Machining Titanium - Part 3

Machining the Less Common Titanium Alloys

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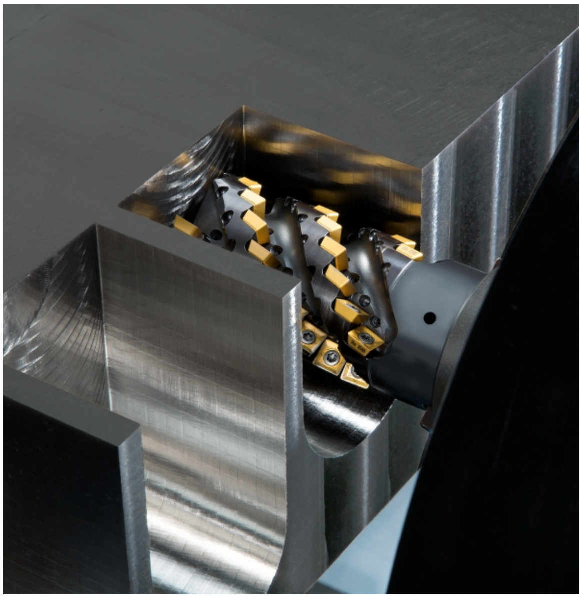
Most of the global titanium usage is of the Ti 6Al-4V alloy. As other titanium alloys come into more common usage, those manufacturing facilities with skills in machining Ti 6Al-4V will likely also find themselves presented with the challenges of working with other titanium alloys as well. Using cutting parameters and guidelines that were developed for Ti 6Al-4V can create problems when working with these other alloys. Common issues include unexpected tool breakage and unproductive machining, which may result in scrapping expensive parts and even machine damage.



The conventional wisdom says that alloys other than Ti 6Al-4V require the surface speed to be reduced by 30-50%. (If you thought machining titanium was slow at 50 m/min (165 sfm), wait until you start machining at 25-35 m/min (82-115 sfm).

In this paper, we are going to investigate and challenge the reduce-the-surface-speed assumption.

Titanium 6 Al-4V Characteristics

- **High tensile strength**—Ti 6Al-4V's strength nears that of stainless steel, requiring high cutting forces.
- **Low thermal conductivity**—Heat does not readily transfer into the chip but rather flows into the cutting tool, which makes the cutting edge very hot during the machining process.
- **High modulus of elasticity**—Titanium is very "springy." For a given force, it will deflect more than steel, which results in a higher likelihood of vibration, chatter, and poor chip formation.
- **Shear mechanism**—Titanium requires a sharp cutting edge to cut the material and avoid tearing and smearing, which will quickly lead to tool failure.

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Characteristics of Other Titanium Alloys

Let's examine how the characteristics of titanium change from alloy to alloy. The first three troublesome characteristics—material strength, modulus of elasticity, and thermal conductivity—are easily quantifiable from the basic material properties table in Figure 1.

Grades 1 through 4 are often referred to as the "Commercially Pure" (CP) grades of titanium. The lower the grade number, the lower the strength and the higher the ductility. In fact, for the two lowest grades (Grade 1 and Grade 2); the ultimate tensile strength approaches that of aluminum.

	Grade 1	Grade 2	Grade 3	Grade 4	Ti 6Al4V	Ti 5553	Ti 10-2-3
Density (g/cc)	4.51	4.55	4.50	4.51	4.43	4.64	4.82
UTS (Mpa)	240	345	440	550	950	1310	1117
Yield Strength (Mpa)	170–310	275	377–520	480–552	880	1364	1048
Modulus of Elasticity (Gpa)	105.0	105.0	105.0	105.0	113.8	120.0	200.0
Thermal Conductivity (W/m-K)	16.0	16.4	19.9	17.2	6.7	5.3	7.8

Figure 1. Material properties of seven titanium alloys

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Figure 2 shows the chemical composition by weight of each titanium alloy. For Grades 1 through 4, the differences come primarily from small changes in the low levels of oxygen, iron, and nitrogen in the alloy. Even very slight changes in the levels of impurities have a significant impact on the tensile strength and ductility.

	Grade 1	Grade 2	Grade 3	Grade 4	Ti 6Al4V	Ti 5553	Ti 10-2-3
C	Max 0.1	Max 0.1	Max 0.1	Max 0.1	Max 0.08	Max 0.05	Max 0.05
Fe	Max 0.25	Max 0.3	Max 0.3	Max 0.5	Max 0.25	Max 0.3	Max 2.2
H	Max 0.015	Max 0.015	Max 0.015	Max 0.015	Max 0.015	Max 0.015	Max 0.015
N	Max 0.03	Max 0.03	Max 0.05	Max 0.05	Max 0.05	Max 0.05	Max 0.05
O	Max 0.18	Max 0.25	Max 0.35	Max 0.4	Max 0.2	Max 0.13	Max 0.13
Ti	99.5	99.2	99.1	99.0	90.0	72.0	77.0
Al	-	-	-	-	6	5	3
V	-	-	-	-	4	5	10
Mo	-	-	-	-	-	5	-
Cr	-	-	-	-	-	3	-

Figure 2. Chemical composition by weight of seven titanium alloys

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Chemical Structure of Titanium Alloys

Grades 1 through 4 titanium exist in what is called the alpha state, which is a close-packed hexagonal structure.

Ti 6Al-4V (Grade 5) or Ti 6-4, has a 6% by weight addition of aluminum and a 4% by weight addition of vanadium. These alloying elements significantly change some key characteristics of the alloy. By adding aluminum and vanadium, Ti 6Al-4V is able to undergo a heat-treatment process that changes some of the metal to a different phase, known at beta, which is a body-centered cubic structure. Because not all the structure is changed to beta, Ti 6Al-4V exists as a mix of both alpha and beta states.

Ti 6Al-4V provides part designers with an increase in material strength without a loss of material flexibility. The disadvantage to machinists, however, is that the mix both lowers the thermal conductivity and simultaneously increases in tensile strength, making machining Ti 6Al-4V more difficult than commercially pure titanium.

Modern alloys such as Ti-5Al-5V-5Mo-3Cr (Ti 5-5-5-3) and Ti 10V-2Fe-3Al (Ti 10-2-3) have additional alloying elements that shift the micro structure of the material to the beta state. These alloys are known as beta-structure alloys.

Machining Grade 2 Titanium versus Ti 6Al-4V

Grade 2 titanium, as compared to Ti 6Al-4V, has 2.4 times the thermal conductivity. This increase in thermal conductivity means it will transfer heat into the chip and material at a higher rate, which will help keep the cutting-tool edge from overheating during the machining process.

Additionally, the lower tensile strength of Grade 2 titanium means that far less spindle power will be required. So, despite the commonly held belief that surface speed needs to be reduced when machining alloys other than Ti 6Al-4V, the material properties of Grade 2 titanium indicate that it could be machined at a higher rate.

Makino R&D has performed test cuts specifically aimed at verifying this belief and quantifying the magnitude of the difference in tool life and cutting forces between Ti 6Al-4V and Grade 2 titanium.

Tool-Life Testing in Grade 2 Titanium

Standard testing has shown that a small 20 mm end mill will last about 60 minutes when machining Ti-6Al-4V, while running at the following parameters:

Surface Speed (Vc)	50 m/min (165 sfm)
Chip Load (Fz)	0.08 mm/tooth (0.0031 in./tooth)
Radial Engagement (Ae)	16 mm (0.63 in.)
Axial Engagement (Ap)	2 mm (0.078 in.)

This tool-life test used a very small axial engagement because if the machining is stable (no vibration), the axial engagement does not affect the tool life. Therefore, a low axial-engagement test-cut will reveal the tool life while minimizing the material consumed during the test.

End of tool life, for this test, was defined as 0.2 mm (0.008 in.) of flank wear on an insert. Generally, after this amount of flank wear, the insert wear is accelerated and the remaining cutting edge degrades rapidly.

This same test was repeated for Grade 2 titanium to see what effect the reduced strength and higher thermal conductivity would have on the tool life and productivity trade-off. The goal of the test was to increase the surface speed to match the 60 minutes of tool life. Figure 3 illustrates the tool life achieved by machining Grade 2 titanium across four different surface speeds.

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As expected, the tool life decreased as the surface speed was increased. Figure 3 shows the tool life for 145 m/min surface speed to be 60 minutes.

Based on the findings of this test, a safe starting point for programming a Grade 2 titanium part would be to increase the roughing from 50 m/min used for Ti 6Al-4V to 145 m/min, which is a 2.9-time increase in cutting speed and productivity. However, the gains don't stop there.

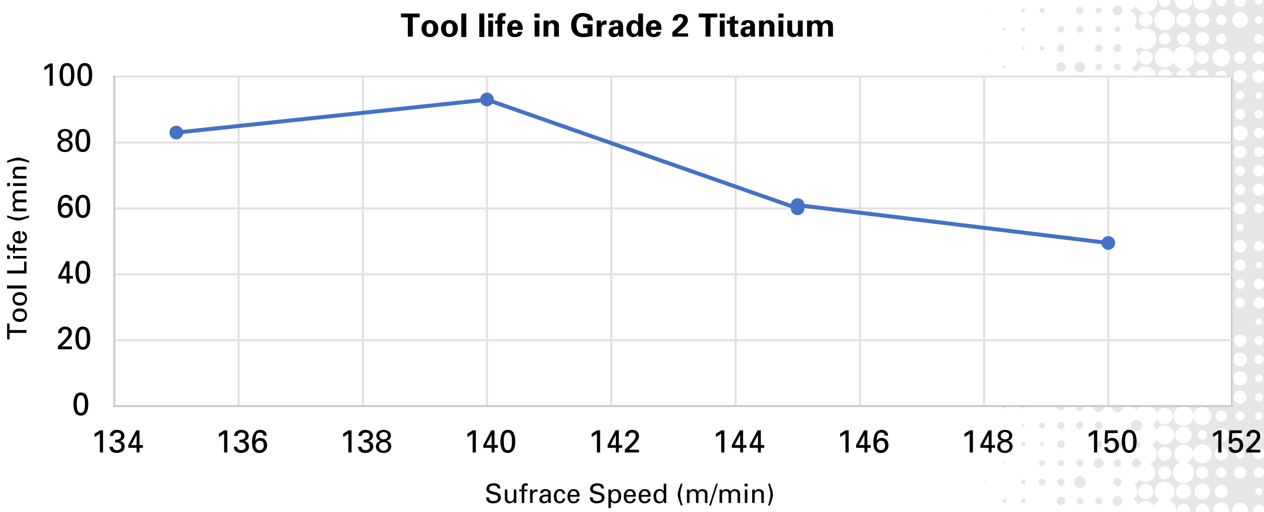

Figure 3. Tool life in Grade 2 titanium

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Cutting-Force Testing in Grade 2 Titanium

The lower tensile strength of Grade 2 titanium also provides an opportunity to take larger depths of cut. In order to determine the magnitude of the differences in the cutting forces, Makino R&D took previously measured Ti 6Al-4V cutting-force data and repeated that test on Grade 2 titanium.

The cutting forces shown on the following charts were measured on a Kistler Dynamometer. A 76.2-mm (3.0-in.) diameter stacked cutter made by Walter was used for the test. All machining passes consistently used the full 76.2 mm (3.0 in.) axial depth of the tool and fed at 0.1 mm (0.004 in.) per tooth. The radial engagement was varied from 5 to 25 mm, and the cutting speed was varied around the surface speed, which achieved about 60 minutes of tool life.

These machining tests provided 25 pieces of data for Ti 6Al-4V and 25 pieces of data for Grade 2 titanium.

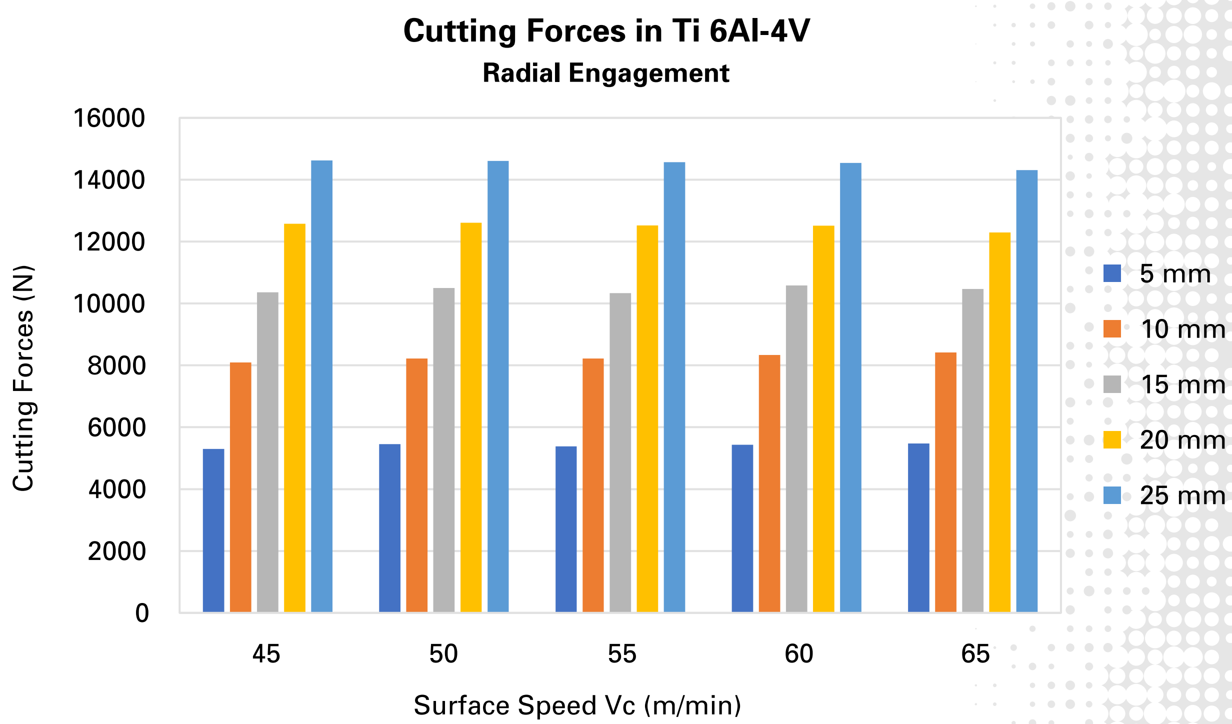

Figure 4. Cutting forces in Ti 6Al-4V

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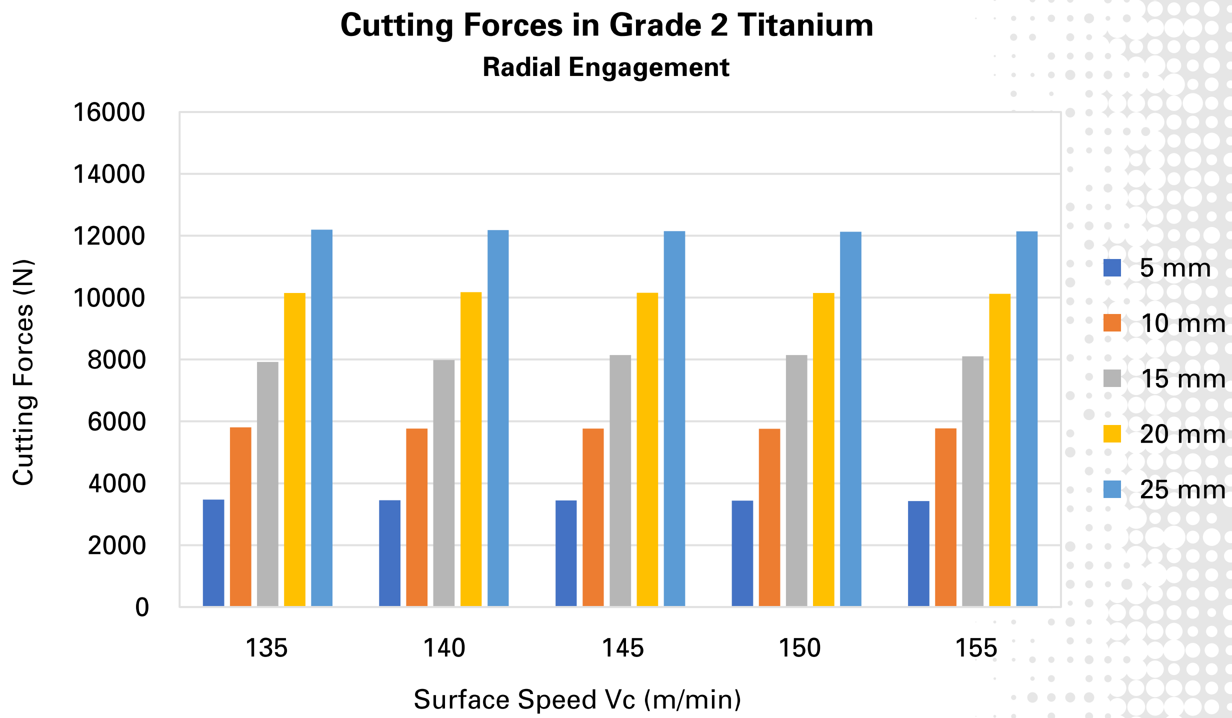

Figure 5. Cutting forces in Grade 2 titanium

When looking at these charts, it is important to point out that increasing the surface speed does not increase the cutting force for either Ti 6Al-4V or Grade 2 titanium. In fact, increasing the surface speed actually slightly decreases the cutting forces. Since the decrease is so small, we can disregard it for the sake of this analysis and keep our focus on the cutting forces for 50 m/min (165sfm) in Ti 6Al-4V and 145 m/min (475 sfm) in Grade 2 titanium.

For both materials, the cutting forces increase as radial engagement increases. It is interesting to note that changing from Grade 2 to Ti 6Al-4V does not decrease cutting forces for each corresponding radial engagement by a consistent percentage. Rather, the entire cutting force chart for Grade 2 titanium is shifted lower than the Ti 6Al-4V chart. Figure 6 plots the reduction in cutting forces observed when a change is made from Ti 6Al-4V to Grade 2 titanium.

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A Consistent Shift in Cutting Forces

Taking the same cut in Grade 2 titanium versus Ti 6A-4V reduces the cutting forces approximately 2,000-2,400 N. In this test, increasing the radial engagement of the 76.2-mm (3-in.) diameter Walter cutter by 5 mm increased the cutting forces by about 2,000 N (see Figure 5).

Therefore, by using the same tool with the same 0.1 mm (0.004 in.) feed-per-tooth and the same 76.2-mm (3- in.) axial engagement, a programmer can expect to be able to machine Grade 2 titanium with a radial engagement that is 5 mm higher than the standard Ti 6Al-4V alloy—without increasing the cutting forces relative to cuts taken on Ti 6Al-4V.

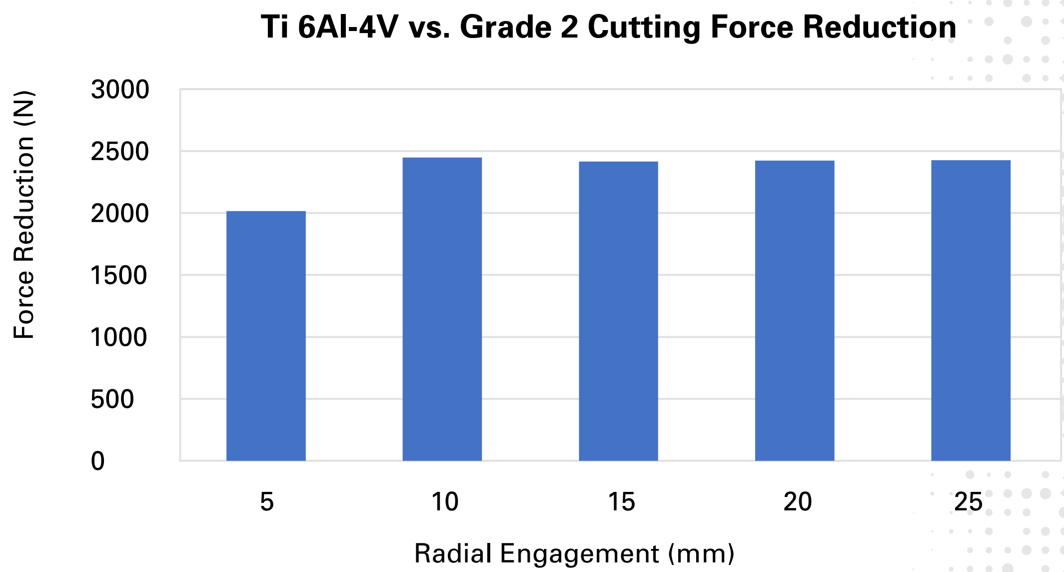

Figure 6. Ti 6Al-4V versus Grade 2 cutting force reduction

In Conclusion

The material tensile strength of Grade 2 titanium is about one-third of Ti 6Al-4V, and the thermal conductivity is about 2.5 times higher. These strength and thermal conductivity characteristics indicated that Grade 2 titanium could be machined faster than Ti 6Al-4V.

However, without the tool-life and cutting-force analysis performed by Makino, this comparison would be impossible to accurately assess. Increasing the radial engagement by 5 mm increases the productivity between 20% and 100%, depending upon the original radial engagement. This higher radial engagement, combined with a surface-speed increase of about 2.9 times, means that Grade 2 titanium can be processed at rates substantially faster than Ti 6Al-4V. Neglecting these realities can be the difference between winning or losing a project—and making or losing money

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