Uncover peak performance in HSM

SIEMENS

White Paper

A practical approach to identify feeds and speeds settings for peak and stable high-speed machining performance

This white paper introduces a practical no-cost procedure, based on the theory of chatter, to identify the maximum rate of material removal for safe and stable machining conditions. To reap the benefits of today's investments in high-speed machine (HSM) tools, NC programmers need to understand the peak performance limits of their system. This paper discusses how to identify the optimum HSM cutting parameters for any given tool, holder, machine and workpiece material combination. In some cases, this approach has resulted in cutting efficiency improvements as high as 6X.

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Executive summary

One of the major challenges an NC programmer faces every day is identifying critical machining parameters, such as depth of cut, step over, spindle speed and feed rate. Traditionally, the starting point for this data has been either a machining data handbook or the experience of senior machinists on the floor. In a majority of cases, this data is very conservative and/or outdated. When problems arise, the usual recourse is to reduce one or more critical machining parameters. These remedies invariably reduce the metal removal rate (MRR). While this may have been acceptable in the past, today's highly competitive die/mold machining market is forcing users to push the limits of productivity.

The widespread application of high-speed machines in the past several years necessitates a fresh look at how things are done on the shop floor. Simply increasing the spindle speed and feed and decreasing the chip-load significantly do not constitute high speed machining. To reap the benefits of significant investments in high-speed machine tools and accessories, NC programmers need to optimize and reach the safe limits of the system.

Figure 1: Two cuts showing stable and chatter machining conditions.

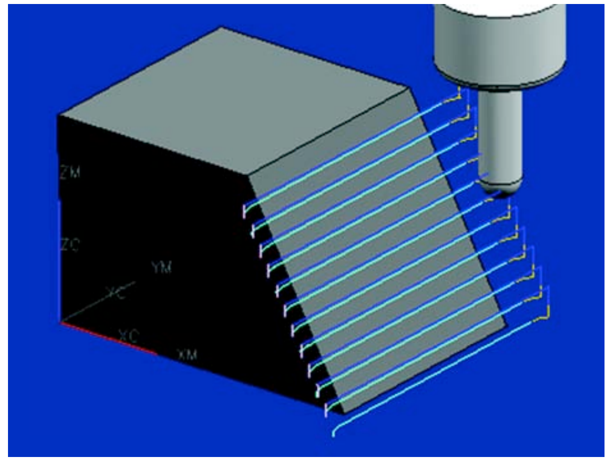

Figure 2: NX™ software screen shot showing Z level cuts on the test piece.

This white paper discusses the relationship between critical machining parameters and high speed machining. It introduces a new process that stresses the importance of obtaining cutting data for high speed milling applications. This method follows the theory of chatter and leverages stability lobe diagrams to suggest a practical no-cost implementation.

Unstable machining results in poor and wavy surface finishes that many people associate with the pinging noise of chatter.

A new methodology leverages these simple characteristics to identify optimum spindle speeds and cutter loads for any given tool, holder, machine and workpiece material combination. In essence, this method cuts a number of Z level passes at varying spindle speeds to identify stable machining conditions.

A series of identical passes are made on an inclined face of a test block, as in Figure 2. Each pass is performed at increasing spindle speed and feed, maintaining the same chip load for all passes. Listening to cuts and inspecting the surface finish of each pass can identify stable-cutting conditions.

Each horizontal line in Figure 3 shows a series of Z level passes at increasing spindle speeds. The parallel lines, as they go up, indicate increasing metal removal rates. The vertical lines indicate how you can find the limits at each identified stable spindle speed.

The trial conditions and cutting pass results are plotted in a stability lobe diagram (Figure 3). Based on the diagram and simple equations, the material removal rate (MRR) for each spindle speed and depth of cut combination can be calculated. Operating the system at peak MRR, and within safe and stable limits, ensures optimum utilization of machining equipment.

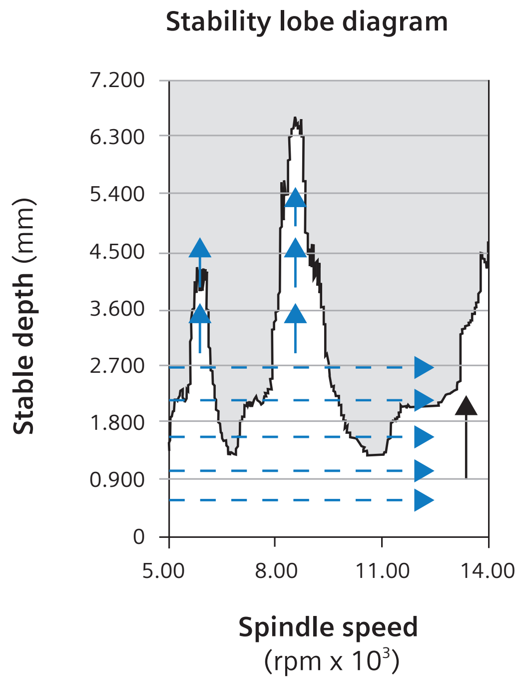

Figure 3: Trail cutting conditions shown on a stability lobe diagram.

A newly proposed process

A newly proposed alternative was put into practice on a Makino V33. In this instance, a 10mm diameter Jabro Tornado Ball end Mill was analyzed. The length of the tool was set at 30mm on an HSK holder. A P20 workpiece measuring 82mm in length, 65mm in width and 48mm in height was used as a test piece. A 30-degree taper was cut on one side of the block to accommodate the holder and to view each cut distinctly.

For this example, assume a depth of cut equal to approximately 30 percent of the tool diameter. If there are other considerations limiting the load on the tool, follow the lesser one. Make sure the tool creates clear cusps to distinguish one depth from another. The height of the block should accommodate at least 12 depths of cut. The slope on the cutting side should clear the tool holder. The length of the block should be sufficient to hang off the vise to allow at least 10 side passes. The width should be sufficient to be able to see the cuts.

Picking up relevant data from the tool catalog

Cutting speed Vc

Material	Seco group no.	Slot milling roughing m/min	Helic./ramp finishing m/min	Side milling roughing m/min	Side milling finishing m/min	Copy milling roughing m/min	Copy milling finishing m/min
Soft steel	1-2	90/225*	250	375	450	325	500
Normal steel	3-4	80/180*	210	310	390	280	385
Tool steel <48 HRc	5-6	50/160	180	280	350	240	325
Hardened steel >48-56 HRc	7	125	150	250	300	200/170*	280
Hardened steel >56-62 HRc	7	80	90	150	175	120/100*	150
Hardened steel >62-65 HRc	7	50	55	80	90	100/80*	110
Hardened steel >65 HRc	7	35	35	55	60	80/60*	85
Stainless steel	8-9	95	100	155	200	125	210
Difficult stainless steel	10-11	60	70	120	145	80	125
Soft cast iron	12-13	175	185	250	285	250	345
Hard cast iron	14-15	150	160	200	245	200	290
Aluminium with <16% Si	16	Max	Max	Max	Max	Max	Max
Aluminium with >16% Si	17	250	280	295	325	300	345
Super alloys	20	50	60	80	120	100	150
Difficult super alloys	21	25	30	40	50	50	75
Titanium based alloys	22	75	80	120	145	100	170
Graphite		600	600	600	400	800	500
*Plastic soft * **		300	400	385	450	Max	Max
*Plastic hard * **		150	175	190	250	200	175
Copper		350	450	450	550	Max	Max

* Refers to alternative tools in the tool selection table.
* * In case of melting of the plastic, reduce the cutting speed (in case of high wear as a result of added elements, reduce the cutting speed).

Feed/tooth Fz Ø 8-10 mm

Material	Seco group no.	Slot milling roughing mm/tooth	Helic./ramp finishing mm/tooth	Side milling roughing mm/tooth	Side milling finishing mm/tooth	Copy milling roughing mm/tooth	Copy milling finishing mm/tooth
Soft steel	1-2	0.090/0.045*	0.057	0.081	0.085	0.130	0.117
Normal steel	3-4	0.80/0.042*	0.053	0.076	0.079	0.121	0.109
Tool steel <48 HRc	5-6	0.070/0.041*	0.051	0.072	0.076	0.115	0.105
Hardened steel >48-56 HRc	7	0.039	0.049	0.070	0.074	0.150/0.112*	0.101
Hardened steel >56-62 HRc	7	0.036	0.045	0.065	0.068	0.120/0.104*	0.093
Hardened steel >62-65 HRc	7	0.030	0.038	0.054	0.057	0.100/0.086*	0.078
Hardened steel >65 HRc	7	0.030	0.038	0.054	0.057	0.090/0.086*	0.078
Stainless steel	8-9	0.045	0.057	0.081	0.085	0.091	0.117
Difficult stainless steel	10-11	0.042	0.053	0.076	0.079	0.085	0.109
Soft cast iron	12-13	0.045	0.057	0.081	0.085	0.104	0.117
Hard cast iron	14-15	0.042	0.053	0.076	0.079	0.097	0.109
Aluminium with <16% Si	16	0.060	0.076	0.108	0.113	0.173	0.156
Aluminium with >16% Si	17	0.050	0.063	0.090	0.095	0.144	0.130
Super alloys	20	0.040	0.050	0.072	0.076	0.081	0.104
Difficult super alloys	21	0.036	0.045	0.065	0.068	0.073	0.093
Titanium based alloys	22	0.042	0.053	0.076	0.079	0.085	0.109
Graphite		0.055	0.069	0.099	0.104	0.159	0.143
Plastic soft		0.050	0.063	0.090	0.095	0.144	0.130
Plastic hard		0.045	0.057	0.081	0.085	0.123	0.117
Copper		0.048	0.061	0.086	0.091	0.138	0.124

* Refers to alternative tools in the tool selection table.

Figure 4: Tables showing manufacturer's recommended cutting data.

The tool manufacturer provides two very important pieces of information: the maximum cutting speed and the chip load. The maximum cutting speed depends on the type of coating on the tool and the maximum temperature it can safely withstand. The chip load (feed/tooth) is based on the material and the geometry of the tool tip.

According to the accompanying table, the maximum cutting speed is 280mm/min and the chip load is 0.072mm/teeth. This example assumed side rough milling conditions for the trial.

In order not to violate the maximum cutting speed, you need to stay below 9000 rpm.

(Note: This can be increased for finishing conditions.)

$$Maximum\_RPM = \frac{Max\_Cutting\_Speed\_in\_mm/min}{\pi * Tool\_Diameter}$$

$$Maximum\_RPM = \frac{280*103}{\pi * 10} = 8912 \approx 9000$$

Narrowing the trial range

For these trials, the spindle speed was varied from 6000 to 11500 at intervals of 500 rpm. The maximum rpm was increased to keep the results applicable to finishing conditions as well. The depth of cut for each Z level cut was 4mm. The program was manually edited to reflect the changing spindle speed at each cut level.

Keeping a constant chip load

The feed was correspondingly adjusted to maintain constant feed/teeth throughout the trial.

*Feed_mm/min = Feed_per_Teeth * Number_of_Teeth * RPM*

Machining

An initial cut with a 0.5mm side stepover was cut on the slope. The side stepover was adjusted on the X offset register of the machine. This eliminates the need for a new program for each cycle.

The initial cut with 0.5mm stepover was repeated once again to allow similar starting conditions for each cycle. This cut produced stable cutting conditions throughout the slope. (Some of the cuts were dull at the bottom of the cusp due to decreased cutting speed.)

The stepover was increased to 1mm and the cycle was repeated. Even though the stability lobe diagram predicts stable-machining conditions at all spindle speeds, very low chatter signals were noticed at both extremes of the spindle speed. This process was repeated with increasing stepover values until severe chatter signals were noticed at 2mm. This cycle clearly showed stable cutting at 7000 rpm and 9500 rpm.

The stepover was progressively increased all the way to 3mm. The cuts at 7000 and 9500 rpm remained stable.

The results

The part in Figure 5 shows stable and unstable machining conditions. This indicates a 4mm depth of cut and 3mm side step. Notice that the third and eighth steps indicate clean cuts at 7000 rpm and 9500 rpm.

Note: The stability lobe diagram shown in Figure 6 was computed for the same tool/holder/machine set up. Notice that the actual behavior follows the general predicted pattern but the actual numbers are off by around 1000 rpm.

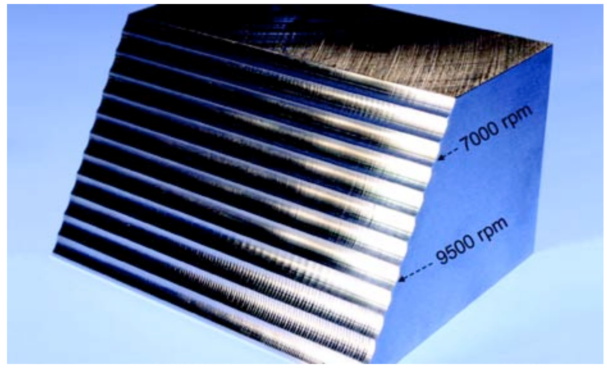

Figure 5: The final proof.

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

Figure 6: Stability lobe diagram.

Conclusion

The stability lobe diagram is a useful tool for identifying stable cutting conditions at varying spindle speeds and MRRs (material removal rates). The diagram can be used to find the maximum allowable MRR, a key performance indicator for machining efficiency, for a given spindle speed. It is important to note that stable machining can be achieved at any RPM, but at the cost of MRR. A global view of the stability lobe diagram, either computed with chatter prediction hardware tools or by the method prescribed in this white paper, helps users achieve high MRRs at certain stable RPMs.

Reducing speed may not be the most efficient remedy for chatter

In many cases, when chatter is encountered, machinists tend to reduce spindle speed to eliminate chatter. While this technique will result in a stable cutting condition, it may not be the most efficient. Instead, it is often possible to increase the spindle speed, which will eliminate chatter, while also improving cutting efficiency.

In the diagram below, slight chatter is encountered at Point A (8,000 rpm with 2.0mm side step over). Outside of re-programming the part with a smaller step over, there are two easy options to remedy the chatter, either decrease or increase the spindle speed. Because the lobe diagram clearly illustrates that a stable cutting condition can be achieved by increasing the spindle speed, this is best option because it is more efficient.

Spindle speed (rpm)	**Feed rate** (mm/min)	**Chip load** (mm/teeth)	**Depth of cut** (mm)
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

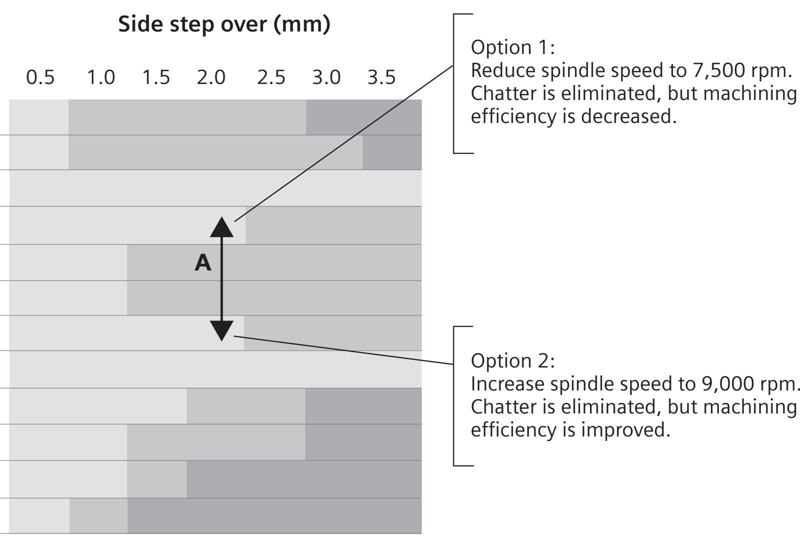

Figure 7: An increase in spindle speed results in stable cutting condition and improved machining efficiency.

Machining at higher speeds may not be the most efficient

Often times, when using high speed machines, the inclination is to run the machine at its top permissible speed. While chatter free conditions can be achieved at extreme speeds, the machining efficiency as measured by the MRR (material removal rate) can be quite low.

*Material_Removal_Rate = Feed_rate_mm/min * Depth_of_Cut_mm * Side_Step_Over_mm*

In the diagram below, stable cutting is achieved at 11,500 rpm with 0.5mm side step over (Point A). Because the spindle is running at a high rpm, it is quite common to assume that the system is performing efficiently. However, as illustrated in the lobe diagram, this is not the case. Point B, a much slower rpm but with a greater depth of cut results in nearly six times greater machining efficiency.

Usage notes

- Follow practical, repeatable conditions (for example, tighten the collet-holder with the same torque every time). This needs to be repeated for every tool/holder/machine combination. While this sounds like a lot, it can easily pay off.
- The sweet spots are transferable to other workpiece materials directly. The corresponding maximum depth of cut and stepover values will vary.
- You could replace the tool with a similar replacement tool from the same manufacturer. The results are still valid. It is true for holders as well.
- Reset the tool length as close as possible to the testing conditions.
- You could increase the depth of cut while decreasing the stepover correspondingly and vice-versa.
- Do not use this data on thin walled parts since the natural frequency of the part being machined changes during the machining process.

Spindle speed (rpm)	**Feed rate** (mm/min)	**Chip load** (mm/teeth)	**Depth of cut** (mm)
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

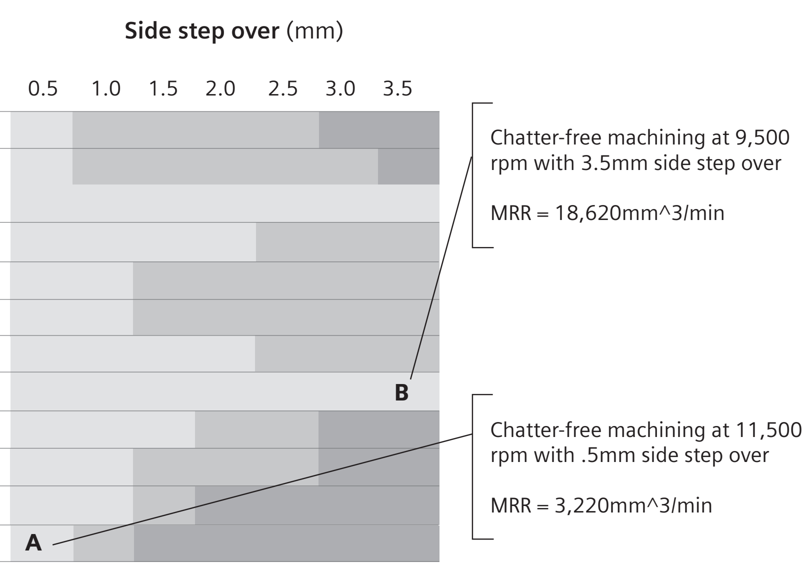

Figure 8: Stable machining at a slower rpm with a greater depth of cut is much more efficient than machining at a much higher rpm with a lighter depth of cut.

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