
BOEING

Shattering Instead Of Shearing

Machining composites is so different from machining metals, it involves a fundamentally different mechanism of material removal. As composites are used more widely in various industries, a growing number of shops will take on the challenge of machining these complex materials.

BY PETER ZELINSKI

The Boeing 787 will be the world's first large commercial airplane made mostly of carbon-fiber composite materials. The photo on this page shows the plane's composite fuselage. Composites make up 50 percent of the structural weight of this plane and something like 80 percent of the volume. By comparison, the Boeing 777 is just 11 percent composites by weight. Boeing is making a huge commitment to composites, and the economics of aircraft ownership explain why.

For an airplane, the initial purchase price does not account for the majority of the ultimate cost of the plane. However, maintaining and fueling the airplane together do account for the majority of this cost, and composites bring down both of these expenses. Aircraft composite materials are inherently more fatigue-resistant and corrosion-resistant than metals, contributing to maintenance cost savings that could be as high as $30 to $40 million over the life of a 787. The composite structures also deliver a greater strength-to-weight ratio, contributing to fuel cost savings. It has been estimated that a 787 flying the same route as a 767 would consume $5 million less per year in fuel.

The total of these and other savings from composites comes somewhere near the price of the plane. That observation has been expressed this way: If the plane is made from composites, then you get the plane for free.

Yet the dramatic shift in materials for aircraft

General Tool routinely needs diamond-plated tooling to mill composites, but it does not necessarily need speed. The shop used to assume that it needed high cutting speeds to let diamond tools peform well, but it has since learned to use tools like this one effectively even on a machine tool capable of just 5,000 rpm.

parts entails a similarly dramatic shift in how those parts are made. If the plane is mostly composites, what are the implications for manufacturing?

More specifically, what are the implications for machining?

Compared to an aluminum aerostructure component, the amount of machining in a composite part is actually very slight. The composite part is near-net-shape. The form is laid up onto a tool that was custom-made to give the part its shape.

Then again, the machining that the composite part does require can be challenging indeed. By definition, composites are not homogenous the way metal is. A "composite" is a combination of two or more materials engineered to achieve better properties than the component materials could achieve on their own. In a composite, one material is the matrix and at least one other is the reinforcement. Carbon fiber reinforced plastic (CFRP), the chief composite material in aircraft parts, consists of a plastic matrix with carbon fiber reinforcement. This combination material presents a combination of challenges during machining. The matrix could melt from too much heat, the carbon fibers don't cut well because they fracture instead of shearing smoothly, and the layered CFRP structures can easily splinter and delaminate during machining.

A final source of challenge is this: By the time the composite structure is ready for machining, it has already become a valuable part. The cost of scrapping it may be quite large.

Therefore, as more composite parts come to market, a growing number of shops will face this reality: They will machine composite workpieces for which the amount of machining is small compared to a metal part, but the relative difficulty and value of that machining is considerably higher.

It is not just Boeing driving this. Practically all aircraft manufacturers are increasingly turning to composites to replace certain metal components and assemblies. Helicopters have been mostly composites for a while now. In fact, manufacturers of various high-value products are increasingly looking to composites of one form or another to take advantage of their strength, stiffness, durability, corrosion resistance, wear resistance or light weight. One estimate says that in 10 years, there may be even more CFRP going into wind turbines than into all aircraft. Meanwhile, another type of composites, metal matrix composites, are being applied to higher-performance automotive components such as brake rotors. And because composites can be transparent to X-rays, they are likely to find many new medical applications as well.

But the phrasing above—that manufacturers are looking to composites "of one form or another"—hints at an important caveat when discussing this class of materials. That is, composites are not a unified class of materials at all.

For example, CFRP is a type of polymer reinforced plastic, of which there are many varieties. Other, similarly broad varieties of composites are metal matrix composites and ceramic matrix composites. The word "composite" actually refers to a broader range of materials than the word "metal" does.

Earl Wilkerson, a CNC programming and tooling supervisor, has faced various composites machining challenges as part of his work for General Tool, a contract manufacturer in Cincinnati, Ohio. A composite, he says, is "any two materials that someone wants to glue together."

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Getting To Know "Black Aluminum"
CFRP. It has been called black aluminum, and its design and fabrication sometime resemble black arts. Sara Black, technical editor with High Performance Composites and Composites Technology magazines, has provided a detailed article on CFRP—covering what it is, how it's made, how the material is used today and how it will be used in the future. To find this article, visit www.mmsonline.com/composites and click on the link for "Understanding Composites Machining."

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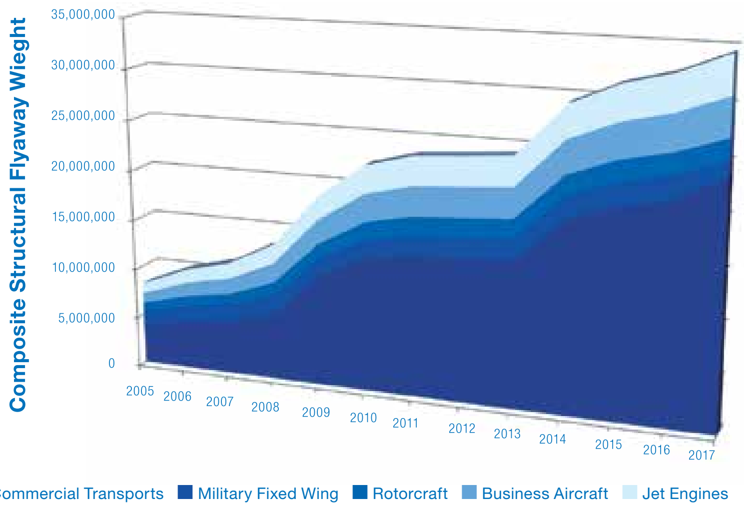
Therefore, this article will address the general question of how to machine composites by focusing on a specific example. The focus here will be CFRP—describing the tooling and techniques that have worked successfully to machine this increasingly common composite material, along with some of the important ways that machining CFRP is a challenge apart from machining metal.

How do you *know* how to machine a composite material that you are facing for the first time? Quite likely, you don't. That is part of the reality

COMPOSITE MATERIAL IN AIRCRAFT

How much composite material will be in the air? As this chart from Composite Market Reports shows, the amount of composite material in aircraft will more than triple during the next 10 years.



of these materials. General Tool is something of a composites machining expert at this point, having developed machining experience in aircraft composites early on. Thanks to the company's work on an early jet engine that used composites, it has now been machining aerospace composite materials for over 15 years. Even so, every new composite part is still different for this shop.

In fact, every new CFRP part is different. The term "CFRP" is broad. After General Tool succeeded machining its first CFRP part, the company struggled with the second, until it discovered that cutting parameters had to slow down and the leftover stock on some features had to increase. The properties and composition of the second CFRP were different from the first CFRP—and this is the way it has been with CFRP ever since.

"You can't just go to a handbook and look up 'composites' to get the right tools, speeds and feeds," Mr. Wilkerson says. You can't even look up "CFRP." None of these materials is defined or consistent enough for that.

However, there are some lessons that this shop and other shops have learned—lessons that have allowed them to consistently succeed at machining a class of materials that continues to grow and change. The first step is to recognize just how different machining composites is. If machining composites looks like machining metal, that appearance is deceiving.

A DIFFERENT PROCESS

Composite parts can be set up and run on the same machine tools as metal parts. The composites might even be machined with similar cutting tools—though this is less likely. As soon as the cutting edge hits the workpiece, however, machining composites is revealed to be a fundamentally different process. The very mechanism of material removal is different.

In metal cutting, that mechanism is plastic deformation. The material is softer than the tool, and the chip flows over the cutting edge.

In machining of composites—namely CFRP—there is no chip to speak of. The material removal mechanism might be better described as *shattering*. Instead of shearing material away, the impact of the cutting edge fractures the hard carbon fibers. In the process, the cutting edge undergoes considerable abrasion that can lead to rapid wear.

In any cutting tool application, tool geometry drives cutting performance and tool material

With CFRP, cutting tools and machining processes are developed to avoid unacceptable splintering, fraying and delamination of the workpiece. The splintering visible on the drilled holes illustrates the sort of defect that is often challenging to avoid. On the milled workpiece, the edge shows a level of delamination, or separation of the layers, that is barely visible but still unacceptable to the end user. Onsrud Cutter shared this workpiece, illustrating the kind of delamination control that the cutting tool company is sometimes asked to help achieve.

EVEN MORE COMPOSITES ON MILITARY COPTER

Helicopter manufacturers were among the earliest adopters of advanced composites. While commercial aircraft are only now reaching 50 percent composites by weight, some helicopters have long been 90 percent composites by weight. Even in this market, however, composites continue to find new applications.

A representative of Boeing described an example at a recent Society of Manufacturing Engineers conference on composites. In the Apache AH-64 helicopter, CFRP recently replaced metal not because of its fatigue strength, corrosion resistance or light weight, but instead because of its resistance to ballistic impacts.

The horizontal stabilator at the rear of the aircraft used to be made of aluminum. The aluminum part was sometimes damaged by the Apache's missile ejecta, which shoots back toward the stabilator at about 2,000 feet per second.

The composite part better withstood this barrage. As a bonus, the new stabilator design was also lighter and less costly to manufacture. Composites achieved all of these improvements at once.

drives life. This is true of composites machining as well. However, in composites, tool material also becomes a driver of performance. Composites can cause the tool to wear so rapidly that the geometry can change rapidly as well—unless the edge material can withstand the abrasion well enough to hold its geometry and stay sharp. A common phenomenon in machining composites is the drill that can machine two holes with good exit-side characteristics but shows delamination or splintering as quickly as the third hole, simply because tool wear has produced a geometry that no longer cuts cleanly.

In a way, machining composites actually turns the machining process upside down, because the burden of the shop's attention shifts to different parts of the process. An aircraft part machined out of metal might involve a high-power machine tool that relies on just commodity tooling and simple clamps to secure the work. By contrast, milling and drilling of composites can generally be done with a much lighter-duty machine—but *high-end cutting tools* are likely to be required, as well as *custom-built workholding* that closely supports the work to prevent vibration and fraying of the part's thin walls.

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Could The Highest Priced Cutter Be The Least Expensive?

Authors from cutting tool suppliers Smith MegaDiamond and Star Cutter provide a paper comparing four cutting tool materials for milling CFRP. The materials are: solid carbide, CVD diamond, polycrystalline diamond (PCD) and veined PCD.

That last choice, veined PCD, consists of a carbide tool body packed with a "vein" of diamond to give it the helical geometry typical of a carbide tool. When the greater cutting speed and tool life are taken into account, this tool actually has the least cost overall.

The paper that lays out these numbers is accompanied by video showing test cuts in action. Find all of this content by visiting www.mmsonline.com/composites and clicking on the link for "Milling Composites."

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Trimming is a common machining operation for composite parts. While the machining pass may be relatively simple, the workholding and cutting tool investment for a part such as this is high. The photo was provided by Hydrojet, a shop described on page 76.

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Composites Keep A Big Machine Busy

"The thing to understand about machining composites is that you only get one shot," says Jeffrey LeDuc, general manager of Reno Machine Company in Newington, Connecticut. Unlike a metal part, there is little or no possibility of repairing a CFRP part if it is machined incorrectly.

But there is still another way that composite parts get only one shot at Reno—one shot to get on and off of the machine tool without delay. The shop's five-axis Henri Liné machine is booked for a year with composites machining work. Part of the way the shop machines large, tight-tolerance composite parts efficiently is by letting the machine serve as its own CMM with inspection software from Delcam.

Learn more by visiting www.mmsonline.com/composites and clicking on the link for "Milling Composites."

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Here is a summary of what a machining process for CFRP is likely to require:

The Tool Material

Carbide can work, though carbide tools machining composites often have to be changed frequently.

Diamond tooling is likely to last much longer. The choices in diamond tooling for CFRP include diamond grit plated onto a mandrel, diamond coating or solid inserts made from polycrystalline diamond (PCD).

A more unusual choice developed specifically for composites machining is "veined" diamond tooling, in which a vein of diamond fills an engineered slot in a carbide shank.

The Tool Geometry

The shattering of composites is like the deformation of metal in at least one way: Just as in metal cutting, the energy of the cut is still transformed into heat.

CFRP has a particularly hard time dissipating this heat. No chip is generated to carry the heat away, and the material has low thermal conductivity. The resulting heat buildup poses the danger of melting or otherwise damaging the matrix. Coolant might not help, because coolant might not be allowed in the machining of certain composite parts. Therefore, the tool and the tool path are all that remain to hold down the heat of machining.

Sharp angles are generally one of the keys to accomplishing this. Milling and drilling tools for composites feature high positive rake angles for a quick, sharp, clean cut that keeps heat to a minimum. Such tools also incorporate clearance angles that are sufficient to prevent the edge of the tool from rubbing as it passes.

Workholding

Though the machining operations required for composite parts may be simple—often just drilling and trimming—the fixtures designed to support these parts can be small feats of engineering.

In fact, the fixture for machining a composite part can represent a considerable engineering investment. Clean cutting—without fraying, delaminating or otherwise separating the layers—requires the part to be secured firmly against vibration. Vacuum fixtures form-fitted to the part are typical of composites machining. Shops that opt for mechanical clamping often employ pads to damp vibration.

The Machine Tool

The contoured shapes of composite aircraft parts generally demand a five-axis machine tool. Some shops machining metal parts may use the five-axis machine tools they already have in-house. However, the amount of power and torque required for hogging metal usually is not needed for composites, at least not for CFRP. In fact, CFRP and other composites are often machined efficiently on lighter-duty CNC routers that generally would never see a metal part.

DIAMOND MILLING

General Tool is an example of a shop that uses its metal cutting machines for composites. The company has around 40 major CNC metal cutting machine tools, but so far, the shop has limited composites machining to two machining centers and one large-travel milling machine. Part of the reason for focusing only certain machines on composites relates to the difficulty of managing the grit that comes from cutting CFRP. This plan probably won't hold, however. The demand for composites machining is getting so large that Mr. Wilkerson doubts three machines will continue to fill the need for long.

Milling is used extensively for composite workpieces here. The large and relatively thick composite parts that this shop sees, particularly jet engine casings, involve considerable side milling and face milling. Hole making usually involves milling, too, because the shop meets demanding

Vacuum workholding is often necessary to keep a thin composite workpiece stable. The vacuum fixtures shown here were built by Hydrojet. In each case, the channels outlining the shape of the part provide the clearance for the path of the milling tool. The larger fixture from Reno Machine (photo at top left) uses mechanical clamping, but pads damp the vibration.

quality requirements by drilling the holes undersize before milling them to the final diameter.

Diamond-plated tools are commonly used here for milling CFRP. A typical roughing tool uses 25-grit diamond and might take a 0.375-inch radial depth of cut. A typical finishing tool uses 100- to 180-grit diamond and probably would cut to only 0.010-inch radial depth of cut.

Mr. Wilkerson says the shop was once convinced that it needed high speed to make diamond work well. On its largest machine for composites, the spindle speed is only 5,000 rpm. Therefore, the shop tended to use large-diameter diamond-plated tools in order to convert the low rpm value into a high surface speed value. Over time, the shop discovered that the diamond-plated tools can perform well in composites even at low speeds. In fact, low speed arguably helps by holding down the heat.

General Tool's experience and inventory of diamond-plated tools has now turned into a considerable asset when quoting composite machining jobs. Even though a particular variety of CFRP may be different from what the shop has encoun-

WATERJET IS ALSO AN OPTION

Hydrojet of Reading, Pennsylvania, has two abrasive waterjet machines from Flow International Corporation. Jack Seibert, one of the company's engineers, says the small shop has found a niche for itself by efficiently machining composite parts that other, larger aerospace contractors have difficulty machining in a cost-effective way. Many of these parts are trimmed through abrasive waterjet. However, not all of the parts that the shop sees lend themselves to waterjet cutting. The shop eventually added milling machines as well, and it now has three machining centers from Haas Automation in addition to a large CNC router with 160 inches of X-axis travel.

Mr. Seibert says the part geometry determines whether to use waterjet or conventional machining. Waterjet is preferred, in no small part because no special tooling is needed to hold the workpiece if a waterjet machine does the cutting. However, a more extremely contoured part presents a problem for waterjet because the jet shooting out of the intended cut might perform an unintended cut on some other surface of the part. If a part is so contoured that it doubles back to nearly parallel itself, then the machining work probably has to be done on a machining center.

Other factors can influence the decision, too. Precision is one such factor. The machining center is more precise, Mr. Seibert says, so tight-tolerance work tends to go there. Another consideration is the material. The waterjet machine can cut a wider range of materials efficiently. Kevlar is an example of a composite material difficult enough to mill that the shop generally tries any way it can to run a Kevlar part through waterjet.

Machining centers running composites demand the extra expense of vacuum fixtures, and Hydrojet produces this tooling itself. In fact, one of the Haas machines is devoted primarily to tooling. In addition to fixture tooling for machining, the shop also uses this machine to make layup tooling for its customers to use in making composite parts.

Company owner Michael Rado says this suggests where Hydrojet's next investment should be. He says the shop will add staff specifically to perform composites layup for its customers, and the shop will also buy an autoclave for curing composite parts. These additions will allow the shop to provide full-service composites production from before layup through to machining and beyond.

After all, Mr. Rado notes that the shop already provides the tooling that makes lay-up possible and the machining services that complete the parts. He jokes, "We already do all the hard stuff."

tered before, the shop knows the right tooling and parameters to at least get a good start at machining a new part number effectively. In addition, the shop probably already has the right tool on hand. This is no small advantage, because diamond tooling for a major composites machining project might cost well over $10,000, and specifying and purchasing such tooling from scratch could introduce a lead time as long as 12 weeks.

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What About Stacked Materials?

Composite structures are often mated to metal parts, with the two materials drilled together in production. The composite and the metal have vastly different machining properties, so how does one drill penetrate both?

Drill manufacturer Precorp offers a paper on using PCD to drill CFRP/aluminum and CFRP/titanium stacks. To find this paper, visit www.mmsonline.com/composites and click on the link for "Drilling Composites."

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DRILLING DIFFICULTIES

As difficult as milling may be, however, drilling tends to be the real challenge of machining composite parts. A drill cutting through a metal part simply has to remove the material and clear the hole. In composites, the hazards of machining a hole increase. The drill cutting through a layered composite structure is likely to push the layers ahead of it, producing unacceptable delamination on the exit side. Similar to drilling an unsupported piece of plywood, "a standard drill would just blow out the back of the hole," Mr. Wilkerson says. In many cases, drilling an acceptable hole in composites requires a drilling tool tailored to the material.

One example of a cutting tool company that has developed some tools for composites machining is Onsrud Cutter. For milling CFRP, the company has a couple of proven and reliable tooling concepts, including carbide burr tools and tools with PCD edges, some with serrated edge designs. However, for drilling, the range of tool offerings is greater because the range of hole requirements and potential holemaking problems is greater, too. Designs for CFRP drills include:

- Brad-and-spur point designs in which a point centers the tool to let peripheral cutting edges

For General Tool **(TOP)**, having an inventory of diamond tooling on hand allows the shop to respond quickly to composite-machining challenges. Both diamond-plated tools and carbide burrs are among the composites machining tools seen here at Reno Machine **(RIGHT)**.

machine like a fly cutter.

- Drill-reamer tools with separate cutting edges for drilling and reaming in one tool.
- An eight-facet point grind that lets the tip's secondary angles perform a self-seating function. The same design extends life by spreading wear across a larger number of discrete edges.
- Double-margin piloted step drills for close-tolerance holes in composite stacks

Another example of a tool supplier developing cutting tools for composites is Kennametal. Karthik Sampath is a research engineer with Kennametal who has studied CFRP drilling. Based on his observations, he offers these general points on what makes a tool more effective tool for machining holes in this material:

- Positive geometry is vital to reduce the cutting forces that lead to delamination, he says.
- Helix angle, clearance angle and gash rake angle are similar in this respect: As any of these angles gets larger, hole quality tends to improve.
- A smaller point angle tends to produce better exit quality. However, too small of a point angle can give the tool poor edge strength. The optimal compromise for drilling CFRP seems to be a point angle of 90 degrees.

Mr. Sampath says diamond coating generally delivers 10 times more tool life in CFRP than an uncoated tool. In his experiments, evaluations of various thicknesses of diamond coating, ranging from 5 to 16 microns, suggest that a 12-micron coating delivers the best value in terms of cost versus tool life.

General Tool uses a drill such as this one to machine holes in composites undersize, then completes the hole through circular milling to ensure that exit quality meets the customer's requirements.

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Tool Selection For Composites

Cutting tool supplier Onsrud offers a summary of various cutting tool designs for composites machining and how they are used. To find this information, visit www.mmsonline.com/composites and click on the link for "Drilling Composites."

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Here is an example of a drill designed for composites. The point design reduces delamination, splintering and fraying by reducing pressure on the material and reducing thrust and torque to improve cutting efficiency. The reduction in forces has the additional benefit of reducing the heat generated in the cutting area. Photos courtesy of Precision Dormer.

The most unusual requirement of a machining center used for machining composites may simply be extreme five-axis travels. Video of this five-axis machining application at Hydrojet can be found at www.mmsonline.com/composites.

Hole quality concerns tend to focus on the exit side when drilling composites, but Mr. Sampath notes that problematic hole *entry* defects are sometimes a concern as well. As the drill enters, it can wind up the top layer of the composite material. He says this problem is typically an indication of too light a feed rate. Entry defects can often be reduced by increasing the feed, though this does pose the danger of exacerbating exit defects. The optimum feed rate balances quality on both the entry and exit sides.

Mr. Wilkerson of General Tool says the drill he tends to specify most frequently for his shop's particular composite parts is the "WonderDrill" from International Carbide Corporation. This tool uses a positive "hook" to draw fibers into the cutting tip for a smooth and clean hole. This simple-looking tool eliminates any excessive fluting to improve strength and rigidity. However, even with this tool, General Tool typically does not rely on drilling to achieve a hole's final size because the risk of break-out defects is so great. Instead, holes are generally drilled 0.020- to 0.030-inch undersize. Then, a plated diamond finishing tool mills the hole to final size through circular interpolation.

MACHINE WITH CARE

For General Tool, taking the extra step of milling these holes represents no small investment. A large CFRP jet engine casing might require 400 holes. Total machining time might easily be 50 hours for a recurring part number that General Tool knows how to do well, and circular milling of holes accounts for a considerable amount of that time. However, the shop has found that, given the particular quality requirements of this type of part, milling the holes to size offers the best way to ensure that holes are acceptable.

The example illustrates a fundamental point: Seemingly simple metalworking operations acquire added difficulty in composite materials, because a composite part increases the number of ways that the machining process can go wrong. As a result, a shop often has to invest significant time, attention and cost in order to take an engineered composite part and successfully perform the last step—completing the part through a small but relatively critical amount of machining.

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