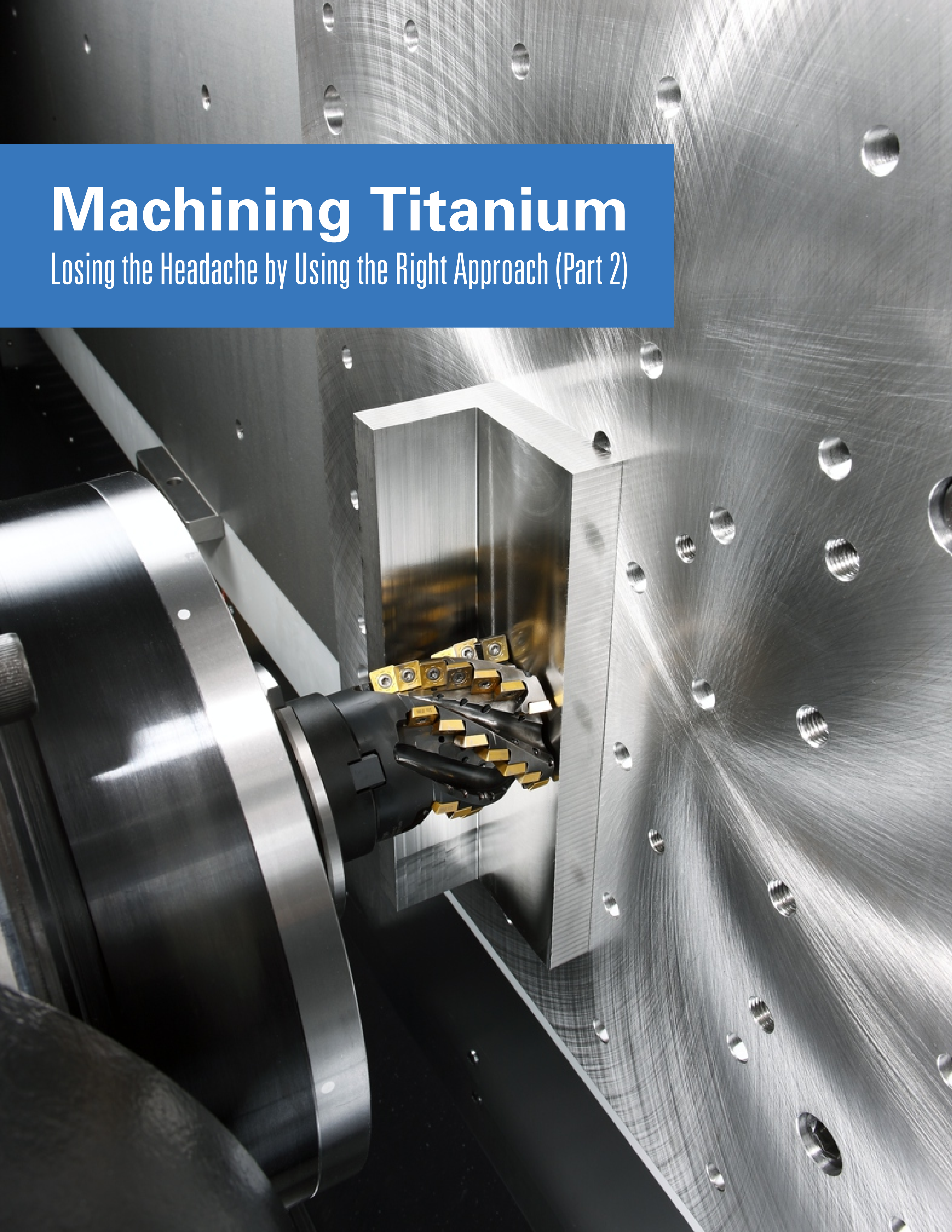
Machining Titanium

Losing the Headache by Using the Right Approach (Part 2)



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Quick Review

Part 1 of this three-part whitepaper covered the challenges of machining titanium due to its high strength, low thermal conductivity, high modulus of elasticity, and shearing mechanism; and discussed how a holistic approach using the right machines and processes can significantly reduce these challenges.

In Part 2, we will define tool-bending moment and address bending-moment limitations. We will also explain what happens when tool-bending moment is exceeded, as well as how to calculate cutting forces.

What Is Tool-Bending Moment?

Archimedes, the second-century B.C. Greek mathematician, has been permanently penned into world history for his quote "Give me a lever long enough and a fulcrum on which to place it, and I shall move the world." This statement has been shared for generations in physics classes to express the power of levers and the concept of torque. The same notion applies to tool-bending moment in many ways.

Put simply, bending moment is basically a force that causes something to bend. If the object is not well-restrained, the force will cause the object to rotate around a certain point. A bending moment occurs when a force is applied at a given distance away from a point of reference, causing a bending effect. In the milling process, tool-bending moment is created whenever a side force is applied to a cutter. Tool-bending moment is directly linked to radial cutting force and tool length.

Machine builders generally expect that the highest-force cutting will be performed by short-length tools such as face mills or inserted cutters. But when manufacturers begin to use longer tools to access deep pockets or hard-to-reach features, they begin moving the cutting force out further from the spindle and the supporting spindle bearings. As tool length grows, the machining process begins to create a very large torque, known as tool-bending moment, across the front of the spindle (Figure 1).

Bending moment is typically measured by a force (N) multiplied by a length (m). The formula used to calculate bending moment is the same formula used to calculate torque, which is force (N) times distance (m).

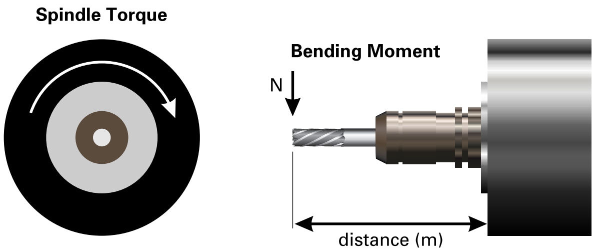

Figure 1. Front and Side view of Torque and Tool-Bending Moment on a Spindle

Example: An end mill that is machining Ti 6Al-4V may produce a cutting force of 4000 N of side load. If the tool is 150 mm long, we could approximate that this force is being applied to the end of the tool. In this example, the tool-bending moment being applied to the face of the spindle is 4000 N times 0.150 meters (150 mm), which equals 600 Nm. It is important to note that this torque is not the same as the spindle torque, which is a description of the spindle's ability to rotate the tool.

Limitations of spindle load: Spindle-load monitoring can be a quick way to assess if a particular process is placing too much load on a machine tool. However, this method has several limitations. First of all, not all machines are built in a well-balanced manner. Some machine builders will put a higher torque or higher power spindle on a machine to appeal to specific markets, and these machine structures will have trouble supporting the forces created by these spindles. Secondly, spindle load will not provide any feedback to the operator regarding vibration. Vibration and chatter create highly varying forces that can damage machine components even while spindle load is very low. Finally, spindle load cannot monitor tool-bending moment.

Understanding and calculating tool-bending moment is often ignored by machinists. This is due to a common assumption that the spindle load is the only limit that needs to be monitored when evaluating the stress that a process is placing on a machine. However, if the tools being used are long, one could easily create a tool-bending moment that damages the machine, even while the spindle load is very low. Another reason tool-bending moment is often not considered is that it can be difficult to obtain or estimate accurate cutting-force data.

Tool-Bending-Moment Limit

Each of the main tool tapers available on the machine market has an associated tool-bending-moment limit based on the mechanical design, tool clamping method, and tool clamping force. This limit is essentially a measurement of how much side force a tool can take before the tool taper begins to separate from the spindle taper. The associated tool-bending-moment limit puts a very real boundary on what level of material-removal rate can be achieved by a machine. Figure 2 illustrates the various bending-moment limits associated with each tool taper.

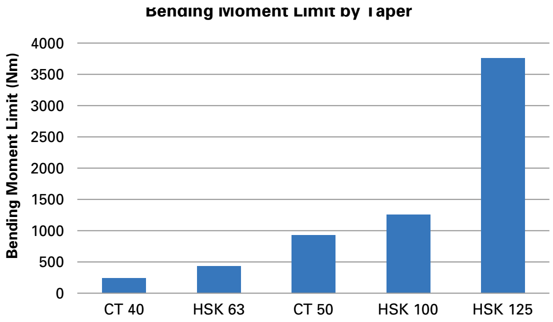

Figure 2. Tool-Bending-Moment Limit by Taper Type

Exceeding Tool-Bending Moment

It is imperative to understand and accurately estimate tool-bending moment in order to prevent damage to the machine tool. Without realizing it, many manufacturers are running processes that regularly exceed the tool-bending-moment limit of their machines.

What takes place when the tool-bending moment is exceeded depends upon how far it was exceeded. If it was exceeded only minimally, it may go unnoticed in the short term; however, a couple of scenarios may result.

One scenario is that the tool taper, which is no longer in solid contact with the spindle taper, will be more likely to permit chatter, resulting in a damaged cutting tool. Another scenario is that the tool may experience significant deflection from the programmed path, leaving more material on the part for the subsequent semi-finish or finish operation.

In either case, the spindle is likely to survive in the short term. In the long term, however, the user will certainly experience shortened spindle life, and fretting on the tool taper and spindle taper. (Fretting is a gradual wear condition caused by rubbing due to vibration and to motion between the tool taper and spindle taper.)

You have probably seen demonstrations and YouTube videos that seem to exhibit impressive metal-removal rates on small taper machines. These processes get great responses from visitors and viewers, whose reaction may be something along the lines of, "I can't believe they can do that on a CAT 40 machine!" But considering the damage these processes inflict on a spindle, they can't be done on a CAT 40 machine long-term.

Damage from exceeding tool-bending moment doesn't just come from continuously heavy cuts in hard metals, it can also occur in softer material, such as aluminum castings, when a cutter moves across highly varying thicknesses of material. These spikes in load are accompanied by temporary spikes in the tool-bending moment, which create instances of wear on the tool, spindle taper, and spindle bearings.

When tool-bending moment is exceeded significantly, the outcome will be much more serious and memorable (although it will likely make for an entertaining lunchroom story!) Excessive tool-bending moment typically occurs due to machine crashes, misloaded parts, or program-feed rate errors. When tool-bending moment is exceeded to a great degree, the tool is likely to be pulled either partially or entirely out of the spindle, which can cause immediate and irreparable damage.

Everyone understands the importance of avoiding catastrophic failures, but it is also necessary that machinists understand how to avoid the hidden damage caused by even slightly exceeding the tool-bending moment during all parts of the process. Catastrophic failure is impossible to overlook, but the results of exceeding the tool-bending moment consistently over time are more insidious—over years of production, it will drain profitability by increasing both tooling and machine-maintenance costs.

Calculating Cutting Forces

The most challenging step in calculating tool-bending moment is measuring, or calculating, the cutting forces. The reason this can be tricky is because cutting forces often involve a lot of guesswork. There are factors associated with machinability, the class of material being cut, and the geometry of the cutting tool that can dramatically affect the result of the calculation—and most of this information is not accurately known before running a tool path. This can make determining tool-bending moment for a milling operation very difficult.

In order to eliminate uncertainty, and provide some perspective on forces and moments involved in machining Ti 6Al-4V, Makino's R&D center in Mason, Ohio recently made several machining passes in titanium. Makino used a long-edge milling cutter and measured the cutting forces directly, using a Kistler dynamometer.

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 cutting speed was varied from 45 to 65 m/min, and the radial engagement was varied from 5 to 25 mm. This provided 25 pieces of data for use in bending-moment calculations (Figure 3).

In Makino's test, the axial engagement was not varied because it was already established that the relationship between cutting force and axial engagement is linear. For example, if you double the axial engagement, you double the cutting forces.

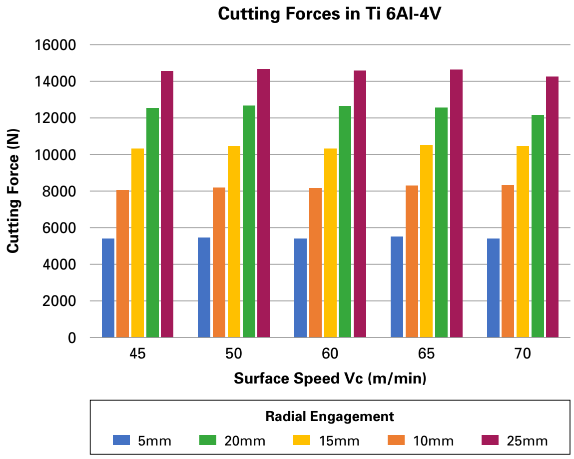

Figure 3. Cutting Forces in Ti 6Al-4V

Feed-per-tooth was also not varied for this test because the range for chip thickness for titanium is already well known and documented.

Radial engagement, however, was increased from 5 to 25 mm in 5-mm increments. When varying the radial engagement, the increase in cutting forces was not linear. For example, doubling radial engagement from 5 to 10 mm did not double the cutting forces but instead increased in a more complex fashion (Figure 3). The non-linear increase of force was due to the fact that increasing radial engagement changes the arc of engagement for the cutting insert, as well as the chip thickness, in ways that are not entirely linear.

Finally, cutting speed was varied to demonstrate the often surprising relationship between cutting force and cutting speed. As shown in Figure 3, the cutting force remains practically level as surface speed

One method that can be used to calculate the cutting forces is based on the spindle load, tool diameter, and spindle-torque curve. The following variables are used to calculate the cutting force:

Dc - Tool diameter (mm)
n - RPM
S% - Spindle load percentage consumed during cutting
Tn - Maximum available torque at RPM (n)
Fr - Radial force (parallel to the radius of the cutter and against the spindle connection and bearings)
Ft - Tangential force (perpendicular to the radius of the cutter)
Kf - Conversion factor for Ft to Fr (approximately 0.67)

Formula for calculating the tangential force from the spindle load and torque-curve chart:

Ft = (S% x Tn) / (Dc / 2 / 1000)

Formula for converting the tangential force into a radial force used in tool-bending-moment calculations:

Fr = Ft x Kf

increases; in fact, it goes down slightly, as surface speed is increased.

Many machinists in the industry believe that increasing the cutting speed, feed rate, and metal-removal rate must increase the cutting forces. However, the test data shown in Figure 3 demonstrates just the opposite. If all other cutting conditions are held steady, increasing the surface speed and maintaining the same feed per tooth will slightly reduce the cutting forces on the tool.

(Note: This finding can lead machinists to think that in order to achieve a higher metal-removal rate on a light-duty machine, you can simply increase the surface speed. Unfortunately, while this would decrease the cutting forces slightly, titanium has a definite speed limit around 50-65 m/min in roughing with carbide. Increasing the surface speed beyond this to decrease cutting forces will severely shorten tool life.)

Makino's test data provides the elusive and often-hard-to-obtain cutting-force data at a very accurate level that can be used for calculating tool-bending moment.

Calculating Tool-Bending Moment

We now have the force numbers needed to run tool-bending-moment calculations. Typically, multiplying the cutting forces by the tool length provides a fast and easy estimate. (This was the method used in the example at the beginning of this paper). However, to be even more accurate, it is necessary to consider the axial depth of cut.

For Makino's test, the axial engagement was 76.2 mm (3.0 in.), which means the force was, on average, applied to the tool at about 38.1 mm (1.5 in.), half of the axial engagement, back from the tool tip. Tool-bending moments were calculated using the measured cutting forces, and the tool length was adjusted for the axial engagement. Furthermore, since the relationship between axial engagement and cutting force is linear, tool-bending moment could be calculated for every combination of radial and axial engagement across the range of values measured (Figure 4).

Using the cutting force data, a curve was plotted across axial and radial engagements, highlighting the limit of what cross-section of material could be removed according to each taper's bending-moment limit. The chart in Figure 4 can be used by an operator to determine the maximum material-removal rate possible for a given taper at 55 m/min, 0.1 mm (0.004 in.) per tooth, in a 180-mm-length, 76.2-mm (3.0-in.) diameter tool.

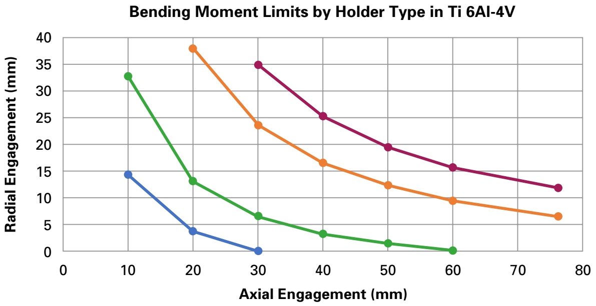

Figure 4. Tool-Bending Moment Limits by Holder Type in Ti 6Al-4V

As demonstrated in Figure 4, the axial and radial engagements are directly limited by the tool taper available in the machine tool. (These limits are also dependent upon the pull force/clamping force the spindle applies to a clamped tool. Reduced pull force significantly reduces the allowable tool-bending moment.)

If using a CAT 50 or CAT 40 tool taper to machine a 20-mm deep pocket, a manufacturing engineer could improve productivity by moving up to the HSK 100 taper. According to the chart in Figure 4, the productivity could be triple that of the CAT 50 taper and provide ten times that of the CAT 40 taper. The HSK 125 taper, which is available on Makino's purpose-built titanium milling machines, has a bending-moment limit that is an additional three times larger than that of the HSK 100.

Figure 4 does not include the bending-moment limit on the HSK 125 because it is so much higher than other standard tapers—significantly higher than the tool-bending moments that can be generated for the ranges of parameters tested here.

Since tool-bending moment is directly linked to tool length, it is important to note that the data presented in Figure 4 is for a standard 180-mm, gauge-length tool. If the tool was longer—to improve part access or cut deeper axially—it would significantly reduce the amount of radial engagement possible due to the increased tool-bending moment.

In Conclusion

Although spindle load is one way to assess the amount of stress and wear that a process is placing on a machine platform, it is not a comprehensive check. A machinist could exceed the tool-bending moment with a relatively low spindle load, depending on tool length. In order to most profitably balance productivity and process integrity, it is imperative to keep tool-bending moment in mind as you design processes.

In ***Machining Titanium, Part 3: Machining Those Other Titanium Alloys***, we will discuss the characteristics and chemical structure of titanium alloys other than Ti 6Al-4V. We will also go into detail about the differences between machining Grade 2 titanium versus machining Ti 6Al-4V, and touch on Ti-5Al-5V-5Mo-3Cr and Ti-10V-2Fe-3Al as well.

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