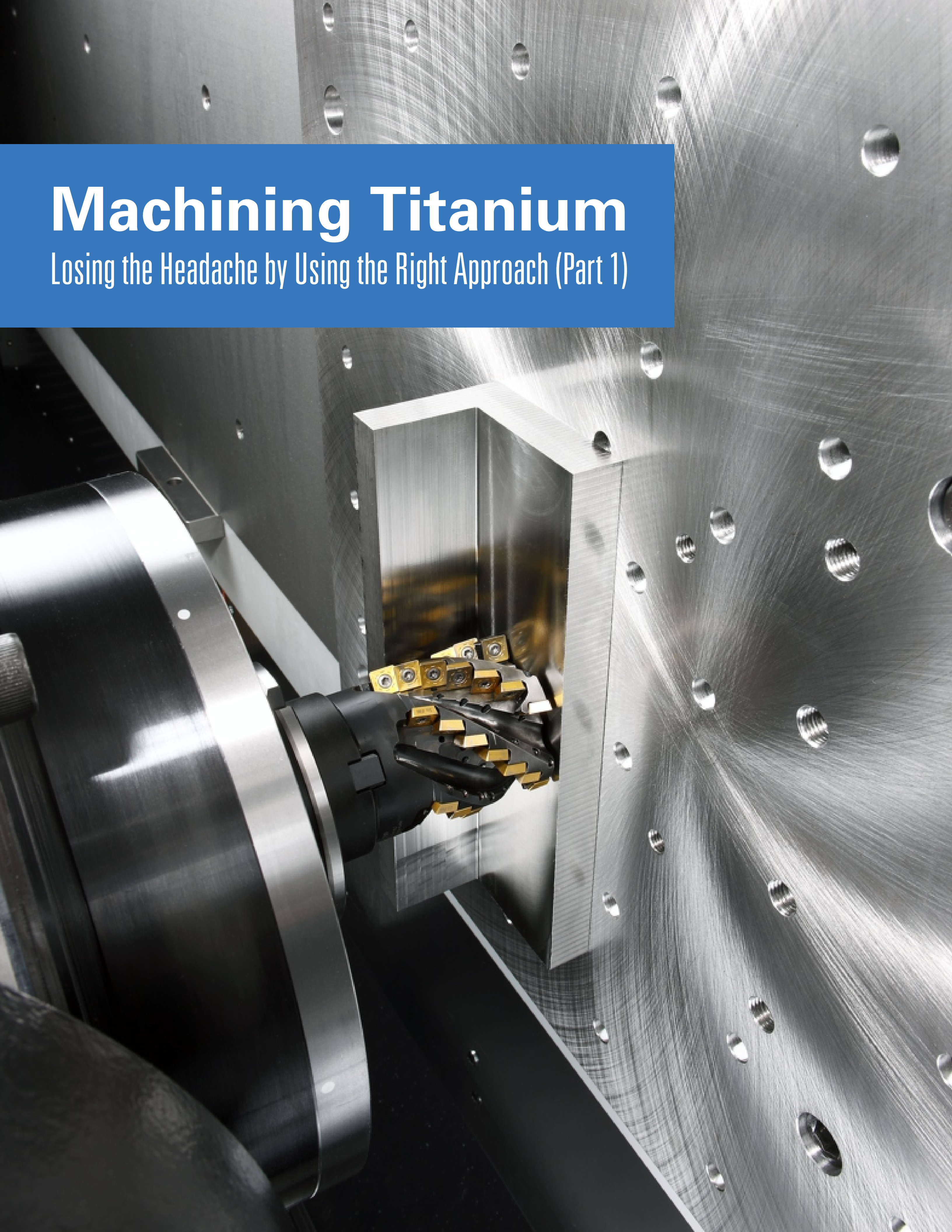
Machining Titanium

Losing the Headache by Using the Right Approach (Part 1)



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Titanium Alloy Ti 6Al-4V

If you are reading this white paper, it's likely that you have either heard about or experienced first-hand the challenges associated with machining titanium. You probably know all too well that its unique characteristics combine to create a perfect storm of machining challenges!

When machinists refer to issues with titanium, they are often actually referring to a specific titanium alloy called Ti 6Al-4V (also known as "Grade 5" titanium). Ti 6Al-4V is the most common titanium alloy; it makes up about 50% of all global titanium consumption.

Design Characteristics of Ti 6Al-4V

Designers love using titanium just as much as machinists hate machining it. The old aphorism "strong as steel, light as aluminum" continues to draw designers toward titanium, even though (as shown in Figure 1) that saying isn't exactly true. Ti 6Al-4V is actually 10-30% weaker than typical aerospace steels and about 60% heavier than typical aerospace aluminum alloys.

Even so, there are valid reasons for choosing titanium. Its strength-to-weight ratio is impressive, and it has excellent flexibility and toughness, as well as the ability to maintain strength at high temperatures. Additionally, its outstanding chemical inertness allows it to resist oxidation such as rust and corrosion.

These characteristics not only solve a multitude of design problems, they 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.

Machining Characteristics of Ti 6Al-4V

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

Low Thermal Conductivity (W/m-K): 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

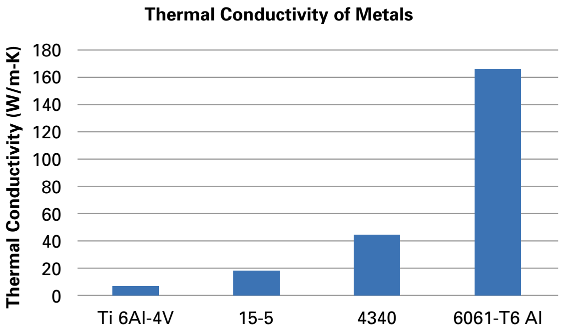


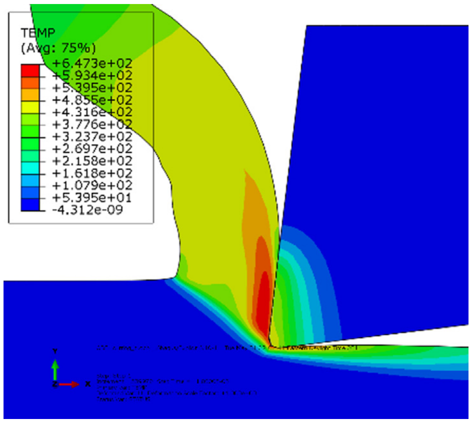
Figure 1. Comparison of Material Properties

	Grade 2	Ti 6Al-4V	4340	15-5	6061-T6 Al	7075 Al-T6
Density (g/cc)	4.55	4.43	7.85	7.8	2.7	2.81
UTS (Mpa)	345	950	1110	1438	310	572
Yield Strength (MPa)	275	880	710	1385	276	503
Elongation at Break (%)	20	14	13.2	9.4	12	11
Modulus of Elasticity (GPa)	105	113.8	205	200	68.9	71.7
Thermal Conductivity (W/m-K)	16.4	6.7	44.5	17.9	167	130
Specific Heat (j/g-°C)	0.523	0.5263	0.475	0.42	0.896	0.96

So why is low thermal conductivity relevant to machining titanium? First we must remember the definition of "work" from our high school physics class, which is: Work is a measure of energy expended over time.

During the machining process, a lot of work is being done to deform Ti 6Al-4V 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.

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



High Modulus of elasticity (GPa): Ti 6Al-4V also has a high modulus of elasticity, which means that the material is very springy. As you have probably experienced, 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 conditions on the inserts. Built-up edge (BUE) 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. Sound familiar?

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.

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 Ti 6Al-4V plays a crucial part in determining profitability for a manufacturer,

Makino has taken a holistic, balanced approach in the design of the T-series machines. These machines offer a 1000-Nm (787 ft-lb), continuous, high-torque, HSK 125 spindle; 12-inch-wide guideways; a large cast structure; and 1000-psi, 53-gallon-per-minute through-spindle coolant. The T-series machines effectively address all of the limitations and risk factors associated with machining titanium. (Makino's purpose-built philosophy has now expanded to support cases, covers, blocks, and blades.)

It is also important to remember that the geometry of titanium parts often requires complex simultaneous 5-axis tool paths. That means that all the rigidity, the high-spindle torque, and the large volumes of through-spindle coolant need to be applied to a part in a continuous 5-axis tool path. Equipped with Super Geometric Intelligence (SGI)—a collaborative Makino/Fanuc contouring technology— Makino's 5-axis T-series machines provide both superior roughing and superior finishing for this infamously challenging material.

The Right Processes

So now we understand the importance of using the right machine. However, without the use of equally effective processing techniques, even the best machines offer only a partial solution. Using the most up-to-date processing techniques are enabling manufacturers to thrive in this difficult machining environment. In the following paragraphs we will discuss four of them:

- 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, Ti 6Al-4V's low thermal conductivity creates a cutting-speed limit. This in turn requires that the machine tool have a high-torque capability to drive the cutter through the material at a low 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 is created—and it takes 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 1000 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.

Eliminating Chip Recutting

In the manufacturing of aerospace parts, it is typical for 95% of the material to be removed. 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 (it is nearly impossible for the operator to adequately protect the tool from recutting chips) and reduces productivity.

The risk of recutting chips has prevented many manufacturers from taking advantage of the carbide tooling made specifically for cutting titanium, because the brittle nature of the carbide is very susceptible to damage from recutting chips. Therefore many manufacturers used 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 needs to be run around 1/3 of the carbide surface speeds.

Horizontal machining centers (HMCs) 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 rather than simply building up in another location. This easy chip-shedding is supported 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 is excellent for applying additional tool cooling and chip removal.

Figure 4. T4 Machine High-Flow Coolant Systems

Reducing the Cutting (Surface) Speed

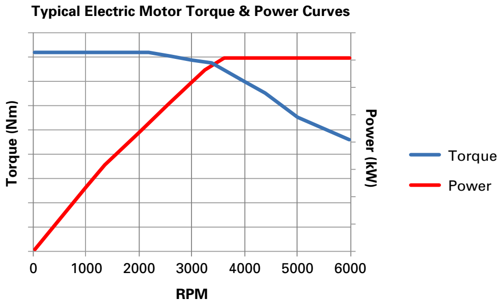
There is a limit on cutting speed when machining Ti 6Al-4V—and exceeding this limit drastically reduces cutting tool life. Due to the low thermal conductivity of titanium, heat builds up on the cutting edge, which weakens the tungsten-carbide cutting material. Since this heat generation is proportional to the cutting speed being used, the most effective way to correct the issue is to slow the cutting speed down. (The speed must be significantly reduced compared to effectively process Ti 6Al-4V.)

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 by providing 30-45 minutes of tool life. However, in real-life machining conditions, tool life is often shortened due to parts of the process having sections with heavier cutting, part or machine vibration that is weakening or chipping the cutting edge, having to recut chips that were not cleared by the coolant, and cutting edge being periodically starved of coolant in deep pockets or corners of the part.

Applying additional techniques can not only overcome these additional challenges, but also increase the speed to 65 or 70 m/min. However, 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 due to the fact that they do not have sufficient power 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 1000 Nm of torque up to 1000 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.

Figure 5. Typical Electric Motor 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 as long as the process does not exceed the stability and stiffness of the machine tool.

Figure 6. Long-Edge Cutter with Deep Axial Engagement

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.

Each of the main tool tapers available on the machine market has an associated bending moment limit. The bending moment for a particular machining operation can be approximated by multiplying the cutting forces by the gage length. Each taper type has a different bending moment limit, and because it creates a very real limit on what maximum material removal rate can be achieved, it is vital that machinists understand this limitation. To learn more about the importance of bending moment, please see "Part 2: Understanding Bending Moment."

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.

An element that must be thoroughly understood is bending moment. Machining Titanium, Part 2—The Baffling Issue of Bending Moment goes into detail about what bending moment actually is, bending-moment limit, what happens when the bending moment is exceeded, and how to calculate cutting forces.

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Note: The information in Figure 1 was obtained from the following two websites:

http://www.supraalloys.com/titanium-grades.php

http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma6061t6