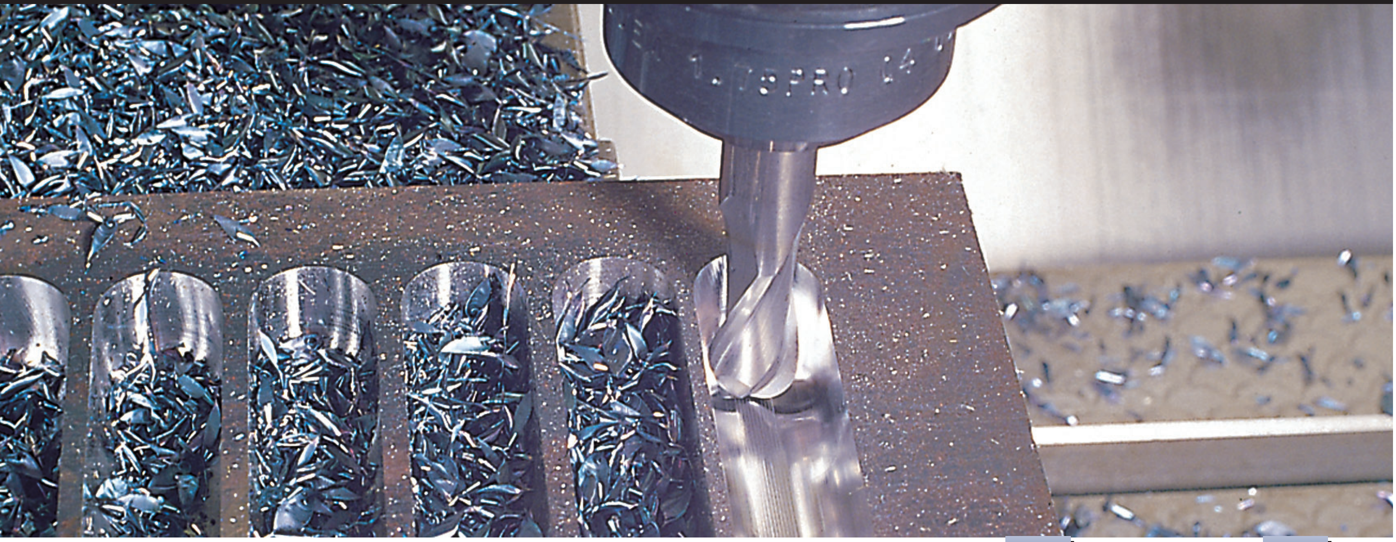
JUNE 2005 / VOLUME 57 / NUMBER 6

➤ BY JASON WELLS



All images: SGS Tool Co.

Material Matters

To optimize an application, learn as much as possible about the workpiece material.

Asking questions is one of the best ways for cutting tool application people to learn about—and control the outcome of—a metal-cutting operation. That includes inquiring about the workpiece material.

It may seem obvious to ask about the type of material being machined, but is that information enough? The question generally engenders a multitude of answers, ranging from the most simplistic of descriptions to one requiring a visit to the old periodic table.

The question needs to be developed further to achieve the desired results. The choices in cutting tool geometries are too great to stop at "What type of material are you machining?"

If you are told an end user is machining steel, is this enough information? If the end user goes on to say it is an alloyed steel, is that enough information? If you are then told it is a hardened alloyed steel, do you have enough information yet?

Simply put, the answer is no.

Our goal as application engineers is to optimize cutting tool performance. It is our responsibility to ask enough appropriate questions to choose the best tool. It is the end user's responsibility to provide enough details to successfully address the application.

Cutting tools incorporate many geometries, coatings and substrates that are material- and application-driven. Tools can be engineered with substrates that offer toughness over rigidity. Tools can be built that exhibit high-shearing characteristics, which means that certain tool-strength components are sacrificed. Coatings are available for heat resistance when dry machining, but a coating for abrasion resistance in a highly abrasive environment may be needed.

As you can see, choices must be made before a tool is ever chosen. The starting point for this entire process is identifying the material to be machined. If you do not understand what material you will be applying your tool to, how can you know what to expect from the tool or how to apply it in the first place?

The Material's Recipe

Begin analyzing materials by looking at their alloying elements. Various elements are added to materials to enhance key characteristics and properties, such as better corrosion resistance or improved ability to harden the material. These elements help enhance the performance of the end product, but often pose additional challenges to the cutting tool.

Common alloying elements like nickel, chromium, cobalt and molybdenum affect the thermal properties and ductility, having a negative impact

Identical drilling applications involving 316 stainless steel result in different chip formation due to geometrical differences in tools.

on machinability. Vanadium, tungsten and cobalt can add strength and toughness to the material, creating a more difficult-to-machine condition. Lead, silicon and manganese are sometimes added to make steels more free-machining. It is important to realize that the higher percentage of each element increases the presence of those elements' properties.

These alloying elements, combined with the base elements of a workpiece material, possess certain key properties. Each of these properties needs to be evaluated prior to machining. The properties to be aware of are thermal conductivity, ductility, workhardening tendencies, inclusions, strength and hardness.

Energy created during the cutting process becomes heat, causing the temperature in the cutting zone to increase and negatively influence chip formation and removal. A rise in temperature also might cause adhesion of chips to the cutting edge and chemical reactions between the tool and the workpiece. Materials high in thermal conductivity move up to 80 percent of the heat away from the cutting zone quickly through the chips created and the workpiece itself.

A high thermal-conductivity rating improves the machinability of a material, but there are groups of materials designed specifically to resist the effects of heat and they purposefully possess low thermal-conductivity properties. These materials are often referred to as high-temperature alloys. Because of their design, these materials create higher tool wear and a large cutting force—about twice the force compared to medium carbon steels.

Optimal machining requires a strong tool geometry with sharp shearing capabilities and high-quality tool coatings that can withstand extremely high temperatures. Selecting the proper machining parameters is critical due to the delicate balance required for optimal results. Higher machining parameters produce more energy, which means more heat in the cut. But if the parameters are too low, a built-up edge will develop on the cutting tool.

Ductility is the state of being flexible or elastic. Ductile materials tend to resist being separated from themselves to create a chip and instead separate through a process known as "necking," which is a stretching of the material until it separates. Often, machining highly ductile materials does not require a lot of power, but these materials do tend to develop BUE on a cutting tool and create long, difficult-to-manage chips. A ductile material can create a chip five times as thick as the programmed feed rate. This requires tools that can manage high-volume chip creation through proper flute configurations that help move the chips at a rapid pace and prevent them from clogging in the fluted area.

Many nonferrous materials such as aluminum are quite ductile. They need to be machined using cutting tools with positive rake angles and high clearance angles. These sharp, narrow cutting edges efficiently and cleanly enter and shear the material.

Hardening in the Cut

During machining, the material undergoes a high rate of deformation and pressure near the cutting edge, which causes the material's surface to experience an altered structure and increase in hardness. This process is known as workhardening. The level of increase depends on the material and the rate at which the deformation occurs. Materials that workharden easily require more energy to create a chip. Workhardening is a major problem when taking multiple passes along a workpiece. It is important to machine at feed rates that exceed the depth of the workhardened layer. If you fail to adjust the feed rate appropriately, the cutting edge will experience severe and adverse conditions.

Austenitic stainless steels and high-temperature alloys have a tendency to workharden, while carbon steels do not prove as challenging. Large rake angles and sharp cutting geometries reduce the rate of deformation and help decrease the depth of the workhardened layer. This reduces stress on the cutting edge, but extremely high rake angles and sharp cutting geometries can weaken a tool's cutting edge. As with all machining situations, a compromise needs to be found in the geometry. The one advantage workhardening does offer if controlled appropriately is a reduction in the tendency of material to adhere to the cutting edge.

During the manufacturing and refining of metals while in their liquid state, there is an opportunity for particles to get trapped in the material. These particles are known as inclusions. Normally, these inclusions are hard, abrasive materials that interrupt the chip flow and create additional shock or stress on cutting edges. Sudden, unexpected tool failure in a proven application may be traced to the interference of inclusions in the material. The size of the inclusion determines if it is a severely damaging macroinclusion (greater than 0.006") or a microinclusion. Microinclusions are always present in steels to some degree.

A material's resistance toward deformation under load is an expression of its strength. A material with high strength requires a high level of force to initiate chip formation, which requires stronger cutting edges and less

Long and large aluminum chips are created from a ductile material. The shallow flutes of the tool on the left would clog and cause the tool to fail.

positive cutting geometries. As strength increases, hardness increases proportionally. Increasing the strength and hardness of a material leads to a decrease in ductility. This may be necessary to more efficiently machine some gummy materials that tend to adhere to a tool's cutting edge.

Increased hardness has a negative effect on productivity and tool life, because the cutting load and temperatures increase as the material becomes more resistant to metal removal.

A cutting tool's geometry needs to be engineered to address a high level of workpiece hardness. Tools with more edge strength, rigidity and flutes may be needed for machining hardened materials. Hard materials are short chipping, but penetrating the material to create that chip and the high-impact loads experienced when the tool meets the workpiece create the problems faced when choosing tool geometry. To choose the best geometry, the operator must know the hardness of the workpiece material and the depth of that hardness (see sidebar, page 62).

Workpiece Condition

The condition of the workpiece or the way it was processed plays a role in the machinability of a material. Some processes are designed to improve machinability, while others challenge the metalworking process. Common workpiece processes are hot rolled, normalized, annealed, cold worked, and hardened and tempered.

A hot-rolled material has an inconsistent and coarse material structure, which can include voids. Machining can be inconsistent, depending on the degree of voids or inconsistencies.

A hard case to crack

I fully appreciated the importance of understanding workpiece materials a couple of years ago while working with an end user on a difficult application, which involved machining casehardened steel. The application called for drilling and chamfering a blind-hole and it was giving the end user poor tool life and a high cost per part.

When machining casehardened steel, the workpiece is only hardened to a specific depth. In this application, the case was hardened to 57 HRC to a depth of 0.020", and then transitioned to 32 HRC. The material contained chromium, nickel and molybdenum.

The material was originally being machined with a tool designed for hardened steel. The tool was built for strength, with a heavy chisel and straight cutting lip. The flutes were designed for strength and did not assist in chip evacuation.

To begin optimizing this application, I analyzed the workpiece with the shop's engineer. He measured the exact depth of the casehardened area and had the transition hardness levels mapped. We then looked at the material's alloying elements and the percentages of each. This gave us a road map to start the cutter development process and optimize results.

The steel needed to be addressed as two different materials, as the cutter reacts to the casehardened layer in a totally different fashion than the softer core. Also, nickel was present, so built-up edge when machining the softer core became a concern. The solution was a new tool design and approach.

The new tool had strength features, such as a corner radius and a strong web, shearing capabilities and a helix angle to assist in chip evacuation. A more heat-resistant coating with a very low coefficient of friction was selected to prevent BUE. Finally, parameters were chosen so the tool entered the hardened layer at one set of parameters and finished to depth in the softer core at another set.

A better understanding of the material allowed us to increase tool life from 35 to 90 parts per tool. The tool was designed around the material and the parameters were created to address the specific characteristics of this material. In addition to the tool life jump, cycle time was reduced by nearly 1 minute per part.

— J. Wells

Regarding thermal conductivity, chips from 4140 steel show heat transported to the chips. The color change indicates a high level of heat contained in the chips.

A normalized material has a finer and more homogenous structure than one that is hot rolled. Normalizing increases toughness, but the more uniform structure allows the material to be machined more consistently.

An annealed material is processed to change the structure in a way that reduces the amount of hard and abrasive particles, compared to a nonannealed material. Annealing can also help to release stresses, which can affect tolerances on the workpieces that developed in the material during cooling or cold working.

Generally, a cold-worked material has been normalized or annealed. Although cold working helps to improve surface finish and reduce burr formation, the process increases the material's strength. The material may pose more of a challenge to machine because of its increased strength, but it has less of a tendency to cause BUE.

Hardening and tempering a material increases the strength and resistance of the material toward deformation or cutting.

All of these aspects of the material are interrelated and influence whether a cutting tool is successful in an application. The challenge we face in applying tools is understanding these interrelationships and influences. We do that by asking questions. △

About the Author

Jason Wells is a journeyman toolmaker who works as director of product development and marketing for a major solid-carbide round tool manufacturer.