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Chatter Control For The Rest Of Us

A shop making prototype molds illustrates how to find stable milling speeds quickly using a systematic pattern of test cuts.

By Peter Zelinski

When Kevin Berry's shop bought its first high speed machining center, Mr. Berry didn't realize he was getting the metalworking equivalent of a violin. But that's one way to think about high speed milling.

A bow passing across the string of a violin creates a continuous interaction between bow and string that produces a sound. The sound is either sweet or grating, depending on the finesse of the violinist.

In the same way, a milling cutter passing over a workpiece sets up an interaction between the tool and work. The tool and spindle together are vibrating. The vibration leaves tiny waves on the part. The waves might cause the cutting edge to experience a variable load. We call this effect chatter. Like the sound of the violin, the high speed milling pass can be either grating or sweet.

Finessing The Cut

One common way to deal with chatter is to reduce the depth of cut so there is less force to feed the vibration. Another common approach is to increase the system's rigidity, perhaps by switching to a shorter tool, Both of these slots were milled with the same tool in the same machine. Chatter is the difference between them. The smoother pass was run at some optimal milling speed where the chatter quiets down, making it possible to achieve a higher rate of metal removal.

or perhaps by adopting a type of toolholder (such as shrink fit) that has a tighter grip.

With a high speed milling spindle, there is potentially an even better option. "High speed" here means a spindle that is capable of at least 10,000 rpm or 15,000 rpm. When the spindle can go at least that fast, chances are good that some seemingly magic speed along the rpm range will cause the chatter to quiet down, making it possible to take a heavier depth of cut.

The effect may seem like magic, but the explanation is quite rational. At that particular speed, the rate of cutting edge impacts synchronizes with a natural frequency of the system. Although the tool is still vibrating, the cutting load is no longer fluctuating. As a result, it may be possible to cut *much* deeper before reaching the chatter threshold. Metal removal rate goes up. Efficiency goes up. The trick is simply to find this optimal speed.

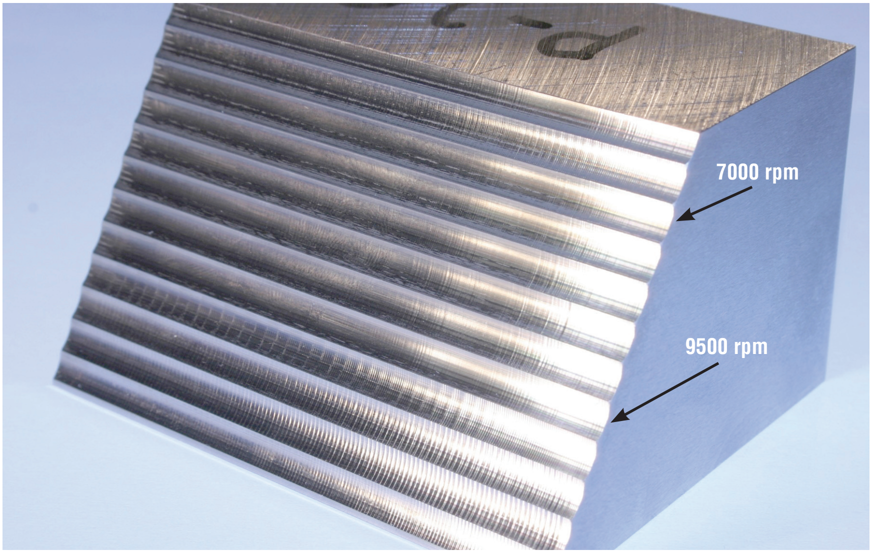
Because the spindle and the tooling make up a single system, this optimal spindle speed will be different every time a different style of toolholder or cutting tool is used. Finding and using these optimal speeds can therefore entail the odd challenge of remembering various particular speeds for various combinations. However, the challenge is not insurmountable.

Mr. Berry knew all of this. What he did not know is how—from a practical standpoint—to go about finding these speeds.

What If A Few Tools Do A Lot Of Work?

Mr. Berry works for Lexmark, the maker of laser and inkjet printers. At the company's headquarters in Lexington, Kentucky, a machine shop helps to prototype new printer designs for evaluation and testing. Early stages of a printer's evaluation can use physical models as stand-ins for the printer components, but when the testing of a printer's performance becomes more rigorous, only a molded component can be used wherever the design will call for a molded part. Mr. Berry is part of the mold and tool services department that makes molds for this purpose. The molds that his shop makes have short leadtimes and they are made for short-run use. Many of the molds are also subject to ongoing modifications, as engineers continually refine their designs.

Kevin Berry and Edwin Gasparraj oversee a milling cycle designed to isolate optimal cutting conditions. The two use a quick, systematic pattern of test cuts to determine productive spindle speeds and depths of cut for particular combinations of spindle and tooling.



Here is a test workpiece, photographed after machining the last stepover depth listed in the chart on the facing page. Stable cutting occurred at 7,000 rpm and 9,500 rpm.

EDM previously made this tooling, and EDM is still used where challenging features of the mold demand it. But the shop has gotten away from relying on EDM so extensively for short-run tooling. The process of making an electrode and burning a part was not responsive enough when a mold was needed particularly quickly, so the shop bought a Makino V33 vertical machining center with 30,000 rpm to help it deliver its mold tooling in less time.

Mastering chatter was the key to maximizing the responsiveness of this machine. Chatter is no fault of the machine tool; it's the fault of physics. Every system of spindle, toolholder and tool has some set of frequencies at which it naturally wants to vibrate. At certain higher spindle speeds, it becomes possible for cutting edges to strike the part frequently enough that the impacts cleanly synchronize with one of these natural frequencies. The smooth cutting that results makes it possible to mill deeper without straining the tool or the machine. In too many machining processes, chatter is the barrier that defines the maximum cutting parameters, when the limits should instead be defined by the strength of the tool and the power of the machine. The narrow zones of stable, optimal spindle speed are the gaps in the wall of chatter that allow this barrier to be surpassed.

Some users of CNC machine tools do recognize this. These shops tend to make aircraft parts. They mill big aluminum workpieces at high spindle speeds, and overcoming chatter makes it possible for them to hog out the metal at a much faster rate. Shops such as these use electronic instruments to measure the frequency response of every combination of spindle, tool and toolholder they are likely to put together. But Mr. Berry's application

Spindle Speed (rpm)	Feed rate (mm/min)	Chip Load (mm/teeth)	Depth of Cut (mm)	Side Step Over (mm)						
				0.5	1.0	1.5	2.0	2.5	3.0	3.5
6000	840	0.072	4							
6500	910	0.072	4							
7000	980	0.072	4							
7500	1050	0.072	4							
8000	1120	0.072	4							
8500	1190	0.072	4							
9000	1260	0.072	4							
9500	1330	0.072	4							
10000	1400	0.072	4							
10500	1470	0.072	4							
11000	1540	0.072	4							
11500	1610	0.072	4							

Stable ~ Slight Chatter ~ Severe Chatter

This chart summarizes the test results for one combination of tool, toolholder and spindle. Running this test took about half an hour. The green region indicates stable cutting.

couldn't justify the expense of purchasing this equipment along with the time that would be required to learn how to use it well.

"I have four favorite roughing tools," he says. "Each one uses the same toolholder every time. I have one high speed machine. If I can learn the right speeds for just these four cases, then that would cover 90 percent of all the roughing that I do."

Relying on an outside source to perform this testing was another option, but Mr. Berry preferred to be able to do the work himself. What if some unusual mold called for a long-overhang tool that wasn't running effectively because of chatter? Mr. Berry wanted to be able to respond to such a problem without waiting for outside help.

The answer came from his CAM software supplier, UGS. Edwin Gasparraj, based at UGS's office in Milford, Ohio, had given some thought to this problem. Mr. Gasparraj is product manager for the company's NX Machining products, which include CAM software engineered for the elaborate tool paths of mold machining. This emphasis on intricate tool paths is ironic, because Mr. Gasparraj's patent-pending program for finding optimal speeds involves nothing but milling straight and parallel lines.

The Results

This program from UGS offers a systematic approach for machining at various speeds and depths of cut in order to locate the most efficient conditions. The specific procedures—procedures you can replicate—are outlined in the shaded box that starts on page 68.

A set of results is shown in the chart above. In this particular test, the tool cut smoothly at 7,000 rpm and 9,500 rpm, even though it might have been capable of 11,500 rpm in the P20 steel used to test it. Having two different stable speeds available in this way is not overkill, says Mr. Berry. As long as the machine, tool and toolholder are the same, the stable values of rpm transfer from one workpiece material to another. The corresponding depths of cut do not transfer (these have to be determined separately), but the speeds remain the same. Therefore, Mr. Berry would run this tool at 9,500 rpm in P20, but if the same tool was used in some harder-to-machine metal that demanded a lower value of cutting speed (sfm), then having the option of 7,000 rpm available would be valuable.

A limitation of this test-cutting procedure relates to tool size. Mr. Berry uses these test cuts to find the right parameters for tools 6 mm, 8 mm and 10 mm in diameter. For tools much smaller than this, the procedure doesn't work. The sound of the cut becomes too faint to hear the chatter, and the chatter marks in the workpiece become too small to see.

When the tool is large enough, though, the simplicity of this procedure makes it a valuable resource. The right speed and depth for a new tool can be obtained in less than half an hour. When Mr. Berry needs to run a new tool, establishing stable cutting conditions in advance can provide an efficient approach. Even to run just one part, finding the right parameters before machining the job may take less time than it would take to struggle with that tool at some less-than-ideal set of conditions.

MRR Multiplier

The chart illustrates the productivity improvement for one of those tools that the Lexmark shop uses all of the time. In the hope of machining as productively as possible, Mr. Berry might have chosen to run this tool at its top permissible speed of 11,500 rpm (based on the tool supplier's recommendations). If he did that, his chatter-free radial depth of cut would be limited to 0.5 mm. Metal removal rate would be 0.5 × 4 × 1,610, or 3,220 mm^3/min.

Compare that to cutting at a stable speed. Slowing down to 9,500 rpm permits a chatter-free radial depth of 3.5 mm. Now the metal removal rate is 3.5 × 4 × 1,330, or 18,620 mm^3/min. Productivity increases by **almost six times**. Even the slower stable speed, 7,000 rpm, permits a metal removal rate that is four times as high.

Ironically, cutting in this way doesn't look much like high speed machining. On a machine with 30,000 rpm available, the natural desire is to use as much of that rpm as the tool can take. But that approach doesn't necessarily make sense. The practice of combining high spindle speeds with light depths of cut might be wasteful if a dramatically deeper cut is possible at some lower speed.

If the machine is like a violin, in other words, then Mr. Berry wants to use it like one. He doesn't want to waste his company's time on using it inefficiently (or otherwise fiddling around). ■

How To Find Stable Milling Speeds

Here are the procedures UGS's Edwin Gasparraj applied to find chatter-free milling speeds at Lexmark:

1. Identify a combination of machine, holder and tool.

Select the combination of machine, tool, toolholder and tool length to be tested. The results of the test will be valid only for this combination. The particular Lexmark test described here involves a Makino V33 machining center and a 10-mm Jabro Tornado ball end mill set at a length of 30 mm in an HSK toolholder.

2. Prepare an angled workpiece.

Prepare a test workpiece that presents an angled slope to the cutting tool. See the illustration. Choose the angle of the workpiece to allow clearance for the toolholder. Choose the workpiece height to be at least 12 times the depth of cut (see step 3), and choose the workpiece length so that the top face of the part (the shorter face) can hang off of the vise by a distance of at least two times the cutter diameter.

Lexmark used a test piece that made a 30-degree angle with the vertical. The material was P20 steel, the most common material the shop uses to make molds.

3. Choose depth and chip load.

Choose an axial depth of cut of about 1/3 of the tool diameter. Use the tool supplier's recommendations to choose a chip load. Both parameters will remain constant throughout the testing. Lexmark used a 4 mm depth of cut and a chip load of 0.072 mm/tooth.

4. Identify the range of spindle speeds to be tested.

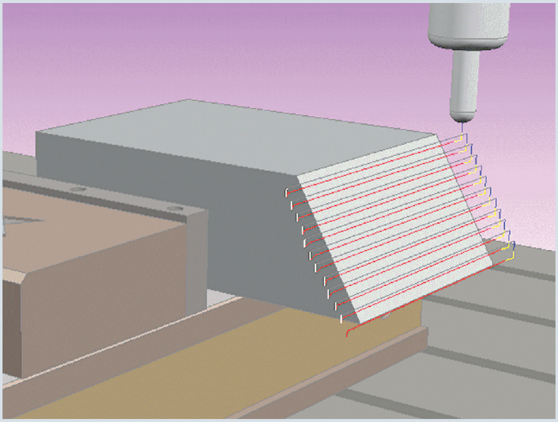
Use the tool supplier's recommendations to find a maximum spindle speed for the tool in the workpiece material tested. For this test, the tool supplier's sfm value suggested a top speed of 9,000 rpm at full diameter. Because the test would not use the full diameter of the tool's ball, Lexmark established a faster top speed of 11,500 rpm.

5. Run parallel test passes at a fixed stepover.

Write a program for taking a series of parallel milling passes at different Z heights. Increase the spindle speed from one pass to the next. Lexmark took 12 passes, increasing from 6,000 rpm to 11,500 rpm in increments of 500 rpm.

For these passes, keep the chip load constant. This means the programmed feed rate in ipm or mm/min. will change as the rpm changes.

Use the machine's X-offset register to establish the radial depth of cut for all of the passes. Lexmark started with a radial depth of 0.5 mm.



This illustration of the test setup shows the pattern of milling passes for the angled test piece. The radial depth of cut (stepover) is the same for each of these passes, but the spindle speed for each pass is different. When these passes are run again, the radial depth is increased and all of the same spindle speeds are repeated. Testing continues in this way until stable speeds are isolated.

6. Evaluate the cutting and the workpiece.

Listen, then look. The sounds of different passes may provide a sense of where chatter is occurring. Then, after the cutting is done, examine the workpiece. A sufficiently close examination might involve leaning over the setup with a flashlight, or using some quick-release method of workholding that allows the part to be taken out of the work zone for study and quickly re-loaded to its previous location.

For each separate pass on the workpiece, make a determination as to whether the machined surface shows *stable cutting*, *slight chatter* or *severe chatter*. Record this information.

In the beginning, when the radial depth is still small, all of the passes may show stable cutting.

7. Run the test at the next larger stepover.

Change the X-offset register to achieve an incrementally larger radial depth, then run the test again with only the radial depth changed. Lexmark's second test took each pass at a radial depth of 1.0 mm.

8. Continue.

Keep going in this way, progressively increasing the radial depth of cut and noting the differences in chatter at different speeds. If radial depth is increased high enough, certain speeds will chatter severely. Hopefully some speeds will chatter less. One or more speeds might continue to cut smoothly.

If one or more speeds clearly perform better, then it is not necessary to continue testing at speeds where severe chatter has already set in. From that point forward, just the stable speeds can be tested to see how much depth is fully possible at these speeds.

See the shaded box on page 72 for additional notes related to these procedures.

Putting Chatter-Free Milling To Use—Additional Notes

■ In order to make sure that the stable speeds found during test cuts also apply to production, make sure setup conditions are as repeatable as possible. For example, tighten the collet toolholder with the same torque every time.

■ Repeat testing for every different combination of machine, toolholder, tool and tool length. This may sound like a lot of work, but the potential benefits are substantial.

■ The optimal spindle speeds transfer from one workpiece material to another. However, the corresponding axial and radial depths of cut will have to be scaled to the material's demands.

■ You can replace the tested tool with a similar tool from the same manufacturer. The results are still valid.

■ You can replace the toolholder with another one like it as well.

■ The procedures described on page 68 involve keeping the axial depth constant and increasing the radial depth. You can devise a test that takes the opposite approach, holding the radial depth constant and increasing the axial depth. Either approach should identify the same optimal speeds.