JUNE 2008 / VOLUME 60 / ISSUE 6

PCD in the Fast Lane

Improving medium-grade PCD for high-speed milling, including interrupted milling of high-silicon aluminum.

All images: MegaDiamond

A selection of PCD tool blanks.

cover focus

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High-speed milling with PCD tools is becoming more prevalent in manufacturing. In general, PCD material technology is reaching maturity, but the demands of high-speed milling, especially interrupted cutting of high-silicon aluminum, challenge PCD suppliers to improve their offerings.

Medium grain-size PCD materials are generally used to make milling inserts because of their ability to strike a balance between achieving effective abrasion resistance, which extends tool life, and imparting fine workpiece surface finishes. The typical failure mode for milling inserts is loss of cutting edge sharpness, resulting in burr formation on the workpiece. The challenge is to minimize burr formation while improving surface finish.

Specific material properties, such as flexural strength and toughness, can be improved through an engineered diamond grain size distribution and advanced PCD processing techniques. The result is a PCD material with improved cutting edge retention, which results in finer workpiece surface finishes without sacrificing wear resistance.

Materials Engineering

PCD is a composite material manufactured by sintering a mass of diamond grains under ultrahigh-pressure and high-temperature conditions. Pressures are upwards of 55,000 to 60,000 bar, and temperatures are from 1,200° C to 1,400° C. At the same time the PCD layer is fused, it is integrally bonded to a tungsten-carbide substrate. Sintering diamond particles relies on diffusion of cobalt metal—in this case, coming from the carbide substrate—to facilitate diamond grain growth between crystals and to form strong diamond-to-diamond bonds. The residual pore spaces between the diamond crystals are filled with cobalt metal, forming metallic pools throughout the diamond matrix. The resulting PCD product combines the extreme hardness, high thermal conductivity and abrasion resistance of diamond with toughness properties approaching that of tungsten carbide.

The cobalt does not hold the diamond grains together but instead acts as a catalyst to promote strong intergranular bonding and provide enhanced toughness. If the cobalt was leached away with an acid, the PCD wouldn't convert into a powder again but would remain as a bonded matrix with a strong intergranular structure.

PCD products for metalcutting have traditionally been classified into four general grades, or categories: extra fine, fine, medium and coarse. The main controlling factor determining a PCD grade is the relative size of the diamond particle. It is generally accepted that abrasive wear resistance increases with increased grain size. While simply increasing grain size does provide better abrasive wear resistance, several other desirable properties, such as tool edge quality, edge toughness and surface finish, can be diminished as a result. This is because as the material wears, the metallic phase and intergranular bonds are weakened and diamond particles pull away from the cutting edge. When this occurs, the microedge sharpness diminishes. A fine grain is prone to this

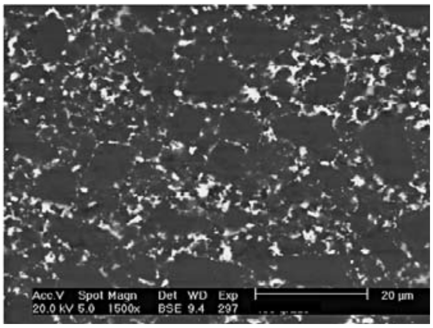


Figure 1: A micrograph of a typical medium-grade PCD shows some large grains and a metallic second phase with an uneven distribution, which results in an agglomeration of grains that are difficult if not impossible to wire EDM.

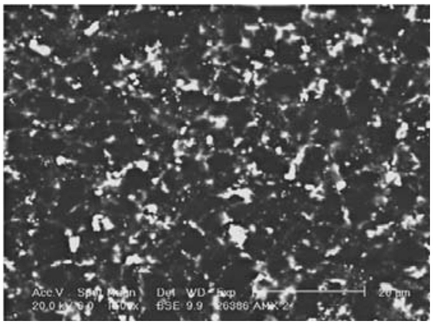


Figure 2: A micrograph of the AMX medium-grade PCD shows a microstructure with uniform diamond particle size distribution and evenly dispersed metallic pools.

Automotive milling applications

CONTROLLED FIELD TEST applications have indicated up to a 100 percent increase in tool life in high-speed milling for automotive applications when applying AMX-grade PCD tools. Two examples are presented here.

Low-silicon aluminum application
Component: Road car cylinder head made of aluminum with 10 percent silicon
Operation: milling
Tool diameter: 315mm
Number of teeth: 28
Cutting speed: 2,000 m/min.
Feed per tooth: 0.07 mm/tooth
DOC: 0.5mm
Results
AMX PCD: 12,000 components
Competitive medium-grade PCD: 5,000 components

High-silicon aluminum application
Component: V6 sports car cylinder head made of aluminum with 18 percent silicon
Operation: milling
Tool diameter: 200mm
Number of teeth: 20
Speed: 3,800 m/min. at 6,000 rpm
Table feed: 12,000 mm/min.
Feed per tooth: 0.1 mm/tooth
DOC: 0.5mm
Results
AMX PCD: 9 parts per edge
Competitive medium-grade PCD: 5 parts per edge

same phenomena but, because the grain size is smaller to begin with, it has the ability to maintain an inherently finer cutting edge.

Milling and turning automotive materials, such as aluminum-silicon alloys, typically require a medium-grade PCD to achieve an optimal combination of tool life and component surface finish. This is especially important for the more abrasive Al-Si alloys with more than 16 percent silicon content, which require application of more abrasion-resistant PCD tools. However, because current market conditions demand faster machining operations, tool performance has been reduced by the loss of cutting edge sharpness. Once this happens, burr formation begins, indicating that a new tool is needed to minimize secondary deburring operations.

To maintain acceptable tool life, some toolmakers have attempted to introduce coarse-grade PCD. Unfortunately, the increase in grain size has typically lead to rougher surface finishes on components even before a tool wears.

In response to this increased demand on medium-grade PCD cutting tools, MegaDiamond has developed a medium-grade PCD called AMX. Using a select blend of diamond particles coupled with proprietary methods of powder preparation and the addition of toughening agents, the PCD material's durability is increased. The grain-size distribution is from 8 to 12 microns. A

Engineering application-specific superabrasive tools

SIMILAR TO OTHER TYPES of cutting tools, off-the-shelf superabrasive tools are becoming commodity items. Application-specific PCD and polycrystalline cubic boron nitride specials are an exception, and CITCO Products, Chardon, Ohio, is one toolmaker that produces such tools.

An end user going through an optimization process may feel that his application is completely unique, but it's likely that similarities exist with applications at other manufacturers. CITCO gathers case history information so when it needs to develop specials, that information can help determine what specific tool geometry and PCD or PCBN grade is appropriate based on similar applications, according to Ed Galen, sales manager for CITCO. "We do a lot of testing and database accumulation," he added.

Besides accumulating data about an end user's workpiece material, toolholders and type of coolant—if any—being applied, a customer's equipment capabilities plays a major role in designing superabrasive specials. "In many cases, the equipment itself will dictate to a large extent what you can do with the tools," Galen said.

Purchasing or upgrading a machine tool or other piece of equipment to achieve the process requirements is typically not an option. "Usually, the customer says, 'I've got this job, I want to run it on this piece of equipment and don't tell me I need to buy a new piece of equipment,' " Galen said. If a machine isn't capable of running at the required parameters, for example, or meeting tolerance specifications, CITCO will recommend a piece of equipment that should. "There have been cases where customers said they don't want to do that, and then we say, 'Sorry, we can't help you.' "

Galen said about half of end users switch from carbide to superabrasive tools to achieve their goals, often after testing other carbide tools because sometimes they're trying to avoid costlier superabrasive tools or reduce tool costs even when a superabrasive tool can reduce their cost per part.

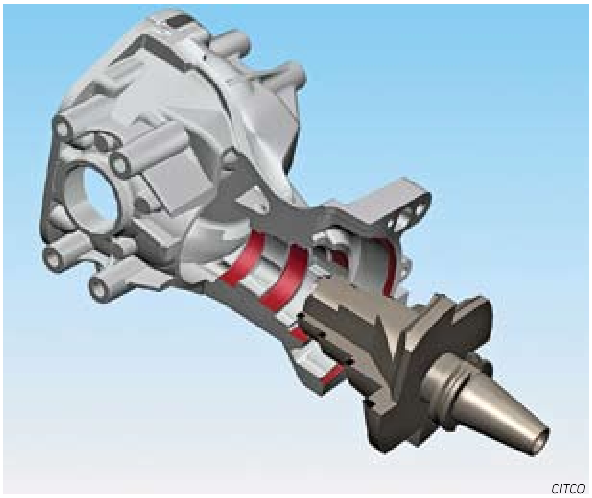
"We've found, in most cases, that if you can reduce cycle time or increase tool life by a relatively small percentage," he said, "the cost of the tool doesn't mean much of anything in the equation."

Combining multiple operations into a single superabrasive tool can result in a tooling solution with a high acquisition cost, but one that is cost effective when focusing on the cost to use. The percentage being saved to justify switching to a superabrasive special depends on the company and application, but Galen said the rule of thumb is 15 percent. "Some companies realize that a 5 percent savings on something that's costing $20 million to produce is a huge savings," he said, "but there are others that if they can't show 15 percent, then it gets lost in the shuffle. Ninety-nine times out of a hundred 15 percent will catch somebody's attention. If you're under 10 percent, they'll attribute it to luck."

Cost, however, isn't the only factor when considering switching to an application-specific superabrasive tool.

In one application, CITCO replaced a carbide drill for creating a valve hole with a PCBN-tipped drill with a K-land hone. The new drill reduced production costs by only 12 percent. The customer, however, was experiencing a quality problem with valves sticking, which was eliminated by switching to the slower-wearing PCBN drill.

The PCBN tool costs $275—$119 more than the carbide one—but the customer was able to complete 23 parts per hour with the new drill vs. 20 parts per hour previously. The PCBN drill is run at a spindle speed of 4,800 rpm and a feed rate of 21 mm/min., while the carbide drill ran at 2,300 rpm and 18 mm/min.


CITCO

A Dipax D3-grade differential bore finishing tool from CITCO replaced three carbide tools and reduced cycle time from 2.6 minutes to less than 1 minute. According to CITCO, the initial tool has been in operation for 18 months and shows no sign of wear.

"He went from 700 parts per tool to 1,000 parts per tool, which hardly sounds like it would be enough to justify almost double the price of the tool, but when you work up the increased output," Galen said, "the labor costs went from $7.25 to $6.30 per part," using a labor and machine overhead rate of $145 per hour. He added that the tool cost increased about 5 cents per part for a net savings of nearly 90 cents per part. The customer consumed 35 tools per year for the application, resulting in an annual savings of $31,454.06.

Sometimes a newly designed tool costs less than the previously applied one and reduces production costs. That was the case when CITCO replaced one PCD tool to machine an aluminum differential housing with a Dipax D4-grade PCD boring tool. The old tool cost $112 and produced 12,000 parts, and CITCO's is $89 and produces 20,000 parts.

When switching tools, the customer didn't make any changes in the machining parameters of a 3,200-sfm cutting speed, a 0.008-ipm feed and a 0.020" DOC and therefore the production rate was identical at three parts per minute. But extending tool life meant that the parts manufacturer didn't have to produce as frequently a production-delaying inspection report on the first part machined after a tool change.

For more information about CITCO's PCD and PCBN cutting tools, call (440) 285-9181, visit www.citcodiamond.com or ***enter 312 on the IS card.***

—Alan Richter

proprietary process is used to achieve a high-shear compaction prior to the sintering process. The high-shear compaction process results in an improved microstructure and increased intergranular bonding compared to typical medium-grade PCD materials.

During high-shear compaction, a load is placed on the grains, forcing them together and causing some grain breakage on a nanolevel. The high-shear compaction process enables the grains to bond closely during high-pressure, high-temperature sintering. When sintering loose powder, the feed-stock powder is placed in a refractory metal can before a carbide disk is positioned over the can. With just powder in the can, PCD manufacturers have difficulty controlling how tightly packed the powder becomes, which may cause interstitial gaps to form in the matrix after sintering.

The compaction techniques, combined with a unique sintering technology, produce a material with improved diamond-to-diamond bonds and a more uniform polycrystalline microstructure than standard medium-grade PCD. AMX's PCD structure not only improves wear resistance, but also enhances edge quality, edge toughness and wire EDM

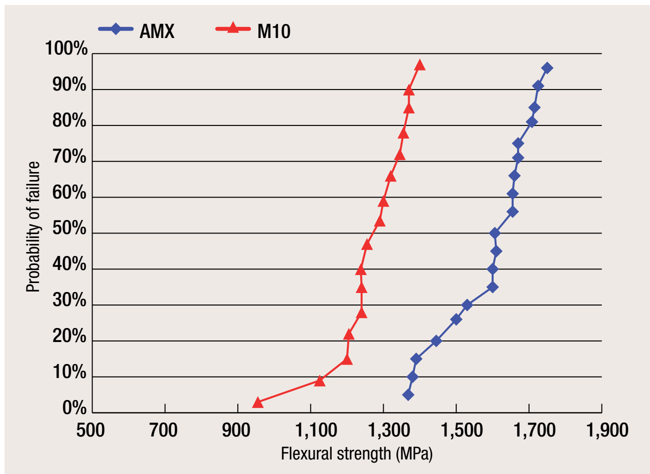


Figure 3: The transverse rupture strength values of a typical medium-grain PCD and the AMX grade. The AMX has a higher flexural strength, which reduces the incidence of tool edge chipping and thereby extends tool life.

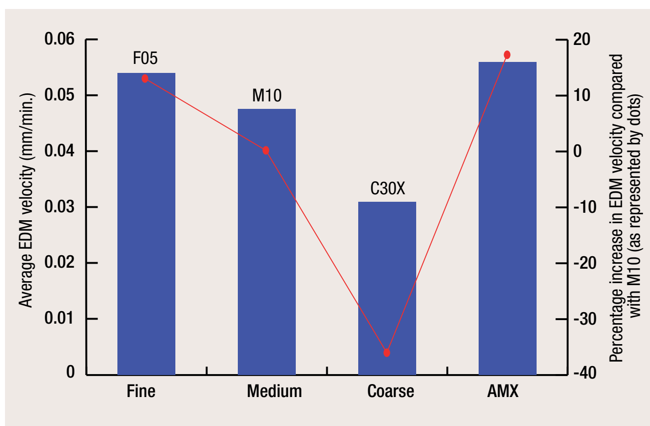


Figure 4: The results of EDM cutting tests performed with AMX and typical fine-, medium- and coarse-grain PCD grades.

machinability.

PCD Tool Fabrication

Medium-grain PCD grades are typically cut with a wire EDM during the tool manufacturing process with varying degrees of success. EDMing PCD is difficult because diamond is not typically conductive and EDM is a process for vaporizing conductive materials.

Cobalt, on the other hand, is conductive, and wire EDM machinability of PCD is a function of how uniformly the conductive metallic phase is dispersed throughout the diamond matrix. If the cobalt is not evenly dispersed, an agglomeration of diamond grains can cause the wire to break or deviate as the EDM tries to erode a material that it cannot. Additionally, coarse-grain PCD grades are inherently more difficult to cut because of their relatively large grain size. Cutting with an EDM may also produce an undercut at the interface between the diamond and carbide substrate, which requires more grinding to finish the tool's periphery. Typically, an extra 0.010" to 0.015" of PCD remains after EDMing, and a tool is peripherally ground to final size.

The quality of the ground edge that can be produced is crucial in achieving optimal medium-grade PCD tool life performance and workpiece surface finish. Grinding typical medium-grade PCD can cause larger grains to pull out from an edge, creating a rough cutting edge. By tailoring the diamond particle distribution and improving the packing density of the diamond grains, PCD tool manufacturers can achieve a higher-quality edge.

Microstructure Modification

To produce a material that exhibits improved edge toughness combined with similar wear resistance, several modifications to the polycrystalline microstructure are necessary. The modifications are achieved by two approaches. First, the feedstock diamond powders are carefully selected and blended.

keywords

DIAMOND: Cubic crystalline form of carbon produced under extreme pressures at elevated temperatures. The hardest natural substance, it has approximately five times the indentation hardness of carbide. Its extreme hardness, though, makes it susceptible to fracturing.

PCD, POLYCRYSTALLINE DIAMOND: Cutting tool material consisting of natural or synthetic diamond crystals bonded together under high pressure at elevated temperatures. PCD is available as a tip brazed to a carbide insert carrier. Primarily used for machining nonferrous alloys and nonmetallic materials at high cutting speeds.

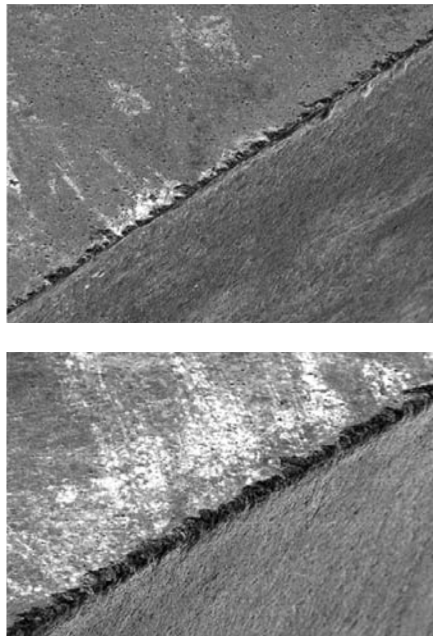
SUPERABRASIVE TOOLS: Abrasive tools made from diamond or cubic boron nitride, the hardest materials known.

—CTE Metalworking Glossary

Grains larger than 12 microns, which provide superior abrasion resistance but detract from a tool's edge quality, are removed. This reduces the material's average grain size. Second, a new powder preparation process increases the packing density and surface activity of the diamond grains prior to sintering. This facilitates and maximizes diamond-to-diamond bonding. The resulting polycrystalline microstructure has minimal interstitial gaps compared to traditional medium-grade PCD products.

The metallic second phase, or cobalt, provides a toughening effect but must be dispersed as evenly as possible throughout the microstructure to provide uniform and consistent properties. If excessive interstitial metallic pools or gaps exist between diamond crystals, a weakness becomes inherent by degrading a cutting tool's desired properties, such as abrasion resistance and chemical and thermal stability.

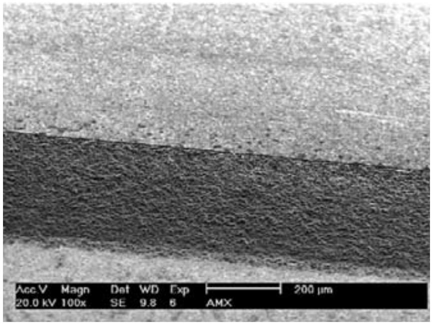
The patented manufacturing process for AMX provides a dense structure of diamond crystals adjacent to other diamond crystals, with a maximum amount of surface contact between each grain. This minimizes the amount of metal pools that form during sintering. In addition, it enhances a cutting tool's thermal and chemical properties, which are also critical to overall performance.

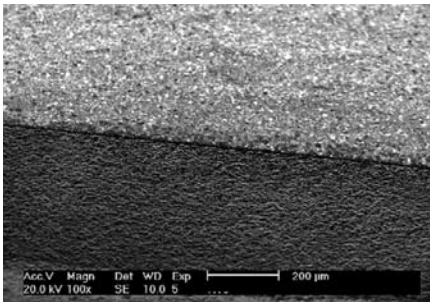


Figures 5 and 6: The magnified edge (400x) of finish-ground PCD inserts shows a higher-quality cutting edge for the AMX grade (top) than the edge for a typical medium-grade PCD.

The general failure mode of medium-grade PCD when milling abrasive, nonferrous materials such as high-silicon aluminum is a dulling or breakdown of the cutting edge through attrition. This means the boundaries between two adjacent diamond particles, normally filled with a second-phase binder material, become weakened during milling, eventually causing diamond grain pull-out and leading to tool edge chipping and burr formation on the component. With the AMX manufacturing method, the intergranular bonding is increased, minimizing these defined grain boundaries that become weakened during cutting. The result is more effective edge retention of the PCD cutting tool, which extends tool life.

Through blending of diamond pow-

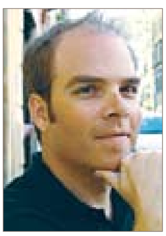




Figures 7 and 8: The magnified edge of a rotary tool cut with a wire EDM shows higher edge quality for the AMX grade PCD (top) compared to a typical medium-grade PCD.

ders of tightly controlled particle-size distributions and the use of propriety powder preparation techniques that maximize diamond packing density, it is possible to produce a material with enhanced physical and mechanical properties compared to standard medium-grade PCD. **CTE**

About the Authors:



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