CARPENTER TECHNOLOGY

DATASHEET

CP TI

Applicable specifications: AMS 4901, AMS 4902, AMS 4941, AMS 4942, AMS 4951, ASTM B265, ASTM B348, ASTM B367, ASTM B381, ASTM F67, ASTM F 1341, AWS A5.16-2013

Associated specifications: ISO 5832-2, MIL-T 9047

Type analysis

Single figures are nominal except where noted. Other, Each = 0.1% maximum and Other, Total = 0.4% maximum values are applicable for ASTM B 348-99 only. For ASTM B 348-99 Carbon = 0.08% maximum and ASTM F67-13 = 0.1% maximum.

ELEMENT	COMPOSITION, % (MASS/MASS)			
	GRADE 1	GRADE 2	GRADE 3	GRADE 4
Titanium	Balance	Balance	Balance	Balance
Iron, max	0.20 %	0.30 %	0.30 %	0.50 %
Oxygen, max	0.18 %	0.25 %	0.35 %	0.40 %
Carbon, max	0.08 %	0.08 %	0.08 %	0.08 %
Nitrogen, max	0.03 %	0.03 %	0.05 %	0.05 %
Hydrogen, max	0.015 %	0.015 %	0.015 %	0.015 %

Forms manufactured

Bar-Rounds	**Bar-Shapes**	**ULTRABAR® Precision Bar**	**Dynalube Coil**	**Wire**
Weld Wire	**Wire-Shapes**	**SMART Coil® Titanium Coil[1]**		

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

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 880°C (1616°F).

Commercially pure, or CP, titanium is unalloyed. At service temperature, it consists of 100% hcp alpha phase. As a single-phase material, its properties are controlled by chemistry (iron and interstitial impurity elements) and grain size. CP titanium is classified into Grades 1 through 4, depending on strength and allowable levels of the elements iron, carbon, nitrogen, and oxygen.

Applications vary by grade; see the grades section below.

Key Properties:

- Grade 1: Can meet a wide range of mechanical property levels
- Grade 2: Excellent formability and corrosion resistance
- Grade 3: General-purpose; good formability, strength, and corrosion resistance
- Grade 4: High strength, corrosion resistance

Markets:

- Aerospace
- Industrial
- Marine
- Medical

info@cartech.com | 610 208 2000

> CP TI

Grades

CP Ti Grade 1 is often referred to as "Super Pure" titanium. The mechanical properties of this "Super Pure" material can be manipulated to meet a wide range of property levels. We can produce very low strength wire with UTS of 45 ksi and 0.2% yield strength of 25 ksi. Conversely, cold work can be introduced to increase the tensile properties to a UTS of 130 ksi and a 0.2% yield strength of 110 ksi. (All mechanical properties are nominal representation of typical values. Please contact Carpenter Technology for more information.)

CP Ti Grade 2 has a minimum yield strength of 275 MPa (40 ksi), and relatively low levels of impurity elements, which places it between Grades 1 and 3 in terms of strength. Grade 2 is widely used because it combines excellent formability and moderate strength with superior corrosion resistance. This combination of properties makes CP Grade 2 titanium a candidate for a large variety of chemical and marine as well as aerospace and medical applications.

Some examples of Grade 2 aerospace applications have included airframe skins in "warm" areas, ductwork, brackets, and galley equipment. CP Ti Grade 2 has also been widely used in marine and chemical applications such as condensers, evaporators, reaction vessels for chemical processing, tubing and tube headers in desalinization plants, and cryogenic vessels. Other uses have included items such as jigs, baskets, cathodes and starter-sheet blanks for the electroplating industry, and a variety of medical applications.

CP Ti Grade 4 is the strongest, with a minimum yield strength of 480 MPa (70 ksi), and has the highest allowable oxygen and iron content. Grade 4 combines the excellent resistance to corrosion and corrosion fatigue of titanium with high strength that makes it a candidate to compete with steels and nickel alloys for many chemical and marine applications.

Grade 4 also has good ductility, is moderately formable, and has superior corrosion fatigue resistance in seawater. Applicable service temperatures for CP Ti Grade 4 are up to 204°C (400°F). Some applications have included airframe and aircraft engine components, marine and chemical processing machinery, heat exchangers, reaction vessels for chemical processing and desalinization plants, corrosive waste disposal wells, and pulp and paper production.

> CP TI

Corrosion resistance

The corrosion resistance of CP Ti is based on the presence of a stable, continuous, tightly adherent oxide layer, which forms spontaneously and immediately upon exposure to oxygen. If damaged, it reforms readily as long as there is some source of oxygen (air or moisture) in the environment.

In general, the higher the purity of CP Ti, the greater the corrosion resistance. CP Ti Grade 2, with its relatively low impurity levels, has been widely used because it is capable of performing well in many corrosion-critical applications, such as marine environments and chemical processing. CP Ti Grade 4 has outstanding resistance to corrosion fatigue in marine environments.

CP Ti is highly resistant to many chemical environments, including oxidizing media, alkaline media, organic compounds and acids, aqueous salt solutions, and wet or dry hot gases. It also has sufficient corrosion resistance in liquid metals, nitric acid, mildly reducing acids, and wet chlorine or bromine gas (as long as a minimal amount of oxygen or water is present). In seawater, it is fully resistant to corrosion at temperatures up to 315°C (600°F). The possibility of crevice corrosion must be considered, however, and components appropriately designed to avoid tight crevices.

Conditions under which CP Ti is susceptible to corrosion are strongly reducing acids, alkaline peroxide solutions, and molten chloride salts. Crevice corrosion can occur in hot halide or sulfate solutions (>1000 ppm at 75°C or higher), which can be a consideration in marine applications.

CP Ti is fully resistant to stress-corrosion cracking (SCC) in aqueous solutions, and is largely immune to SCC in general. Conditions under which CP Ti is susceptible to SCC include anhydrous methanol or methanol/halide solutions, red fuming nitric acid, nitrous oxide, nitrogen tetroxide, and in contact with liquid or solid cadmium or liquid mercury.

CP Ti is susceptible to hydrogen embrittlement due to the formation of hydrides. Specifications for CP Ti mill products typically specify a maximum hydrogen limit of 150 ppm, but it is possible for degradation to occur at lower levels, especially in the presence of a notch. The presence of a notch or other stress raiser increases the detrimental effect, as hydrogen migrates to the notch area, raising the local concentration of hydrides. It is important to minimize hydrogen pickup during processing, particularly heat treating and acid pickling.

Important Note:
The following 4-level rating scale (Excellent, Good, Moderate, Restricted) is intended for comparative purposes only and is derived from experiences with wrought product. Additive manufactured material may perform differently; corrosion testing is recommended. Factors that affect corrosion resistance include temperature, concentration, pH, impurities, aeration, velocity, crevices, deposits, metallurgical condition, stress, surface finish, and dissimilar metal contact.

Acetic Acid	Excellent	**Humidity**	Excellent
Salt Spray (NaCl)	Excellent	**Sea Water**	Excellent
Sodium Hydroxide	Moderate	**Sour Oil/Gas**	Moderate
Sulfuric Acid	Moderate		

> CP TI

GENERAL CORROSION RATES IN VARIOUS MEDIA

Data included is for both Grade 2 and Grade 4 unless otherwise indicated.

CORROSION RATE BY MEDIUM AND CONCENTRATION

MEDIUM		CONCENTRATION	TEMPERATURE		CORROSION RATE	
		%	°C	°F	MM/YR	MILS/YR
Nitric acid		35	boiling	boiling	0.127–0.508	5.0–20.0
Nitric acid + 0.01% $K_2Cr_2O_7$		40	boiling	boiling	0.010	0.390
Ammonium hydroxide	Grade 2	70	boiling	boiling	nil	nil
	Grade 4	28	100	212	nil	nil
Stearic acid		100	180	355	0.003	0.120
Acetic acid	Grade 2	0–99.5	boiling	—	nil	nil
Adipic acid	Grade 4	67	240	464	nil	nil
Bismuth/lead	Grade 2	molten	300	570	<0.1	<4.0
	Grade 4	molten	300	570	good resistance	good resistance
Bromine, moist		vapor	30	86	<0.003	0.120
Hydrogen peroxide pH 4.3		5	66	150	0.061	2.40
H_2O_2 + 20 g/l NaOH		10 g/l	60	140	55.90	2200

EROSION/CORROSION IN SEA WATER, GRADE 2

EROSION/CORROSION RATE BY TEST LOCATION

TEST DESCRIPTION	FLOW RATE		TEST DURATION	EROSION/CORROSION RATE	
	M/S	FT/S		MM/YR	MILS/YR
Brixham Sea, model condenser	9.8	32.0	12 months	0.0030	0.120
Kure Beach, NC, rotating disk	8.5	28.0	2 months	0.00013	0.005
Kure Beach, NC, jet impingement	7.2	23.6	1 month	0.00050	0.020
Wrightsville Beach, NC, Micarta whl.	9.0	29.5	2 months	0.00018	0.007
Lab test, no solids	7.2	23.6	10,000 hrs	nil	nil
Lab test, 40 g/l 60-mesh sand	2.0	6.5	2,000 hrs	0.0025	0.10
Lab test, 4% 80-mesh emery	4.1	13.5	17.5 hrs	0.0830	3.30

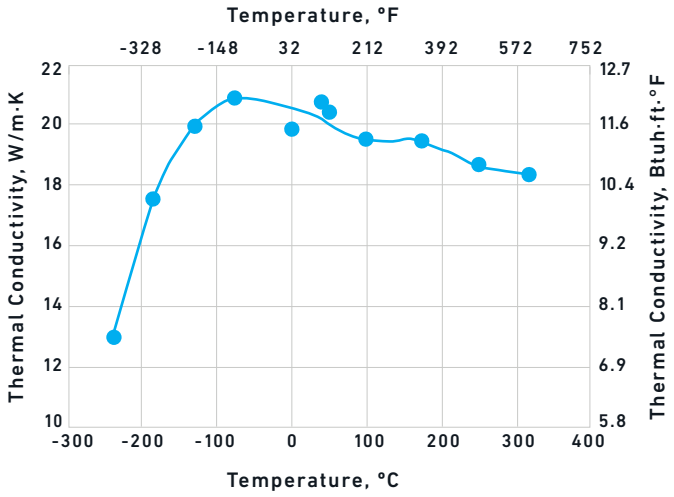
> CP TI

Physical properties

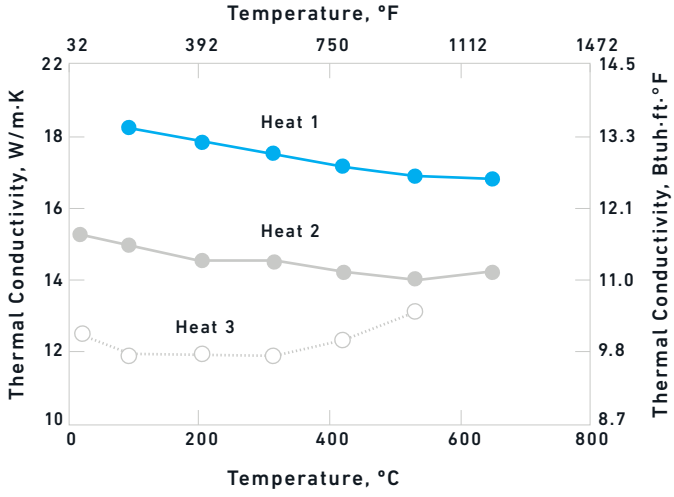
Data included is for both Grade 2 and Grade 4 unless otherwise indicated.

PROPERTY		At or From	English Units	Metric Units
DENSITY		—	0.1630 lb/in^3	—
MEAN SPECIFIC HEAT		73°F	0.1250 Btu/lb/°F	—
ELASTIC MODULUS (E)		—	15.0 x 10^3 ksi	—
BETA TRANSUS	GRADE 2	1650 to 1700°F	—	—
	GRADE 4	1715 to 1765°F	—	—
ALPHA TRANSUS	GRADE 2	1610 to 1660°F	—	—
	GRADE 4	1635 to 1685°F	—	—
LIQUIDUS TEMPERATURE	GRADE 2	3000 to 3040°F	—	—
	GRADE 4	3020 to 3040°F	—	—
ELECTRICAL RESISTIVITY	GRADE 2	104°F	294.8 ohm-cir-mil/ft	—
		210°F	367.0 ohm-cir-mil/ft	—
		606°F	601.7 ohm-cir-mil/ft	—
ELECTRICAL RESISTIVITY	GRADE 4	73°F	60.0 ohm-cir-mil/ft	—

THERMAL CONDUCTIVITY, GRADE 2

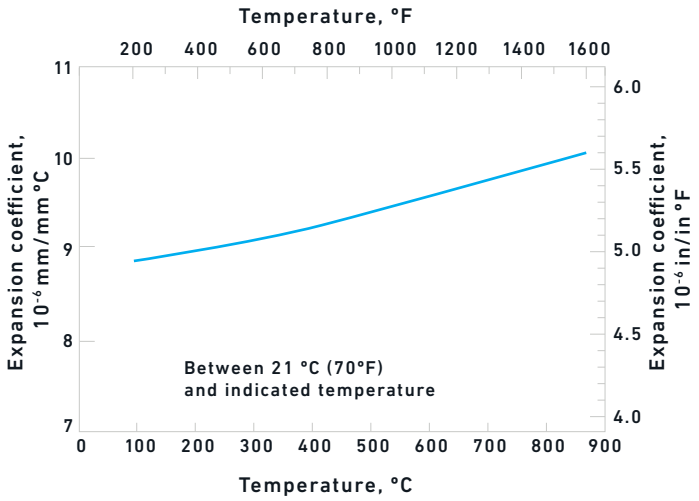


THERMAL CONDUCTIVITY, GRADE 4

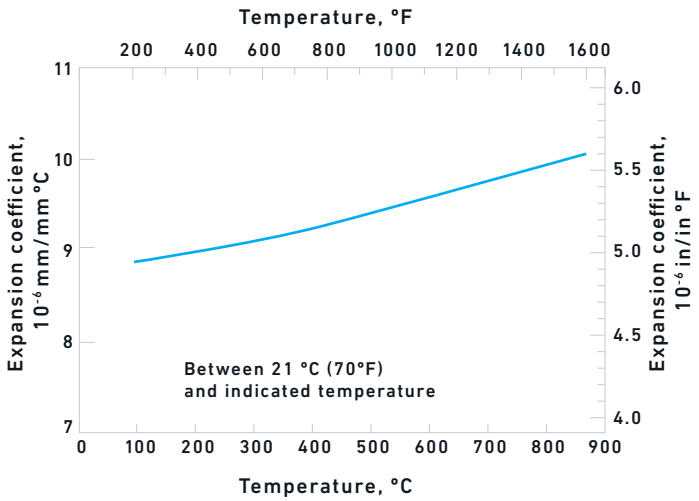


> CP TI

THERMAL EXPANSION, GRADE 2



THERMAL EXPANSION, GRADE 4



Magnetic properties

MAGNETIC ATTRACTION	None

Typical mechanical properties

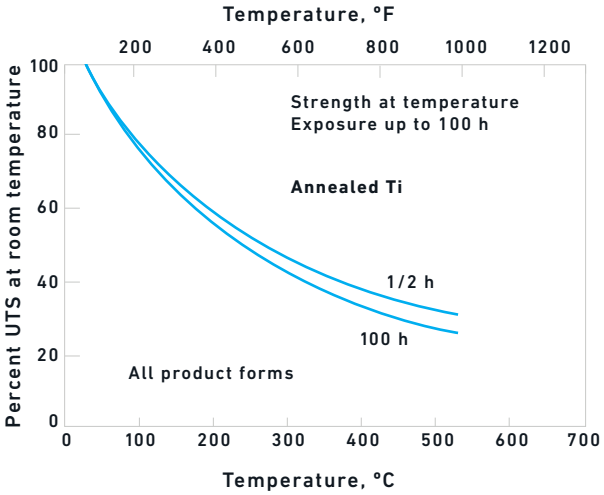
CP Ti Grade 4 has the highest strength of the CP grades, making it competitive with stainless steels for many corrosion resistant applications. Its strength is on a par with annealed stainless steels, and, in addition, it offers lighter weight and superior corrosion resistance. CP Grade 4 titanium is not subject to grain boundary embrittlement or sensitization at elevated temperatures. Specific strength (strength/density) provides a way to compare materials based on a combination of strength and weight.

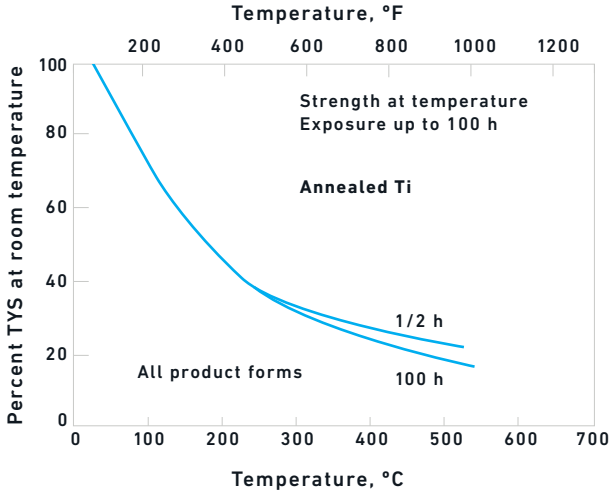
> CP TI

ROOM TEMPERATURE MECHANICAL PROPERTIES

		0.2% YIELD STRENGTH		ULTIMATE TENSILE STRENGTH		ELONGATION IN 4D	REDUCTION OF AREA
		ksi	MPa	ksi	MPa	%	%
Specified minimum properties	Grade 2	40	275	50	345	20	30
	Grade 4	70	480	80	550	15	30
Typical properties	Grade 2	49–79	335–545	74–88	510–605	21–29	47–54
	Grade 4	70–92	480–635	95–100	655–690	20–25	38–51

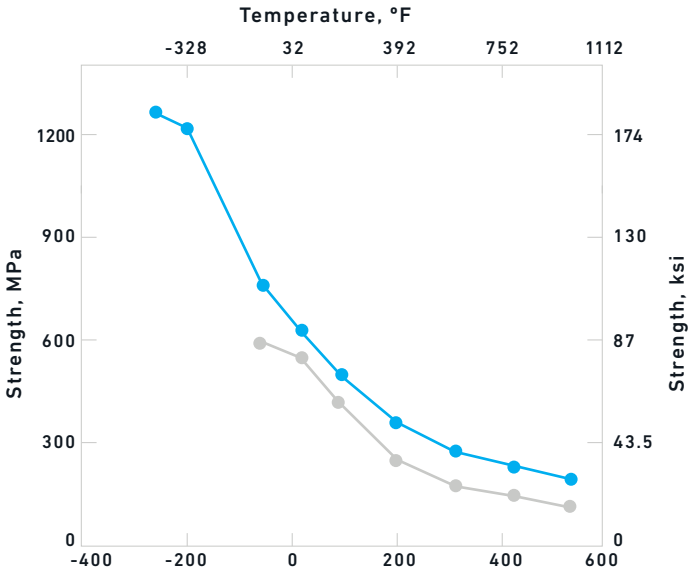
ELEVATED TEMPERATURE MECHANICAL PROPERTIES, GRADE 2

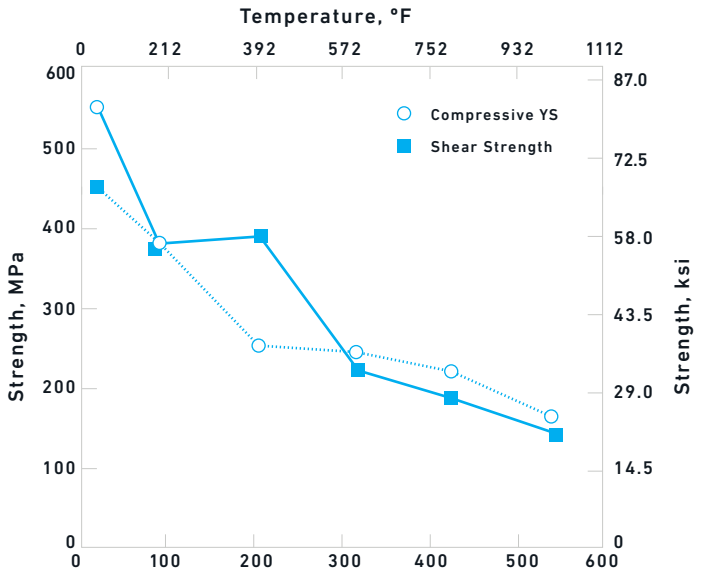




> CP TI

ELEVATED TEMPERATURE MECHANICAL PROPERTIES, GRADE 4





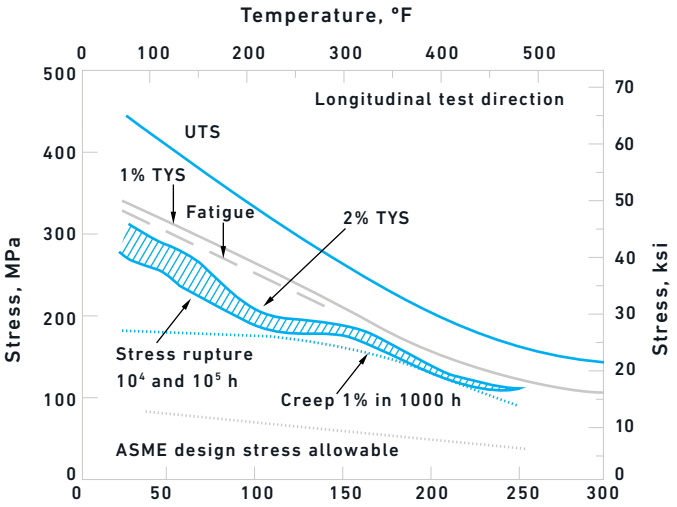
FATIGUE LIMIT RANGES

		ksi	MPa
Smooth axial (R=0.1)	Grade 2	40–50	275–345
Smooth rotating-beam	Grade 4	50–60	340–420
Notched (K=2.7)	Grade 4	35	250

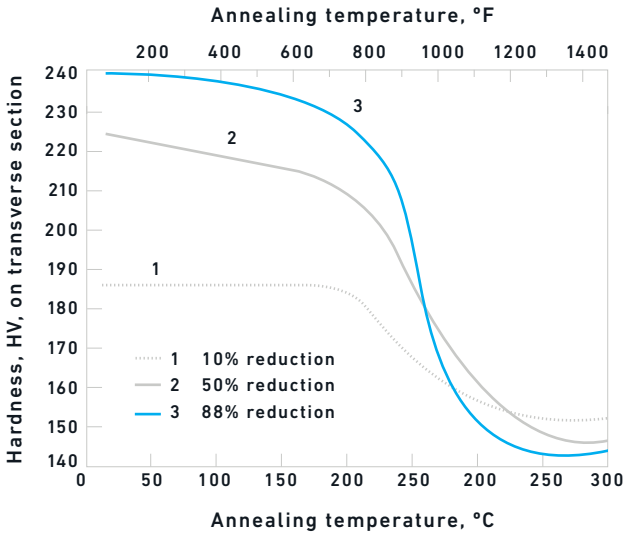
info@cartech.com | 610 208 2000

> CP TI

TYPICAL MECHANICAL STRENGTHS & ASME ALLOWABLES, GRADE 2



EFFECT OF PROCESSING ON HARDNESS, GRADE 2



TYPICAL ROOM TEMPERATURE STRENGTHS, GRADE 4 ANNEALED

	ksi	MPa
Ultimate bearing strength	120	825
Compressive yield strength	70	480
Ultimate shear strength	42	290

STRENGTH, GRADE 4 VS. STAINLESS STEELS

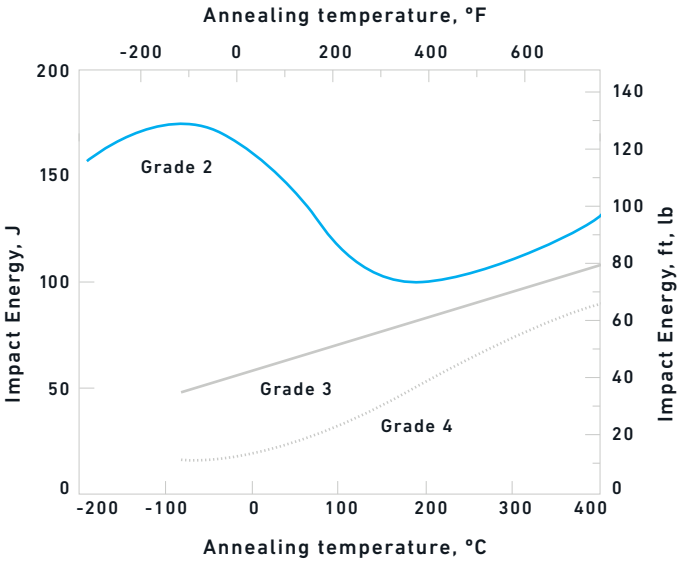
MATERIAL	0.2% YIELD STRENGTH		ULTIMATE TENSILE STRENGTH		ELONGATION IN 4D	SPECIFIC STRENGTH		SPECIFIC YIELD STRENGTH	
	ksi	MPa	ksi	MPa	%	M x 10^2	IN x 10^3	M x 10^2	IN x 10^3
CP Ti 4 min.	70	480	80	550	15	125	491	109	429
CP Ti 4 typ.	80	550	97	670	22	152	595	125	491
316 SS min.	35	240	80	550	30	70	276	31	121
403 SS min.	30	205	70	485	25	64	250	27	107
430 SS min.	30	205	65	450	22	59	232	27	107

> CP TI

Toughness

CP Ti is very ductile and tough. Because of its high toughness and low strength, standard plane-strain fracture toughness testing (K 1c) is impractical for CP Ti. Notched impact (Charpy) testing is generally used to evaluate toughness.

CHARPY V-NOTCH IMPACT TOUGHNESS VS. TEMPERATURE, GRADE 4



info@cartech.com | 610 208 2000

> CP TI

Heat treatment

Heat treatments used for CP Ti are annealing and stress relieving. Annealing is used to fully soften the material and remove all residual stresses. Annealing of wrought products at typical temperatures (below the beta transus) results in a fully recrystallized equiaxed alpha structure. Precise control of grain size (and mechanical properties) can be achieved by adjusting the anneal temperature.

Stress relieving is used to remove some or most of the residual stresses from forming, or to recover compressive yield strength after stretching.

Titanium and its alloys have a high affinity for gases, including oxygen, nitrogen and hydrogen. When CP Ti is heated in air, oxygen absorption results in the formation of an extremely hard, brittle oxygen-stabilized alpha phase layer known as alpha case.

Intermediate and final annealing of CP Ti 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 cleaning notes below).

Heat treatment

Annealing	Grade 2: 595–705°C (1100–1300°F) for 2 hours. Air cool (or equivalent). Grade 4: 595–760°C (1100–1400°F) for 2 hours. Air cool (or equivalent).
Stress relieving	540–595°C (1000–1100°F) for 15-30 minutes. Air cool (or equivalent).

> CP TI

Workability

Hot working	CP Ti can be processed by conventional techniques, such as hot rolling, forging, and hot pressing. Temperatures for initial roughing may be as high as 30-50°C (50–100°F) above the beta transus, and temperatures for finish processing are typically in the alpha/beta phase field, ranging from about 815°C (1500°F) to about 900°C (1650°F). CP Ti can be formed into finished parts by standard methods, such as forging, spin forming, hydroforming, and hot pressing. Typically, more severe forming is done in the temperature range of 480–540°C (900–1000°F) and milder forming from 200–315°C (400–600°F). Care must be taken to prevent the formation of excessive alpha case, and alpha case must be removed after processing.
Cold working	CP Ti work hardens fairly rapidly, which is a limitation in some operations, such as cold drawing. The Bauschinger effect results in a drop of up to 25% in compressive yield strength upon stretching at room temperature; this drop can be recovered by stress relieving. Due to the low modulus of titanium, springback allowances are significant. Hot sizing after cold forming is often used to correct for variations in springback. Grade 2 has good ductility and can be formed at room temperature by various standard methods, including bending, stretch forming, heading, stamping, and drawing. Grade 4 has relatively good ductility and can be formed at room temperature, although cold forming deformation must be less severe than for the lower-strength grades. Standard methods, including bending, stretch forming, heading, stamping, and drawing, are applicable to Grade 4.
Machinability	The machining characteristics of CP Ti are similar to those of austenitic stainless steels. In general, low cutting speeds, heavy feed rates, and copious amounts of cutting fluid are recommended. Sharp tools and rigid setups are also important. 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.

> CP TI

Typical feeds and speeds

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

TURNING — SINGLE-POINT AND BOX TOOLS

DEPTH OF CUT, IN	HIGH-SPEED TOOLS			CARBIDE TOOLS (INSERTS)			
	SPEED, FPM	FEED, IPR	TOOL MATERIAL	SPEED, FPM		FEED, IPR	TOOL MATERIAL
				UNCOATED	COATED		
.150	105	.010	T-15, M-42	250	320	.008	C-2
.025	115	.005	T-15, M-42	290	370	.005	C-3

TURNING — CUT-OFF AND FORM TOOLS

SPEED, FPM	FEED, IPR							TOOL MATERIAL	
	CUT-OFF TOOL WIDTH, IN			FORM TOOL WIDTH, IN				HIGH-SPEED TOOLS	CARBIDE TOOLS
	1/16	*1/8*	*1/4*	*1/2*	*1*	*1-1/2*	*2*		
80	.001	.0015	.002	.0025	.0015	.001	.001	T-15, M-42	C-2
185	.001	.0015	.002	.0025	.0015	.001	.001	T-15, M-42	C-2

ROUGH REAMING

HIGH-SPEED TOOLS		CARBIDE TOOLS		FEED, IPR, REAMER DIAMETER, IN					
SPEED, FPM	TOOL MATERIAL	SPEED, FPM	TOOL MATERIAL	*1/8*	*1/4*	*1/2*	*1*	*1-1/2*	*2*
120	M-1, M-2, M-7	300	C-2	.004	.008	.012	.018	.022	.025

DRILLING — HIGH-SPEED TOOLS

SPEED, FPM	FEED, IPR								TOOL MATERIAL
	NOMINAL HOLE DIAMETER, IN								
	1/16	*1/8*	*1/4*	*1/2*	*3/4*	*1*	*1-1/2*	*2*	
40–55	.001	.002	.005	.008	.010	.012	.025	.017	M-1, M-7, M-10

TAPPING — HIGH-SPEED TOOLS

SPEED, FPM	TOOL MATERIAL
12–40	M-1, M-7, M-10 Nitrited

DIE THREADING — HIGH-SPEED TOOLS

SPEED, FPM				TOOL MATERIAL
7 OR LESS, TPI	8 TO 15, TPI	16 TO 24, TPI	25 AND UP, TPI	
5–20	9–25	10–30	15–40	M-1, M-2, M-7, M-10

> CP TI

MILLING — END PERIPHERAL												
DEPTH OF CUT, IN	HIGH-SPEED TOOLS						CARBIDE TOOLS					
	SPEED, FPM	FEED, IN PER TOOTH				TOOL MATERIAL	SPEED, FPM	FEED, IPT				TOOL MATERIAL
		CUTTER DIAMETER, IN						CUTTER DIAMETER, IN PER TOOTH				
		1/4	1/2	3/4	1-2			1/4	1/2	3/4	1-2	
.050	130	.002	.003	.005	.006	M-2, M-3, M-7	323	.002	.003	.006	.008	C-2

BROACHING — HIGH-SPEED TOOLS		
SPEED, FPM	CHIP LOAD, IN PER TOOTH	TOOL MATERIAL
25	.003	M-2, M-7

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
Annealing	705°C (1300°F) 2 hrs	0.020 mm (0.0008 in)
Stress relieving	540–595°C (1000–1100°F) 30 min	0.005 mm (0.0002 in)

Additional machinability notes

Weldability	CP Ti can be welded using CP Ti 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 CP Ti. 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 CP Ti welding applications.

> CP TI

Other information

Wear resistance	Commercially pure Ti has a tendency to gall and is 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 is 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 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 alloys. 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.
Technical articles	Precision Titanium ULTRABAR® Factsheet

> CP TI

Additive manufacturing process guidance

CP Ti 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% hydrofluoric acid plus 2–6% nitric acid in water) is commonly used for determination of general microstructure. Alpha case in CP Ti cannot be reliably detected by metallography; its presence must be determined by microhardness testing.

For additional information, please contact your nearest sales office:
info@cartech.com | 610 208 2000

The information and data presented herein are typical or average values and are not a guarantee of maximum or minimum values. Applications specifically suggested for material described herein are made solely for the purpose of illustration to enable the reader to make their own evaluation and are not intended as warranties, either express or implied, of fitness for these or other purposes. There is no representation that the recipient of this literature will receive updated editions as they become available.

Unless otherwise specified, registered trademarks are property of CRS Holdings LLC, a subsidiary of Carpenter Technology Corporation.

© 2021 CRS Holdings, LLC, All rights reserved. v 06-21