cover story

BY BILL KENNEDY, CONTRIBUTING EDITOR

HOLDING PATTERN

Bolted to a fixture that is mounted on a pallet, an aircraft bulkhead is machined on a Makino 5-axis machining center.

Makino

Because of their size and shape, aerospace parts require special workholding considerations.

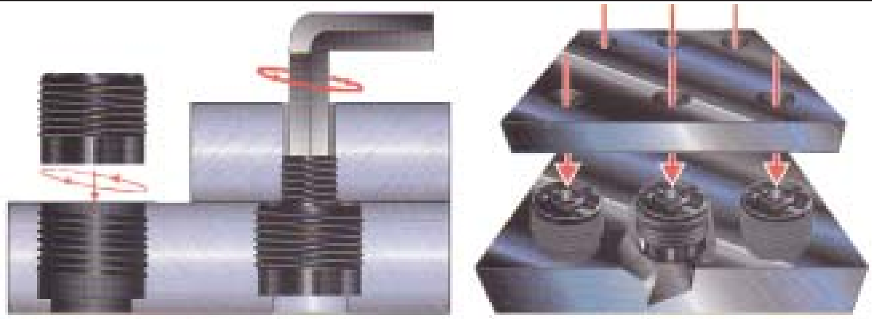
Secure, accurate workholding is crucial to the success of any machining operation. And when it comes to holding their high-value parts, aerospace manufacturers face special challenges. Aircraft components are often large, odd-shaped and made of difficult-to-machine materials. Keeping them on the machine table or in the chuck is the first priority, but an uneven or overzealous grip affects final part quality as well. Aerospace parts makers are combining basic assumptions regarding fixturing and clamping with new approaches to workholding and machining to ensure that their parts fly out the door only when they want them to.

Locate and Support

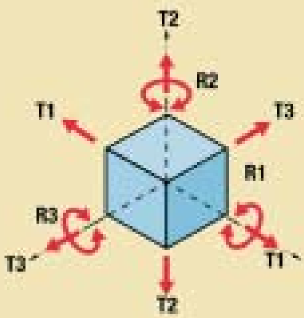
To be accurately and reliably machined, a workpiece must be located in space, supported where necessary and held stationary against cutting forces. Tom Eggert, workholding product manager for hydraulic equipment and workholding systems maker Enerpac, Milwaukee, said, "You've got to have the part in the same place every time so you're always cutting that hole in the same spot. Then, support it where it might deflect or sag. The third step is to clamp over the top and hold it in place, so that it doesn't move no matter what forces you apply to it."

Putting the part in its place comes first. In workholding parlance, an unrestrained 3-D workpiece has "six degrees of freedom." The part can move back and forth ("translationally") along its X, Y and Z axes, and it can rotate around each of those axes as well. Fully constraining a part involves limiting the degrees of freedom in a 3-2-1 sequence. A restricting plane (comprised of three

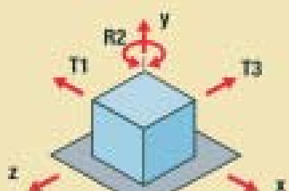
Back bolting a component to the workholding subplate permits machining around five sides of the part. After the workpiece is predrilled and tapped, the Invert-A-Bolt fastener system enables back bolting without requiring access to the underside or rear of the part.



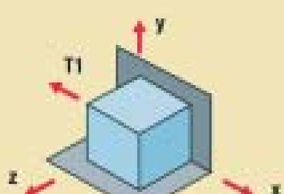
Lines In Motion



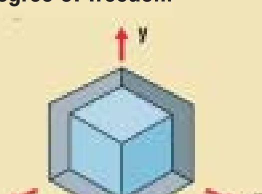
3-D body



Three degrees of freedom



One degree of freedom



Zero degrees of freedom

Enerpac

An unrestrained 3-D workpiece has six degrees of freedom that must be controlled to fully constrain the part for machining.

points of contact) introduced across one side of the part eliminates one translational and two rotational degrees of freedom. Introducing a second plane, consisting of two points, removes one more translational and the remaining rotational degrees of freedom. A final plane restricts the final degree of freedom with one point of contact, fully constraining the part.

Depending on the part configuration, machining operations and cutting forces involved, elimination of all six degrees of freedom may not be necessary. A low-force, unidirectional cut may require minimal effort to restrict movement. On the other hand, it is possible to over-locate a part by providing more than one locating point for any given degree of freedom. For example, it is practically impossible to locate four points on one plane, so a part clamped against four points of contact can rock much like a four-legged table wobbles when one or more of its legs is shorter than the rest.

Solid stops or pins usually provide points of contact for 3-D location. Then, separate from locating functions, work supports can be added to the workholding setup for features distinct from the locating planes and for thin-walled sections that might distort, deflect or vibrate under cutting or clamping forces. Supports are especially crucial when machining asymmetrical shapes and thin sections of aerospace components such as wing spars and bulkheads. Support can be provided by simple pins or blocks, adjustable units that match the part and lock in position, or vacuum pressure.

Get a Grip

While stops and supports locate and stabilize a part, clamps securely fasten the positioned workpiece. Clamping forces must be applied in a way that doesn't distort the part or move it from its location, but must also provide sufficient resistance to cutting forces. As shops seek higher productivity, cutting forces increase. Eggert said, "Everybody's trying to turn up their speeds and feeds and trying to get more parts off the machine faster. That's more and more force you're putting into the part that you've got to resist."

> **Clamping forces must be applied in a way that doesn't distort the part or move it from its location, but must also provide sufficient resistance to cutting forces.**

Clamping arrangements are usually designed to push a part into or against a stop or support rather than resist cutting forces. Therefore, clamping system manufacturers recommend that an operation's main cutting forces be directed toward a solid stop rather than a clamp. Furthermore, when possible, there should be a straight line of force between the place where the clamp is applied and the bearing points under the workpiece.

Parts can be held mechanically with bars, springs, nuts and bolts; with pneumatic or hydraulic clamps powered by elastic media such as air or oil; or with vacuum gripping arrangements.

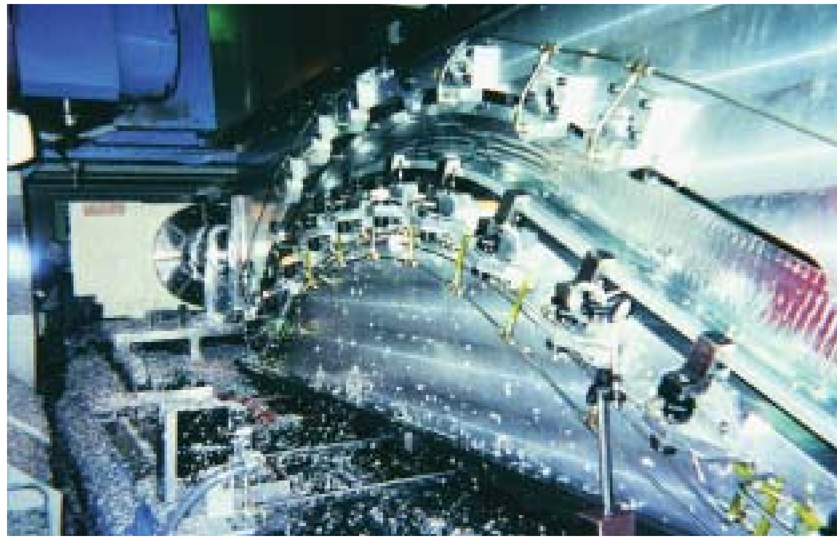
Many aerospace shops dealing with low to moderate production volumes use manual clamps for their economy and familiarity. Often, higher-volume shops employ automated pneumatic or hydraulic technologies. Eggert said compared to manual clamping, hydraulic clamping offers the benefits of strong clamping forces, as well as speed and repeatability.

Reduced changeover time is one result. Eggert said: "Whether it is an automated or manual load situation, you've got to unclamp a finished part, take it out and put a new one in its place to be machined. With hydraulics, you can clamp that part again in a matter of seconds. Moving manual clamps into place and tightening them down with a wrench can take 2 minutes or more."

Also, hydraulic clamping forces are automatically repeatable. Manual clamps may require use of a preset torque wrench to assure consistent clamping.

Eggert added that during machining, hydraulic oil can serve as a shock absorber. "In some larger clamps, you have a large volume of oil that will absorb a lot of the vibration and cutting forces," he said.

To assure part security, workholding equipment manufacturers strongly urge that users do not simply estimate clamping forces. Accurate force levels can be calculated using formulas that take into account machine horsepower, cutting speed and metal-removal rate.



Enerpac

In this automated workholding system, hydraulic swing clamps secure a wing spar during machining.

Other factors, such as the presence of interrupted cuts, can also affect cutting forces. After determining the strength and direction of cutting forces involved in the intended machining operations, workholding suppliers advise applying a safety factor of 2 when using mechanical clamping and 1.5 for hydraulic clamping to determine the amount of clamping force necessary.

Whether mechanical or hydraulic, sometimes the clamping can get in the way of machining. "We don't see many toe clamps in structural machining, because you need to get around every face of the part, and if you clamp it you've got clamps in the way," said Jeff Wallace, CAD/CAM applications engineer of the Makino Aerospace Group of machine tool builder Makino Inc., Mason, Ohio.

He said one effective way to hold such parts is the Invert-A-Bolt fastener system from Lines In Motion Inc., Fort

Cutting tools and machines

The less you push on a part, the easier it is to hold. Toolmakers work continually to develop cutters and insert materials that can machine aerospace materials productively while minimizing cutting forces.

Regarding aerospace components and the materials they are made of, Jim Flaherty, senior systems engineer for Kennametal Inc., Latrobe, Pa., said, "The problem with this stuff is that it's so darn unique. How many people build airplanes?"

As an example of new technology developed in response to the specific needs of aerospace manufacturers, he cited tools like Kennametal's indexable long-edge finishing endmill that leaves just a 0.0002" lap line remaining between insert paths. In the aerospace industry, he said, "there are tools like that being developed every week."

Workpiece material characteristics also drive machine tool development. "We've done a tremendous amount of work in the hard-metal cutting area," said Jeff Wallace, CAD/CAM applications engineer of the Makino Aerospace Group. "We now have a super high-torque, high-power spindle that enables rough hogging and high-speed finishing of titanium."

For tough nickel-base alloys, Makino has achieved the greatest metal-removal rates via grinding. "We have developed a machine tool platform that enables grinding and machining to be done on the same machine, in the same workholder," Wallace said.

Metal-removal rates for aluminum also are increasing. Wallace said one driver for that is the aerospace industry's continuing move to the production of monolithic parts: Components that formerly were assembled from separately machined units are now cut from a single workpiece.

"The industry on both sides of the pond is pushing toward monolithic parts," Wallace said. "They don't want the assemblies anymore with 5,000 rivets. That means we've got a lot of material to come out in a short amount of time, so we have to be very aggressive with metal removal."

Wallace noted Makino's MAG machines, for example, have a spindle technology that was developed for the aerospace industry. The 80-hp unit offers 30,000-rpm capacity in a compact housing engineered to provide kinematic freedom and maneuverability. With unlimited C-axis rotation and ±110° of freedom in the tilting head, "we can generate nearly any geometry around five sides of a part."

—B. Kennedy

Worth, Texas. Each fastener consists of a 1"- or 1½"-dia. threaded steel housing with a central stud—5/16", 3/8", ½" or 5/8" in diameter—threaded into it. The housing is screwed flush into the fixture faceplate with a spanner wrench, and the workpiece is through-drilled and tapped to match the diameter of the stud. After the workpiece is positioned over the housing, a hex wrench is inserted through the workpiece to back the stud out of the housing about ½" into the part. "Basically, you are back bolting your workpiece to your subplate," Wallace said, "but you don't have to get through the back of your subplate to get to the part."

In addition to their unique sizes and shapes, many structural components also feature thin floor and wall sections, a response to aircraft makers' desire for the lightest, most fuel-efficient parts possible. Wallace said some sections can be as thin as 0.025", creating a need for vacuum workholding to stabilize the section during machining. "We create vacuum fixturing to hold the floors down so we can cut them at high speed."

General Tool Co.

Mechanical clamps constrain this titanium jet engine fan frame for machining.

As an example of the speeds involved, Wallace pointed out that Makino's MAG series machines can cut aluminum structural parts at feed rates over 470 ipm, a 30,000-rpm cutting speed and at a DOC of 0.700" for a 1" channel. "You have to hold that floor down when you are buzzing around at 400 ipm, because it tends to pull up and you'll scrap the part," he said.

A vacuum workholding setup can be relatively simple, consisting of a subplate drilled with 1" to 1½" holes and surrounded by an O-ring seal. Shop air is used to generate a vacuum pressure in the neighborhood of 25 to 30 psi. "It's not a whole lot of pressure, but because of the actual surface area, you get tremendous holding force," Wallace said.

Vacuum can be stored in an accumulator-mounted outboard of the machining area, or, in more elaborate setups, autocoupled with the machine's vacuum system after a pallet moves into the machine. Fixtures are usually designed with a few clamping bolts on the periphery. "We could actually get away with just using vacuum, but we do the belt and suspenders approach just in case the vacuum goes away," Wallace said.

Material Effects

In addition to the influence of part configuration on workholding strategies, the machining characteristics of the materials encountered in aerospace applications can help dictate the way a part is held.

Titanium, for example, is known for its tendency to "spring back" after machining. When clamping titanium parts, a shop must "sort of pinch them and cut them as close to a free state as possible," said Brian Purdy, engineering manager for Capo Industries Inc., Chino, Calif., a manufacturer of aerospace turbine components up to 80" in diameter.

Clamping arrangements are usually designed to push a part into or against a stop or support rather than resist cutting forces.

"If you distort them when you hold them, they are going to maintain that distortion and spring back. You have to structure the fixturing so that's not the case." A titanium part that is simply clamped down as tightly as possible, he said, "will just come right back. You've got to let it move and not machine too close."

Bobby Wilson, owner of prototype and short run shop Acinch Development, Susanville, Calif., concurred: "I've seen so many people lose parts to overtightening. They clamp it down, then they machine it and release it, and

The following companies contributed to this report:

Acinch Development
(530) 257-5694
www.acinchdev.com
Information Services #330

Capo Industries Inc.
(909) 627-2723
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Enerpac
(800) 433-2766
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Kennametal Inc.
(800) 446-7738
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Lines In Motion Inc.
(877) 462-2658
www.invert-a-bolt.com
Information Services #334

Makino Inc.
(800) 552-3288
www.makino.com
Information Services #335

there is so much stress inside of it that the part just goes everywhere. Moderating machining parameters as well as clamping forces can be a solution."

Wilson said his shop often combines higher cutting speeds and feed rates with lighter DOCs. With those parameters "You don't have to secure the part with huge clamps and put cheater bars on it, because you're taking less of a cut," he said. "At the same time, there is not as much stress on the part or heat buildup."

Another strategy is machining the part in two steps. "If you have a part with a whole bunch of pockets and bosses and different detailed work on it, you go through and you rough the whole thing out. Let the material spring, and then come back and do your finish machining," Wilson said.

He said his shop often creates one fixture to rough a part on both sides, then builds another fixture to finish it. In these cases, the solution is not workholding equipment alone but "the process as well," Wilson said.

Similarly, Wilson said, tough nickel-base alloys like Inconel require a balance of gripping and cutting power. "Even though Inconel moves when you cut it, it's primarily so hard that you have high tool pressures and it has to be held securely. That's a situation where you have to get the right combination of machine and tool."

Aerospace, with its acute global competitiveness and high-value, flight-critical components, presents many unique workholding challenges. Machining these large, delicate parts often involves combining different workholding technologies with machining strategies to achieve the high productivity and top quality the aircraft industry demands. △