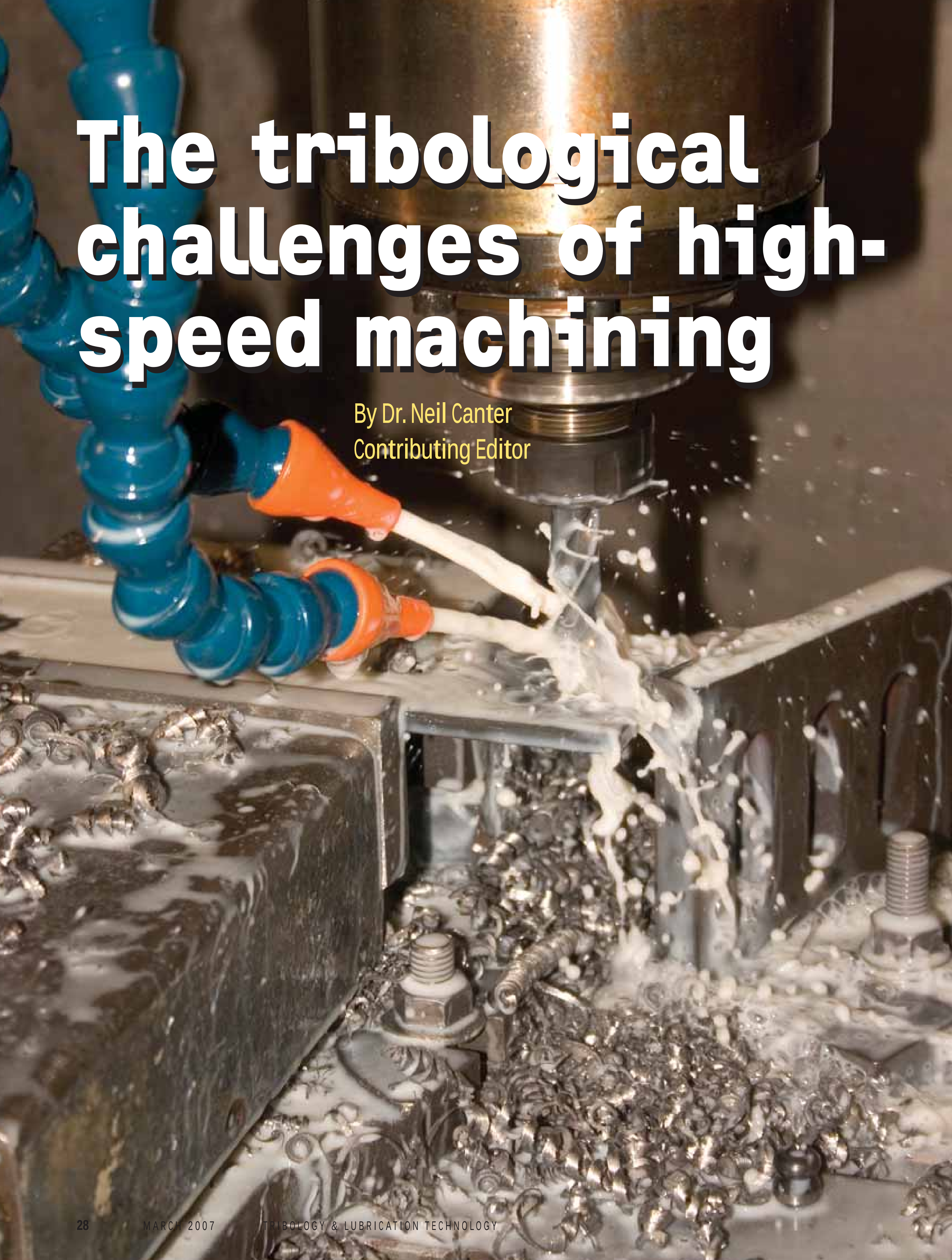

The tribological challenges of high-speed machining

By Dr. Neil Canter
Contributing Editor

While there is no universally agreed-upon definition for this manufacturing technique, everyone agrees on its potential to increase speed of production, reduce costs and improve surface finish of the workpiece.

In today's competitive manufacturing environment, end-users of metalworking fluids seek to maximize their productivity by manufacturing metal parts faster and faster. One of the approaches that is being taken is to utilize high-speed, high-feed machining as a means to achieve this goal.

High-speed machining was originally developed by the German inventor, Dr. Carl Salmon, in the 1920s. Salmon determined that for a specific workpiece metal, the heat generated at the interface between the cutting tool and the workpiece would peak at a certain critical spindle speed. This critical cutting speed is different for each metal alloy being machined. Salmon also determined that on either side of this peak there was a specific spindle speed range at which the cutting tool could not remove metal.

Research on high-speed machining was picked up by Vaughn at Lockheed Aircraft in 1959. Additional research in the 1980s and 1990s, particularly in the aerospace industry, showed that high-speed machining could, in a practical fashion, provide benefits as compared to conventional machining. Faster metal removal can be realized with a combination of lower machining forces and reduced power exerted by the machine tool.

What is high-speed machining?

The answer to seeking the definition of high-speed machining would seem at first thought to be relatively straightforward. STLE member Gary Rodak of Machining Efficiencies, Inc., in Gregory, Mich., says, "There are several definitions of high-speed machining, but the most common is based on the revolutions per minute (rpm) of the machine tool spindle. Some machinists consider 8,000 rpm to be the starting point for high-speed machining, but with current machine capability anything over the 15,000 rpm should be considered high speed. Operating above that spindle speed requires special attention to details such as spindle balance, machine setup, coolant application, tool paths and wear patterns."

Dr. Yung Shin, professor of mechanical engineering at Purdue University, believes that the spindle speed designating high speed is dependent on the workpiece material. He says, "There is no universal definition of high-speed machining. For metals such as aluminum and cast iron, high-speed machining can occur at surface speeds of 2,500 feet per minute (fpm). In contrast, such high speeds cannot be attained with titanium. High-speed machining of titanium can occur at speeds of 400 fpm or slightly higher."

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Dr. David Dilley of D3 Vibrations Inc., in Royal Oak, Mich., looks at high-speed machining from a frequency perspective. He says, "Every tool/holder/machine combination has a characteristic dominant, natural frequency. High-speed machining can be defined as the point where the tooth passing frequency of the cutting tool approaches the dominant natural frequency."

The tooth passing frequency is defined in equation (1). Dilley explains, "A cutting tool with eight teeth might approach the machine tool's dominant frequency, while a tool with two teeth might not. The selection of rpm, number of teeth and depth of cut (DOC) are the most important parameters for machine tool vibrations."

$$\text{Tooth passing frequency (Hz)} = \text{rpm}/60 * \text{number of teeth} \quad (1)$$

This definition means that the shape and size of the cutting tool also plays a signifi-

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Chatter wear shown on the cutting tool can significantly reduce operating life and even cause failure.

cant factor in determining if high-speed machining can be attained in a specific operation. Dilley adds, "Cutting tools that are longer in length have lower natural frequencies, thus reaching high speed at a lower rpm. For example, a long line boring operation can be in a high-speed machining environment at a cutting speed as low as 150 rpm."

Dilley indicates that this definition of high-speed machining is different from others, as most are referring to high speed spindles that relate to the DN number of the spindle bearing. He says, "High-speed machining often takes place even at low DN numbers."

STLE member Tom McClure, vice president of TechSolve Inc., in Cincinnati, believes that high-speed machining has many definitions, several of which have been discussed above. He says, "The key concept is the need to manipulate speed, feed and depth of cut to increase metal-removal rates while lowering cutting forces."

The need for speed

Sufficient work has been done on high-speed machining to show that it provides several benefits. Rodak says, "End-users can realize faster cycle times and better finish on the metal parts. In fact, cycle times for specific machining operations can be reduced by as much as a third."

Rodak adds, "The finish improves part quality due to less residual stress remaining in the part surface. A better quality finish also will have a beneficial impact on subsequent assembly and coating processes."

Shin points to three unique advantages end-users can have in utilizing high-speed machining. He says, "High-speed machining generates a much higher level of metal removal. The end-user can increase the depth of cut during machining. Less heat is conducted into the workpiece in high-speed machining, which can lead to less thermal distortion, reduce the forces needed and also reduce the surface roughness. Finally, less heat into the workpiece also reduces the level of residual stress."

Chatter audio analysis

One of the biggest problems encountered by end-users in increasing spindle speeds is the onset of chatter. Dilley says, "Machinery systems can encounter free vibration, forced vibration and self-excited (chatter) vibration during use."

Free vibration and forced vibration are typically less destructive compared to chatter. Dilley explains, "Chatter occurs when the depth of cut and specific cutting energy required during a specific machining operation exceeds the dynamic stiffness of the cutting tool or workpiece."

Chatter creates large cutting forces that can accelerate tool wear and even cause tool failure, as shown in Figure 1. Chatter also can negatively impact the workpiece quality and the machine tool integrity. The surface finish can be adversely affected to the point of rejection, and the operating life of machine components can be reduced.

The challenge to the end-user is finding a methodology for eliminating the chattering problem while maintaining throughput or cycle time. Dilley indicated that work done by Tlusty and others in the 1950s showed that there was a relationship between the depth of cut in a machining operation and the spindle speed.[1, 2] Unfortunately, machine tool technology was not adequate enough to take advantage of this relationship until the late 1980s.

At that point, the aerospace industry was able to use spindle speeds up to 20,000 rpm but had trouble making metal parts any faster due to chattering until they began to utilize a "Stability Diagram." Such a diagram for a specific tool/holder/machine combina-

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The shape and size of the cutting tool also plays a significant factor in determining if high-speed machining can be attained in a specific operation.

tion is illustrated in Figure 2.

Dilley maintains that no two machining setups are identical, so a given tool will perform differently in a different toolholder, and a given tool/holder combination will perform differently in Machine A vs. Machine B. However, once a given tool/holder/machine is optimized, the same parameters can continue to be used with consistent setup, as many users have been doing for the past 3-5 years.

Dilley has broken the stability diagram into five regions. He says, "The high-performance region occurs when the spindle speed is sufficiently high that the depth of cut can be increased into the wide open (white) chatter-free pockets. This region is tool/holder/machine specific, as it may start as low as 100 rpm or as high as 15,000 rpm. The optimal conditions for machining vibration are often found in this region."

The Figure 2 diagram shows that the conventional machining zone is always chatter-free, which seem perfect. However, this area may not be productive for some tools, as this zone may again start at a higher rpm due to the tool/holder/machine and workpiece.

The "poor man" region begins when the spindle speed increases to the point where tool/workpiece rubbing reduces and chatter is capable of developing. This is the region where most machinists reduce the rpm and increase the feed and run. Dilley states, "I, unfortunately, see many processes running in this region that could easily be moved into the high-performance region."

The $B_{lim}1$ and $B_{lim}2$ regions are chatter-free at any rpm because the DOC is below the B_{lim} line, which is determined by the dynamic stiffness of the system, workpiece material, number of teeth and Radial DOC (for milling).

$B_{lim}1$ is directly below the Poor Man Region, but as the spindle speed increases, the machining process moves into the $B_{lim}2$ region. Dilley says, "This is the metalworking industry's definition of high-speed machining, where tools are run at high speeds, high feeds and low DOC. Unfortunately, productivity, mainly in roughing and semi-finishing operations, can suffer because the end-user is underutilizing the cutting and machine tools."

In order to be more productive, Dilley maintains that the depth of cut needs to be increased and the spindle speed adjusted until the end-user maximizes the metal removal rate in the high-performance region. He says, "The optimal parameters are difficult to find without the proper equipment and software. You can come close, but the trial and error method takes a considerable amount of time, and many end-users are only at 25% of their possible maximum metal removal rate (mrr). Without technology, machinists and engineers do not know when to stop, as they always question if they have found the optimal parameters."

Dilley indicates that a systematic procedure can be done on each individual machining system to determine the sweet spot. This process is done using one of two techniques. The first technique is more detailed, as it develops a stability diagram using an instrumented hammer and an accelerometer. The second technique utilizes the stability diagram theory by using audio analysis with a microphone.[2] An example is shown in Figure 3 for a 2-fluted cutting tool.

The points determined by audio analysis on the chatter frequency vs. spindle speed plot (lower curve) utilized the theory to locate the chatter-free cutting zone in the upper curve. A test coupon in the third diagram (Figure 3) correlates the specific points to their respective depths of cut.

Dilley explains, "The first position reached in the evaluation is point (a) which has a spindle speed of 30,000 rpm and a depth of cut of 0.5 mm. Chatter was detected, so the process called for the rpm to be reduced to just over 25,000 rpm at the same depth of cut. After moving to point (b), no chatter was found, so the next step was to increase the depth of cut to determine if a higher productivity can be achieved without chatter. Unfortunately, chatter was seen at point (c) which had a depth of cut of one mm. This prompted a further reduction of the spindle speed to point (d). No chatter was observed and the depth of cut was increased to point (e)."

Further attempts in this case to increase the depth of cut [points (f), (g) and (h)] proved to be unsuccessful because a two-mm cut by the tool is above any stable machining pockets. Dilley says, "The net result of this analysis is that the metal-removal rate at point (e) is 140% better than point (a)."

Dilley, in conjunction with Manufacturing Laboratories, continues to do research using audio analysis to better understand how to optimize high-speed machining processes for specific machine tool, cutting tool and workpiece combinations.

Other variables

Overcoming chattering is a major challenge in conducting high-speed machining but not the only parameter that needs to be considered. Rodak says, "The setup used in high-speed machining is very important to ensure that the operation is done successfully. A chatter wear pattern on the cutting tool shows up early and is very distinctive. It is usually the first destructive wear pattern that would-be high-speed machinists encounter. It is very different from a diffusion or high temperature wear pattern, which are encountered when the machine setup is correct."

"High surface or contact speeds naturally increase cutting edge temperatures, which decreases tool life," Rodak continues. "The metalworking fluid should be delivered through the cutting tool in order to ensure that it reaches the cutting zone. With metal removal taking place at a much faster rate than conventional machining, small particulate filtration of the metalworking fluid becomes more critical in order to extend its operating life."

McClure sees machining as a system encompassing the various elements shown in Figure 4. He says, "In a similar fashion to conventional machining, six key parameters (machine tool, machining parameters, machining accessories, cutting tool, work material and the metalworking fluid) must be evaluated as a complete system. This procedure will enable machining to take place in the most productive fashion possible."

High-speed machining has not been applied successfully to all types of machining operations and metal alloys. Shin says, "The applications best suited for use in high-speed machining are milling, drilling and turning, in that order."

The limit on developing methodology for high-speed machining of aluminum and cast iron has been reached, according to Shin. But he believes there is plenty of room for improvement in working with hardened steel and titanium alloys.

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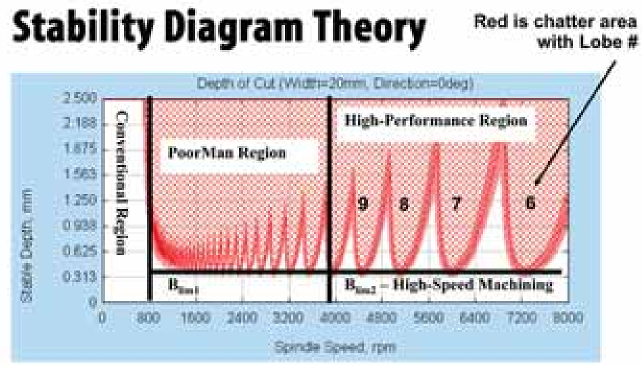
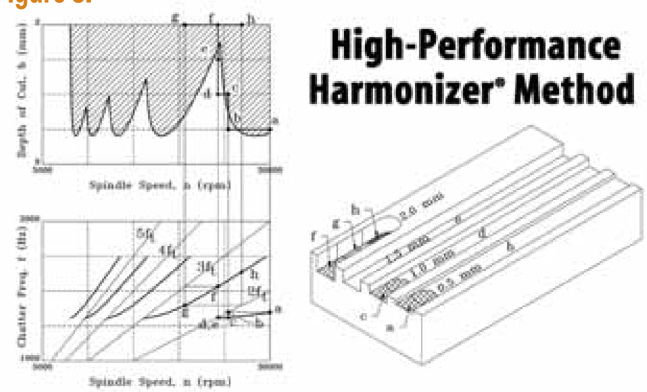
Figure 2.



(Courtesy of D3 Vibrations, Inc.)

The chatter-free white pockets present in the high-performance region are areas where machining can be optimized and productivity increased.

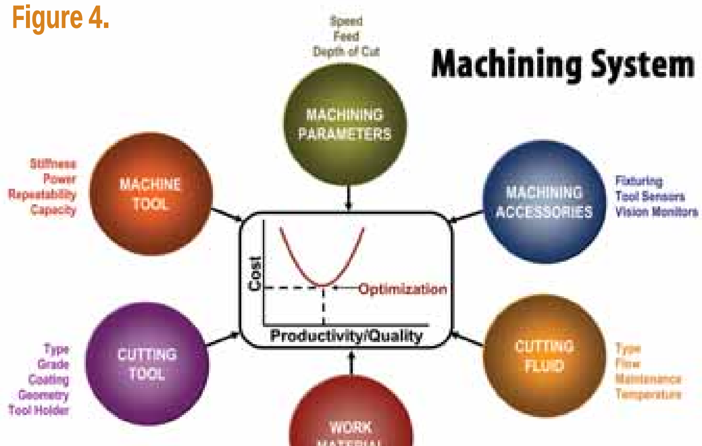
Figure 3.



(Courtesy of D3 Vibrations, Inc.)

Audio analysis technique can be used to determine the sweet spot of each individual machining system. The curves generated on the bottom chart are used to develop the chatter-free zones shown in the top chart. A test coupon in the diagram to the right correlates the specific points to their respective depths of cut.

Figure 4.



Six parameters must be evaluated as a complete system to optimize the machining process.

(Courtesy of TechSolve, Inc.)

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A machining setup used by Shin to study high-speed machining is shown in Figure 5. This particular machine tool has a 30,000 rpm spindle and is used to study high-speed machining, modeling of high-speed spindles, control of high-speed machining processes and studies looking to monitor and predict chatter."

MWF challenges

High-speed machining presents some unique challenges for the metalworking fluid. STLE member Robert Evans, senior scientist for Quaker Chemical Corp., in Conshohocken, Pa., says, "An important consideration with high-speed machining over conventional machining lies in the increased rate of metal removal and the subsequent difficulties associated with greater heat formation and the increasing demands for rapid removal of chips from the cutting area."

Evans continues, "Minimizing temperature increases in the workpiece is of particular importance with softer metals such as aluminum alloys, which have relatively high coefficients of thermal expansion. Heat formation at the point of cut, if not controlled and minimized, can easily lead to loss of dimension control of the machined part.

"Minimizing heat formation also is important in the high-speed machining of other light and ductile metals such as titanium (Ti-6Al-4V), which undergoes a sizeable loss in strength properties as the metal temperatures increases above 800 F, thus making machining extremely difficult. The ability of the metalworking fluid to lubricate and cool under such conditions is critical."

Overcoming chattering is a major challenge in conducting high-speed machining but not the only parameter that needs to be considered.


(Photo courtesy of Purdue University)

Figure 5. A machine tool with a 30,000 rpm spindle is used to study high-speed machining, model high-speed spindles and analyze chatter.


(Photo courtesy of Ultra Additives, LLC)

Figure 6. The higher speeds, flow rates, fluid velocity and pressure encountered with high-speed machining leads to a greater chance for the generation of foam.

Rodak adds, "Small particulate level filtration of the metalworking fluid is often suboptimized and needs to be bolstered. The metalworking fluid will need to stand up to this type of filtration and also reject the buildup of tramp oil. Leakage of hydraulic, spindle and way oils into the fluid can lead to a change in the lubrication in the cutting zone, affecting cutting conditions and tooling performance. It is recommended that high-speed machining coolants should be filtered to two micron particles and tramp oils held to a maximum of 1%."

Foam is also a very important consideration because the metalworking fluid is subjected to conditions very favorable for its formation (*see Figure 6*). Evans says, "The higher speeds will lead to more shearing of the coolant and, as a consequence, the greater potential for generation of foam. The ultimate goal for fluids in high-speed machining operations is to have a functional composition with low inherent foam tendencies and, thus, have little or no dependency on the use of antifoam additives. If they are used however, they should provide effective and extended antifoam properties to the coolant."

STLE member Mary Taylor, technical service director for Ultra Additives, LLC, in Bloomfield, N.J., says, "Higher flow rates, fluid velocity and pressure involved in high-speed machining combined with increased part movement and heat facilitates the incorporation of air into the metalworking fluid and, as a result, produces foam. The detergency of the coolant can act to stabilize the foam."

Taylor contends that a variety of foam diameters can be formed. She explains, "Smaller bubbles (microfoam) tend to be

(Photo courtesy of Protomatic Inc.)

High-speed milling of aluminum 7075-T73 is much more efficient and furnishes superior metal parts as compared to conventional machining.

produced preferentially as compared to large bubbles at higher machining speeds. The mechanism of defoaming is due to the process of microfoam coalescing or unifying from a small single bubble into larger ones, which support and increase the transport line or buoyancy of the air bubbles out of the system."

Both Evans and Taylor agree that proper selection of a defoamer added tankside may be needed to address foam problems. Taylor adds, "The engineering of the machining system is important to allow for adequate space for the foam to dissipate and settle."

Higher levels of mist also can be formed during high-speed machining operations. Adequate ventilation and machine enclosures are probably the best way to control mist levels as was discussed in a recent feature article in TLT.[3]

End-user perspective

Protomatic Inc., in Dexter, Mich., carries out custom manufacturing of prototype parts for use in a large number of applications. Doug Wetzel, vice president and general manager, says, "High-speed machining is an integral part of our approach in providing service to our customers. We use high-speed machining because it is much more efficient than conventional machining, and we can produce superior parts."

Wetzel believes that high-speed machining can reduce vibration, which leads to an increase in tool life and improved finish. He says, "We have to machine many different metal alloys (including steel, titanium and plastic) for a large variety of applications. It is very difficult to shift gears without being able to use a systematic, diagnostic approach in machining. Our customers are demanding tighter parts tolerances, which puts the pressure on us." High-speed milling of an aluminum alloy is shown in Figure 7.

Protomatic uses the vibrational analysis described earlier to optimize machining parameters. This end-

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user conducts two basic metal-removal operations. Wetzel says, "Approximately 70% of the work we do is milling with the remaining operation being turning. Over 50% of the parts we make are turned and then milled."

From a metalworking fluid standpoint, the biggest issue Protomatic faces is mist, especially when the parts are warm. Foam also can be an issue, according to Wetzel. Protomatic uses a water-based synthetic fluid for 90% of its operations. Wetzel says, "The metalworking fluid is selected based on need. In some cases we can conduct high-speed machining without any coolant. This is particularly useful in machining plastic parts for medical applications. We cannot risk coolant contamination of parts in these cases."

Table 1. Audio Analysis on End Mill Machining Process

Test	Chatter	Rpm	DOC	Feed	Cycle Time
Original Process	Yes	8,500	0.050 inch	0.0009 inch/tooth	155 seconds
Higher Feed	Yes	8,500	0.050 inch	0.0030 inch/tooth	
Lower DOC	Yes	8,500	0.040 inch	0.0030 inch/tooth	
Optimized 1	No	7,550	0.040 inch	0.0009 inch/tooth	
Optimized 2	No	7,550	0.040 inch	0.0030 inch/tooth	65 seconds
Optimized 3	Yes	7,550	0.050 inch	0.0030 inch/tooth	

Case studies

Dilley discussed a problem occurring at a machine shop that was machining a pocket in an aluminum component. The company had tested many tools and toolholders over months with minimal success, which they attributed to the length of the 0.25-inch end mill (10:1 length:diameter).

Audio analysis improved this company's process by 90 seconds per part for a production schedule of 300 parts per month (*see Table 1*). This represents a 7.5-hour reduction in machine time per month or 90 hours per year. The small change freed up this machine for over two weeks per year, which amounts to a yearly savings of $7,200 (at $80/hour machine time).

The machine shop later eliminated the finish pass because the surface finish improved so dramatically after the process was optimized. An additional reduction of 20 seconds was realized in the cycle time. The machine shop also stopped chipping tools, which reduced tooling costs.

A second case study involved machining a steel part using a Makino V55 CNC machine. The operation involved using a 19.05-mm, 4-flute solid carbide end mill. This CNC machine can operate at a maximum spindle speed of 20,000 rpm.

McClure says, "Machining at 20,000 rpm could only be done at a depth of cut of one mm prior to chattering. Reduction of the spindle speed to 17,300 rpm led to an increase in the depth of cut to five mm."

The metal-removal rate increased significantly from 152 cm^3/minute to 659 cm^3/minute. As a result, the time needed to machine the part was cut by 17 minutes.

Additional progress can be made in the future to further improve upon the high-speed machining process. McClure says, "The cutting tools and metalworking fluids need to be updated to the extent of the machine tools in order to be able to machine at faster speeds. On a scale of 1 to 10 (where 1 represents a very rudimentary understanding of high-speed machining and 10 represents optimal utilization of the technique), the metalworking industry is now between a 6 and a 7. We still do not have the skill set to better utilize high-speed machining."

Rodak suggests a holistic approach to high-speed machining, which includes applying world-class techniques to the elements of good machining. He says, "By unknowingly applying suboptimized practices in any of these elements, the end-user is virtually assured of problems within the high-speed machining environment."

Dilley adds, "The challenge in high-speed machining is to impart to the end-user a change in philosophy for running the technique. Most end-users do not know the capabilities of their machine tools and often underutilize them. Another hurdle is the lack of end-user training, and much of the existing knowledge base is disappearing. If carried out properly, high-performance machining can enable an end-user to attain a 300%-500% improvement in productivity." <<

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