Machining Titanium - Part 2

Tool-Bending Moment

MAKINO

Tool-Bending Moment

What is Tool-Bending Moment?

A bending moment is a force that causes an object to bend. If the object is not well-restrained, the force will cause it to rotate. A bending moment occurs when a force is applied at a distance from a pivot point, causing a bending effect about that point. During any milling process there are forces created by the cutter geometry and the cutting parameters. These various forces are normally extrapolated to be an equivalent combination of a radial force and an axial force. The tool-bending moment is created whenever a radial force is applied to a cutter. **The tool-bending moment is directly linked to radial cutting force and tool length.**

Machine builders generally expect that the highest-force cutting will be generated by short-length/larger diameter tools such as face mills or inserted cutters. However, when manufacturers begin to use longer tools to access deep pockets or hard-to-reach features, they begin moving the cutting force farther out 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 defined as a force (N) multiplied by a length (m). The formula used to calculate bending moment is the same used to calculate torque, which is force (N) times distance (m).

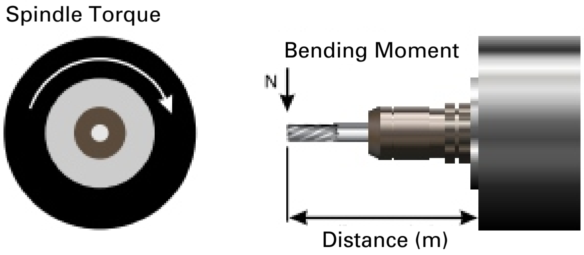

Figure 1. Front and side view of torque and tool-bending moment on a spindle.

Example: An end mill that is machining Ti 6Al-4V may produce a radial cutting force of 4,000 N. If the tool is 150 mm long, for calculation simplification purposes, we would approximate that this force is being applied at the end of the tool. In this example, the tool-bending moment being applied to the face of the spindle is 4,000 N times 0.150 meters (150 mm), which equals 600 Nm.

(It is important to note that this bending moment torque is not the same as the spindle's rotational torque, which is a description of the spindle's ability to rotate the tool.)

Historically, the traditional assumption was that the spindle load is the only limit that needed to be considered when evaluating the overall stress a process is placing on a machine. However, if the tools being used are long, one could easily create a tool-bending moment that exceeds the expected load limits and potentially damages the machine, even while the spindle load itself (torque) is very low. Although it should be an important consideration in the overall machining process, tool-bending moment is often not considered since it can be difficult to obtain or estimate accurate cutting-force data.

Limitations of spindle load: Spindle-load monitoring can be a quick way to assess if a process is placing too much load on a machine tool. However, this method has several limitations. Not all machines are designed and 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—while 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.

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Tool-Bending-Moment Limit

Each machine/spindle/holder configuration available on the market has an associated tool-bending-moment limit based on its specific mechanical design, tool clamping method, and tool clamping force. This limit is a measurement of how much side force a tool/holder assembly can take before the tool taper begins to separate from the spindle taper. These associated tool-bending-moment limits (usually defined as 0.050 mm or 0.002" deflection) put a very real boundary on what maximum material-removal rate can be achieved by a machine. Figure 2 illustrates the various bending-moment limits associated with each tool taper.

Exceeding the Tool Bending Moment Limits can result in several adverse effects such as:

- Poor surface finishes due to unexpected tool motion
- 'Fretting' or micro-erosion of the tool taper and, eventually, the machine spindle taper; resulting in higher tool and machine repair costs. (Fretting is a wear condition caused by vibration and motion between the tool taper and spindle taper. These frequent compressive stresses create surface fatigue and metal flaking of both the holder and spindle tapers.)
- An inevitable safety issue if not corrected due to eventual tool breakage

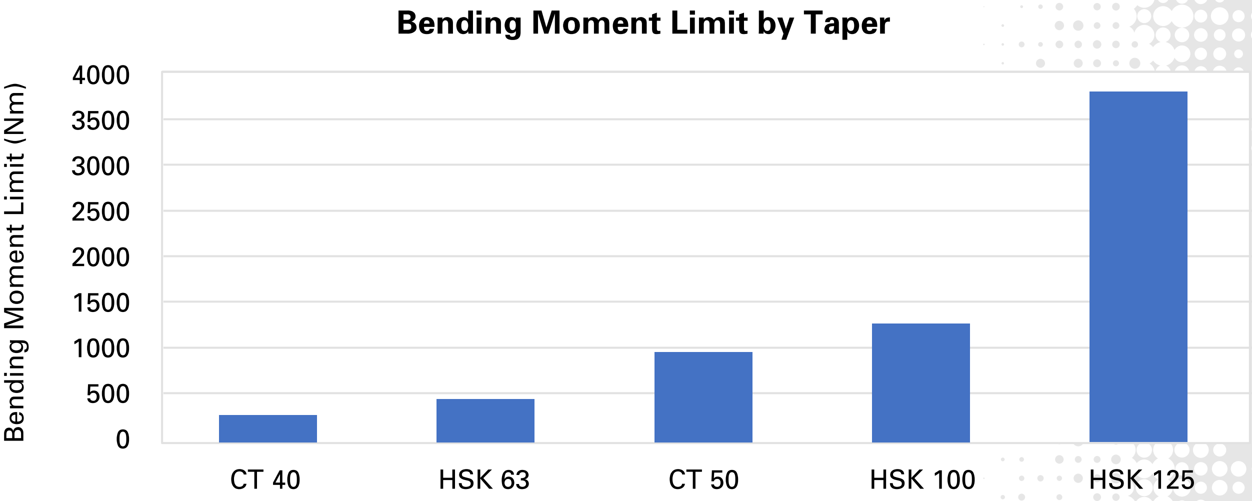

Figure 2. Tool-bending moment limit by taper type

Exceeding Tool-Bending Moment

It is important to understand and accurately estimate tool-bending moment in order to prevent damage to the machine tool and avoid destabilizing the machining process. Without realizing it, many manufacturers are running processes that regularly excee 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; but there will be long-term consequences

These limits reduce the usefulness of very high torque spindles when combined with small, undersized tool interfaces.

You have probably seen demonstrations and videos that appear 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 for the long term.

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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 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. 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 will cause immediate and, perhaps, irreparable damage.

Clearly everyone understands the importance of avoiding catastrophic failures, but it is also necessary that machinists understand how to avoid the hidden damage caused by slightly, or even occasionally, exceeding the tool-bending moment limits during all parts of the machining process. Catastrophic failure is clearly impossible to overlook. However, the consequences of exceeding the tool-bending moment limits consistently over time are more insidious, as they will reduce or eliminate 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. Most of this information is not accurately known before running a tool path. These estimations can make determining tool-bending moment for a milling operation very difficult.

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 (transmitted through the cutter, spindle interface 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: calculate the cutting force:

$$\mathbf{Ft = (S\% \times Tn) / (Dc / 2 / 1000)}$$

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

$$\mathbf{Fr = Ft \times Kf}$$

In order to provide some perspective on the forces and moments involved in machining Ti 6Al-4V, Makino's R&D center in Mason, Ohio has performed multiple cutting tests in titanium using a long-edge milling cutter; measuring the cutting forces directly, with a Kistler dynamometer.

All machining passes used the full 76.2 mm (3.0 in.) axial depth of the tool, with a feed rate of 0.1 mm (0.004 in.) per tooth. The surface speed was varied from 45 to 65 m/min, and the radial engagement was varied from 5 to 25 mm. These tests provided 25 points of data for use in bending-moment calculations (Figure 3).

Tool-Bending Moment

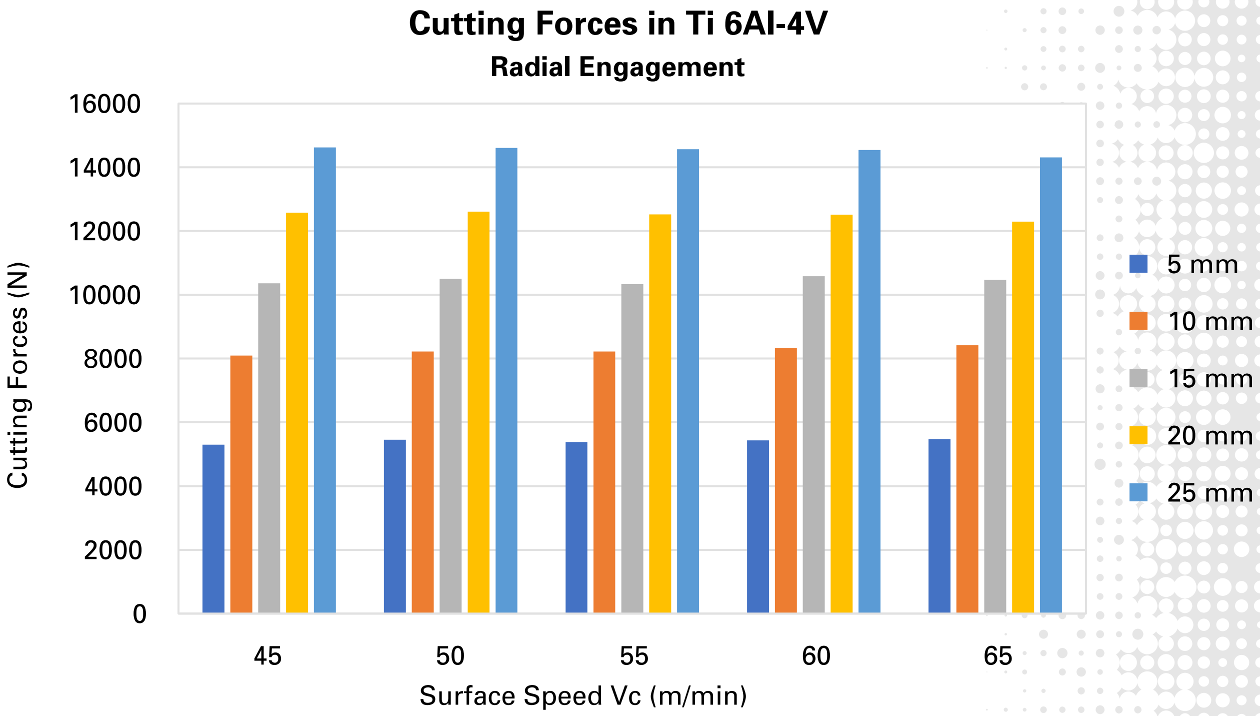

Figure 3. Cutting forces in Ti 6Al-4V

.During this testing, the axial engagement was not varied because the relationship between cutting force and axial engagement is linear. For example, if you double the axial engagement, you double the cutting forces. Feed-per-tooth was also not varied for this test because the range for acceptable chip thicknesses for titanium is already well known and documented.

Radial engagement was increased from 5 to 25 mm in 5 mm increments. When varying the radial engagement, the increase in cutting forces was not linear. Doubling radial engagement from 5 to 10 mm did not double the cutting forces; rather it increased it in a non-linear manner. (Figure 3). The force increases in a non-linear manner because increasing radial engagement increases the arc of engagement for the cutting tool and, therefore, the chip thicknesses.

Cutting surface speed was varied to demonstrate the relationship between cutting force and cutting speed. As shown in Figure 3, the cutting force remains mostly steady as surface speed increases; in fact, it goes down slightly, as surface speed is increased.

Many machinists in the industry intuitively 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 might 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, tool life is inversely proportional to the cutting speed. Increasing the surface speed beyond normal limits will decrease cutting forces but it will also severely shorten tool life.)

Makino's testing provided accurate cutting-force data that can be used for calculating tool-bending moment.

Tool-Bending Moment

Calculating Tool-Bending Moment

Typically, multiplying the cutting force 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 testing, 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 equivalent tool length was adjusted for the axial engagement. 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.

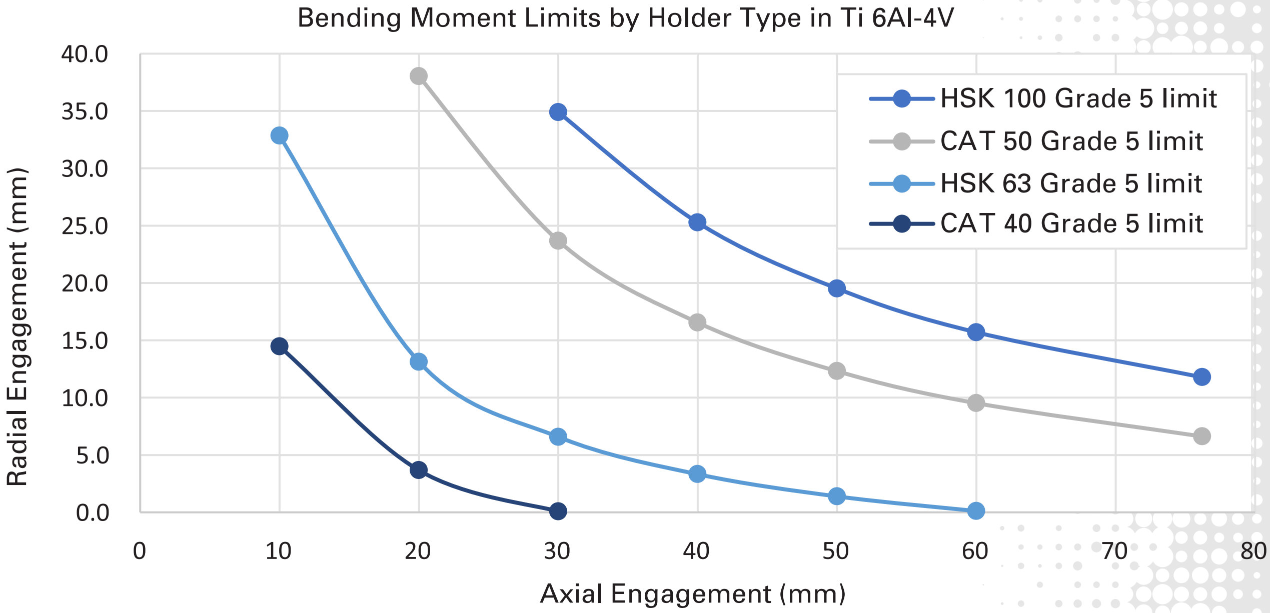

Figure 4. Tool-bending moment limits by holder type in Ti 6Al-4V

Tool-Bending Moment

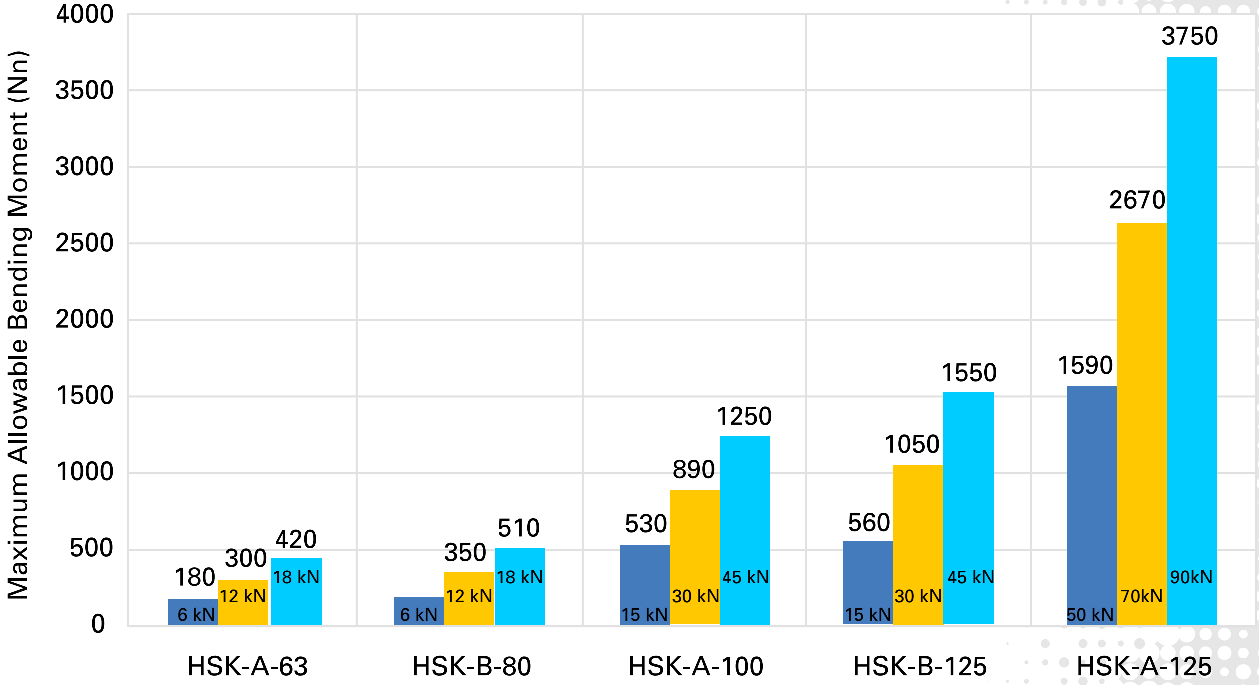

Figure 5. Relative tool-bending moment limits by HSK holder style and size

Tool Bending Moment and Limits

The distance away multiplied by the force applied is the Tool Bending Moment (TBM)

TBM = Fr x TL (resultant cutting force x tool length)

Every tool-spindle interface has a bending moment limit (usually defined as 0.050mm or 0.002" deflection)

Typical limits by taper

Taper	Limit (lb-ft)	Limit (Nm)
Ct40	169	230
HSK63	309	420
Ct50	678	920
HSK100	922	1250
HSK125*	2766	3750

* This is at 90kN clamp force, for the Makino T2/T4 with a 100kN clamp force, it is slightly higher at up to 4166Nm (3073lb-ft)

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. Productivity would be multiple times that of the CAT 50 taper and as much as ten times that of the CAT 40 taper. The HSK 125 taper, which is available on Makino's larger, 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.

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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.

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