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FOCUS: MAKING MEDICAL PARTS

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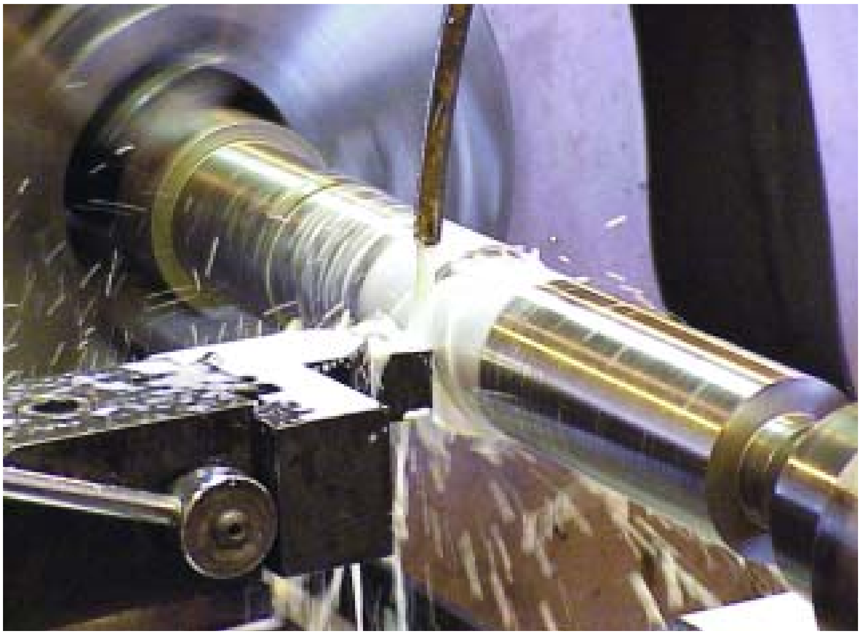
Medical Advice

Cutting tool considerations for effectively machining titanium medical parts.

Titanium's high strength and low weight make it desirable for many industries. The material's immunity to corrosion, resistance to crack propagation and capacity for fusing with bone and tissue make titanium parts ideal for implantation into the human body and for other medical purposes.

Similar to other high-performance metals, the mechanical and physical properties that make titanium parts attractive also cause titanium and its alloys to be classified as "difficult to machine." Titanium's low thermal conductivity tends to cause heat to build up on the edges and faces of cutting tools, its springiness permits greater workpiece deflection and its chemical reactivity with cutting tools contributes to galling and seizing. But once titanium's unique characteristics as a workpiece material are accounted for, the proper cutting tools and accessories are selected and the appropriate machining parameters are set, its stigma as being difficult to machine fades—to a point.



TIMET

Use a generous amount of cutting fluid when machining titanium to carry away heat and prevent workpiece ignition.

Small Differences

Machining titanium medical devices isn't much different than machining other titanium parts where specifications include tight tolerances, fine surface finishes and aesthetically pleasing appearances. Many medical parts are tiny and produced on Swiss-style machines using small cutting tools. Such tools are numerous and additional offerings are on their way.

As the tools get smaller, having adequate chip clearance becomes a bigger issue. "Enough clearance for the chip is needed so you don't get chip packing," said P.J. Agnew, product specialist for solid-carbide endmills at Irvine, Calif.-headquartered Mitsubishi Materials USA Corp.

He added that the toolmaker plans to introduce a line of Swiss-style tools. "We have endmills that go down to 0.1mm, which are pretty small but able to tackle a lot of the parts for the dental and medical fields. Of course, when you get that small, those light DOCs also play a part in making sure you don't chip pack."

Making the Grade

The grade of titanium can also distinguish medical parts from those for other industries. Bill Cox, president of Cox Manufacturing Co., a San Antonio producer of medical implants and instruments, said his company frequently machines Ti-6Al-4V-ELI, a surgical grade. Similar to part sizes, the difference in machining various grades is more a shade of gray than black and white. Cox noted that, if anything, surgical-grade titanium machines more consistently than other titanium alloys. "But we've never seen a problem with consistency in titanium. It's all consistently difficult to work with," he quipped.

Commercially pure grades are also used for making devices such as orthopedic hip- and knee-joint implants. According to Titanium Metal Corp. (TIMET), Henderson, Nev., the mechanical properties of CP titanium are influenced by small additions of oxygen and iron. The titanium supplier's CP grade with the lowest oxygen and iron levels is the most formable, and higher oxygen content corresponds to higher strength levels.

Titanium tends to produce stringy chips, so Bob McFarland, TIMET's senior research machinist, recommends applying a cutting tool that has a chipbreaker that can effectively control chips.

According to Chris Wills, Mitsubishi Materials' turning product specialist, such a chipbreaker has a 12° to 20° variable rake angle. The chipbreaker should also have curved cutting edges for smooth chip discharge at varying DOCs and a flat land to strengthen the cutting edge or double rake angles (25° and 15°) to reduce cutting resistance by decreasing the contact area for the rake face and chips.

McFarland added that a tool with a positive rake provides a smoother cutting action when machining titanium than a cutter with a negative rake, which has a tendency to cause the material to drag over the tool face.

An endmill with Unimerco's tangential UM-Wave form breaks up harmonics as it forms and evacuates chips. In addition, rigid tools with a solid body up to the point where chip evacuation is needed and short flute lengths help break up harmful harmonics when milling.

Unimerco

A tool with a positive rake "gets underneath the surface," McFarland explained. "Titanium has a tendency to workharden if you don't get below the surface while machining. The positive rake gives the tool more of a knife edge."

And a sharp leading edge is just what the doctor ordered for titanium operations. Such an edge reduces the amount of tool pressure and tool wear, Wills said. He said the toolmaker starts with a radius of 0.002", but tools are available without any edge radius.

Going too sharp can cause problems, though, especially when applying carbide cutting tools, because geometries that are too sharp and too positive create an overly brittle edge. David Fujioka, cutting tool engineer for Saline, Mich., toolmaker Unimerco Inc., explained that chipping is the most common failure mode for carbide tools because titanium has a high fracture toughness and is abrasive. To prevent chipping, "try to not use up-sharp cutting tools," he said. "You want some radius to strengthen the tip."

Even if the geometric requirements are correct, Wills emphasized the importance of applying G-class inserts, with all ground surfaces, rather than lower cost molded inserts.

Learn not to Burn

Because titanium is a poor conductor of heat, the heat generated during cutting does not dissipate quickly. Therefore, the concentration of heat buildup on the cutting edge accelerates edge and corner wear. To keep the heat down, Fujioka said "you want to minimize the cutter's radial immersion, or engage-

To machine or not to machine?

Instead of hogging titanium to produce an orthopedic implant, some titanium medical parts are forged. "Some forged parts require zero machining," said Jeff Speicher, vice president of marketing for FPD Co.

The McMurray, Pa., company uses 4-axis horizontal and vertical machining centers with quick-change pallet systems and subspindle milling lathes to machine hip and knee replacements, and mechanical and hydraulic presses to produce precision forgings.

Speicher said FPD is unique in that it has grown its machining and forging technologies together throughout the company's quarter century of existence. "We have core competencies in both."

Having expertise in both areas allows FPD to determine and select the lowest cost method for producing a part: machining it, forging it or a combination of both. Speicher explained that determining the most cost-effective approach is based on the part's material requirements, geometric features and annual volume. For example, precision forgings are easier to justify for high volumes, since the tooling costs for forgings are high.

He added that machining can achieve tighter tolerances to "tenths or millionths. With a forging, plus or minus two to three thousandths is as good as you can get," Speicher said. Also, "we can go to a mirror finish."

Although titanium medical parts are produced on the same machines with the same cutting tools as titanium parts for other industries such as aerospace, which makes up the majority of FPD's work, Speicher said medical devices often have more complex curved surfaces. "There are very few planar surfaces." Because of this, medical parts require a lot of ballnose endmilling with small and rapid incremental moves, removing a little amount of metal per pass, which generate long CNC programs.

—A. Richter

ment. You want the flute out of the cut more than in it to give it time to cool."

He recommends reducing the radial DOC to 0.1 times the tool diameter or less to reduce the radial engagement. "Also, avoid slot, or channel, milling whenever possible," Fujioka said. Once the radial engagement is reduced, the axial DOC can be increased to maximize the material removal rate.

In addition to shortening tool life and workhardening the material, the heat generated can raise safety issues, depending on the type of cutting fluid being applied. "It can, if you're running an oil-based product, generate enough heat to start a fire," warned Cox. He added, however, that Cox Manufacturing does use an oil-based cutting fluid exclusively when machining titanium, as well as the other metals.

4 Axis Machining Inc. is another manufacturer of medical devices that applies oil-based fluids when machining titanium. "We use water-based coolants, but oil works the best," said Bob Nickerson, president of the Denver-based company. "It's my first choice, since tool life is 10 times better."

Nickerson also noted that many of the company's machines are set up to use soluble oil and he doesn't want to switch the cutting fluid to machine titanium. "If the chip doesn't get too small, you won't have a fire."

Although oil-based fluids extend tool life, TIMET's McFarland recommends using a water-soluble fluid because it's more important to cool titanium than lubricate it. A water-based fluid's cooling properties not only help to prevent workpiece ignition, but a cooler titanium workpiece is easier to machine, especially when holemaking.

Cox Manufacturing

These spinal implant devices are made of Ti-6AI-4V-ELI and machined complete on a 12-axis Tornos Deco machine.

The following companies contributed to this report:

Cox Manufacturing Co.
(800) 900-7981
www.comaco.com

4 Axis Machining Inc.
(303) 295-1544

FPD Co.
(724) 941-5540
www.fpdinc.com

Mitsubishi Materials USA Corp.
(800) 486-2341
www.mitsubishicarbide.com

Titanium Metals Corp.
(702) 564-2544
www.timet.com

Unimerco Inc.
(734) 944-4433
www.unimerco.com

Unlike steel, titanium doesn't expand during machining. "It has a tendency to grab a hold of the drill bit, so you need to cool it as much as possible," McFarland said. "As far as drilling goes, you need to use copious amounts of water-soluble fluid."

Tool Talk

Titanium's tendency to workharden is generally not a problem as long as the tools cut below the workhardened layer. Problems arise when not enough material is left for the finishing pass.

The only real difference with titanium in terms of workhardening is when removing less than 0.010" of material from drilled holes, explained McFarland. "There is that much of a workhardened layer after you've machined it. That's why when doing a finish pass, you want to do at least 0.010", preferrably 0.015", to get under that workhardened layer."

When milling, McFarland said that conventional, or up, milling is the preferred method because it's most effective for removing metal with a sharp edge. Climb, or down, milling, on the other hand, involves plunging into the workpiece and the tool "grabs a hold of the titanium and pulls it in instead of cutting it nice and smooth," he said. "The only time I've ever used climb milling was for finishing."

Mitsubishi Materials' Agnew disagrees. "We recommend climb milling, because tools start to wear out a lot quicker if you up-cut, so to speak, because you're going from a thin to a thicker chip," he said. "Basically, the tool is rubbing, causing premature tool wear."

Unimerco's Fujioka agrees that climb milling is better than conventional milling for machining titanium. "Ninety percent of the time climb milling is preferred," he said. He added that climb milling, unlike conventional milling, prevents workhardening.

Ensuring a uniform tool deflection is also key to prolonging cutter life and increasing part quality. According to Fujioka, "all tools deflect." Minimizing and controlling the amount of tool deflection falls into his category of "milling smarter, not harder."

In addition, interpolating corners and engaging the cutter gradually by ramping in, arcing in or engaging helically—to avoid "shocking the tool"—are techniques Fujioka recommends.

Tool coating is another aspect of machining titanium that generates a variety of opinions. Nickerson said the majority of the 7-diameter, carbide endmills 4 Axis Machining applies are coated with titanium carbonitride to extend tool life and help prevent breakage.

However, cutting the springy material with uncoated tools isn't unheard of. McFarland said TIMET's technical laboratory generally uses uncoated tools, since the titanium being machined usually has the alpha case layer, an abrasive layer produced during heat treatment. "The coating on most carbide tools would be smeared right off, rendering it ineffective," he said. But he added that tools coated with titanium aluminum nitride, which are common in production environments, withstand heat buildup.

Others favor the AlTiN coating with its higher aluminum content.

Whether it's titanium nitride, TiCN, TiAlN or AlTiN, Unimerco's Fujioka stated titanium-based physical vapor deposition coatings rarely provide any benefit, due to the high affinity titanium has to itself at elevated temperatures. He added that there hadn't been any suitable coating for machining titanium

Tool geometries and parameters for machining titanium

Recommended tool geometries for rough turning and interrupted cutting of titanium

Tool geometries	Carbide tools	HSS tools
Back rake	-5° to 5°	0° to 5°
Side rake	-8° to 0°	0° to 15°
Side cutting edge	5° to 25°	6° to 15°
End cutting edge	6° to 10°	5° to 6°
End relief	5° to 10°	5° to 7°
Side relief	5° to 10°	5° to 7°
Nose radius	0.03" to 0.045"	0.02" to 0.03"

Recommended machining parameters for rough turning and interrupted cutting of titanium

	Commercially pure	Annealed alloys	Heat-treated alloys
Carbide tools	100-240 sfm	75-120 sfm	50-95 sfm
	0.008-0.015 ipr	0.008-0.015 ipr	0.008-0.015 ipr
	> 0.100" DOC	> 0.100" DOC	> 0.100" DOC
HSS tools	25-124 sfm	25-60 sfm	10-50 sfm
	0.004-0.050 ipr	0.004-0.015 ipr	0.004-0.015 ipr
	> 0.100" DOC	> 0.100" DOC	> 0.100" DOC

Recommended tool geometries for finish turning of titanium

Tool geometries	Carbide tools	HSS tools
Back rake	0° to 5°	0° to 5°
Side rake	0° to 15°	0° to 5°
Side cutting edge	0° to 20°	5° to 6°
End cutting edge	6° to 10°	5° to 6°
End relief	5° to 10°	5° to 7°
Side relief	5° to 10°	5° to 7°
Nose radius	0.030" to 0.045"	0.020" to 0.030"

Recommended machining parameters for finish turning of titanium

	Commercially pure	Annealed alloys	Heat-treated alloys
Carbide tools	200-350 sfm	100-300 sfm	75-275 sfm
	0.003-0.012 ipr	0.003-0.012 ipr	0.003-0.012 ipr
	0.003"-0.030" DOC	0.003"-0.030" DOC	0.003"-0.030" DOC
HSS tools	76-160 sfm	45-60 sfm	30-50 sfm
	0.002-0.005 ipr	0.002-0.005 ipr	0.002-0.005 ipr
	0.003"-0.030" DOC	0.003"-0.030" DOC	0.003"-0.030" DOC

Recommended tool geometries for milling titanium

Tool geometries	Carbide tools	HSS tools
Radial rake	-10° to 0°	0°
Axial rake	-10° to 0°	0°
Face or end cutting edge	6°	0°
Peripheral cutting edge or corner angle	60°	30°
Face relief	12°	12°
Peripheral relief	12°	12°
Chamfer	0° to 45°	0° to 45°
Nose radius	0.040" to 0.125"	0.040" to 0.125"

Source: TIMET

Recommended machining parameters for milling titanium

	Commercially pure	Annealed alloys	Heat-treated alloys
Carbide tools	160-190 sfm	80-120 sfm	55-95 sfm
	0.004-0.008 ipt	0.004-0.008 ipt	0.004-0.008 ipt
	facemill up to 0.050" DOC	facemill up to 0.050" DOC	facemill up to 0.050" DOC
	slabmill up to 0.100" DOC	slabmill up to 0.100" DOC	slabmill up to 0.100" DOC
HSS tools	80-110 sfm	40-70 sfm	25-60 sfm
	0.003-0.006 ipt	0.003-0.006 ipt	0.003-0.006 ipt
	facemill up to 0.050" DOC	facemill up to 0.050" DOC	facemill up to 0.050" DOC
	slabmill up to 0.100" DOC	slabmill up to 0.100" DOC	slabmill up to 0.100" DOC

Recommended tool geometries for general and deep-hole drilling of titanium

Tool geometries	Carbide tools	HSS tools
Point (< ¼" dia.)	single hip	140°
Point (¼" to ½" dia.)	gundrill	90° or double angle
Helix	—	28° to 35°
Relief	6° to 8°	9° to 10°

Recommended machining parameters for general and deep-hole drilling of titanium

	Commercially pure	Annealed alloys	Heat-treated alloys
Carbide tools	200 sfm	100-170 sfm	75-145 sfm
(deep-hole only)	0.005 ipr	0.005 ipr	0.005 ipr
HSS tools	40-60 sfm	20-50 sfm	5-40 sfm
(< ⅛" dia.)	0.0015 ipr	0.0015 ipr	0.0015 ipr
(⅛" to ¼")	0.002-0.005 ipr	0.002-0.005 ipr	0.002-0.005 ipr
(¼" to ½")	0.005-0.009 ipr	0.005-0.009 ipr	0.005-0.009 ipr

Recommended tool geometries for tapping titanium (T-1 HSS)

Tool geometries	
Spiral point	10° to 17°
Spiral	110°
Relief	2° to 4°
Cutting rake	6° to 10°
Heel rake	-3°
Chamfer	5 threads
Number of flutes	
(¼-20 and less)	2
(over ¼-20)	3

Recommended machining parameters for tapping titanium (T-1 HSS)

Commercially pure	Annealed alloys	Heat-treated alloys
40-50 sfm	10-20 sfm	5-20 sfm

until Unimerco developed its C7 nanocomposite coating for titanium and nickel-base superalloys, or “nastyloys,” as Fujioka refers to them. The company says the coating is comprised of minute ceramic particles embedded into an amorphous matrix and can triple the cutter life when machining titanium.

Developed within the last year, Fujioka said the tough C7 coating is 40 percent harder than TiAlN and AlTiN coatings—and can withstand temperatures up to 1,000° C compared to 800° C for AlTiN and TiAlN. This makes the coating more suitable for dry machining, he said.

Minimizing heat generation is critical to machining titanium productively and profitably. That can be accomplished by selecting the proper cutting tools and machining parameters, rendering titanium, the fourth most abundant element in the Earth’s crust, no longer exotic or difficult.