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A ½"-dia., diamond-coated compression router from Amamco machines a 3/8"-thick test workpiece made of an organic-matrix composite, creating the dustlike chips characteristic of composite machining. In this application, the tool would typically run at 6,000 rpm and a feed rate of 75 ipm.

B. Kennedy

Competently Cutting Composites

By Bill Kennedy,
Contributing Editor

The variety of composite materials and their application requirements dictate an equally wide range of machining options.

If the 1967 movie "The Graduate" were remade today, the one word of career advice for the graduating Benjamin Braddock would be "composites," not "plastics." Composite workpiece materials offer high strength and stiffness, resistance to fatigue and corrosion, low weight and the ability to be formed into complex shapes. As such, they provide performance and energy-saving advantages that make them excellent substitutes for traditional materials in applications ranging from aerospace and automotive components to sports equipment.

However, the characteristics that boost a material's performance can reduce its machinability. A composite represents a combination

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of material strengths, consisting of a continuous matrix material reinforced by particles or strands of another material (see sidebar on page 56). Both the matrix and the reinforcing elements can be highly abrasive, limiting tool life. Machining forces can promote workpiece failure such as composites laid in layers delaminating when drilled or otherwise cut. Heat generated during machining may melt the matrix material, and worn, chipped cutting edges will oftentimes cause additional damage to the material.

Many Variations

A major composite machining challenge is determining how the particular material being processed will behave when it's cut. Glenn Sheffler, manager of new business development at the National Center for Defense Manufacturing and Machining (NCDMM), Latrobe, Pa., said, "When you say 'machining composites,' that's like saying 'machining metal.'" One shop may claim that composite machining is easy while another finds it nearly impossible. One composite material can be so different from another that the shops may be "comparing apples to oranges," Sheffler said. "It's like one guy machining aluminum and the other guy machining Inconel."

NCDMM works with Department of Defense organizations and their industrial supply base to develop solutions that boost manufacturing productivity and reduce costs. Despite extensive experience and full access to advanced machining technology, even NCDMM often has difficulty determining the best way to machine defense-related components made of proprietary composites when relevant material information is not available.

The solution could be selecting the appropriate geometry, coating, tool substrate or cutting parameters or cutting techniques outside of traditional machining. The growing trend of subcontracting aerospace and other components to tiered suppliers and smaller manufacturers means that more shops are facing the challenge of machining composites. "Many times the small shops don't know what they don't know when facing tooling and techniques for composite machining," Sheffler said. "So they rely on using standard metalcutting techniques and tools, changing parameters, adding operations or the old trial-and-error method to make it work. Typically this adds time and requires additional tools to complete the job, which can be costly. Finding the best solutions takes time, which many of the smaller suppliers do not have. That's why they engage with the NCDMM."

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Amamco

The multiple teeth on this ½"-dia. diamond-cut router, resembling those on a bur or file, enable it to perform composite roughing operations even when a tooth is broken or worn.

The Application at Hand

Peter Diamantis, plant manager at toolmaker Amamco, Duncan, S.C., often fields calls from shops seeking tools and advice regarding composite machining. "Number one, you want to know what they are actually using the cutters to do," he said. Tool choice depends largely on customer requirements. For example, if a shop is simply trimming a panel edge or roughing a window, a router geometry that will handle a rough cut and provide reasonable tool life is an effective choice. "Finish on the laminations is not important for that particular purpose," he said. "A ½"-dia. diamond-cut router with a 15° rake on the flutes will do the job." The teeth on that style of router resemble those on a bur or file. "It has about 15 crosscuts, so even if you break off a tooth, the tool is designed so it will still cut," said Diamantis.

The large size and irregular shape of many aerospace composite components dictate that machining operations often must be performed with motorized hand-held drills. Applied with a hand tool, "a diamond-cut router is a little more forgiving because it's got a lot of teeth; the more teeth it has, the smoother the cut," Diamantis said. "An operator will drill a hole to start and then go around a feature with a coarse, uncoated carbide router and cut it out." He added that such a router typically is run at about 15,000 rpm, and larger-diameter tools are preferred for hand-held routing. Routers as small as 11⁄64" in diameter permit machining of small-radius corners, but, "If the part geometry allows it, you can push a ½"-dia. router a lot harder and don't have to worry about it breaking," Diamantis said.

Compressive Forces

For operations requiring a fine finish, fine-toothed diamond-cut routers

Composite composition

COMPOSITES CAN BE categorized by their base matrix materials and the reinforcing material that produces specific performance characteristics.

There are three basic classes of matrix material: organic (polymer or carbon), metal and ceramic. Reinforcement material usually is classified by its form, either particles, whiskers, continuous fibers or filaments, and woven reinforcing cloth. To determine part thickness, create contours and produce specific performance characteristics, the organic matrix composites (OMCs) used in aerospace structural components typically are built up from layers of fibers, tapes or cloth that have been impregnated with the matrix material. After being laid up dry, the components are cured (heated) in an autoclave at specified temperatures and pressures.

Composites for aerospace structural components generally are OMCs that employ polymer matrices in which the molecules are chemically bonded or crosslinked with other molecules during curing. After curing, these "thermoset" polymers do not soften when subjected to heat in use. Early composites featured epoxy matrices that could withstand temperatures up to about 250° F; while more recently developed bismaleimide- and polyimide-matrix composites can handle temperatures from 400° to 550° F.

Reinforcement materials include glass, carbon, boron, polyamide (Aramid) or organic fibers. Tapes and fabrics generally range from 3" to 60" wide and are increasingly applied by CNC automated tape laying machines. State-of-the-art machines, such as the Viper fiber placement systems from manufacturing equipment and automation provider MAG Cincinnati, Hebron, Ky., are engineered to create complex parts such as huge fuselage sections of commercial airliners. The Viper system features 7-axis CNC control and can manipulate up to 32 epoxy-impregnated "tows" (lengths of fiber, tape or cloth) in laying up concave or convex shapes in varying thicknesses around fixed or rotating molds. The variety of layup schemes possible with these sophisticated machines means the resulting component's machining characteristics can change significantly from one section of the part to another.

B. Kennedy

NCDMM Project Engineer Jeff Poklembo (right) and John Winebrenner, manager of advanced manufacturing technology, check the quality of chamfered holes drilled in a composite workpiece.

A high-performance variation in OMCs are carbon-carbon materials, which are reinforced with graphite fibers and whose matrix consists of a carbon-based polymer that is pyrolyzed to remove noncarbon elements. Carbon-carbon composites can operate at temperatures greater than 3,632° F and are therefore used for applications such as aircraft brake pads, rocket nozzles and missile nose cones. A drawback is that the materials can oxidize at about 1,110° to 1,290° F, and must be protected in use by a coating, such as silicon carbide.

Metal matrix composites (MMCs) are composed of a metallic matrix, commonly aluminum, but also other metals, including superalloys, magnesium and iron. Reinforcing materials include boron, graphite, silicon carbide and alumina, in particle, whisker and fiber forms. MMCs are generally produced by casting, where with more than 15 crosscuts can suffice. "But where you need a really fine finish, everybody gravitates to the compression router," Diamantis said.

A compression router has separate sets of left- and right-hand flutes that overlap at about a third of the way up the router shaft from the tip. These routers were first developed for cutting wood and stacks of metals that include copper or aluminum layers.

"When you cut copper or aluminum with an endmill, it smears against the edges of the stack," Diamantis said.

the base metal is remelted and the reinforcing material is introduced. MMCs resist wear and elevated temperatures more than polymer-matrix composites do and have higher stiffness and strength. Machining MMCs is much like machining the base metal, except for the abrasiveness of the reinforcing material, and PCD tools are often required to cut them. Typical applications include brake rotors, machinery components, golf clubs and various structural uses.

Ceramic matrix composites (CMCs) are composed of a ceramic matrix and embedded fibers or particles of other ceramic material. According to John Winebrenner, manager of advanced manufacturing technology for NCDMM, CMCs are being developed as replacements for high-temperature alloys. In some cases, a CMC component can offer 10 times longer service life, weigh 80 percent less and withstand higher temperatures than an Inconel part. Typical applications are jet-engine exhaust nozzles, flaps and shields.

Again, the material's abrasive nature may require the use of PCD tools or grinding to achieve final dimensions.

Winebrenner said while abrasive wear of a tool cutting composites is a problem, heat can also damage the tool. "The big downside is that a lot of these materials are heat resistant, like high-temp alloys. Your tool becomes a heat sink, which can be very detrimental to the tool, no matter what type of material you are machining," he said.

—B. Kennedy

Competently Cutting Composites *(continued)*

With a compression router, "the left-hand flutes push the metal down and the overlapped right-hand flutes come past and pull it right back up, so it shaves it cleanly and gives you a perfect edge. It works with composites because many composites are all strands. One flute shaves the strands down and the other comes by and shaves the strands off. It's almost like that TV commercial where the razor blade lifts up your beard."

Andrew Gilpin, Amamco's business development manager, said the company engineers custom compression routers for machining composites "with tolerances of ±0.003" on some of the overlap."

Unlike the diamond-cut routers for roughing, compression routers are best applied on rigid CNC machine tools that can hold the tool and part in a consistent relationship to one another. "You program the machine to keep that overlap within a couple of thousandths of the center of the laminations," Diamantis said.

MegaDiamond

This ½"-dia., 4-flute, 30° helix endmill from MegaDiamond has PCD sintered directly into contoured veins on a carbide tool body through the V-tec process, which permits the production of complex cutting edge geometries in PCD.

Gilpin described the development of a typical compression router application. Aerospace OEM Lockheed Martin Corp. was experiencing delamination and poor tool life when using a straight-flute PCD router to machine the edges of a composite wingskin for the F-35 Lightning II joint strike fighter. Working with NCDMM, Amamco engineered and provided an uncoated, solid-carbide compression router for tests. Following positive initial results, NCDMM sought to increase tool life through application of a diamond coating from Diamond Tool Coating, North Tonawanda, N.Y. Unlike thick, single-layer, large-crystal diamond coatings, the company's CVD DiaTiger coating is comprised of interlocking layers of polycrystalline and nanocrystalline diamond. In addition to resisting abrasive and adhesive wear, Diamond Tool Coating said the coating structure diverts the path of cracks and thereby slows their propagation, increasing tool life.

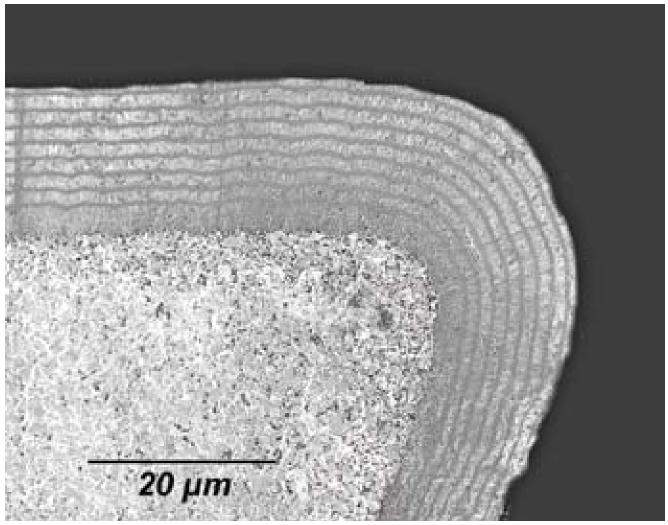
The coated compression router minimized delamination and extended tool life six fold. In addition, quality assurance reports on out-of-spec parts decreased by 90 percent. "Just being able to save on the quality reworks has been a huge savings for them," Gilpin said. "The project is really starting to ramp up, and anything they can do to save time and produce more parts is a huge benefit."

Gilpin noted that because of the difficulties of developing tooling for machining composites, major manufacturers are beginning to share details of composite machining to their subcontractors handling similar jobs.

Sharp and Complex

Scott Horman, manager of cutting tool material product engineering at Sii MegaDiamond Inc., Provo, Utah, said the key to success in machining composite materials is maintaining a sharp cutting edge. As the composite's abrasive elements dull the edge, it begins to push material rather than shear it, and cutting forces increase. High cutting forces lead to delamination, binder pullout and frayed edges. The tool edge may chip or break, and the higher cutting forces can pull the composite plies apart.

PCD cutting edges provide excellent wear resistance, but a traditional disadvantage of these tools has been lack of flexibility in tool geometries. Most PCD cutting material is produced as a flat disk bonded to a tungsten-carbide backing plate during the high-pressure, high-temperature process used to sinter the diamond particles. Segments are cut from the disk via wire EDM and brazed to a tool body to form cutting edges. However, MegaDiamond said its V-tec process offers a solution to this problem by permitting PCD to be directly sintered into contoured veins on a tool body. "We are putting PCD exactly where it needs to be, within geometries more



Diamond Tool Coating

This micrograph of the DiaTiger coating shows its interlocking layers of polycrystalline and nanocrystalline diamond which, according to Diamond Tool Coating, resist abrasive and adhesive wear and divert the path of cracks, slowing their propagation.

complex than those possible with flat segments of PCD," Horman said of the veined tools. He added that the V-tec process to make those tools causes the PCD to form a metallurgical bond with the carbide during sintering, eliminating the need for a braze between the cutting edge and the tool, thereby avoiding problems from heat during cutting that would weaken the braze joint.

Horman said the veined tools are best applied on fixed machines, such as the large CNC units used to machine features on aircraft fuselage segments. He added that the tools typically are run fast—8,000 to 10,000 rpm—and have been applied at speeds up to 30,000 rpm. "In composite cutting applications, most of the heat has to go into the tool, since the chips are not very thermally conductive. The vein technology enables the tool to manage heat more effectively," he said. Coolant can be used in some materials, but the coolant creates a disposal problem when mixed with the dustlike chips generated in composite machining. "A lot of people have vacuum systems right at the cutting head, sucking up the dust," Horman said.

To demonstrate the advantage provided by the veined tools' complex geometries, Horman outlined a test comparison involving edge trimming of a 0.40"-thick, carbon fiber-reinforced composite panel. A straight-flute, ½"-dia. PCD endmill ran at 12,000 rpm, a 0.001-ipt chip load, a feed rate of 36 ipm and a finishing step-over of 0.050". It machined 1,500 linear inches of composite before replacement was necessary. A ½"-dia., veined PCD tool with a 30° helix in the same application ran at 8,000 rpm, a 0.0045-ipt chip load, and a 144-ipm feed rate at the same 0.050" step-over. Running nearly 75 percent faster than the straight-flute tool, the veined tool machined 10,000 linear inches before replacement was necessary.

A veined PCD tool may cost nearly three times as much as the straight-flute

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endmill. However, seven straight-flute tools were required to machine the same 10,000 linear inches. Including savings in machine and tool-change time, the veined tool cut the cost of machining 10,000 linear inches by nearly 70 percent, according to Horman.

He said MegaDiamond's initial focus has been on providing routers and endmills to cut and trim composite components, but the company is expanding the V-tec process for drills.

B. Kennedy

This bottom view of a ⅝"-thick composite test workpiece shows significant delamination at the exits of one set of holes drilled with a 0.251"-dia., 3-flute, uncoated, solid-carbide drill, but clean exits on holes drilled with an identical drill that featured a diamond coating. By maintaining cutting edge sharpness in the abrasive composite material, the coating enabled the drill to cleanly shear the composite matrix and fibers.

No Best Tool?

Amamco's Gilpin said there's no single answer regarding the best tool material for machining composites. He estimated that for about 20 percent of applications, uncoated carbide roughers may be the best choice. When the uneven cutting forces and impact associated with hand routing are absent, the high wear resistance of PCD tools may make them preferable another 20 percent of the time. For the 60 percent of applications between those two extremes, he said, "A shop will call three different experts and get three different answers."

The growing trend of composite material application, according to Gilpin, is "changing the tooling that is being used because you can't go into composites with the same tools you use to punch holes in aluminum, titanium and other materials. Finding the right tooling for a particular application can give you a few extra gray hairs." **CTE**

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