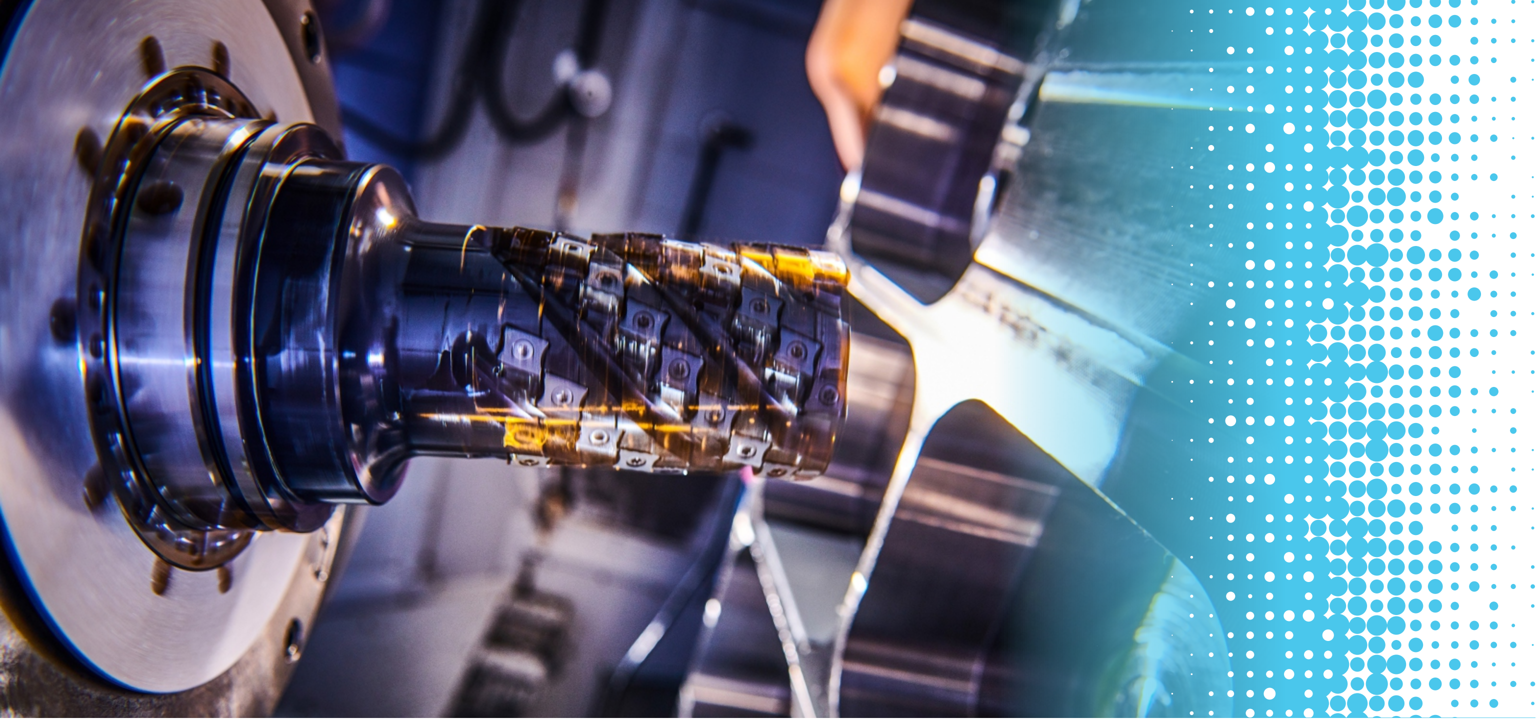

Machining Titanium - Part 1

Things to Consider When Machining Titanium

MAKINO

Things to Consider When Machining Titanium

Titanium Applications

- Aerospace
  - Aircraft and Engines
- Automotive
  - Engine and Structural Components
    - Valve Trains, Connecting Rods, Structural Braces
    - Z06 Performance Exhaust
- Apparel
  - Eyeglasses, Necklaces, Earrings,
  - Watches and Jewelry
- Marine
  - Ships / Submarines
    - Structural
    - Propulsion Components
- Medical
  - Implants
    - Orthopedic / Dental
- Recreational
  - IBicycle Frames, Golf Clubs, Tennis Rackets, Motorcycles, etc.

Titanium Grades

α	Pure Titanium (Grade 1-4)	Medical Heat Exchangers
	Ti-5Al-2.5Sn	Airplane (Hydrolic Pipes)
Near α	Ti-6Al-2.5Sn-4Zr-2Mo	Airplane (Compressor Disk)
α–β	Ti-6Al-4V	Airplane (Wing Box)
	Ti-10-V-2Fe-3Al	Airplane (Landing Gear)
Near β	Ti-6Al-2Sn-4Zr-6Mo	Airplane (Compressor Blade)
β	Ti-15V-3Cr-3Sn-3Al	Airplane (Duct)
	Ti-5Al-5Mo-3Cr	Airplane (Landing Gear)

Things to Consider When Machining Titanium

Titanium Properties Which Impact Machining Behavior

In general, to a greater or lesser extent, all titanium grades exhibit the following characteristics:

- Low thermal conductivity

  Cutting heat cannot dissipate and the cutting temperatures increase rapidly.

- Strong alloying tendency and chemical reactivity with tool materials

  Chemical reactions can weaken the cutting tools.

- Low Young's Modulus (a measure of elasticity)

  Deflection or chatter will occur easily when machining thin-walled parts.

- Serrated Chips

  Chatter or abnormal tool wear will occur due to change in cutting forces with chip formation.

- Small contact area between the chip and the tool

  Cutting forces will concentrate at the edge and rapid tool wear or chipping will occur easily.

Titanium Alloy Ti 6Al-4V

Ti 6Al-4V (also known as "Grade 5" titanium) is the most common titanium alloy, making up about 50% of all global titanium consumption. When machinists refer to issues with titanium, they are usually referring to this alloy.

Design Characteristics of Ti 6Al-4V

Designers love using titanium because of its material characteristics. These characteristics not only solve a multitude of design problems, they particularly make titanium an excellent choice for aerospace components, medical prosthetics, tools, high-performance auto parts, and even sporting equipment such as racing bicycles and golf clubs. It is also a superb choice for use in corrosive environments such as food production, chemical processing, and marine applications.

While it is the most appropriate material in these applications, it is also one of least machinable materials. The old saying "strong as steel, light as aluminum" continues to draw designers toward titanium, as even though that saying sounds good, it doesn't hold entirely true with aerospace applications. Ti 6Al-4V is actually 10-30% weaker than typical aerospace steels and about 60% heavier than typical aerospace aluminum alloys.

Things to Consider When Machining Titanium

Machining Characteristics of Ti 6Al-4V

When deciding whether to make a part out of Ti 6Al-4V, there are four important characteristics to consider—strength, thermal conductivity, modulus of elasticity, and shear mechanism.

High Tensile Strength: Titanium alloys are metals that contain a mixture of titanium and other chemical elements. While not as robust as high strength steel, such alloys have a very high tensile strength and toughness (even at extreme temperatures).

Low Thermal Conductivity: Thermal Conductivity is a measure of how fast a material can transfer heat—and Ti 6Al-4V's thermal conductivity is low. Think about the insulation in your house. You want a low thermal conductivity in the insulation so that the heat stays in your home and isn't "conducted" out through the walls.

Figure 2 shows how Ti 6Al-4V measures up to other common metals regarding thermal conductivity. Thermal Conductivity is rarely discussed in machining because in the world of aluminum and steel machining it is rarely of significant consequence. In the world of metals, however, titanium is much more an insulator of heat as opposed to a conductor.

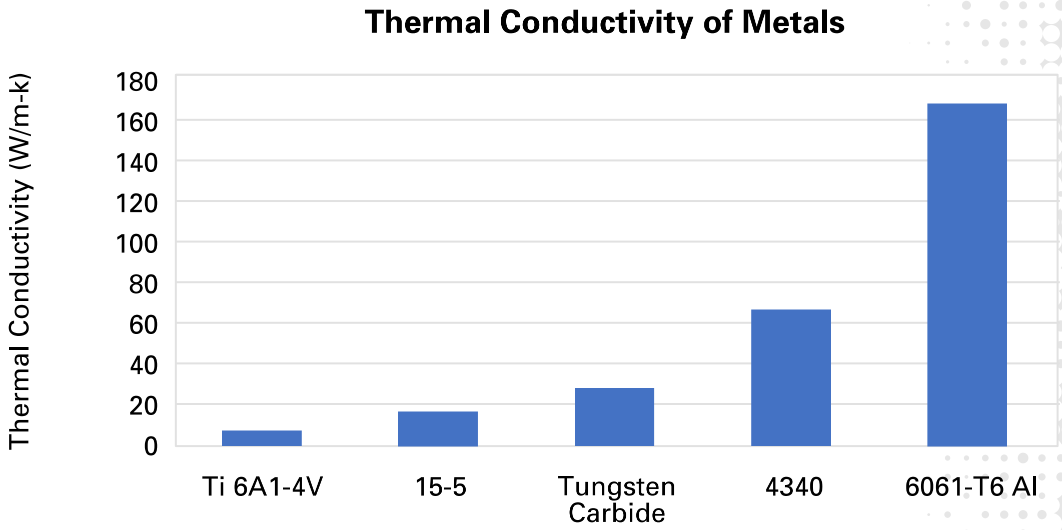

Figure 2. Thermal conductivity of metals

So why is low thermal conductivity relevant to machining titanium?

During the machining process, a lot of "mechanical work" is being done to deform the material and turn it into chips. The chip-making process converts the bulk of the energy supplied by the spindle into heat, which leaves the cutting zone by being absorbed into the chips or into the workpiece itself (see Figure 3). Since Ti 6Al-4V doesn't conduct heat energy very well, the energy finds the path of least resistance and conducts into the cutting tool instead.

Things to Consider When Machining Titanium

High Modulus of Elasticity:

Ti 6Al-4V also has a high modulus of elasticity, which means that the material is very springy. This springiness makes it hard to aggressively cut titanium with traditional tools. Thin walls push away from the cut very easily and create chatter. Even solid sections of material push away from the cutting tool, creating vibration on a micro level. This can often be seen in the machining chips. If your titanium chips are not smooth, you are likely hammering the cutting edge as each chip is formed.

Shear Mechanism:

Ti 6Al-4V doesn't fracture like irons and many steels. It needs to be sheared apart like gummier materials such as aluminum or magnesium in order to avoid built-up-edge (BUE) conditions on the cutting tool. Built-up edge is a condition that occurs when the metal being machined begins to weld or attach to the cutting edge. Built-up edge increases the cutting forces and will eventually result in damaged cutting edges as the built-up material breaks off and takes pieces of carbide with it.

Issues Related to Ti 6Al-4V's Unique Characteristics:

Both the high modulus of elasticity and the shearing mechanism characteristic of Ti 6Al-4V dictate that machinists use sharp, smooth tools with aggressive rake angles and high relief angles to avoid tearing or smearing the titanium workpiece material. Machining a high-strength material with a sharp-edged tool—where the low thermal conductivity is driving the heat into the edge of the tool and the springy material is beating the cutting edge like a jackhammer—results in very poor tool life.

Using A Multi-Faceted Approach for Profitably Machining Titanium

A manufacturer cannot successfully machine Ti 6Al-4V by addressing only one of its challenges. For example, even a machine that addresses the heat and strength issues by use of a high-torque, low-speed spindle could leave a manufacturer at the mercy of vibration conditions, chip clearing, and possible chip-packing due to inadequate through-spindle coolant.

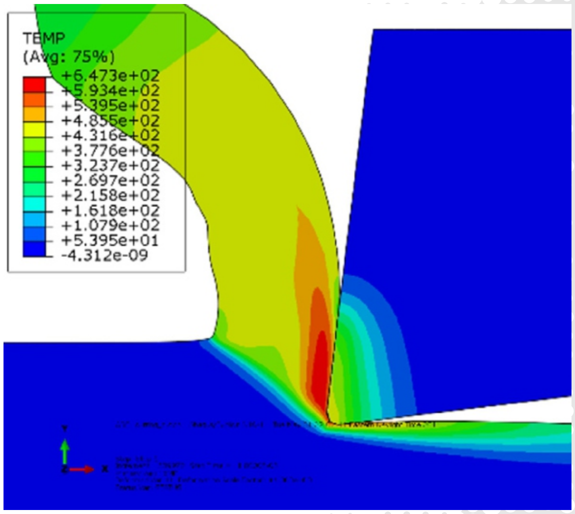

Figure 3. Heat map illustrating the concentration of heat on the tool edge during machining

Just as addressing only a single characteristic of Ti 6Al-4V doesn't provide a solution, neither does addressing just a machine or just a process. Both the proper equipment and the proper processes are required to achieve success. In order to leap ahead of the crowd, savvy manufacturers are buying machines and using processes that are designed specifically to handle the challenges associated with Ti 6Al-4V.

The Right Machines:

Utilizing machines that are designed for the specific purpose of machining titanium and other hard metals plays a crucial part in determining profitability for a manufacturer.

Although Makino has many machines which may be configured for titanium applications, the T-series machines were designed specifically with titanium in mind. Makino took a holistic, balanced approach in these machine designs. The larger T2 and T4 machines offer 1,000-Nm (787 ft-lb), continuous, high-torque, HSK 125 spindles; 12-inch-wide guideways; large cast structures; and 1,000-psi, 53-gallon-per-minute through-spindle coolant. These T-series machines effectively address all the limitations and risk factors associated with machining titanium.

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(Makino's purpose-built philosophy has now expanded to support cases, covers, blocks, and blades.)

Many titanium parts often require simultaneous 5-axis tool paths to create their complex geometries. This means that all the rigidity, high-spindle torque, and large volumes of through-spindle coolant need to be applied to a part following a continuous 5-axis tool path. Makino's proprietary Super Geometric Intelligence (SGI)—a collaborative Makino/Fanuc contouring technology— allows Makino's 5-axis T-series machines to efficiently provide superior part roughing and finishing when cutting difficult materials.

The Right Processes

Although using the right machine might be most important consideration, without the use of equally effective processing techniques, even the best machines offer only a partial solution. By using the most up-to-date processing techniques, manufacturers will thrive in this difficult machining environment. In the following paragraphs we will discuss four of these techniques:

- Using the correct type of coolant
- Eliminating chip recutting
- Reducing the cutting speed
- Reducing the radial engagement of a tool

The Correct use of Coolant

As we know, titanium's low thermal conductivity creates a cutting-speed limit. This in turn requires that the machine tool must have a high-torque capability at a lower speed.

In order to protect and cool each individual insert and cutting edge, it is critical that manufacturers support the machining process with large volumes of coolant at a high pressure. Typical machines supply through-spindle coolant tools with only 3-8 gallons of coolant per minute. This low coolant volume manages to get the tools wet, but when driving large tools at high torque values, a significant amount of energy (heat) is generated; requiring a lot of coolant to remove that heat. Makino's T2 and T4 machines, however, supply through-spindle coolant tools with a massive 53 gallons of coolant per minute, at 1,000 psi.

The type of coolant can have a significant impact on tool life as well. Many users are looking for coolant that can prevent foaming issues with high-pressure systems, minimize rancid smells, and remain stably emulsified in the coolant tank. While these are all important requirements for coolant, they are not adequate criteria for evaluating coolant for use in the titanium machining process.

Makino discovered through internal R&D testing that different types of coolant provide highly varying levels of tool life. The effect was so significant that Makino designed a special test for evaluating how coolant type affects tool life. To date, Makino has tested over 100 types of coolant—and discovered that cutting-tool life can vary drastically (from 10 to 90 minutes) simply by changing the type of coolant.

Things to Consider When Machining Titanium

Eliminating Chip Recutting

In the manufacturing of aerospace parts from billets or forgings to have a very high "buy to fly" ratio, it is not uncommon for 95% of the material to be removed going from raw material to finished part. When machined on a vertical machining center (VMC), this results in massive piles of chips that accumulate around the cutting tool and on top of the part. Recutting even a few of these chips can instantly damage cutters. To avoid this costly situation, manufacturers often have an operator stationed at the machine to periodically interrupt the cycle and clear away chips. However, this frequent stopping of the process is ineffective as it is nearly impossible for the operator to adequately protect the tool from recutting chips and this delay also reduces productivity.

The risk of recutting chips has prevented many manufacturers from taking advantage of the carbide tooling made specifically for cutting titanium, as the brittle nature of the carbide is very susceptible to damage from recutting chips. Therefore, many manufacturers still use high-speed steel tools which have a higher toughness and are less likely to chip and crack when recutting chips. However, use of these tools significantly decreases productivity since high-speed steel tools are typically run at one third, or less, of typical carbide tool speeds.

Horizontal machining centers (HMC's) let "gravity be your friend" and are an excellent choice for machining titanium because they provide outstanding chip-management capability — ensuring that as the chips are ejected from the cutting area, they fall away from the part. This efficient chip-shedding is enhanced by the 53-gallons-per-minute through-spindle coolant, as well as an additional 26-gallons-per-minute of nozzle coolant (see Figure 4), which provides additional tool cooling and chip removal.

Reducing the Cutting (Surface) Speed

There is a limit on cutting speed when machining titanium. Exceeding this limit drastically reduces cutting tool life. Due to the low thermal conductivity of the workpiece material, heat builds up on the cutting edge, which weakens the cutting tool material. Since this heat generation is proportional to the cutting speed being used, the most effective way to correct the issue is to slow the cutting speed down. (The speed for tungsten carbide tooling is typically reduced to 50 m/min to effectively rough machine Ti 6Al-4V.)

Figure 4. T4 machine high-flow coolant systems

Things to Consider When Machining Titanium

Reducing the Cutting (Surface) Speed

Under lab conditions, with a light tool engagement and plenty of coolant, using a speed of 50 m/min (165sfm) is a safe place to start roughing and should provide 30-45 minutes of tool life. However, in real-world machining conditions, tool life is often shortened due to changing part geometries which necessitate multiple transitions into and out of heavier and lighter cuts. Accelerated weakening or chipping of the cutting edges due to workpiece or machine vibrations, re-cutting chips that were not cleared by the coolant, and cutting edges being periodically starved of coolant in deep pockets or corners of the part can significantly shorten tool life as well.

By applying proper machining techniques, not only can these additional challenges be overcome, but the speed may be increased to 65 or 70 m/min. Running this fast without the proper machine and processes can cause tool life to drop from 60 minutes to 15 minutes with very little warning.

Running at a low cutting speed results in low rpm—which can be a challenge for many machines because they do not have enough torque available at low rpms to drive the tools at the torque required for machining titanium. This means that manufacturers are often forced to reduce the cutter engagement—thus sacrificing productivity in order to keep on machining. Makino's high-torque spindles address this challenge by providing 1,000 Nm of torque up to 1,000 rpm, which is a unique offering in the market. Figure 5 displays a typical chart for a high-torque motor, showing the relationship between power and torque.

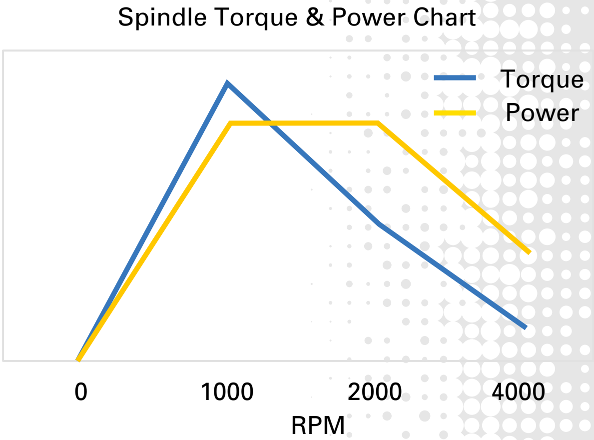
Spindle Torque & Power Chart

Figure 5. High torque spindle torque and power curves

Reducing the Radial Engagement of the Tool

Another way to reduce the temperature of the cutting edge is to reduce the radial engagement of the tool (see Figure 6). Large radial engagements in milling increase the amount of the time that the tool is engaged in the titanium material, which results in high cutting-edge temperatures. In order to protect against early tool failure, as well as maintain a profitable metal-removal rate, the radial engagement must be decreased, and the axial engagement increased.

This claim may seem counter-intuitive since many machinists have found they can improve tool life by reducing the axial engagement. However, this improvement is actually due to reducing the cutting forces and the bending moment (see sidebar) created on the tool, which results in improved stability of the machining. It is not related to the heat experienced on the cutting edge. Increasing the axial engagement is not detrimental to tool life if the process does not exceed the stability and stiffness of the machine tool.

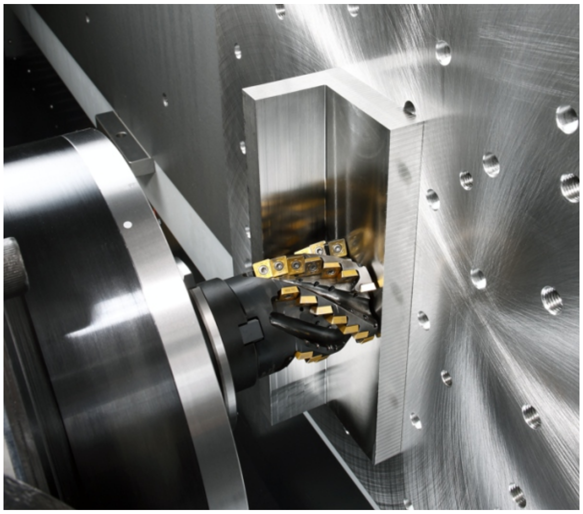

Figure 6. Long-edge cutter with deep axial engagement

There are many tool-to-spindle interface designs and sizes available in the market. The most popular are CAT, BT or HSK style. Each of these styles are available in multiple sizes. Each of these available tool taper style/size combinations has an associated bending moment limit. The bending moment for a machining operation can be approximated by multiplying the cutting forces by the gage length. Each bending moment limit creates a very real limit on what maximum material removal rate (MRR) that can be achieved, it is vital that machinists understand this limitation. To learn more about the importance of bending moment, please see **"Machining Titanium: Part 2 — Understanding Bending Moment."**

Reducing the Cutting (Surface) Speed

Some machine builders have lost sight of the goal of successful machining. By adding high-torque spindles to existing machines, they have created imbalanced platforms that are unable to support the cutting forces created by their spindles. Finding a balance in the cutting parameters and using the right machine to optimize those parameters is crucial.

In Conclusion

Although machining Ti 6Al-4V presents unique and formidable challenges, these challenges can be greatly reduced—and even eliminated—by understanding them thoroughly and using the right machines and processes.