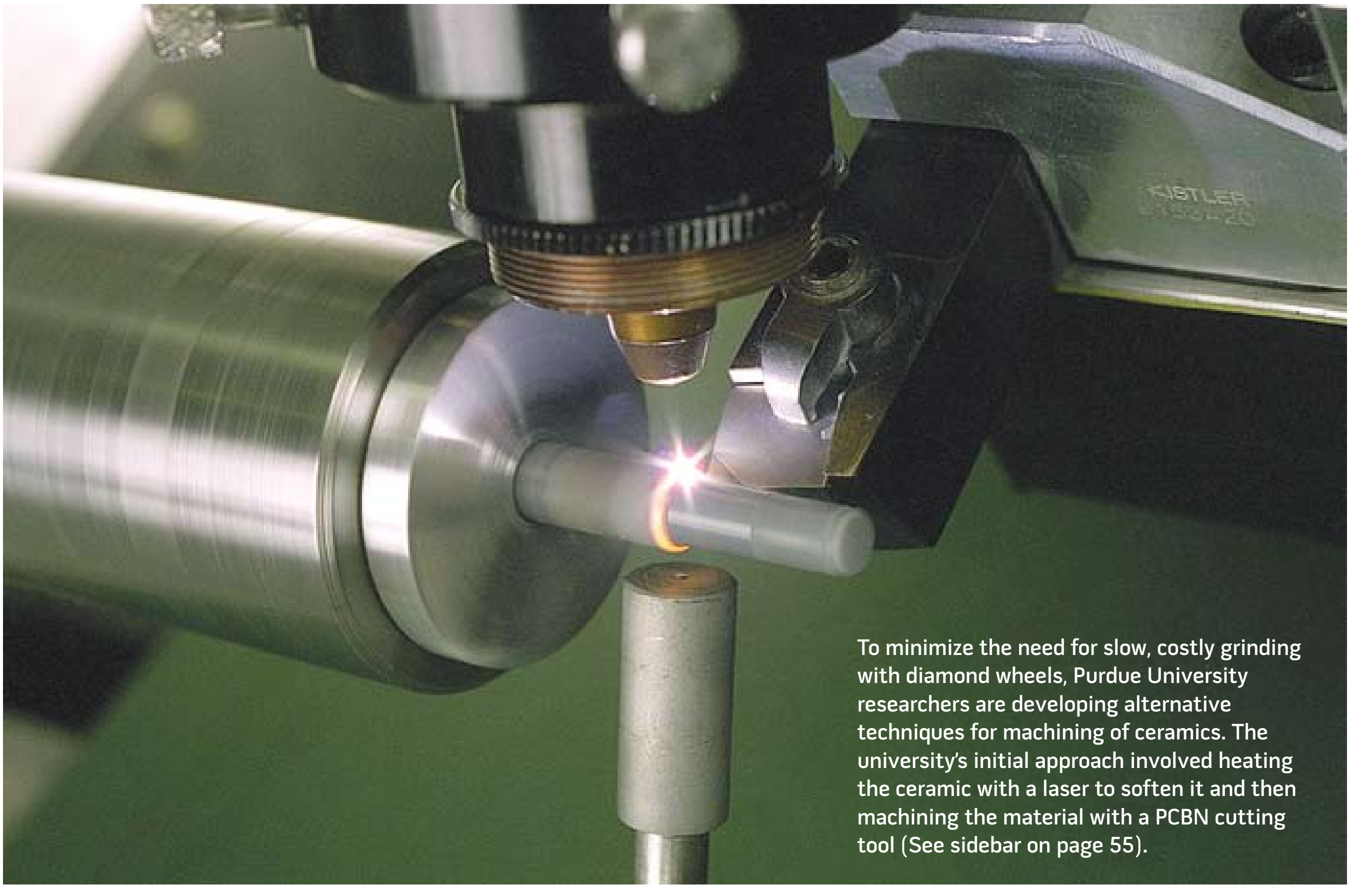

To minimize the need for slow, costly grinding with diamond wheels, Purdue University researchers are developing alternative techniques for machining of ceramics. The university's initial approach involved heating the ceramic with a laser to soften it and then machining the material with a PCBN cutting tool (See sidebar on page 55).

Purdue University

cover story

By Bill Kennedy, Contributing Editor

Ceramic Healing

Shops are machining versatile, corrosion-resistant ceramic parts for medical applications ranging from dental implants to replacement joints and implantable neurotransmitters.

Advanced or engineered ceramics play a growing role in the rapid evolution of medical diagnosis and treatment. Like the ceramic materials employed in metalcutting inserts, these ceramics are not teacup technology. Engineered ceramics are mixtures of inorganic substances heated to create crystalline or partially crystalline structures. Based on oxides, such as alumina and zirconia, as well as nonoxides, such as carbides, nitrides and borides, ceramic materials include aluminum oxide, silicon nitride and partially stabilized zirconium oxide.

The physical properties of ceramics determine their suitability for medical parts. Long-wearing alumina and zirconia ceramics are employed in replacement joints, toughened alumina-zirconia ceramics are used in tooth implants, and dental drills feature hard silicon-nitride ceramic ball bearings. The electrical insulating properties of zirconium-oxide ceramics are applied in housings for high-voltage components of implantable cardiac defibrillators; zirconia-based ceramics are also found in surgical blades. Alumina ceramics provide insulation and support for cauterization probes. Devices called feed-throughs—ceramic-to-metal seal assemblies that permit electricity or drugs to pass through an implanted device—are machined from silicon-nitride ceramics.

Learn more about machining medical parts

Read more commentary on ceramic medical parts by visiting Bill Kennedy's blog in the CTE Community section online at www.ctemag.com.

Frank Gorman, vice president and

general manager of advanced ceramics manufacturer Astro Met Inc., Cincinnati, said the bioinertness, structural properties and wear and friction characteristics of advanced ceramics make ceramics an increasingly popular choice for designers of medical components.

Part Production

Ceramic parts are formed via techniques like those employed to make P/M products. Ceramic powders are compacted to shape by various methods, including powder-injection molding and cold isostatic pressing. The formed part is subjected to solid-state sintering—heating to temperatures below the material's melting point—to bind the crystals and form the final, hard structure. After sintering, typical Al_2O_3 ceramics possess a Moh's hardness value of 9, close to diamond's value of 10.

The bioinertness, structural properties and wear and friction characteristics of advanced ceramics make ceramics an increasingly popular choice for designers of medical components.

While some ceramic parts are machined from plain sintered blanks, in most cases the powders are molded to near-net or net shape before sintering. Details that can't be molded can be machined relatively easily into the presintered, or "green," materials using conventional cutting tools and machines.

Green ceramic is like chalk, Gorman said. "It's soft, though abrasive, and, for the most part, we machine it with carbide tools for turning and milling." Some green ceramics are ground with open-grit Al_2O_3 grinding wheels, but a lot of green machining is done on conventional lathes, mills and drilling machines. In some cases, the abrasive nature of the ceramic powders wear carbide tools quickly; diamond-coated cutting edges can boost tool life by as many as 50 times, according to diamond coating provider CVD Diamond Corp., London, Ontario.

Even though fine details can be machined into green ceramic parts, sintered components may not be precise enough for medical applications. Depending on the part size and material, part tolerances can vary as much as ±1 percent after sintering.

As a result, Gorman estimates that 80 percent of Astro Met's products are finish machined to their specified tolerances via grinding with metal-bonded and resin-bonded diamond wheels. (See sidebar on page 55, which describes researchers' efforts to cut rather than grind ceramics).

"You can't cut hardened ceramic with an edge," Gorman said. "It's like carbide in the sense that it has to be done through abrasive machining. All of our finishing work on ceramics is done with diamond abrasive tools, including ID grinding, OD grinding, jig grinding, surface grinding, lapping and diamond core drilling."

Grinding ceramic involves brittle fracture of the workpiece material. Gorman said: "You are microscopically fracturing the ceramic grains when you grind the material. Different ceramic materials have different fracture toughness levels, so each ceramic we grind has separate machining parameters. The challenge of grinding ceramics is to understand the material and what it will allow to be done to it."

Generalizing about the grindability of various ceramic materials, Gorman said, "The zirconias tend to be the most forgiving because they are denser, not as brittle and are just stronger. The aluminas tend to be the more brittle materials, and the silicon nitrides and silicon carbides tend to be somewhere in between."

Single-pass creep-feed grinding usually is not appropriate for ceramics. "Ceramics can be damaged by grinding if it is done improperly because they are prone to thermal shock," Gorman said. Grinding has to be done fairly cautiously, under high coolant flow, with small DOCs and slow feed rates. "Otherwise, the diamond wheels will take material off the ceramic faster than the ceramic will allow and will result in cracking. You can thermally shock and crack the ceramic if it is ground too aggressively," he said.

Astro Met's specific grinding parameters are proprietary, Gorman said, but he offered that grinding finishes on ceramic are like grinding finishes on metal. "The finer the grit, or abrasive, the finer the finish you get." The finest finishes are imparted through lapping and honing after grinding. "A lot of ceramic parts, including some parts for medical applications, require finishes less than 2µin. R_a," he said. "You can't get there by grinding, so you grind down to somewhere between 8µin. R_a and 16µin. R_a, then you finish the parts with either a fixed abrasive or a loose abrasive diamond polishing mechanism, such as lapping." Lapping is accomplished with equipment such as cast iron lapping plates or felt bobs, using compounds featuring 1- to 30-micron grit.

Asked whether a typical shop can handle precision ceramic grinding, Gorman said: "We do have a lot of customers who buy ceramic blanks and finish them with our help. Some of them might be familiar with hard grinding because they are replacing carbide with ceramic in applications where ceramic's resistance to corrosion and high temperatures are required. Once they tell me what part they want to machine themselves, I can recommend the type of equipment and diamond wheels to do it." In most cases, those shops are successful, but most customers prefer to buy a finish-machined ceramic part, Gorman said.

Stiffness and Smallness

Beyond the influence of the cutting tool itself, the rigidity and vibrational stability of the machine doing the grinding can affect the tendency of a ceramic part to chip. Dr. Stuart C. Salmon, president of manufacturing and abrasive consultant Advanced Manufacturing Science & Technology, Rossford, Ohio, said grinding ceramics requires "a stiff and vibrationally stable machine, not necessarily one with high power. It doesn't take much power to machine a ceramic; the power range for a ceramic grinder is from 5 to 25 hp. But it takes

Astro Met

A selection, except the paper clip, of alumina and zirconia-ceramic medical components from Astro Met.

an incredible amount of stiffness to keep the system deflection to a minimum." The low end of grinding machine stiffness is 20,000 to 80,000 lbs./in., and machines are available with a stiffness of 400,000 lbs./in. or more.

When machining ceramics, Salmon said, the force between the wheel and the workpiece "is probably a good 10 to 20 times that for the equivalent amount of machining steel, sometimes more. System deflection and uncontrolled vibration will cause the parts to crack and chip. You are looking for a machine that has high stiffness, on-machine wheel balancing and a well-damped structure."

He noted that the stiffness of the part itself can be a concern. "Medical parts can be quite delicate," Salmon said. "Although you could make the machine and fixturing ridiculously stiff, the part itself may not be. The part then would be the weakest link in the chain. You're

Perfecting a medical partmaking process

MICRO PRECISION PARTS MANUFACTURING LTD., Qualicum Beach, B.C., makes small parts for several applications, including advanced medical applications (see Productive Times on page 118 in this issue for more about the shop's work). Micro Precision machines standard ferrous and nonferrous metals, as well as titanium and other exotic alloys, plastics and ceramics. Ceramics' properties are ideal for medical applications, according to Steve Cotton, owner and president of Micro Precision. "The only problem is that they are very expensive to manufacture," he said. "A part we can produce in titanium in 4 days takes 7 to 10 days in ceramic to achieve the same accuracy. Titanium and other materials are machined with carbide tools, but ceramics require diamond-impregnated grinding wheels. We tried a range of tools, some PCD, CBN and cubic zirconia, and they couldn't touch ceramic. It just blew them up," he said.


Micro Precision Parts Manufacturing

Micro Precision Parts Manufacturing Ltd. President Steve Cotton (right) and Matthew Cotton, his son and workshop manager, gage a ceramic component produced on the company's Haas OM-2A Office Mill vertical machining center.

As an example of the challenges of dealing with ceramic parts, Cotton described machining a silicon-nitride component for a neurological application. Ceramic was selected for its biocompatibility and nonconductive properties.

Micro Precision machined the ½"-long parts from solid blanks of silicon nitride. The parts featured complex 3-D contours with three contact surfaces, two of which specified no tolerance. "They had to be perfect," Cotton said. Tolerances otherwise were ±0.0004".

The diamond-tipped tools Cotton applied included custom endmills as small as 0.016" in diameter, featuring grit as fine as 800 (25 microns) for finish passes. "If it's a drill or an endmill," he said, "you really need to be up about 150,000 rpm." The small diameter tools had to be run at high rpm to produce sufficient cutting speed.

Cotton machined the parts on a Haas OM-2A Office Mill vertical machining center. The machine is relatively small with about a 5'x6' footprint and X-, Y- and Z-axis travels of 12", 10" and 12", respectively, but Cotton said it provides more than enough rigidity and accuracy for his work. To permit effective use of small tools, Haas recommended that Cotton acquire an air-driven supplementary spindle from NSK. "We put the main spindle in the M19 hole position, which holds it still, then put in the always doing that balancing act." If the part is not stiff, grind less aggressively or modify the fixturing to better support the part.

Regarding the advanced grinding machines needed to effectively machine small ceramic parts, Salmon said he considers the industry in general to be "slow in incorporating what I consider to be mature technology." He feels much of the inertia results from customer expectations regarding what a grinder

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NSK unit," he said. The spindle can achieve speeds as high as 200,000 rpm. When running the tools at 150,000 to 200,000 rpm, feed rate was 15 to 18 mm/min. and step-over was as low as 0.02mm.

Before machining the contours, Cotton ground the ceramic stock to a zero-tolerance surface on two sides. Those surfaces enabled him to clamp the part in a vise and establish datum points. Accuracy concerns led the customer to specify that a 4th axis not be used, but that the part instead be flipped in the vise between machining operations on each side, "which for me was hair raising," Cotton said. "They wanted us to datum the flip. It sometimes took 2 hours to dial it up." Large temperature changes would alter the setup dimensions, so the shop has a temperature-controlled atmosphere and the machine was run to be at operating temperature before machining the parts.

Developing and fine-tuning the process to machine the parts took about 6 months and included much collaboration between the shop and the customer. During that time, Cotton said, "we got a 4-week process down to 8 days."

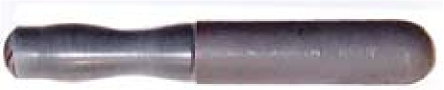
The extended development and production time for the parts magnified the effect of errors. After one set of parts had been worked on for 3 weeks, the customer asked Cotton to try a different grinding grit. "We did because the people who were paying asked us to do it, and the new grit chipped the part," he said. "So the part was a write-off. In those final finishing stages, if we made one mistake, all the work and time that was put into getting to that point was over."

—B. Kennedy

Laser assistance

PRECISION MACHINING of hard materials, such as tool steels, P/M compositions and high-temperature alloys, has traditionally involved time-consuming grinding operations. Recently, however, advances in cutting tool material and machine tool technology have permitted more hard turning and milling, with significant improvement in cycle times.

Researchers at Purdue University's School of Mechanical Engineering, West Lafayette, Ind., have been developing alternative techniques for machining of ceramics since the early 1990s. The aim is to minimize the need for costly and slow grinding with diamond wheels. Their initial approach involved heating the ceramic with a laser to soften it, then machining the material with a PCBN cutting tool.


Purdue University

In a search for alternative techniques for machining ceramics, Purdue University researchers developed 3-D thermal modeling techniques that facilitate turning of contoured features, such as those on this silicon-nitride ceramic shaft.

The researchers found it was possible to successfully turn silicon-nitride ceramic with PCBN by heating the workpiece to about 1,800° F with 300w to 600w of power from a CO_2 laser. Feed rates of 0.1 to 0.2 mm/rev., DOCs from 0.5mm to 1mm and cutting speeds of 1 to 2 m/sec. were typical.

A study of the resulting chips showed they were relatively congruent and segmented (albeit small), indicating plastic deformation and a cutting action, as opposed to the brittle fracture that occurs when grinding. Energy required to remove the material typically decreased from 40 to 100 J/mm^3 when grinding to about 6 J/mm^3 when laser-assisted machining, indicating that LAM is less likely than grinding to induce subsurface damage in the ceramic.

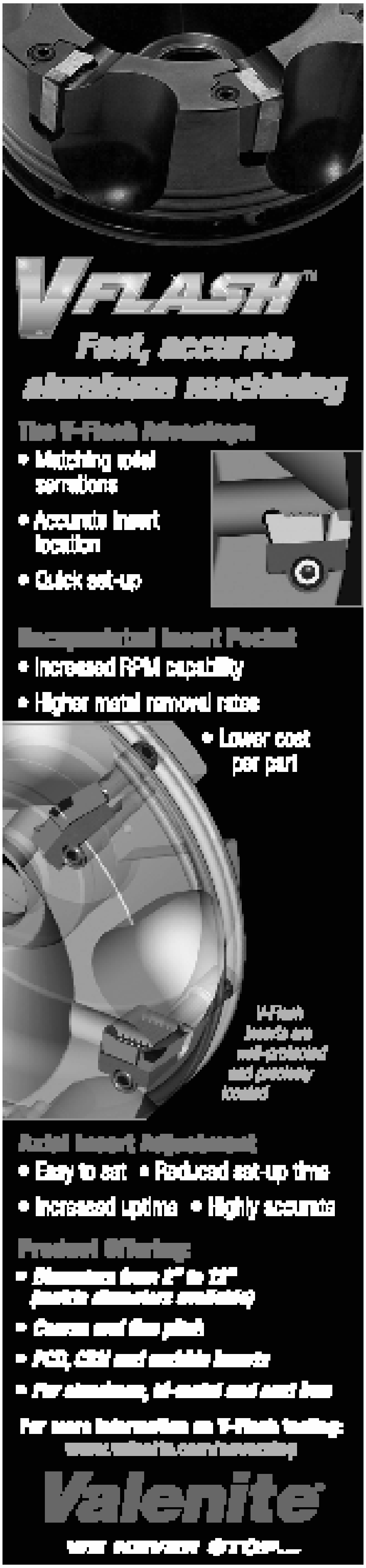
Researchers also observed that the elevated temperature produced by the laser did not apparently damage the cutting tool, as tool life of up to 40 minutes was possible. The tool wear mode was desirable, slow-developing flank wear, without cratering.

In further efforts, the Purdue team developed 3-D thermal modeling techniques that permit turning of parts with complex features, as would be required in commercial applications. Similar modeling techniques were also developed for milling, resulting in successful LAM of silicon-nitride ceramics using TiAlN-coated endmills.

Most recently, the researchers supplemented laser-assisted P/M part production techniques (as used in rapid prototyping) with laser-assisted machining. The combination permits creation of precision parts consisting of layers of different materials, including ceramics, and complex inner features that could not be produced otherwise.

Professor Yung C. Shin, Ph.D., said an internal economic study has estimated that LAM can save as much as 70 percent of ceramic machining costs compared to grinding. Regarding commercialization of the techniques, he said: "I think it is very close, with strong interest in this technology from various industrial sectors and government agencies. We are currently doing projects with five companies [in the automotive, aerospace and ceramics industries] and another one is about to start. I am currently working with a Texas company to develop a commercial system through SBIR [small business innovation research] funding."

—B. Kennedy

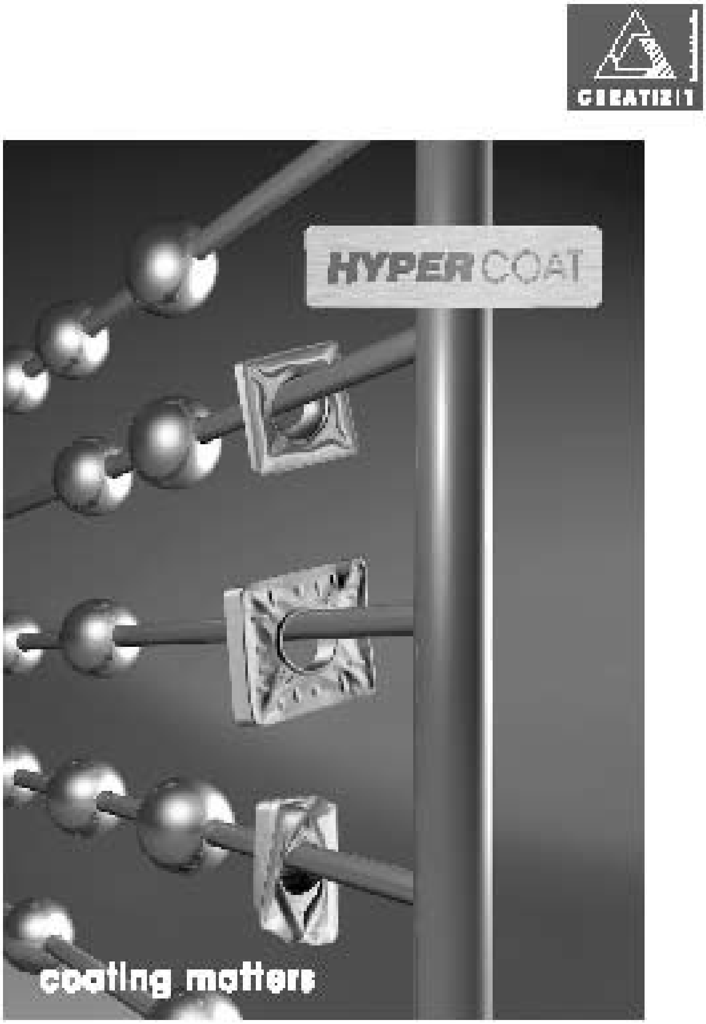


should look like. End users want to see a grinder “that looks like a grinder,” he said. “What the industry associates with stiffness and rigidity is a machine that is made of cast iron and is the size of a ship.” A machine that is “the size of a dining room table, with superhigh stiffness” is thought to be too high-tech. “With all the granite-type bases, hydrostatic slideways, shear dampers, magnetically levitated bearings and configurations available today, you can build a machine that is extremely stiff and stable, and yet wouldn’t necessarily look like a conventional grinder,” he said. It’s hard to sell the latest technology to the traditional machine tool buyer who has been successful with the old method, he added.

Because many ceramic medical parts are extremely small, parts manufacturers need to match their machine tool to the parts, according to Andy Phillip, president of Microlution Inc., a designer and manufacturer of CNC milling machines for micromachining applications. Phillip said any machining application, no matter the part size, involves a number of key factors, including workpiece material, the size of the features to be produced and surface finish and tolerance requirements. “In a sense, the small scale of micromachining magnifies the results of changes in those factors,” he said. “If you change just one or two of those characteristics, you need to have a substantial understanding of what to do from there and how to address that application.”


CoorsTek

Several machined and injection molded components made with CeraPure high-purity alumina from advanced ceramics manufacturer CoorsTek.



The design of Microlution’s machines, for example, results from study of micromachining’s process mechanics, Phillip said. “There are specific design considerations, including placement of components to maximize rigidity, very high resolution feedback, stiction-free motion and ironless linear AC motors.”

Toolmaker Recommendations

Toolmakers are another source of ceramic machining application knowledge and recommendations for medical applications. For example, among the products supplied by Technodiamant USA Inc., Mt. Arlington, N.J., are diamond core drills. A diamond core drill consists of a hollow tube with a matrix of diamond grit and bonding material at the business end. The company produces the drills in diameters down to 0.0225", and the tools can hold hole tolerances of ±0.00025". Sales Manager David Slaperud said metal-bonded drills are most commonly recommended for machining ceramics, with the specific mix of grit size, grit concentration and binder determined by the intended application. “The more the customer tells us about the material they are drilling, the better idea we have of what recipe is going to work best,” he said.

The harder the material, the more friable the diamond grit should be. Friability describes a diamond grain’s tendency to fracture and generate new sharp edges while in the cut. A less-friable diamond grain will not break off and expose fresh edges that would cleanly fracture a ceramic workpiece. For example, South African diamonds are known for being well shaped and rounded and are generally not preferable for some ceramic machining applications. Natural diamonds from other sources, as well as synthetic diamonds, may have different friability.

Slaperud said Technodiamant’s smallest-diameter core drills usually feature 325 grit (about 50 microns), which can be used uncoated or coated with nickel or copper. The metal coating combines with the metal binder to hold the diamond grain more tightly in the matrix, which is advantageous when drilling hard materials.

The concentration of the diamond in the binder—measured in carats per cubic centimeter—is another consideration. “If you have too much diamond, then you may not have enough binder material to hold it,” Slaperud said. He added that more diamond is not necessarily better, because there may not be enough force to break the diamond particles into sharp cutting points.

Slaperud said grinding parameters are application specific, but when core

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meweb.ecn.purdue.edu/~simlink

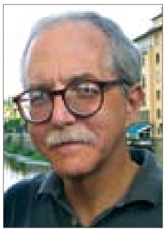
Technodiamant USA Inc.
(888) 462-9700
www.technodiamant.com

Technodiamant

Technodiamant offers metal-bonded diamond core drills to machine ceramics, such as these 0.066" and 0.220" OD drills.

drilling alumina ceramics with smaller drill sizes up to 0.050" in diameter, typical feed rates range from 0.2 to 0.5 ipm, running at 3,500 to 4,000 rpm.

Coolant flow is crucial in keeping the drill cool and clearing away grinding swarf. Technodiamant recommends up to 200 psi of through-tool coolant pressure. Without sufficient coolant, a drill will overheat. "If it heats up too much, then the binder will break down, the diamond will fall out or burn and your tool will fail," Slaperud said, noting that a blunt drill can produce scrap. **CTE**



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