CARPENTER TECHNOLOGY

DATASHEET

TI 6AL-4V ELI

Applicable specifications: AMS 4930, AMS 4931, AMS 4956, AMS 4996, ASTM F136, ASTM F620, AWS A5.16-2013

Type analysis

Single figures are nominal except where noted. Other, Each, max = 0.1%. For AMS 4930 rev. D, Hydrogen = 0.0125% and Yttrium = 0.005%.

Titanium	Balance	**Aluminum**	5.50–6.50 %	**Vanadium**	3.50–4.50 %
Iron	max 0.25 %	**Oxygen**	max 0.130 %	**Carbon**	max 0.080 %
Nitrogen	max 0.050 %	**Hydrogen**	max 0.013 %	**Other, Total**	max 0.40 %

Forms manufactured

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

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

Description

Ti 6Al-4V ELI is the extra-low interstitial version of Ti 6Al-4V. Its content is arrived at by the careful selection of ingot raw materials with lower specified limits on iron and the interstitial elements carbon and oxygen. Ti 6Al-4V ELI has been the material of choice for many medical and dental applications due to its excellent biocompatibility, good fatigue strength, and low modulus. 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. The high-purity alloy is also known as ASTM B348 Grade 23.

Key Properties:

- Alpha + beta alloy
- Higher purity version of Ti 6Al-4V
- Lower limits on iron, carbon, and oxygen than Ti 6Al-4V
- Excellent biocompatibility, fracture toughness, and fatigue crack growth rate
- Improved cryogenic performance than Ti 6Al-4V
- Good corrosion resistance, low modulus, and lightweight

Markets:

- Dental
- Medical

Applications:

- Biomedical, particularly implantable components
- Joint replacement
- Bone fixation devices
- Surgical clips
- Cryogenic vessels

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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.

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

CORROSION RATE BY MEDIUM AND CONCENTRATION

MEDIUM	CONCENTRATION	TEMPERATURE		CORROSION RATE	
	%	°C	°F	MM/YR	MILS/YR
Implanted in canine mandibular bone	—	—	—	0	0
Hydrochloric acid	2	37.8	100.0	0–0.030	0–1.20
Hydrochloric acid	10	37.8	100.0	0.508–1.020	20.0–40.0
Hydrochloric acid	vapors	37.8	100.0	8.33–1.040	328.0–408.0
Nitric acid	65	boiling	boiling	0.076–0.130	3.0–5.0
Sulfuric acid	2	37.8	100.0	0.396–0.549	15.6–21.6
Sodium hydroxide	25	boiling	boiling	0.046–0.051	1.8–2.0

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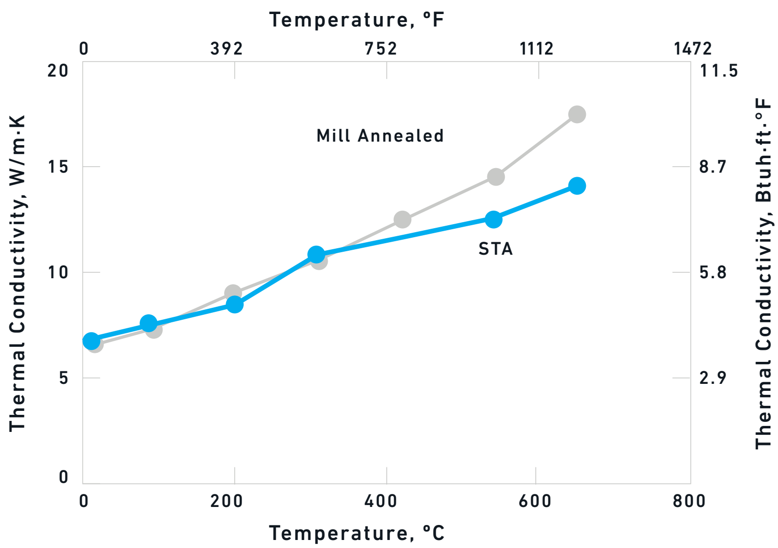
Physical properties

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.

PROPERTY	At or From	English Units	Metric Units
DENSITY	—	0.160 lb/in^3	—
MODULUS OF ELASTICTY (E)	—	15.20 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	1053.0 ohm-cir-mil/ft	—

THERMAL CONDUCTIVITY



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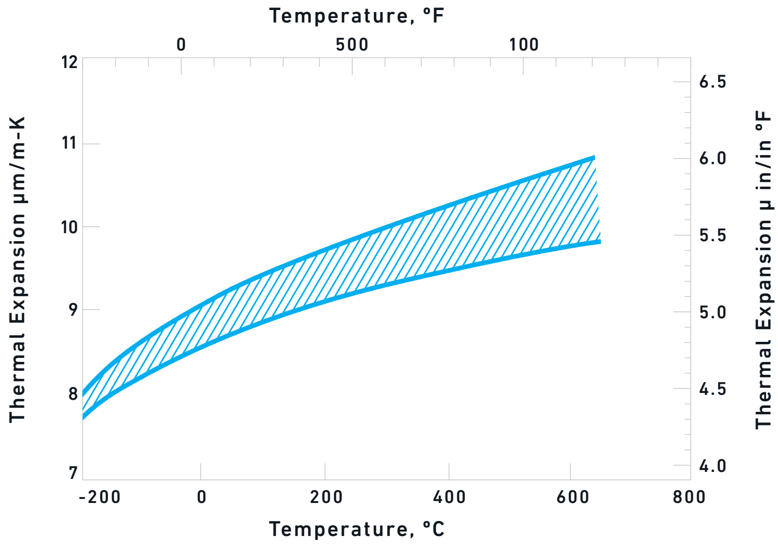
ELASTIC MODULUS AND SHEAR MODULUS BY MATERIAL

MATERIAL	ELASTIC MODULUS		SHEAR MODULUS	
	GPa	PSI X 10^5	GPa	PSI X 10^5
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 Co-Cr-Mo alloy	190–215	27.6–31.2	74–83	10.7–12.0

THERMAL EXPANSION



Magnetic properties

MAGNETIC ATTRACTION	None

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Typical mechanical properties

TYPICAL ROOM TEMPERATURE STRENGTHS	ksi	MPa
Ultimate bearing strength	200–300	1380–2070
Compressive yield strength	120–130	825–895
Ultimate shear strength	70–100	480–690

FATIGUE LIMITS

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

FATIGUE LIMIT RANGES (AXIAL FATIGUE, R = 0.06 TO 0.1)	ksi	MPa
Smooth	60–100	400–700
Notched (KT = 3)	20–40	140–270

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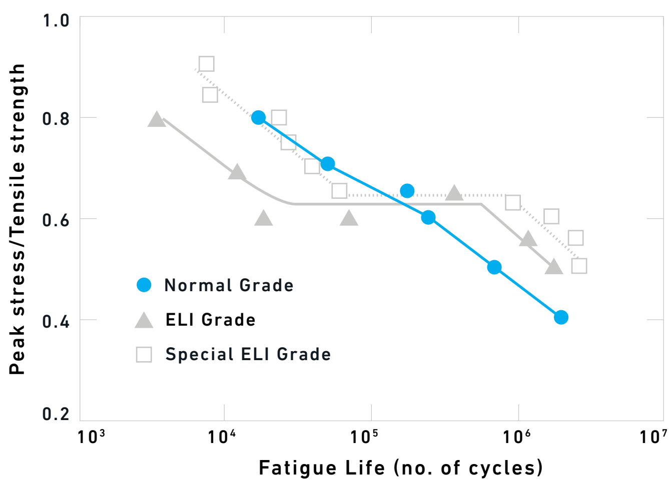
FRACTURE TOUGHNESS

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							
	CONDITION	0.2% YIELD STRENGTH		ULTIMATE TENSILE STRENGTH		ELONGATION IN 4D	REDUCTION OF AREA
		ksi	MPa	ksi	MPa	%	%
Minimum specified tensile properties	Mill annealed	115	793	125	862	10	25
Typical tensile properties	Mill annealed	120	827	130	896	15	45
	Beta annealed	112	770	125	860	11	23
	Recrystallization annealed	103	710	128	860	12	36

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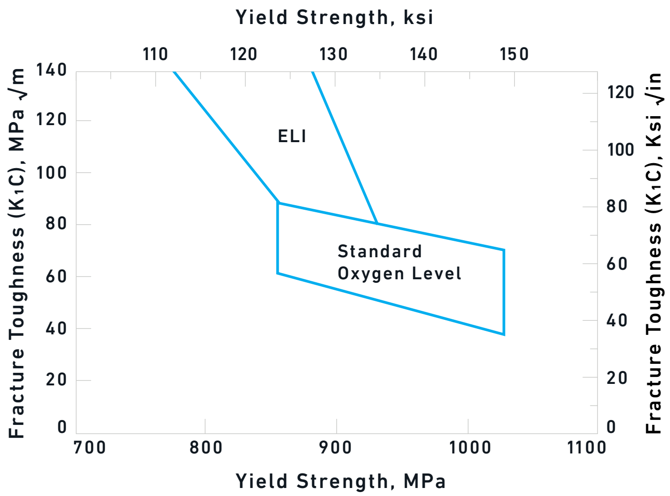
YIELD STRENGTH AND FRACTURE TOUGHNESS OF TI 6AL-4V AND TI 6AL-4V ELI



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-stabilized 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 the descaling (cleaning) notes).

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Mill anneal	705 to 790°C (1300 to 1450°F) 1 to 4 hours. Air cool (or equivalent).
Stress relief	480 to 650°C (900 to 1200°F) 1 to 4 hours. Air cool (or equivalent).
Beta anneal	1035°C (1900°F) 30 minutes. Air cool plus. 730°C (1350°F) 2 hours. Air cool.
Recrystallization anneal	925°C (1700°F) 4+ hours. Furnace cool to 760°C (1400°F). At 55°C (100°F)/hour or slower, cool to 480°C (900°F). At 370°C (670°F)/hour 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 to 950°C (1600 to 1740°F), 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 650°C (1200°F). Ti 6Al-4V ELI can also be successfully processed by superplastic forming, using the temperature range of 870 to 925°C (1600 to 1700°F)
"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.

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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 BRAZED	SPEED, FPM THROW AWAY	FEED, IPR	TOOL MATERIAL
ANNEALED							
.150	60	.010	T-15, M-42	145	195	.008	C-2
.025	70	.005	T-15, M-42	170	225	.005	C-3
AGED							
.150	55	.010	T-15, M-42	135	165	.008	C-2
.025	65	.005	T-15, M-42	160	190	.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*		
ANNEALED									
55	.001	.0015	.002	.0025	.0015	.001	.001	T-15, M-42	C-2
110	.001	.0015	.002	.0025	.0015	.001	.001	T-15, M-42	C-2
AGED									
40	.001	.0015	.002	.002	.0015	.001	.001	T-15, M-42	C-2
85	.001	.0015	.002	.002	.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*
ANNEALED									
65	T-15, M-42	200	C-2	.003	.006	.010	.012	.014	.016
AGED									
30	T-15, M-42	160	C-2	.003	.007	.010	.012	.014	.016

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DRILLING — HIGH-SPEED TOOLS

SPEED, FPM	FEED, IPR — NOMINAL HOLE DIAMETER, IN: 1/16	1/8	1/4	1/2	3/4	1	1-1/2	2	TOOL MATERIAL
ANNEALED									
35	–	.002	.004	.006	.007	.008	.010	.012	T-15, M-42
AGED									
30	–	.002	.003	.005	.006	.007	.009	.010	T-15, M-42

DIE THREADING — HIGH-SPEED TOOLS, ANNEALED AND AGED

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

MILLING — END PERIPHERAL

DEPTH OF CUT, IN	HIGH-SPEED TOOLS: SPEED, FPM	FEED, IN PER TOOTH — CUTTER DIAMETER, IN: 1/4	1/2	3/4	1-2	TOOL MATERIAL	CARBIDE TOOLS: SPEED, FPM	FEED, IPT — CUTTER DIAMETER, IN PER TOOTH: 1/4	1/2	3/4	1-2	TOOL MATERIAL
ANNEALED												
.050	90	.002	.003	.005	.006	T-15	260	.002	3	.006	.008	C-2
AGED												
.050	75	.002	.003	.004	.006	T-15	260	.002	.003	.006	.008	C-2

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TAPPING—HIGH-SPEED TOOLS	
SPEED, FPM	**TOOL MATERIAL**
ANNEALED	
7–20	M-1, M-7, M-10 Nitrided
AGED	
3–10	M-1, M-7, M-10 Nitrided

BROACHING—HIGH-SPEED TOOLS		
SPEED, FPM	**CHIP LOAD, IN PER TOOTH**	**TOOL MATERIAL**
ANNEALED		
8	.003	T-15, M-42
AGED		
5	.002	T-15, M-42

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	760°C (1400°F) 2 hours	.038 mm (.0015 in)
Beta anneal	1035°C (1900°F) 30 min + 730°C (1350°F) 2 hours	TBD by Dynamet
Recrystallization anneal	925°C (1700°F) 4 hours + 760°C (1400°F) or higher 3 hours	TBD by Dynamet

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Additional machinability notes

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.
Technical articles	Higher Performance Material Solutions for a Dynamic Spine Market New, Precision Titanium ULTRABAR™ for Screw Machining Medical and Other Precision Parts

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Additive manufacturing process notes

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 "bum" the surface and produce alpha case. Kroll's reagent (1 to 3% hydrofluoric acid plus 2 to 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 bifluoride solution that stains the entire sample with the exception of any alpha case. Some typical microstructures are illustrated below.

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For additional information, please contact your nearest sales office:
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