Technical Datasheet

CARPENTER

Titanium Alloy Ti 6Al-4V ELI

Type Analysis

Single figures are nominal except where noted.

Carbon (Maximum)	0.08 %	**Titanium**	Balance
Aluminum	5.50 to 6.50 %	**Vanadium**	3.50 to 4.50 %
Nitrogen (Maximum)	0.05 %	**Iron (Maximum)**	0.25 %
Oxygen (Maximum)	0.130 %	**Hydrogen (Maximum)**	0.013 %
Other, Total (Maximum)	0.40 %		

* Other, Each (Maximum) = 0.1%

** For AMS 4930 rev. D, Hydrogen = 0.0125% and Yttrium = 0.005%

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 882.5ºC (1620.5ºF). 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 the 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 ELI is a higher-purity ("extra-low interstitial") version of Ti 6Al-4V, with lower specified limits on iron and the interstitial elements C and O. It is an alpha+beta alloy.

Ti 6Al-4V ELI has been the material of choice for many medical and dental applications due to its excellent biocompatibility. The ELI grade has superior damage tolerance (fracture toughness, fatigue crack growth rate) and better mechanical properties at cryogenic temperatures compared to standard grade Ti 6Al-4V.

Applications

Ti 6Al-4V ELI may be considered in any biomedical application, particularly for implantable components, because of its biocompatibility, good fatigue strength, and low modulus. It could also be considered for any application where a combination of high strength, light weight, good corrosion resistance, and high toughness are required, especially at cryogenic temperatures. Some typical applications where this alloy has been used successfully include joint replacements, bone fixation devices, surgical clips, and cryogenic vessels.

Corrosion Resistance

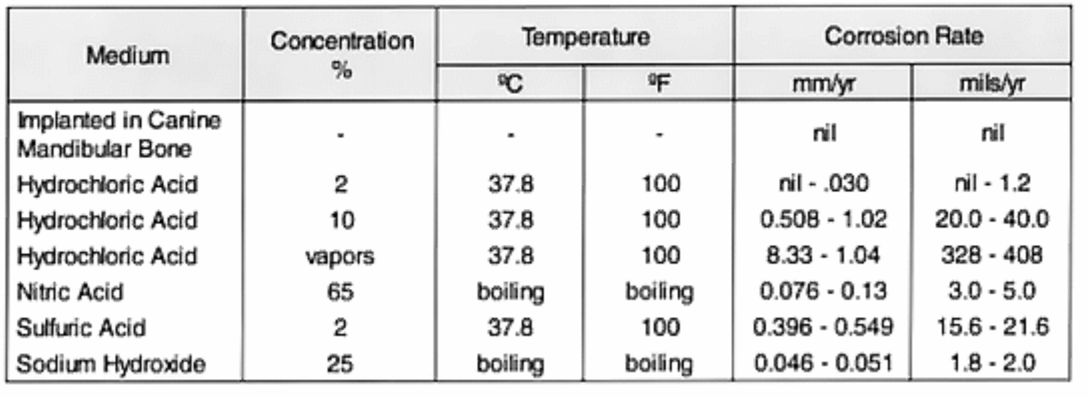
Ti 6Al-4V ELI spontaneously and immediately forms a stable, continuous, tightly adherent oxide film upon exposure to oxygen in air or water. This accounts for its excellent corrosion resistance in a variety of media. Ti 6Al-4V ELI is highly resistant to general corrosion in most aqueous solutions, as well as in oxidizing acids, chlorides (in the presence of water), and alkalis. Part of the reason for Ti 6Al-4V ELI's good biocompatibility is its corrosion resistance. Body fluids are basically chloride brines with a pH range from about 7.4 to acidic, other organic compounds-conditions under which Ti 6Al-4V ELI is highly immune to corrosion.

Stress-corrosion cracking (SCC) and crevice corrosion have been associated with exposure to halide ions at elevated temperatures; for this reason, it is general practice to avoid chlorinated solvents and chlorinated cutting fluids in processing titanium.

Titanium and its alloys, including Ti 6Al-4V ELI, are susceptible to hydrogen embrittlement. It is important to minimize hydrogen pickup during processing, particularly heat treating and acid pickling. Specifications for Ti 6Al-4V ELI (ASTM F 136) mill products typically specify a maximum hydrogen limit of 120 ppm.

Important Note:*The following 4-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



Medium	Concentration %	Temperature		Corrosion Rate	
		°C	°F	mm/yr	mils/yr
Implanted in Canine Mandibular Bone	-	-	-	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	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

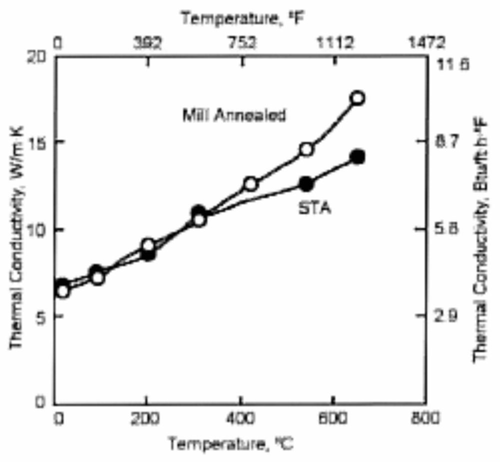
Properties

Physical Properties

One advantage of Ti 6Al-4V ELI over other materials in implantable devices such as joint replacements is its low elastic modulus, which is more similar to that of bone than other biocompatible materials. This is shown in the hyperlink entitled "Elastic Modulus of Some Material."

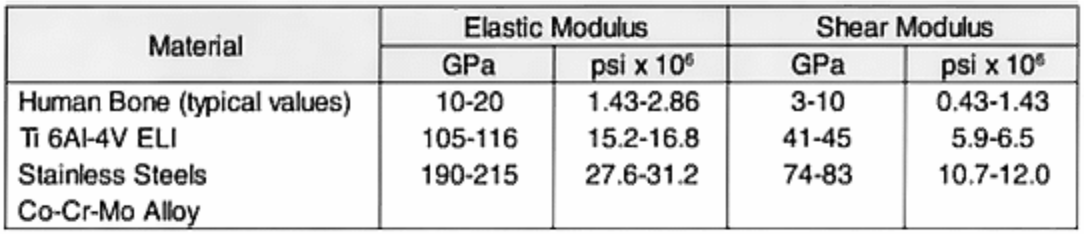
Density	0.1600	lb/in^3

Thermal Conductivity:



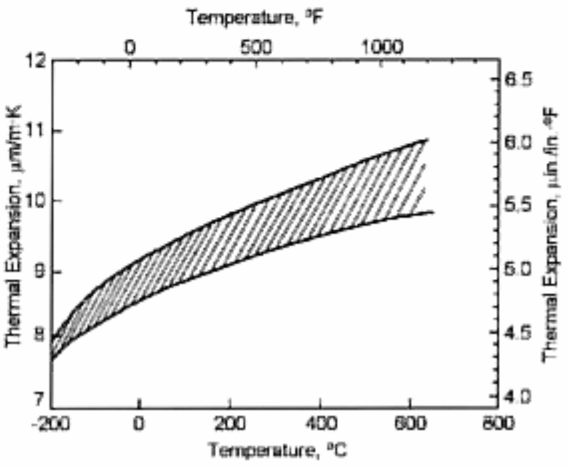
Modulus of Elasticity (E)	15.2	x 10^3 ksi
Modulus of Rigidity (G)	5.90	x 10^3 ksi
Beta Transus	1765 to 1815	°F
Liquidus Temperature	2976 to 3046	°F
Solidus Temperature	2900 to 2940	°F

Electrical Resistivity		
-418°F	782.2	ohm-cir-mil/ft
-112°F	902.5	ohm-cir-mil/ft
32°F	938.6	ohm-cir-mil/ft
73°F	1053	ohm-cir-mil/ft



Material	Elastic Modulus		Shear Modulus	
	GPa	psi x 10^6	GPa	psi x 10^6
Human Bone (typical values)	10-20	1.43-2.86	3-10	0.43-1.43
Ti 6Al-4V ELI	105-116	15.2-16.8	41-45	5.9-6.5
Stainless Steels	190-215	27.6-31.2	74-83	10.7-12.0
Co-Cr-Mo Alloy				

Thermal Expansion:



Magnetic Properties

Magnetic Attraction

- None

Typical Mechanical Properties

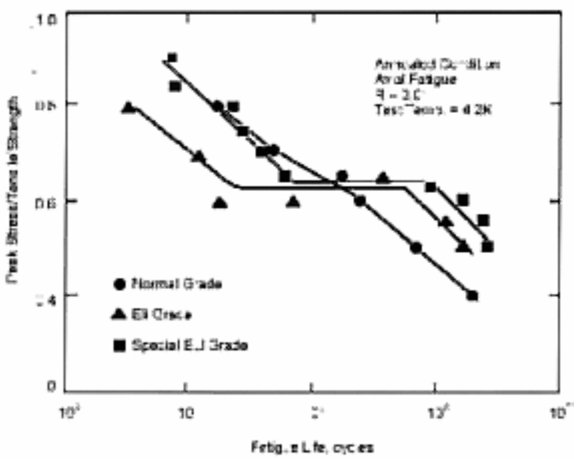
Typical Room-Temperature Strengths for Annealed Ti 6Al-4V ELI:
Ultimate Bearing Strength 1380-2070 MPa (200-300 ksi)
Compressive Yield Strength 825-895 MPa (120-130 ksi)
Ultimate Shear Strength 480-690 MPa (70-100 ksi)

Fatigue Limits:
High-cycle fatigue limits for Ti 6Al-4V ELI 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 ELI (Axial Fatigue, R = 0.06 to 0.1)
Smooth 400-700 MPa (60-100 ksi)
Notched (KT = 3) 140-270 MPa (20-40 ksi)

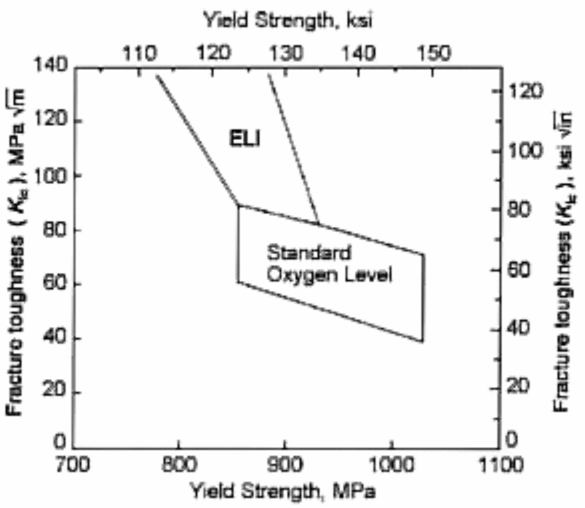
Fracture Toughness:
The fracture toughness (KIc) of Ti 6Al-4V ELI lies between that of aluminum alloys and steels. The ELI grade should be specified whenever toughness is a priority, as its toughness is superior to that of standard grade Ti 6Al-4V. Microstructures that tend to have higher toughness are those with greater amounts of lamellar alpha+beta and coarser structures in general, such as those obtained by beta annealing.

Fatigue Strength of Ti 6Al-4V ELI at Low Temperatures



Typical Room Temperature Mechanical Tensile Properties – Ti 6AL-4V ELI

Condition	Ultimate Tensile Strength		Yield Strength		% Elongation	% Reduction Of Area
	Ksi	MPa	Ksi	MPa		
Minimum Specified Tensile Properties						
Mill Annealed	125	862	115	793	10	25
Typical Tensile Properties						
Mill Annealed	130	896	120	827	15	45
Beta Annealed	125	860	112	770	11	23
Recrystallization Annealed	128	880	103	710	12	36



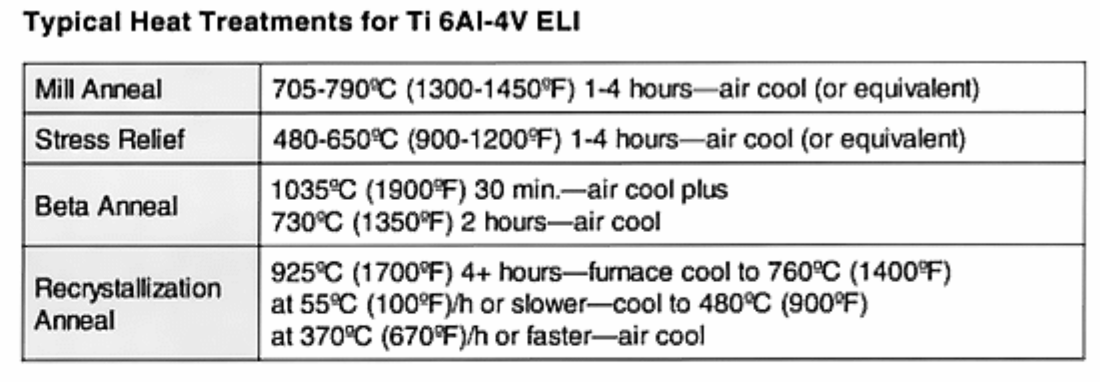
Yield Strength and Fracture Toughness of Ti 6Al-4V and Ti 6Al-4V ELI

Heat Treatment

Ti 6Al-4V ELI wrought products are typically used in either a mill annealed, beta annealed or recrystallization annealed condition. The mill anneal retains the wrought alpha+beta structure and has been used to maximize strength for applications such as total joint replacements. The beta anneal results in a completely transformed structure and is used to maximize damage tolerance at some expense of ductility. The recrystallization anneal produces a partially transformed structure designed to optimize damage tolerance while maintaining ductility. Stress relief heat treatments are also used on Ti 6Al-4V ELI.

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

Intermediate and final annealing of Ti 6Al-4V ELI 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, a process known as vacuum degassing. Parts to be vacuum heat treated must be thoroughly cleaned (see Descaling (Cleaning) Notes).



Typical Heat Treatments for Ti 6Al-4V ELI

Mill Anneal	705-790ºC (1300-1450ºF) 1-4 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
Recrystallization Anneal	925ºC (1700ºF) 4+ hours—furnace cool to 760ºC (1400ºF) at 55ºC (100ºF)/h or slower—cool to 480ºC (900ºF) at 370ºC (670ºF)/h or faster—air cool

Workability

Hot Working

Ti 6Al-4V ELI 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 870-950° C (1600-1740ºF), although there are also applications for beta-range processing. 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 ELI can also be successfully processed by superplastic forming, using the temperature range of 870-925ºC (1600-1700ºF).

"Warm" Working:

The yield strength of Ti 6Al-4V ELI 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 has been used extensively in the manufacture of many products, including aircraft components and medical devices.

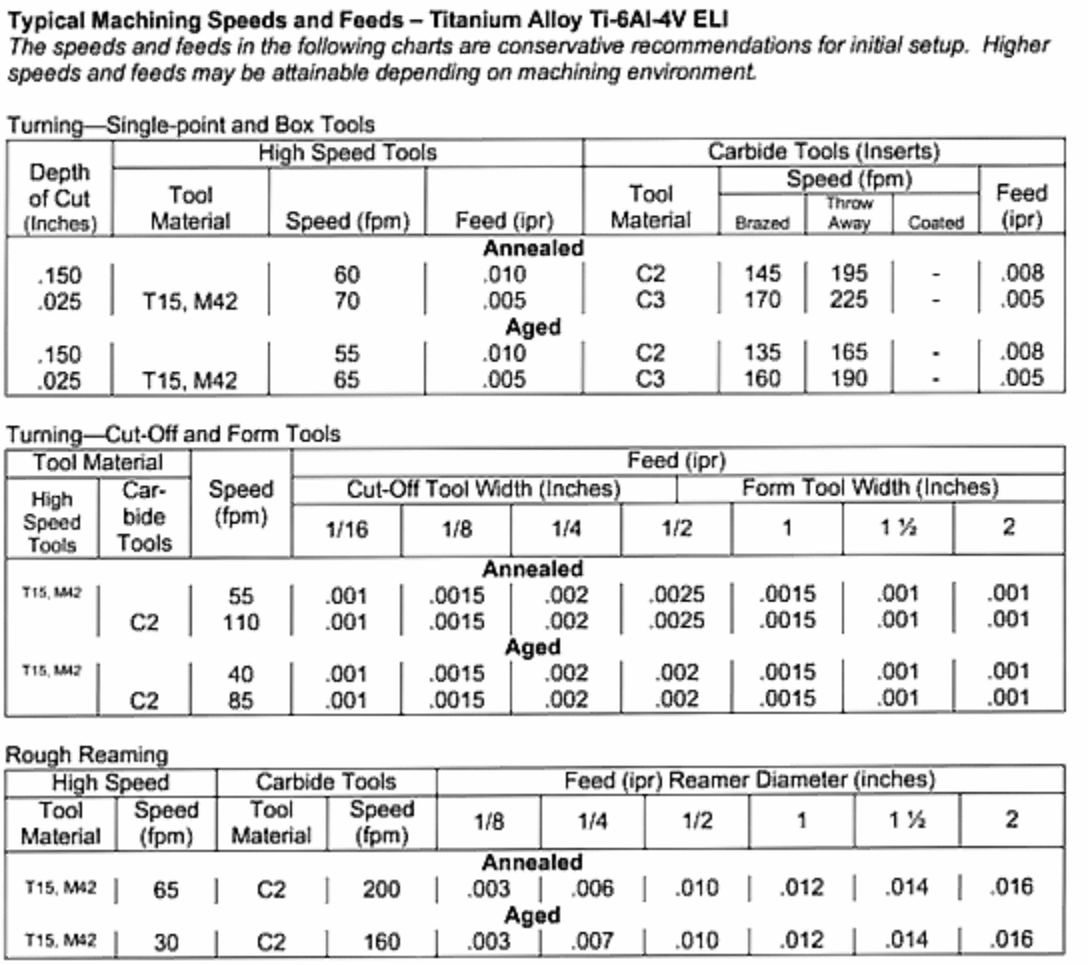
Cold Working

Ti 6Al-4V ELI can be cold drawn and extruded, although the cold workability is somewhat limited. Springback is an issue in room-temperature forming. Theoretically, over-bending alone can compensate for springback, but in practice hot sizing is often used to correct for the variability in springback that occurs.

Machinability

Using the machinability rating system based on AISI B1112 steel, the machinability of Ti 6Al-4V ELI 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 workpiece are in moving contact. Non-chlorinated cutting fluids are generally used to eliminate any possibility of chloride-induced stress-corrosion cracking. 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 ELI.



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

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

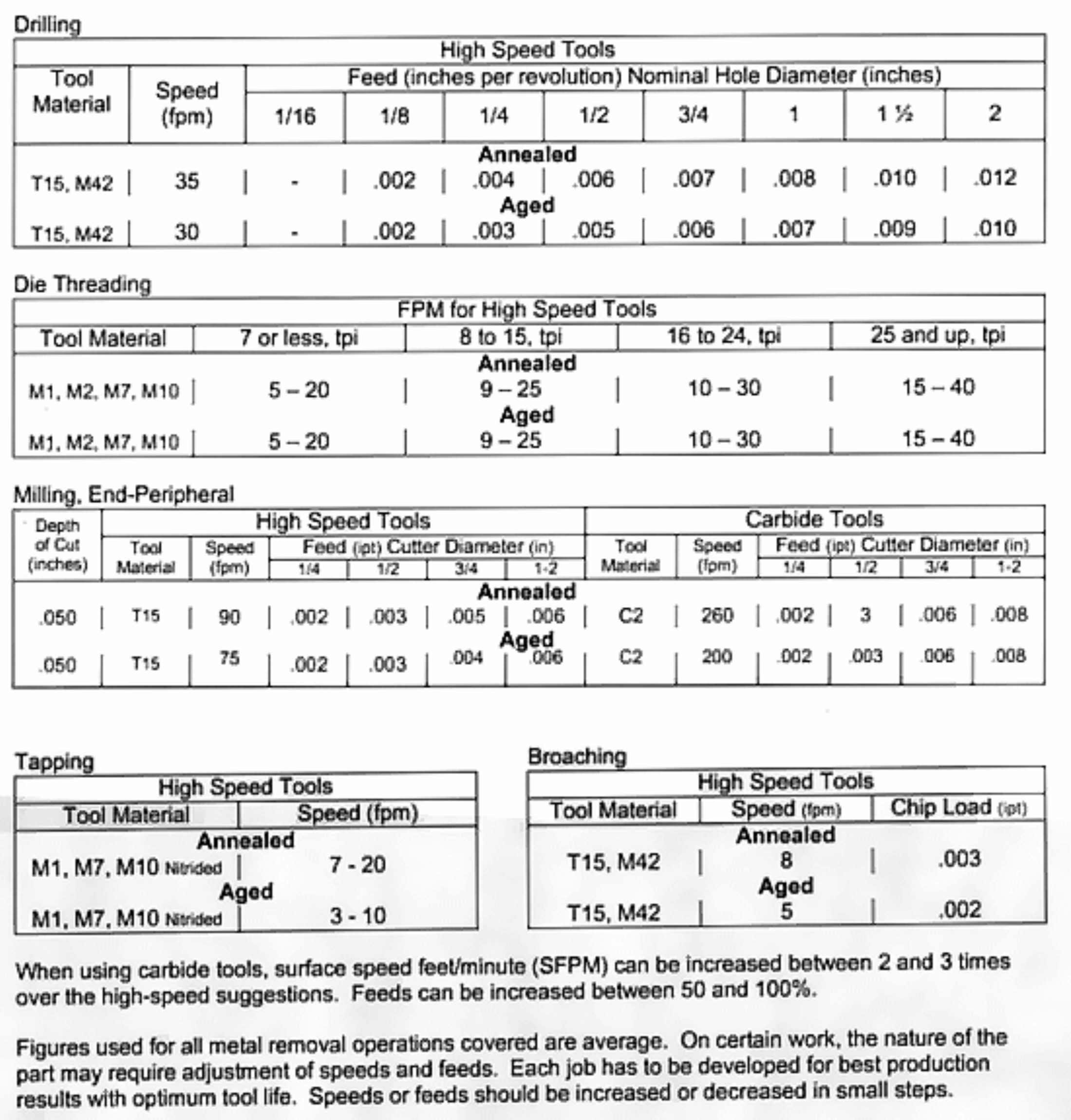
Depth of Cut (Inches)	High Speed Tools			Carbide Tools (Inserts)				
	Tool Material	Speed (fpm)	Feed (ipr)	Tool Material	Speed (fpm)			Feed (ipr)
					Brazed	Throw Away	Coated	
Annealed								
.150	T15, M42	60	.010	C2	145	195	-	.008
.025		70	.005	C3	170	225	-	.005
Aged								
.150	T15, M42	55	.010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

Turning—Cut-Off and Form Tools

Tool Material		Speed (fpm)	Feed (ipr)						
			Cut-Off Tool Width (Inches)				Form Tool Width (Inches)		
High Speed Tools	Carbide Tools		1/16	1/8	1/4	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		Carbide Tools		Feed (ipr) Reamer Diameter (inches)					
Tool Material	Speed (fpm)	Tool Material	Speed (fpm)	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

High Speed Tools									
Tool Material	Speed (fpm)	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

	FPM for High Speed Tools			
Tool Material	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

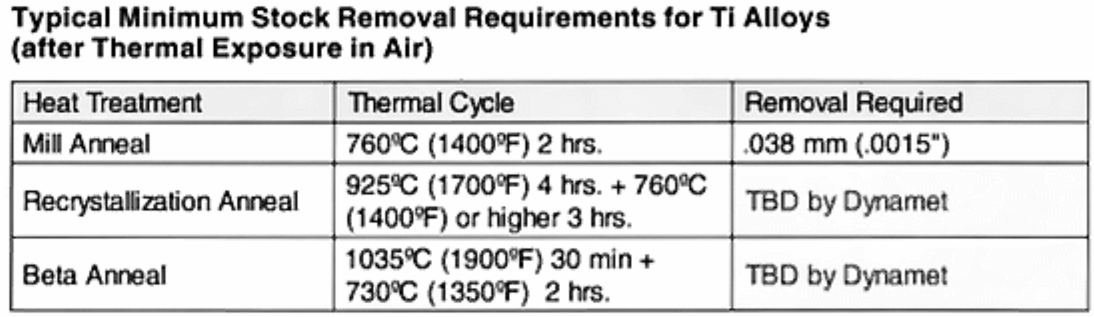
High Speed Tools	
Tool Material	Speed (fpm)
Annealed	
M1, M7, M10 Nitrided	7 - 20
Aged	
M1, M7, M10 Nitrided	3 - 10

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")
Recrystallization Anneal	925ºC (1700ºF) 4 hrs. + 760ºC (1400ºF) or higher 3 hrs.	TBD by Dynamet
Beta Anneal	1035ºC (1900ºF) 30 min + 730ºC (1350ºF) 2 hrs.	TBD by Dynamet

Weldability

Ti 6Al-4V ELI can be welded using Ti 6Al-4V ELI 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 ELI. 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 ELI welding applications.

Other Information

Wear Resistance

Ti 6Al-4V ELI, 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 alpha case formation, even in the vacuum atmosphere. In addition, chlorides found in some cleaning agents have been associated with SCC of titanium. 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

- AMS 4905 (Plate, Annealed)
- AMS 4930 (Bar, Wire, Forgings, Billet, Annealed)
- AMS 4956 (Weld Filler Metal Wire)
- AMS 4998 (Powder)
- ASTM F620 (Forgings for Surgical Implants)
- AMS 4907 (Sheet, Strip, Plate, Annealed)
- AMS 4931 (Bar, Wire, Forgings, Billet)
- AMS 4996 (Billet)
- ASTM F136 (Wrought Alloy for Surgical Implants)
- AWS A5.16-70 (Weld Filler Metal Wire and Rod)

Forms Manufactured

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

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

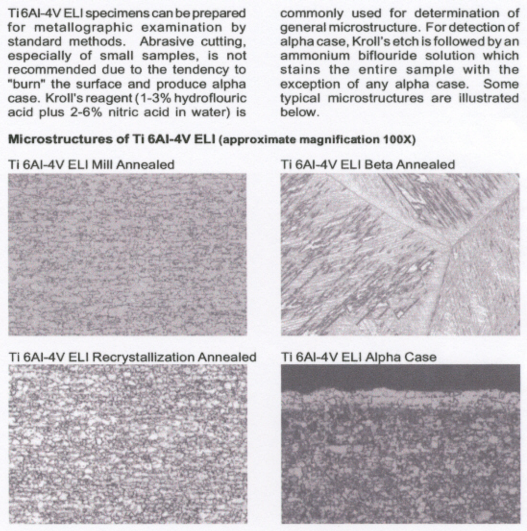
References

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
Titanium Alloys in Surgical Implants, ASTM, 1983
Concise Encyclopedia of Medical & Dental Materials, Pergamon Press, 1990
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

- Higher Performance Material Solutions for a Dynamic Spine Market
- New, Precision Titanium ULTRABAR™ for Screw Machining Medical and Other Precision Parts
- Specialty Alloys And Titanium Shapes To Consider For Latest Medical Materials Requirements



Ti 6Al-4V ELI 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 ELI (approximate magnification 100X)

Ti 6Al-4V ELI Mill Annealed

Ti 6Al-4V ELI Beta Annealed

Ti 6Al-4V ELI Recrystallization Annealed

Ti 6Al-4V ELI Alpha Case

Disclaimer:
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Edition Date: 07/01/2000

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