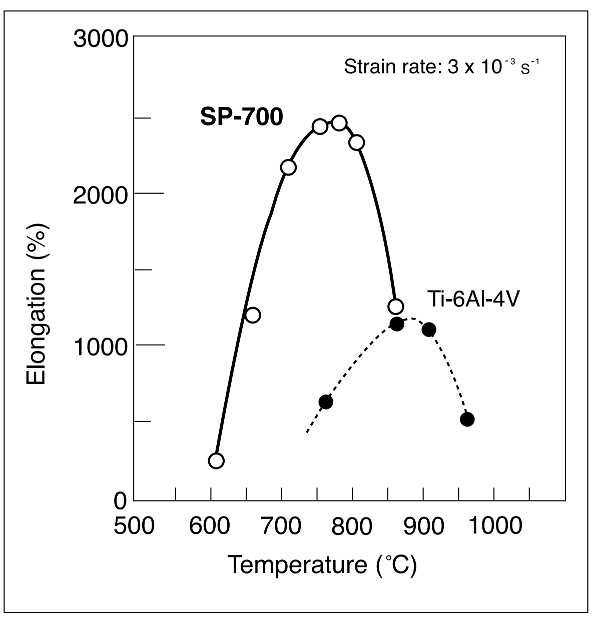
TITANIUM ALLOY SP-700 SHEET (MILL ANNEALED CONDITION)

Thickness mm (inches)	Direction	0.2%YS MPa (ksi)	UTS MPa (ksi)	El (%)	Bend Factor (R/t)
0.8 (0.031)	L	1005 (146)	1063 (154)	11.0	—
	T	1023 (148)	1073 (156)	10.2	—
2.0 (0.078)	L	920 (133)	978 (142)	14.8	<2.5
	T	945 (137)	983 (143)	13.6	<2.5
3.0 (0.118)	L	951 (138)	1010 (146)	16.0	<2.5
	T	939 (136)	1010 (146)	14.0	<2.5
3.8 (0.150)	L	949 (138)	1025 (149)	22.8	2.3
	T	929 (135)	1015 (147)	21.0	1.8

TITANIUM ALLOY SP-700 BAR (MILL ANNEALED CONDITION)

Diameter mm (in.)	0.2% YS MPa (ksi)	UTS MPa (ksi)	El (%)
13 (0.51)	1006 (146)	1048 (152)	19
21 (0.83)	956 (139)	1025 (149)	25

Superplastic Formability of SP-700



Mill-annealed 13.5mm dia. round bar

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RMI SERVICE

RMI Company offers a complete range of titanium and titanium alloy mill products in sheet, strip, plate, billet, bar, rod, extrusions and tubulars. In addition, other subsidiaries under the RTI International Metals corporate umbrella manufacture and distribute titanium and specialty metal mill products and extruded shapes, as well as engineered systems for energy-related applications. RTI's global fabrication and distribution service centers also offer metal processing services including hot-forming (e.g. superplastic forming), extrusion, seamless pipe production, water jet and saw cutting, and machining.

A strong Technology Department, including R & D and Process Control and Metallurgy is a key part of the RMI organization. These technologists are available to assist fabricators, designers and end-users in the application and selection of titanium grades, provide metallurgical consultation, and to advise on forging, welding, machining and other fabricating procedures. This team is backed by the most modern and extensive production and mill fabricating facilities available anywhere.

That's what is meant by "RMI Service" … quality in every step of manufacture and satisfaction in every transaction. Here are some of the steps taken at RMI to assure this kind of performance.

Fabrication Control

Control mechanisms in the fabrication stages, as in earlier process stages, are centered around the use of standardized process procedures. Control parameters are fixed for all operations and in-process tests are taken to verify product quality. Final verification testing and inspection is geared in a large degree to the specific customer specification.

Testing and Inspection

In addition to the chemical analysis and mechanical property requirements specified by our customers, other tests are conducted as required or specified to further ensure the quality of our products as follows:

1. Ultrasonic Inspection - conventional and multizone
2. Eddy Current Inspection
3. Macro Etch Examination
4. Microstructure Examination
5. Dye Penetrant
6. Surface Roughness

For specialized material evaluation, RMI can provide scanning electronic microscopy, EDAX micro-chemical analysis, texture analysis, formability and corrosion testing.

ISO APPROVALS

ISO 9002

NATIONAL ACCREDITATION OF CERTIFICATION BODIES

EN29002/ISO 9002/BS 5750
APPROVED BY BVQI

AS9000

NADCAP - Sonic

NADCAP - Laboratory

REFERENCES

For Corrosion Data/Application Guidelines:

- R. W. Schutz and D. E. Thomas, "Corrosion of Titanium and Titanium Alloys", *Metals Handbook-Ninth Edition*, Vol. 13-Corrosion, ASM, Materials Park, OH, 1987, pp. 669-706.
- R. W. Schutz, "Titanium", *Process Industries Corrosion - The Theory and Practice*, National Association of Corrosion Engineers, Houston, TX, 1986, pp. 503-527.
- *Stress-Corrosion Cracking - Materials Performance and Evaluation*, ASM, Materials Park, OH, July 1992, pp. 265-297.

For Corrosion Testing Guidelines:

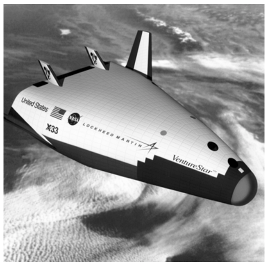
- R. W. Schutz, "Titanium" (Chapter 52), *Corrosion Tests and Standards: Application and Interpretation*, ASTM Manual Series: MNL 20, ASTM, Philadelphia, PA, 1995, pp. 493-506.

For Metallurgy/Mechanical Properties:

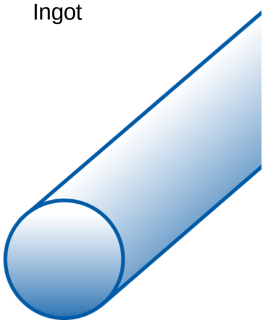
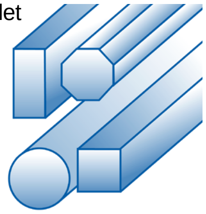
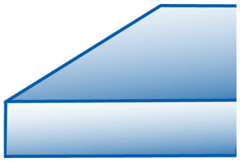
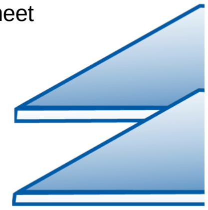
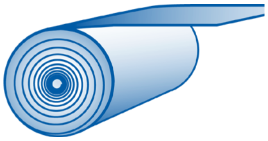
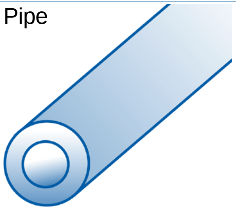
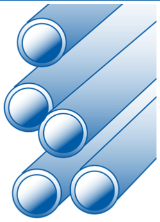
- *RMI Metallography Brochure*, RMI Titanium Co., Niles, OH
- *RMI 6Al-4V Brochure*, RMI Titanium Co., Niles, OH
- *Materials Properties Handbook Titanium Alloys*, ASM International Materials Park, OH, 1994.
- *Metals Handbook*, Volume 2, Tenth Edition Properties and Selection: Non-Ferrous Alloys and Special Purpose Materials, ASM International Materials Park, OH, 1990, pp. 592-660.
- *Titanium – A Technical Guide*, Edited by M.J. Donachie, Jr. ASM International Materials Park, OH, 1988.
- *Titanium and Its Alloys*, Home Study and Extension Course, ASM International, Materials Engineering Institute, Materials Park, OH, 1994. (Developed in cooperation with Titanium Development Association.)
- *Titanium and Titanium Alloys – Source Book* ASM International Materials Park, OH, 1982.

For Fabrication Guidelines:

- *Machining Data Handbook*, Third Edition, Volumes 1 & 2, Machinability Data Center, Metcut Research Associates, Inc., Cincinnati, OH, 1980.
- *Metals Handbook*, Ninth Edition, Volume 14, Forming and Forging, ASM International, Metals Park, OH, 1988, pp. 838-848.
- *Welding Handbook*, Eighth Edition, Volume 4, Materials and Applications, *Part 2*, American Welding Society, Miami, FL, 1988, pp. 487-540.
- *RMI Machining Brochure*, RMI Titanium Co., Niles, OH
- *RMI Welding Brochure*, RMI Titanium Co., Niles, OH



RMI TITANIUM COMPANY: TITANIUM ALLOY MILL PRODUCT CAPABILITIES

Product Form	Type	Alloy Grades	Sizes Offered	
			English Units	Metric Units
Ingot 	VAR-Double Melted	Most aero alloys and unalloyed C.P. alloys	30" Ø (10,000 lbs)	76.2 cm Ø (4545 kg)
			36" Ø (14,000 lbs)	91.4 cm Ø (6364 kg)
			36" Ø (21,000 lbs)	91.4 cm Ø (9545 kg)
	VAR-Triple Melted	Most high-strength aero alloys for critical rotating components	30" Ø (10,000 lbs)	76.2 cmØ (4545 kg)
			36" Ø (14,000 lbs)	91.4 cm Ø (6364 kg)
			36" Ø (21,000 lbs)	91.4 cm Ø (9545 kg)
			42" Ø (21,000 lbs)	106.7 cm Ø (9545 kg)
Billet 	Rounds	All	4.0-28.75" Ø	10.2-73 cm Ø
	Squares	All	≥3"	≥76 mm
	Rectangles + Slabs	All	3-14" thick, 4-84" width	76-356 mm thick, 10.2-213 cm width
	Octagons	All	6-14" (across flats)	152-356 mm (across flats)
Plate 	Alloy (Aircraft Quality)	Most high-strength aero alloys	0.188-4.0" thick, ≤60" width, ≤240" length (for ≤2.25" thick), ≤200" length (for >2.25" thick)	4.78-102 mm thick, ≤152 cm width, ≤610 cm length
	C.P. (Industrial Quality)	All unalloyed and modified C.P. grades, Ti-3Al-2.5V-based alloys	0.188-4.0" thick, ≤96" width, ≤300" length	4.78-121 mm thick, ≤244 cm width, ≤762 cm length
Sheet 	Alloy (Aircraft Quality)	Most high-strength alloys	0.016-0.188" thick, ≤60" width, ≤350" length	0.40-4.78 mm thick, ≤152 cm width, ≤889 cm length
Strip 	Aircraft Quality	1, 2, 3, 4, 9	0.020-0.075" thick, 24-48" width, ≤240" length	0.51-1.91 mm thick, 61-122 cm width, ≤610 cm length
	Industrial Quality	1, 2, 3, 4, 7, 9, 11, 12, 16, 17, 18, 26, 27, 28	0.020-0.188" thick, 24-48" width, ≤240" length	0.51-4.78 mm thick 61-122 cm width, ≤610 cm length
Pipe 	Seamless	All unalloyed and modified C.P. grades, and most high-strength alloys	1.9-36" OD, 0.25-1.5" wall	4.83-91.5 cm OD, 6.4-38 mm wall
	Seam-Welded	1, 2, 3, 7, 9, 11, 12, 16, 17, 18, 26, 27, 28	0.75-8" OD, ≤252" length Sch. 5-40	19-203 mm OD, ≤640 cm length Sch. 5-40
Tubing 	Seam-Welded		0.50-2.375" OD, ≤720" length, Sch. 5-40	12.7-60.3 mm OD, ≤1829 cm length, Sch. 5-40

Capability list includes most common mill products. Contact RMI Titanium Sales for any other product, size, alloy grade or shape not listed.

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