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Counter Intuitive

When it comes to composite materials, 'simple countersinking' isn't so simple.

Aircraft rivet heads are countersunk because they must be flush with the outer skin of the plane after assembly. The head/hole assembly must be tight, to ensure that the aircraft's components stay together for long periods of time.

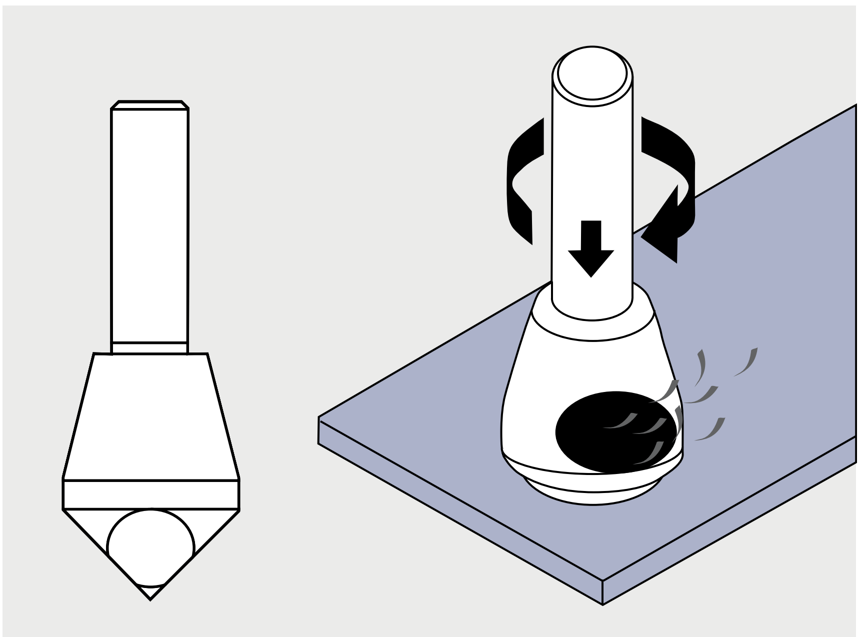
This critical aspect of aircraft assembly means special consideration must be given to the countersink tool used.

More than 102 standard countersink tool styles are available, but they are not adequate to meet the needs of many new composite materials. The countersink tool must cut without leaving burrs or tearing out chunks of the composite matrix. It must cut fibers cleanly—not delaminate the layers of the composite—and be able to withstand the abrasive wear of the fibers and other interior materials.

In addition, the cutting action must not melt the resin, smear matrix materials on other layers or degrade the properties of the matrix around the hole. Melting the resin onto the cutting edge, for example, will lead to increased cutting forces.

Depth accuracy, which is critical to providing the necessary rivet holding force, must be absolute—often less than 0.001" tolerance. Roundness of the countersink is critical, too, as is the smoothness of the countersink and the hole wall. Also, chips from one layer must not damage or contaminate other layers.

"The challenge of newer materials and sandwiches of composites," said Rick Gazak, a carbide tool designer at Guhring Inc., Brookfield, Wis., "is finding just the right combination of angles to provide the necessary shearing. Today, the aerospace challenge is to provide countersink tool designs that provide perfect chamfers for each material and layer in the composite in a single pass."



Countersink with slanted hole.

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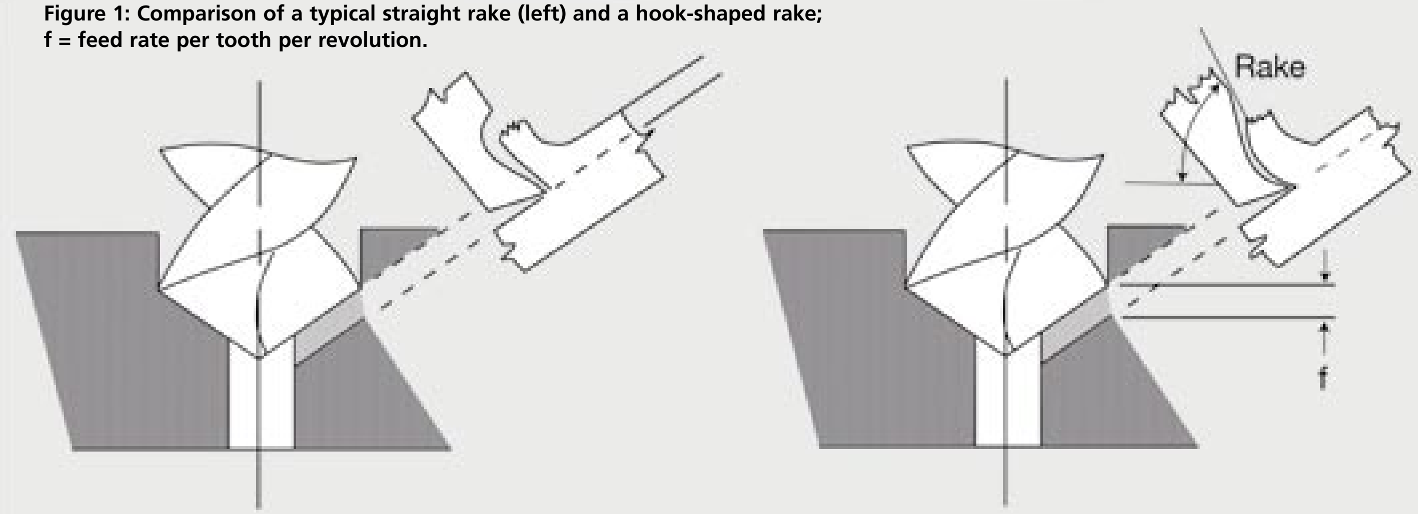
Composite layers, or stacks, can be comprised of glass fibers, polyimide glass, Teflon glass, polyimide quartz, carbon fibers, graphite, silicon carbide-aluminum, aramid (Kevlar), boron, Spectra, and combinations involving resins of polyester, polyetherether ketone (PEEK), polyphenylene sulfide (PPS), acrylonitrile butadiene styrene (ABS), bismaleimide (BMI) and other polyimides. Some are sandwiched with core materials of metal (aluminum, steel and titanium), plastic or aramid and joined with adhesives, such as thixotropic bonding paste or epoxies.

The challenge is that each layer has significantly different material properties and the quality-of-cut requirements are high for each layer. The hardness of Al_2O_3, SiC and B_4C fibers, for instance, is higher than that of solid carbide. If that weren't challenging enough, the top and bottom layers, or face sheets, and the inner layers consist of composite plies oriented in various directions and the machined surface quality is affected by the direction of each ply.

Figure 1: Comparison of a typical straight rake (left) and a hook-shaped rake; f = feed rate per tooth per revolution.



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Cutting Action

Despite being available for 20 years, Kevlar is still one of the most difficult composites to machine to the required quality levels. Some fuzzing, or axial splitting of the fibers, occurs where the tool enters the composite. This material can be removed by wet sanding, but only if liquids can be tolerated.

To minimize fuzzing, the Kevlar fibers must be preloaded by tensile stresses and then cut with a shearing action. For countersinks, this means fibers must be stretched while being pulled over a sharp cutting edge.

A sharp cutting edge and a comparatively high cutting speed (158 m/min.) are necessary to apply the correct amount of tensile stress and prevent the fibers from pulling back into the matrix before being cut. Cutting at too high a speed causes thermal degradation of the matrix and too slow a speed allows the fibers to pull back into the matrix before being cut. Slow feed rates also allow the fibers to recede before being cut. Feed rates of 0.1 to 0.15 mm/rev. per cutting edge are best.

Kevlar is highly abrasive, so tool life may be as short as 10 countersinks per standard tool; a special may produce thousands of countersinks before dulling. Because a HSS tool only produces a handful of holes before it dulls, almost all applications involve the use of tungsten-carbide tools.

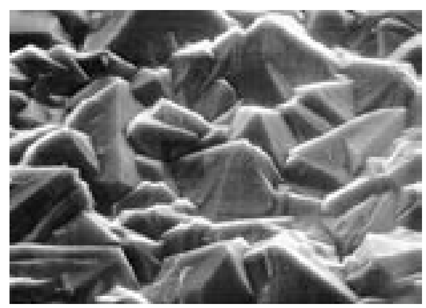
Guhring produced a special sickle-shaped, double-cutting-edge carbide tool for cutting Kevlar (Figure 1). Its hook-shaped rake has a positive axial rake angle of 6° to 15°. Because the hook angle changes along the cutting edge from the ID to the OD to produce the correct cutting action, a single tool will probably not be successful for producing several different countersink diameters. Therefore, different sizes of this design would be needed to accommodate different diameters.

In a test performed with a cutting speed of 45 m/min. and a feed of 0.3 mm/rev. (1,771 ipm and 0.012 ipr), more than 1,500 countersinks were made with a 10.3mm (0.406")-dia. tool of this design without losing quality. Only 80 were produced with a standard countersink tool.

Carbon-fiber composites are cut with PCD-tipped tools, either single or twin flutes. The advantage of PCD vs. carbide is tool life. Where a carbide tool produces 100 countersinks, a PCD tool produces 1,000 to 2,000. PCD tools should be used in fixed machines rather than portable drills because the brittle tools are easily broken. When a pure diamond coating is applied with chemical vapor deposition, the coating should be 20 to 24μm thick. Coatings half this thick can reduce tool life by a factor of 500.

While PCD tools are great for carbon fibers, they are typically not suitable for aramid fibers (like Kevlar) because individual diamond grains have a negative rake, which raises heat levels in the elastic aramid fibers when cut, and there is insufficient clearance to evacuate chips (Figure 2).

Kirk Bennett, engineering manager of sp^3 Cutting Tools, Decatur, Ind., a manufacturer of diamond-coated tools, said: "Diamond adds [tool] life to many applications, but it is a mistake to simply take a sharp tool and add a diamond coating to it. It is much more complicated than that. You have to understand the cutting forces as well as the material properties or you can shear the diamond right off."



sp3

Figure 2: PCD grains have a negative rake, which increases the heat generated while cutting.

Table 1 shows speeds and feeds successfully used for drilling composites. Countersinking should work at these conditions also, because drilling is a much less-forgiving operation than countersinking.

For less-abrasive thermoset composites, speeds of 180 to 300 m/min. (600 to 1,000 sfm) are used with feeds of 0.05 to 0.13 mm/rev. (0.002 to 0.005 ipr). Carbon-epoxy composites fall in the low- to mid-section of these ranges. If tungsten carbide is the only choice, submicron carbides should be used because they last longer than C2 carbide, a standard grade.

A spindle speed of 1,750 rpm is recommended as a starting point for typical countersink diameters.

For Kevlar, as well as all composites, using a firm backup or sacrificial bottom sheet prevents a host of problems, such as delaminating, tearing and burring.

Clamp It

Successful countersinking requires more than just a sharp, well-designed tool. The composites being machined must be clamped tightly to prevent burrs, tear-out and delamination. For high-production applications, machines have a clamping, or pressure, foot built around the drill or countersink tool.

Tight clamping also assures accurate diameters are produced. Compacting forces for drilling and countersinking Airbus A340-600 wing panels can exceed 2,000 lbs. The pressure foot must also be "normal to," or perpendicular to, the surface. A lack of perpendicularity of 20 minutes can lead to a 0.073 mm (0.003") error in the countersink on the A340-600 holes. Dimensional tolerances are 0.001" or less.

Accurate countersink size repeatability demands control, or compensation for, spindle growth caused by thermal expansion (the spindle can grow by 0.0015" or more during machining). This is a major source of inaccuracy for countersink dimensions.

Because the location of the top surface of stacked composites can vary significantly, some compensation is required for this variance. A spring-loaded override holder attached to a microstop countersink cage allows the cage to rise when compressed against a thick workpiece. The microstop ensures that the tool depth is accurate, and the override holder ensures that the microstop pushes tightly against the top surface.

Trade-Offs

There are no easy answers to the problems surrounding the countersinking of composites. Aerospace and cutting tool manufacturers have been working for years, researching tool designs and better approaches to machining these materials. They still do not have all the answers. For most applications, it is a matter of finding the conditions that minimize problems rather than trying to figure out how to prevent them.

Such trade-offs are critical in many applications. It typically requires collaboration between the manufacturer, the next-assembly user and the cutting tool manufacturer to assure the individual countersink characteristics meet the requirements. High-power microscopes, dyes, nondestructive testing and temperature sensing may be required to ensure that the "best" tool is used.

"The first step for any machining of composites is to research what is already known," Bennett stated. "The Web site, www.matweb.com, is the first place I go to gather data on the material properties. It is a free resource with a good library of properties. It may not have the machining suggestions you want, but you will need all those properties to understand the cutting trade-offs."

Most major carbide and diamond tool manufacturers provide some guidance. Bennett noted that he maintains a database of experiments he runs for customers. In return, they share information about how the tools performed under shop conditions. △

Workpiece material	Tool material	Hole diameter (mm)	Material thickness (mm)	Cutting speed (m/min.)	Feed rate (mm/rev.)
Unidirectional graphite-epoxy	Carbide	4.85-7.92 4.25-7.92	0-12.7 12.7-19.1	42.7 33.5	0.0254-0.0508 0.0254
	PCD	4.25-7.92 4.85-7.92	0-12.7 12.7-19.1	61.0 51.8	0.0508-0.0889 0.0508-0.0889
Multidirectional graphite-epoxy	Carbide	4.85-7.92 4.85-7.92	0-12.7 12.7-19.1	61.0 42.7	0.0254-0.0508 0.0254
	PCD	4.85-7.92 4.85-7.92	0-12.7 12.7-19.1	68.6 61.0	0.0508-0.0889 0.0508-0.0889
Graphite-epoxy	Carbide	4.85	6.35	60.9	0.0254
Glass-epoxy	HSS	—	12.5	15.0	0.028
Glass-epoxy	HSS	3	10	33.0	0.05
Carbon-epoxy	Carbide	3	10	33.0	0.05
Glass-epoxy	HSS	8	1.2	1.5-40.2	0.04-0.333
Aluminum metal-matrix composite	PCD Carbide	6	19.2	15-75	0.05
Carbon-epoxy	PCD	6.0	10.4	28-79	0.10
Kevlar-epoxy	Carbide	5.6	—	158	0.05

Table 1: Feeds and speeds for drilling composites, which also can be used for countersinking. (S. Abrate and D.A. Walton, "Machining of composite materials. Part I: Traditional methods," Composites Manufacturing, Vol. 3, No. 2, 1992, pp. 75-83.)

The following companies contributed to this report:

Guhring Inc.
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LaRoux K. Gillespie is a retired manufacturing engineer and quality control manager with a 40-year history of precision deburring and edge finishing. He is the author of 10 books on deburring and almost 200 technical reports and articles on precision machining.