ALLOY Data

Titanium Alloy Ti 6Al-4V

Type Analysis

Carbon (Maximum)	0.10 %	**Titanium**	Balance
Aluminum	5.50 to 6.75 %	**Vanadium**	3.50 to 4.50 %
Nitrogen	0.05 %	**Iron (Maximum)**	0.40 %
Oxygen (Maximum)	0.020 %	**Hydrogen (Maximum)**	0.015 %
Other, Total (Maximum)	0.40 %		

* Other, Each (Maximum) = 0.1%
** For AMS 4928 (Bar, Billet, Forgings) Hydrogen = 0.0125% and Iron = 0.3%

General Information

Description

Pure titanium undergoes an allotropic transformation from the hexagonal close-packed alpha phase to the body-centered cubic beta phase at a temperature of 882.5°C (1620.5°F). Alloying elements can act to stabilize either the alpha or beta phase. Through the use of alloying additions, the beta phase can be sufficiently stabilized to coexist with alpha at room temperature. This fact forms the basis for creation of titanium alloys that can be strengthened by heat treating.

Titanium alloys are generally classified into three main categories: Alpha alloys, which contain neutral alloying elements (such as Sn) and/or alpha stabilizers (such as Al, O) only and are not heat treatable; Alpha + beta alloys, which generally contain a combination of alpha and beta stabilizers and are heat treatable to various degrees; and Beta alloys, which are metastable and contain sufficient beta stabilizers (such as Mo, V) to completely retain the beta phase upon quenching, and can be solution treated and aged to achieve significant increases in strength.

Ti 6Al-4V is known as the "workhorse" of the titanium industry because it is by far the most common Ti alloy, accounting for more than 50% of total titanium usage. It is an alpha+beta alloy that is heat treatable to achieve moderate increases in strength.

Ti 6Al-4V is recommended for use at service temperatures up to approximately 350°C (660°F).

Ti 6Al-4V offers a combination of high strength, light weight, formability and corrosion resistance which have made it a world standard in aerospace applications.

Applications

Ti 6Al-4V may be considered in any application where a combination of high strength at low to moderate temperatures, light weight and excellent corrosion resistance are required. Some of the many applications where this alloy has been used include aircraft turbine engine components, aircraft structural components, aerospace fasteners, high-performance automotive parts, marine applications, medical devices, and sports equipment.

Corrosion Resistance

Ti 6Al-4V immediately and spontaneously forms a stable, continuous, tightly adherent oxide film upon exposure to oxygen in air or water. This accounts for its excellent corrosion resistance in a variety of media. Ti 6Al-4V is highly resistant to general corrosion in aqueous solutions including seawater, as well as in oxidizing acids, chlorides (in the presence of water), rocket propellants and alkalis. Conditions under which Ti 6Al-4V is susceptible to general corrosion are in the presence of reducing acids or dry chlorine gas.

Stress-corrosion cracking (SCC) and crevice corrosion have been shown to occur in environments containing chlorides or other halide ions. For this reason, it is general practice to avoid the use of chlorinated solvents, cutting fluids, etc., in processing titanium.

Titanium and its alloys, including Ti 6Al-4V, are susceptible to hydrogen embrittlement. Gaseous or cathodic hydrogen can diffuse into the metal, forming brittle hydrides. Thus, it is important to minimize hydrogen pickup during processing, particularly heat treating and acid pickling. Specifications for Ti 6Al-4V mill products typically specify a maximum hydrogen limit of about 150 ppm.

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Important Note: *The following 5-level rating scale is intended for comparative purposes only. Corrosion testing is recommended; factors which affect corrosion resistance include temperature, concentration, pH, impurities, aeration, velocity, crevices, deposits, metallurgical condition, stress, surface finish and dissimilar metal contact.*

Sulfuric Acid	Moderate	Acetic Acid	Excellent
Sodium Hydroxide	Moderate	Salt Spray (NaCl)	Excellent
Sea Water	Excellent	Humidity	Excellent

Ti 6Al-4V: General Corrosion Rates in Various Media

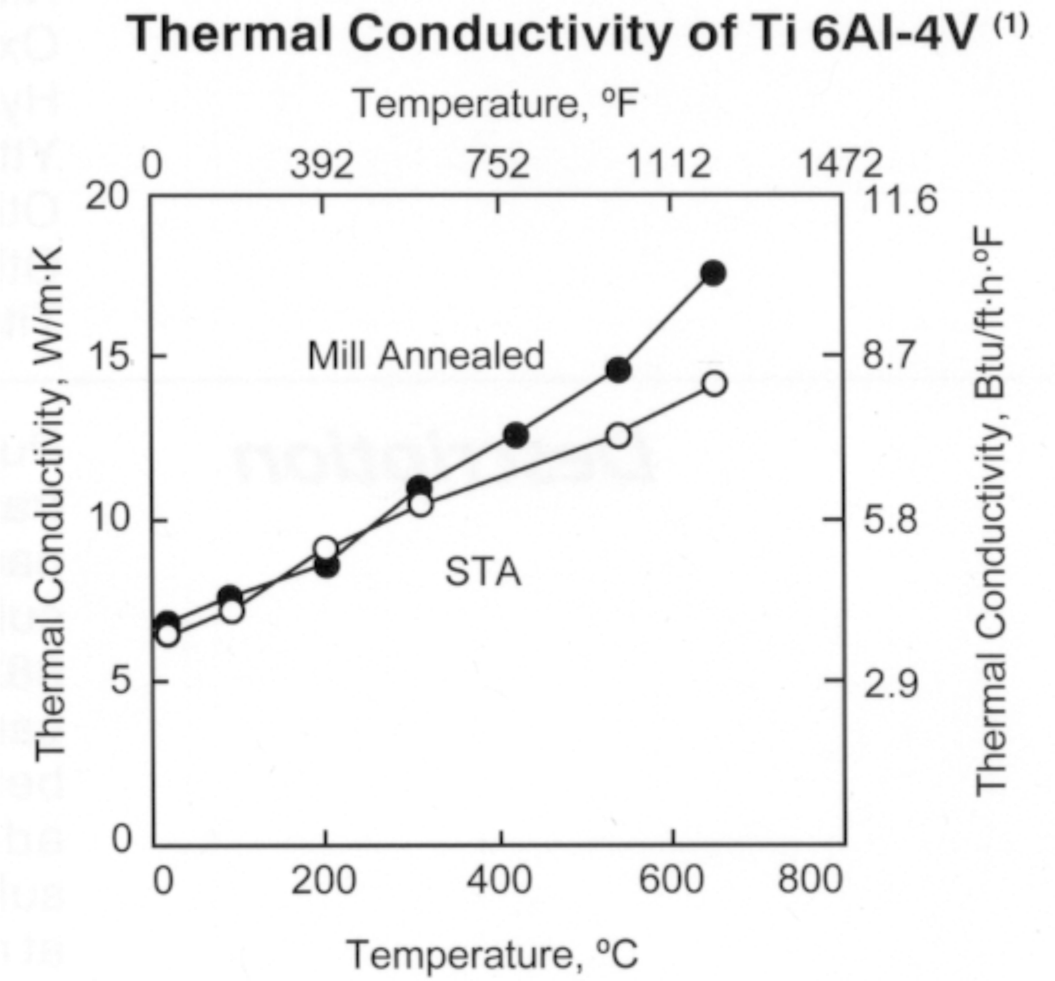
Medium	Concentration %	Temperature		Corrosion Rate	
		°C	°F	mm/yr	mils/yr
Sea Water	n/a	room	room	nil	nil
Hydrochloric Acid	2	37.8	100	nil - .030	nil - 1.2
Hydrochloric Acid	10	37.8	100	0.508 - 1.02	20.0 - 40.0
Hydrochloric Acid + 5% CrO_3	10	65.6	150	nil - 0.005	nil - 0.2
Hydrochloric Acid	vapors	37.8	100	8.33 - 1.04	328 - 408
Nitric Acid	65	boiling	boiling	0.076 - 0.13	3.0 - 5.0
Sulfuric Acid	2	37.8	100	0.396 - 0.549	15.6 - 21.6
Sodium Hydroxide	25	boiling	boiling	0.046 - 0.051	1.8 - 2.0

Properties

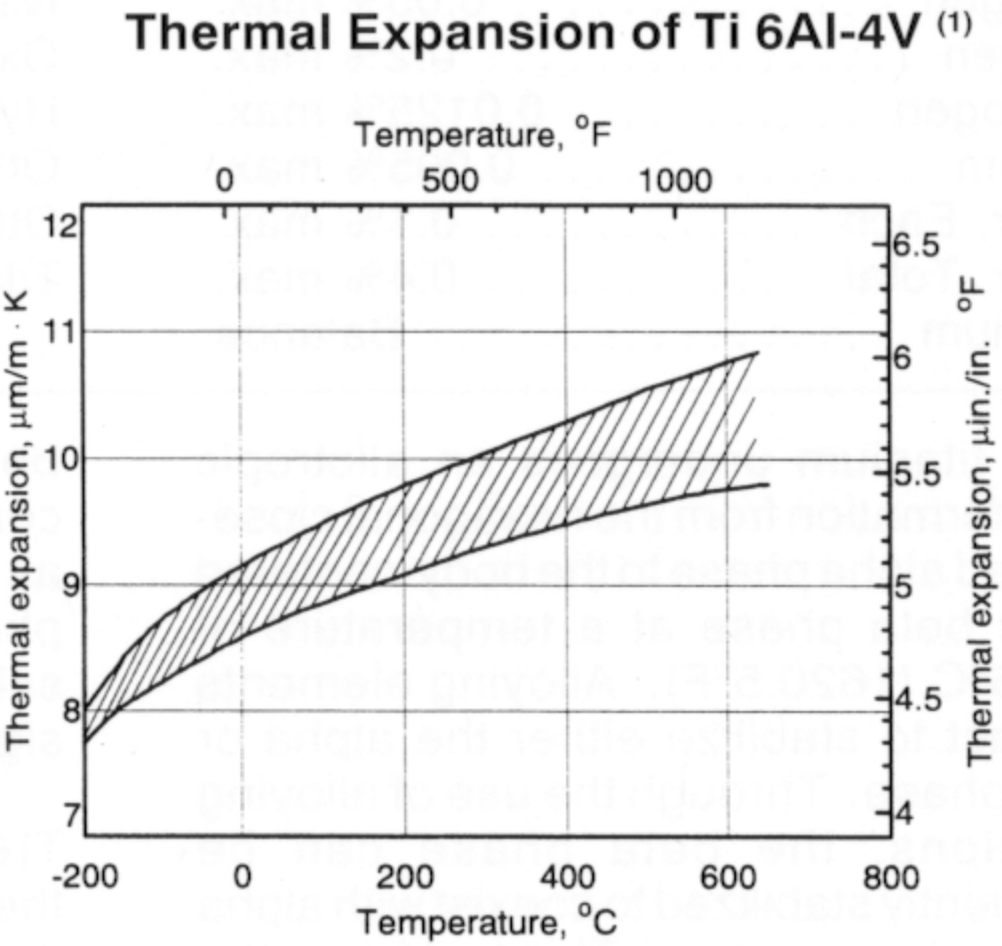
Physical Properties

Specific Gravity

--	0.160



Modulus of Elasticity (E)		
--	15.2	x 10 ^{3} ksi
Beta Transus		
--	1800 to 1850	°F
Liquidus Temperature		
--	2976 to 3046	°F
Solidus Temperature		
--	2900 to 2940	°F
Electrical Resistivity		
-418 °F	902.5	ohm-cir-mil/ft
73.4 °F	1053	ohm-cir-mil/ft
986 °F	1143	ohm-cir-mil/ft



Magnetic Properties

Magnetic Attraction

• None

Typical Mechanical Properties

Typical Room-Temperature Strengths for Annealed Ti 6Al-4V:
Ultimate Bearing Strength 1380-2070 MPa (200-300 ksi)
Compressive Yield Strength 825-895 MPa (120-130 ksi)
Ultimate Shear Strength 480-690 MPa (70-100 ksi)

Fatigue Limits:
High-cycle fatigue limits for Ti 6Al-4V are greatly influenced by both microstructure and surface conditions. Some generalize fatigue limits for annealed wrought material are provided below.

Fatigue Limit Ranges for Ti 6Al-4V (Axial Fatigue, R = 0.06 to 0.1)
Smooth 400-700 MPa (60-100 ksi)
Notched (KT = 3) 140-270 MPa (20-40 ksi)

Fracture Toughness:
The fracture toughness (KIc) of Ti 6Al-4V lies between that of aluminum alloys and steels. Microstructures that tend to have higher toughness are those with greater amounts of lamellar alpha/beta and coarser structures in general. The ELI grade of Ti 6Al-4V exhibits toughness superior to the standard grade.

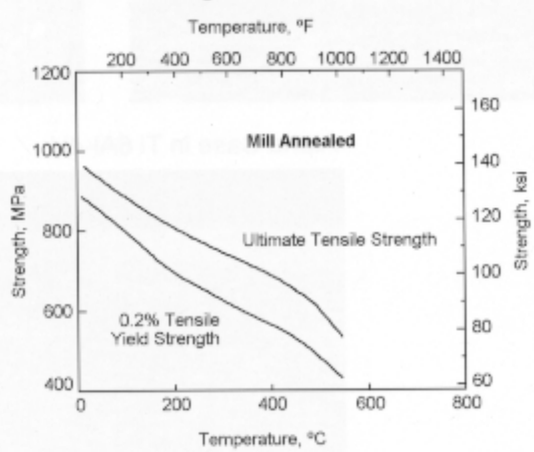
Room Temperature Mechanical Properties

Condition	UTS	YS	%El	%RA
Minimum Specified Tensile Properties				
Annealed	896 MPa (130 ksi)	827 MPa (120 ksi)	10	25
STA (depending on diameter)	1035–1135 MPa (150–165 ksi)	965–1070 MPa (140–155 ksi)	10	20
Typical Tensile Properties				
Annealed	965–1090 MPa (140–158 ksi)	875–995 MPa (127–144 ksi)	16	46
STA (depending on diameter)	1100–1220 MPa (160–177 ksi)	1035–1130 MPa (150–164 ksi)	15	52

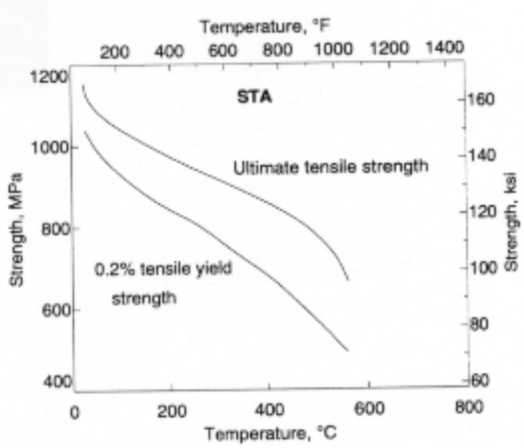
One reason that Ti 6Al-4V has found such widespread use is its relatively high strength for a lightweight material. Specific strength (strength/density) provides a means to compare materials on this basis.

Material	UTS		Specific Strength	
	MPa	ksi	m x 10^3	in x 10^6
Ti 6Al-4V STA	1172	170	27.0	1063
Ti 6Al-4V Annealed	924	134	21.3	838
4130 Steel	1379	200	17.9	707
7075-T6 Aluminum	538	78	19.6	772
2024 T3 Aluminum	441	64	16.1	634
Inconel 718	1276	185	15.3	603

Tensile Strengths - Mill Annealed [1]



Tensile Strengths - STA [1]



Heat Treatment

Ti 6Al-4V wrought products are typically used in either a mill annealed or solution treated and aged condition. Rapid quenching following solution treatment (water quench or equivalent) is important in order to maximize the formation of alpha' martensite phase, which in turn maximizes the aging response. Other heat treatments used on Ti 6Al-4V include stress relieving for formed or welded parts, and beta annealing, which is used for improving damage tolerance.

Ti 6Al-4V, like other titanium alloys, has a high affinity for gases including oxygen, nitrogen and hydrogen. Absorption of oxygen results in the formation of an extremely hard, brittle oxygen-stablized alpha phase layer known as alpha case upon heating in air.

Intermediate and final annealing of Ti 6Al-4V mill products is often performed in a vacuum or inert gas atmosphere to avoid alpha case formation and the associated material loss. Vacuum annealing can also be used to remove excess hydrogen pickup, a process known as vacuum degassing. Parts to be vacuum heat treated must be thoroughly cleaned (see Descaling (Cleaning) Notes).

Heat Treatment

Mill Anneal	705-790ºC (1300-1450ºF) 1-4 hours - air cool (or equivalent)
Solution Treat + Age (STA)	940-970ºC (1725-1775ºF) 10 min. - water quench (or equiv.) plus 480-595ºC (900-1100ºF) 2-8 hours - air cool (or equivalent)
Stress Relief	480-650ºC (900-1200ºF) 1-4 hours - air cool (or equivalent)
Beta Anneal	1035ºC (1900ºF) 30 min. - air cool plus 730ºC (1350ºF) 2 hours - air cool

Workability

Hot Working

Ti 6Al-4V can be hot worked by standard methods such as hot rolling, forging, and hot pressing. Typically, hot working is done high in the alpha/beta temperature range, at approximately 870-980º C (1600-1800ºF). Care must be taken to prevent the formation of excessive alpha case, and alpha case must be removed after processing. Hot forming of sheet is typically done at temperatures around 650ºC (1200ºF). Ti 6Al-4V has also been successfully processed by superplastic forming, using temperatures in the range of 850ºC (1560ºF).

"Warm" Working:
The yield strength of Ti 6Al-4V in both the annealed and STA conditions drops off rapidly with temperature, making it readily formable at intermediate temperatures. For example, heating to just 427°C (800°F) results in approximately a 40% reduction in yield strength. Warm forming is used extensively in the manufacture of many products, including fasteners, aircraft components, and medical devices.

Cold Working

Ti 6Al-4V can be cold drawn and extruded, although the cold workability is somewhat limited. Cold forming is sometimes used for parts such as brackets and clips. Due to the low modulus of titanium, springback is an issue in room-temperature forming. Theoretically, it can be compensated for by over-bending; however, in practice hot sizing is often used to correct for the variability that occurs.

Machinability

Using the rating system based on AISI B1112 steel, the machinability of Ti 6Al-4V is rated at 22% of B1112. In general, low cutting speeds, heavy feed rates and copious amounts of cutting fluid are recommended. Also, because of the strong tendency of titanium to gall and smear, feeding should never be stopped while the tool and work are in moving contact. Non-chlorinated cutting fluids should be used to eliminate the possibility of chloride contamination. It should be noted that titanium chips are highly combustible and appropriate safety precautions are necessary.

Following are typical feeds and speeds for Ti 6Al-4V.

Typical Machining Speeds and Feeds – Titanium Alloy Ti-6Al-4V

The speeds and feeds in the following charts are conservative recommendations for initial setup. Higher speeds and feeds may be attainable depending on machining environment.

Turning—Single-point and Box Tools

Depth of Cut (Inches)	High Speed Tools			Carbide Tools (Inserts)				
	Tool Material	Speed (fpm)	Feed (ipr)	Tool Material	Speed (fpm) Brazed	Speed (fpm) Throw Away	Speed (fpm) Coated	Feed (ipr)
			Annealed					
.150		60	.010	C2	145	195	-	.008
.025	T15, M42	70	.005	C3	170	225	-	.005
			Aged					
.150		55	.010	C2	135	165	-	.008
.025	T15, M42	65	.005	C3	160	190	-	.005

Turning—Cut-Off and Form Tools

Tool Material		Speed (fpm)	Feed (ipr)						
High Speed Tools	Carbide Tools		Cut-Off Tool Width (Inches) 1/16	1/8	1/4	Form Tool Width (Inches) 1/2	1	1 ½	2
					Annealed				
T15, M42		55	.001	.0015	.002	.0025	.0015	.001	.001
	C2	110	.001	.0015	.002	.0025	.0015	.001	.001
					Aged				
T15, M42		40	.001	.0015	.002	.002	.0015	.001	.001
	C2	85	.001	.0015	.002	.002	.0015	.001	.001

Rough Reaming

High Speed Tool Material	High Speed Speed (fpm)	Carbide Tools Tool Material	Carbide Tools Speed (fpm)	Feed (ipr) Reamer Diameter (inches) 1/8	1/4	1/2	1	1 ½	2
				Annealed					
T15, M42	65	C2	200	.003	.006	.010	.012	.014	.016
				Aged					
T15, M42	30	C2	160	.003	.007	.010	.012	.014	.016

Drilling

Tool Material	Speed (fpm)	High Speed Tools – Feed (inches per revolution) Nominal Hole Diameter (inches)							
		1/16	1/8	1/4	1/2	3/4	1	1 ½	2
Annealed									
T15, M42	35	-	.002	.004	.006	.007	.008	.010	.012
Aged									
T15, M42	30	-	.002	.003	.005	.006	.007	.009	.010

Die Threading

Tool Material	FPM for High Speed Tools			
	7 or less, tpi	8 to 15, tpi	16 to 24, tpi	25 and up, tpi
Annealed				
M1, M2, M7, M10	5 – 20	9 – 25	10 – 30	15 – 40
Aged				
M1, M2, M7, M10	5 – 20	9 – 25	10 – 30	15 – 40

Milling, End-Peripheral

Depth of Cut (inches)	High Speed Tools						Carbide Tools					
	Tool Material	Speed (fpm)	Feed (ipt) Cutter Diameter (in)				Tool Material	Speed (fpm)	Feed (ipt) Cutter Diameter (in)			
			1/4	1/2	3/4	1-2			1/4	1/2	3/4	1-2
Annealed												
.050	T15	90	.002	.003	.005	.006	C2	260	.002	3	.006	.008
Aged												
.050	T15	75	.002	.003	.004	.006	C2	200	.002	.003	.006	.008

Tapping

High Speed Tools	
Tool Material	Speed (fpm)
Annealed	
M1, M7, M10 Nitrided	7 - 20
Aged	
M1, M7, M10 Nitrided	3 - 10

Broaching

High Speed Tools		
Tool Material	Speed (fpm)	Chip Load (ipt)
Annealed		
T15, M42	8	.003
Aged		
T15, M42	5	.002

When using carbide tools, surface speed feet/minute (SFPM) can be increased between 2 and 3 times over the high-speed suggestions. Feeds can be increased between 50 and 100%.

Figures used for all metal removal operations covered are average. On certain work, the nature of the part may require adjustment of speeds and feeds. Each job has to be developed for best production results with optimum tool life. Speeds or feeds should be increased or decreased in small steps.

Typical Minimum Stock Removal Requirements for Ti Alloys (after Thermal Exposure in Air)

Heat Treatment	Thermal Cycle	Removal Required
Mill Anneal	760ºC (1400ºF) 2 hrs.	.038 mm (.0015 in.)
Solution Treat + Age (STA)	954ºC (1750ºF) 10 min. + 480ºC (900ºF) 4 hrs	.107 mm (0.0042 in.)

Weldability

Ti 6Al-4V can be welded using Ti 6Al-4V filler metal. Inert gas shielding techniques must be employed to prevent oxygen pickup and embrittlement in the weld area. Gas tungsten arc welding is the most common welding process for Ti 6Al-4V. Gas metal arc welding is used for thick sections. Plasma arc welding, spot welding, electron beam, laser beam, resistance welding and diffusion welding have all been used successfully in Ti 6Al-4V welding applications.

Other Information

Wear Resistance

Ti 6Al-4V, and Ti alloys in general, have a tendency to gall and are not recommended for wear applications.

Descaling (Cleaning)

Following heat treatment in air, it is extremely important to completely remove not only the surface scale but the underlying layer of brittle alpha case as well. This removal can be accomplished by mechanical methods such as grinding or machining, or by descaling (using molten salt or abrasive) followed by pickling in a nitric/hydroflouric acid mixture.

Titanium alloys are also susceptible to hydrogen embrittlement, and care must be taken to avoid excessive hydrogen pickup during heat treating and pickling/chemical milling.

Final heat treatments on finished parts must be performed in a vacuum if machining or pickling is to be avoided.

The cleanliness of parts to be vacuum heat treated is of prime importance. Oils, fingerprints, or residues remaining on the surface can result in the formation of alpha case even in the vacuum atmosphere. In addition, chlorides found in some cleaning agents have been associated with SCC of titanium. Thus, parts to be vacuum heat treated should be processed as follows: thorough cleaning using a non-chlorinated solvent or aqueous cleaning solution, followed by rinsing with copious quantities of deionized or distilled (not regular tap) water to remove all traces of cleaning agent, and finally drying. Following cleaning, parts must be handled with clean gloves to prevent recontamination of the surface.

Applicable Specifications

- A5.16 (ERTi-5) (Weld Wire)
- AMS 4911 (Sheet, Strip, Plate)
- AMS 4920 (Forgings)
- AMS 4928 (Bar, Wire, Forgings, Ring, Annealed)
- AMS 4963 (Bar, Wire, Forgings, Ring, Heat Treatable)
- AMS 4965 (Bar, Wire, Forgings, Ring, STA)
- AMS 4967 (Bar, Wire, Forgings, Ring, STA)
- ASTM B348 (Bar, Billet)
- ASTM B367 (Castings)
- ASTM F1472 (All Forms, Annealed)
- ISO 5832-3

Forms Manufactured

*SMART Coil is a registered trademark of Dynamet Holdings, Inc. licensed to Dynamet Incorporated.

- Bar-Rounds
- Bar-Shapes
- Dynalube Coil
- Ingot
- Plate
- Powder
- Sheet
- SMART Coil® Titanium Coil
- Weld Wire
- Wire
- Wire-Shapes

References

The information in this publication was compiled from a variety of sources, including the following:

Materials Properties Handbook: Titanium Alloys, ASM International, 1994
Aerospace Structural Metals Handbook, Volume 4, CINDAS/Purdue University, 1998
Titanium: a Technical Guide, ASM International, 1988
Metals Handbook, Desk Edition, ASM International, 1984
Specifications Book, International Titanium Association, 1999
Metcut Research Associates Inc. data
Dynamet technical papers and unpublished data

Technical Articles

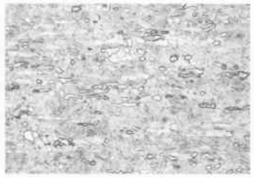
- Aerospace Alloy Has Been A Huge Success in Golf Club Design
- An Evaluation of Alloys for Golf Club Face Plates
- New Requirements for Ferrous-Base Aerospace Alloys
- Selection of High Strength Stainless Steels for Aerospace, Military and Other Critical Applications
- Specialty Alloys And Titanium Shapes To Consider For Latest Medical Materials Requirements

Ti 6Al-4V specimens can be prepared for metallographic examination by standard methods. Abrasive cutting, especially of small samples, is not recommended due to the tendency to burn the surface and produce alpha case. Kroll's reagent (1–3% hydroflouric acid plus 2–6% nitric acid in water) is commonly used for determination of general microstructure. For detection of alpha case, Kroll's etch is followed by an ammonium biflouride solution which stains the entire sample with the exception of any alpha case. Some typical microstructures are illustrated below.

Microstructures of Ti 6Al-4V (approximate magnification 200X)

Ti 6Al-4V Mill Annealed Condition

Ti 6Al-4V STA Condition



Alpha Case in Ti 6Al-4V