BREAKTHROUGHS IN THE ART OF CARVING METAL

Instead of riveting parts together, companies are using ultrafast metal-cutting machines to sculpt them. BY STUART F. BROWN

In creating most of the metal parts that have complex shapes and lots of surfaces, manufacturers have long had only two choices. One was to cast the part in a mold and then machine it, which has some drawbacks. The other was to laboriously rivet or weld it together from dozens, even scores, of pieces. The ideal of sculpting a monolithic part from a block of metal, the way Michelangelo carved the statue of David from stone, was expensive and time-consuming. Known to metal cutters as "hogging," the method was reserved for parts used in performance-at-any-cost spacecraft and Formula One racing cars.

IN ST. LOUIS a Boeing machinist checks newly carved aerospace parts.

Until recently, that is. A new breed of computer-controlled machine tools, running at speeds thought impossible only a few years ago, is turning metal carving from a luxury to an option with broader application. With cutting heads that spin up to seven times faster than those on conventional tools while darting from one corner of the workpiece to another in a blur, these machines can "hog" out one-piece aluminum structural parts for airplanes that are lighter, stronger, cheaper, easier to join to other parts, or all of the above. Because some of these parts can't even be created by traditional methods, the new technology, known as high-velocity machining, is changing the way aircraft are designed and put together.

It's not surprising that the new technology's first big beachhead is aluminum structural parts for planes. High-velocity machining saves weight, a special blessing in flying machines. It also eliminates costly die and mold making for production runs that are typically limited, and prevents unwanted hollow pockets that can result from the casting process, sending a partly machined workpiece to the junk pile.

NEW IN THIS ISSUE: AN EXCLUSIVE SURVEY OF LARGE AND SMALL MANUFACTURERS. SEE PAGE 222[L].

PHOTOGRAPH BY MARK KATZMAN

JETLINER TAIL PARTS are "hogged" from solid aluminum by a 40,000-rpm milling machine at Minnesota's Remmele Engineering.

For the foreseeable future, cost rules out the mass sculpting of parts used in everyday items like cars and appliances. But there's talk of hogging out dies and molds that would be used in the high-volume production of parts such as car stampings and plastic products. Says Red Heitkamp, director of advanced manufacturing engineering at Remmele Engineering in New Brighton, Minn.: "This is a revolution as important as the introduction of numerical-control machine tools a few decades ago." The Association for Manufacturing Technology in McLean, Va., a toolmakers' trade group, expects U.S. sales of high-velocity machines to hit $100 million in 1997 and grow fivefold over the next five years.

A recent reporting foray leaves no doubt that fast machining has arrived, with further advances to come:

- At Remmele Engineering's workshops, superfast machine tools are cutting monolithic aluminum parts as long as 17 feet that will soon be flying around in airliners and military planes. The parts have a surprisingly smooth surface finish, requiring little or no polishing or further work. A surging flow of orders from aircraft makers keeps Remmele's fast machines going around the clock. Not all the company's sculpted parts are large. When a maker of air compressors for trucks was having trouble with heads that cracked, it switched to stronger ones that Remmele carves from solid aluminum.
- Riveting together sheet-metal parts to form larger structures is on the wane at a former McDonnell Douglas aerospace plant, now a unit of Boeing, in St. Louis. New high-speed machines are biting into slabs of aluminum to cut one-piece parts, some 18 feet long, that will find their way into F-15 and F-18 fighters and the C-17 military transport. And ground is being broken for a building that will house one of the biggest high-velocity machines yet built.
- Fast as they are, the new metal-carving machines don't satisfy the folks at Aesop, a Bedford, N.H., company co-founded by an MIT mechanical engineering professor. They have designed a radical turbine-powered gadget that's intended to attack like a metal-eating Tasmanian devil, hogging out material at three times the tempo of today's pacesetters. It's called Turbo Tool, and no group is watching the development more eagerly than the airplane people.

This is intoxicating stuff for the machinery mavens. After years of eking out incremental improvements in the rate at which metal can be cut, they're tasting the kind of excitement long experienced by designers in the microelectronics business, where processor speeds keep on doubling and redoubling. In the thick of this speedup is Remmele's Heitkamp. His company, a giant job shop with about 500 employees located in five plants in the Minneapolis area, has won a respected niche as an early adopter of novel machining technologies for making precision parts used in products ranging from power generators to satellites to large ship radars. Remmele's seriousness about mastering what's new is reflected in Heitkamp's full-time assignment: Scour the world for better technology and put it to work.

Two of the machines he has brought to Remmele epitomize the key improvements that have made high-velocity machining a reality. One is a big blue milling machine built by the French maker Forest-Liné and equipped with a 40,000-rpm, 53-horsepower spindle from Fischer of Switzerland. Designing such a component is a breathtaking adventure for machine builders, who not long ago considered spindle speeds of 6,000 rpm to be plenty fast.

The spindle is the business end of a machine tool. It consists of a powerful electric motor attached to a steel shaft spinning furiously on precision bearings. Fischer's spindle is the fastest in use anywhere for making production parts. Its pricey bearings have lightweight ceramic balls, instead of steel ones, to reduce the distorting effects of centrifugal force at 40,000 rpm. At the shaft's end, a holder grips a specially designed tungsten-carbide bit that takes small bites out of the metal workpiece as it rotates.

Along with a speedy spindle, high-velocity machines need a way to move it rapidly around the work surface. The Forest-Liné machine boasts a faster-than-usual "drive speed." But the champ in this category is a radical high-speed machining center that Ingersoll Milling Machine Co. of Rockford, Ill., unveiled at the International Machine Tool Show in Chicago in 1996. Remmele bought the first one. Equipped with fast linear-motor axis drives, the sliding components that push the spinning cutting tool into the workpiece, the new $1 million machining center, called the Ingersoll HVM 600, was a must to bring home and learn to use.

Reasonably brisk drive speeds can be achieved with the traditional ball screw, a mechanism that translates a rotary motor's motion into linear motion through a nut threaded on a spinning shaft. But to whip the cutter safely around a 90-degree corner, the machine needs really hot "acks and decks"—machinist lingo for accelerations and decelerations. The new linear motors, essentially rotary motors rolled out flat, can sprint and stop with exacting precision. Judging by displays at the machine tool show held in Hanover, Germany, in September, flat motors are getting more and more attention. Some 17 exhibitors there had linear-motor-powered machines, compared with only a few at the 1996 Chicago show.

These advances, fast spindles and linear motors, let machinists crank up the "speeds and feeds" needed to make monolithic parts quickly. In many cases the parts are also lighter. Here's why. At traditional speeds and feeds, the heat of the cutting process flows both into the cutting tool and the workpiece, where it causes stresses and warping. The problem persists if the spindle is speeded up without improving the feed rate. But when both can be cranked up in concert to maintain an optimal "chip load" at the cutting teeth—the rate at which metal is chewed away—wonderful things occur.

Heitkamp says high-velocity machining is considered to be happening when the spindle reaches 25,000 rpm or so and the cutter travels over the workpiece at 600 to 700 inches per minute or more. Under these conditions, the metal that the cutter contacts goes into a "plastic" state partway between solid and liquid.

Happily, in this state most of the heat of the cutting process is carried away by the chips instead of building up in the workpiece, leaving it cool and undistorted. This makes it possible for Remmele to cut aircraft parts with great accuracy. Walls and internal stiffening ribs can be carved that are as little as 20 or 30 thousandths of an inch thick, or about as thick as a credit card. Freed from the constraints of yesterday's methods, aircraft designers are conjuring up amazingly light monolithic parts. After going through the machining process, these components often weigh less than 5% as much as the aluminum plate from which they're cut.

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Before the really fast machines came on line, heat-related headaches and long machining time made it pointless to try to produce such parts. To guard further against thermal expansion that can upset accuracy, the temperature in the Remmele plant is allowed to fluctuate no more than two degrees.

High-velocity machining requires mastery of challenges beyond speeds and feeds. One is rapid removal of all that hogged-out material. When the big Forest-Liné machine's 40,000-rpm spindle powers into a virgin slab, chips fly in a flashing silvery blizzard. Remmele's machines are tended by automatic conveyors that transport the chips to a compactor that squashes the razor-edged metal fluff into disk-shaped "hockey pucks" to be trucked away for recycling.

"It's just amazing how much material that machine goes through," Heitkamp says. "We used to feel pretty good about removing 60 cubic inches of metal per minute. Now we're removing four times that, and we'll be cutting even more as we get faster machines."

The other challenge is programming the computers that run high-velocity machines so the spindles will know how to zip around to carve a particular part. Though this calls for great skill on the part of Remmele's work force, the process of programming a computer often costs less in money and hassles than the old way of producing dies and jigs to make a part.

That's particularly true when a production run is limited, as in the case of an aircraft display-panel cover about the size of a thin book. Since only a few airplanes are built with identical control panels, tooling up to die-cast the covers is expensive. Machining them from solid aluminum has proved cheaper, and Remmele ships the finished parts in less time than it would have taken to make a new die.

Eliminating dies and other expensive tooling also frees the customer to modify part designs as products evolve. If Remmele is the supplier, it merely amends the program driving the machine tool so it can start producing the updated part.

The emphasis on computers in the highly automated world of fast machining is changing the role of production workers. The gleaming machine tools that line Remmele's hospital-clean aisles run largely unattended. Journeyman machinists, as the company's highly trained production people are called, spend much of their time programming and monitoring the computers that orchestrate the cutting performance. Heitkamp expects the trend toward lightly manned production to continue. He is only half joking when he says: "The job shop of the future will have one highly productive machine, 24 programmers, and a dog. The dog is there to keep the people from touching the machine."

Boeing is another pioneer in high-speed machining. It's not only one of Remmele's customers but it has also been pushing the technology on its own since the late 1980s, when McDonnell Douglas in St. Louis was working on a secret Navy stealth plane called the A-12. The plane got canceled, but not before an engineer perusing the technical literature became convinced that machining could be performed much faster. At first, production people told him this would only lead to ruined spindles. But a manager, Ron Aarns, now director of production technology at the St. Louis complex—which houses the world's third-largest machine shop—got interested in the idea and sponsored a modest research effort. The effort grew, and now

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AESOP'S Kevin Wasson (left) and Alexander Slocum display parts for their 100,000-rpm Turbo Tool, shown below, which would spin on a film of water.

several high-speed machines are out on the factory floor cutting production airplane parts.

These days the search is on throughout Boeing to substitute monolithic parts for fabricated ones. Norma Clayton, who oversees fabrication at St. Louis, reports that at the company's plant in Long Beach, Cal., where the Air Force's C-17 transport is built, "we have been able to reduce over a third of the sheet-metal details by going to monolithics. It's a great way to reduce weight on an aircraft."

There are also bureaucratic reasons for eliminating fabricated parts. Every little piece of an airplane is documented with a paper trail that makes it "traceable" if a major failure or crash occurs. Thus, a bulkhead built from 83 parts ends up wearing 83 different part numbers, each backed by sheaves of documents. Its monolithic counterpart gets just one number and one trail of documentation.

Finally, planemakers are eager to eliminate many of the thousands of rivets that go into traditional sheet-metal parts. "One of the most important payoffs for us is the reduction of pan stock, which is what we call fasteners," says Aarns. "We drill a tremendous number of holes here, and every one we get rid of cuts the amount of labor needed and the chance for mistakes." Aarns cites another advantage: "Assembling a monolithic part into an airplane takes only 25% as much time as a built-up part because it fits much better."

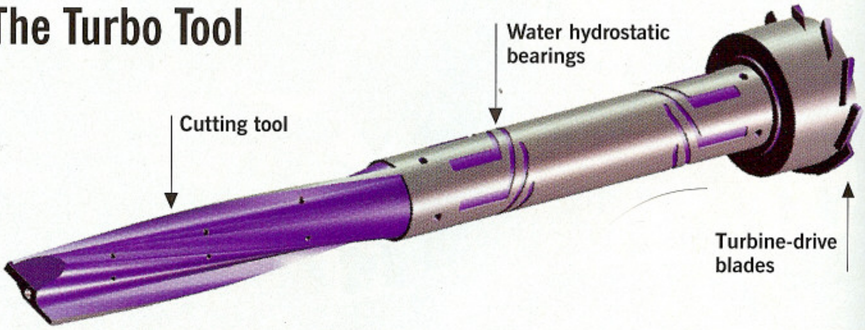
The first production monolithic part Boeing's engineers mastered was an aileron enclosure rib for the Navy F-18 fighter, a component normally assembled from six pieces of sheet metal. This rib forms part of the wing. "We were able to make it with walls and floors 30 thousandths of an inch thick," recalls tooling manager Larry Kuberski. "The total variation at any point was less than three thousandths, and we did it without the typical fancy jigs for holding the parts."

To assess how well the sculpted part would withstand the stresses of flight, the plant made 24 aileron enclosure ribs of the monolithic type and 24 conventional ones for torture testing by the Navy. Word came back that the monolithic parts held up better and were the ones to use on the aircraft. Today Kuberski can show off a trial piece recently made at the plant with precise walls only ten one-thousandths of an inch thick—hardly thicker than industrial-grade aluminum foil but firm to the touch.

Boeing designers are increasingly thinking monolithic when they conceive new parts, with a resulting increase in requests for time on the high-speed machines. For example, cockpit floors for the F-18 E and F versions that weigh just 4½ pounds are being carved out of slabs that start out at 138 pounds. Next year a big new mechanical monster will be up and running to meet the demand.

To house a $30-million-plus bet on the future of metal cutting, Boeing is constructing a 55,000-square-foot building. Inside will be a 236- by 120-foot high-velocity flexible manufacturing system that is undergoing final checkout at Ingersoll's plant in Illinois, where a similar system is being built for British Aerospace. The big machining system, 30 feet tall, will be able to hog out monolithic parts such as wing spars and cargo doors—some as large as 33-by-12 feet—two at a time, if needed. Four high-velocity spindles will do the work, each powered by specially built 100-hp motors and wielding tungsten-carbide cutters designed by Kuberski. Powerful linear motors, equipped with chillers to keep them from overheating, will hustle the spindles around the big parts being cut.

The Turbo Tool



THE NAM / FORTUNE MANUFACTURING INDEX

Producers Are Upbeat

More than 90% of U.S. manufacturing companies are bullish. That's the main finding of a mid-October survey of more than 400 companies by the National Association of Manufacturers and FORTUNE. Says NAM President Jerry Jasinowski: "Manufacturers see a bright future because productivity gains have enabled them to be competitive in world markets."

On the business outlook, 30.7% of large companies—those with more than 1,000 employees—say they are "very positive," a figure that rises to 40% for smaller companies. Most expect little change in the prices of their products, but more small and mid-sized companies foresee price increases. Another finding: 16.8% of big companies derive more than a quarter of their sales from exports, vs. 6.3% for smaller companies.

What is your company's business outlook right now?

	Large Companies	Small and Medium-Sized Companies
Very positive	30.7%	40.0%
Somewhat positive	62.2%	51.9%
Somewhat negative	7.1%	8.1%
Very negative	0.0%	0.0%

How do you expect prices of your company's products to change over the next year?

	Large Companies	Small and Medium-Sized Companies
Rise more than 5%	5.6%	5.6%
Rise 3% to 5%	13.8%	25.1%
Rise up to 3%	24.5%	23.0%
Stay the same	43.9%	41.8%
Fall up to 3%	9.7%	3.5%
Fall 3% to 5%	2.0%	0.3%
Fall more than 5%	0.5%	0.7%

Aarns thinks high-velocity machining is becoming a practical method that can be used by any industry that needs precise aluminum parts, such as key components found in computer disk drives. Next on Boeing's list is learning to do high-speed cutting of much harder metals such as titanium, which is needed in critical aircraft structural parts. Excitement is guaranteed: Titanium tends to overheat and burst into flames when treated brutishly.

If the feats achieved by high-velocity machining already sound awesome, check out the device that Alexander Slocum is working on. The MIT mechanical engineering professor founded New Hampshire's Aesop with a former graduate student, Kevin Wasson. Slocum has a philosophical statement he wishes to make before discussing the extreme realm of ultra-high-speed machining: "History says speed is always better—except in the making of wine, cheese, and love." With that out of the way, the partners get out their show-and-tell items and start explaining the genesis of Aesop and the Turbo Tool idea.

"Some people at Boeing said they would like to have a 40-hp metal-cutting spindle that ran at 40,000 rpm," Slocum relates, "and then they upped it to 60 hp at 60,000 rpm. So I asked them what the ultimate would be. They said 100 hp at 100,000 rpm, to keep up with the fast linear motors that are becoming available."

Formidable problems start to crop up when the goal is achieving a spindle speed of 100,000 rpm. One potential showstopper is the tendency of ball bearings to self-destruct when spun too fast. Another is the tool holder, which works like the chuck in your portable drill. Under the influence of centrifugal force, it can lose its firm grip on the cutting tool, turning it into a potentially lethal projectile. A third question is how to make a 100-hp spindle that's not too big or heavy.

Wasson's doctoral thesis held the answer to the bearing problem. He had worked out the math and software needed to design low-cost hydrostatic bearings that consist of nothing more than a very thin film of water. "Rolling-element bearings with rollers or balls in them are like riding your bicycle on a cobblestone street, while hydrostatics are like snowboarding," Slocum explains. "The reason you don't see hydrostatic bearings everywhere is that traditionally they were intricate and had to be hand-tuned, which made them very expensive."

The much simpler design Wasson worked out uses a steel shaft with shallow hieroglyphic-like passages inscribed on its surface. High-pressure water pumped through these channels keeps the shaft from coming into contact with the housing in which it rotates. The computer program Wasson wrote calculates the appropriate hieroglyphics a particular bearing needs to spin fast with low drag. Working with funding from the National Science Foundation and the National Institute of Standards and Technology (NIST), Aesop has developed a bearing design that General Motors is now using. It is incorporated in a four-spindle device that drills precise holes in steel transmission gears at relatively low speeds.

But how to deliver 100 hp to drive the spindle without making it unwieldy? When Slocum started thinking about that problem, he hit on the idea of a little turbine driven by a pressurized jet of water. "It's unbeatable for power density, far better than electric motors," he says. The final "aha!" moment came when Aesop decided to do away entirely with the idea of a separate shaft, tool holder, and cutter. Why not just etch the magical bearing passages on the shank of the tungsten-carbide cutting tool itself? What was once three components became just one. At last, here was the design for a light and powerful 100,000-rpm spindle the size of a beer bottle (see photo). Engineers at Kennametal, a large cutting-tool supplier in Latrobe, Pa., say they see no major barriers to manufacturing Turbo Tool cutters at a reasonable cost.

So Turbo Tool is moving forward. The Aesop duo is performing high-speed spin tests on its bearing and is forming a research consortium for fully developing the device under the aegis of the National Center for Manufacturing Sciences in Ann Arbor, Mich.

While self-proclaimed "geeks playing in our sandbox" like Slocum and Wasson are seen as inhabiting the wild fringe of the mechanical engineering universe, mainstream types are watching their work with great interest. "We can't afford to ignore the possibility that they may be right," says Heitkamp at Remmele. "If they can make a 100,000-rpm spindle with 100 hp that won't explode and hurt anybody, I want the first one." With ideas like Aesop's on the loose, tomorrow's machines may turn even today's wonders into museum pieces. ■