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➤ BY ALAN ROOKS, EDITORIAL DIRECTOR

Rock solid

Ultraprecise machine tools are literally built on a strong foundation. They typically last longer, cut more accurately and cost more than other machine tools.

If you want to build something to last, start by building it on a strong foundation. That saying is an apt guide to building the highest accuracy machine tools, which not only feature ultrarigid bases, but are literally built on bedrock, in some cases.

That's the case at Mitsui Seiki Kogyo Co. Ltd., Tokyo, a manufacturer of ultraprecise machining centers, jig grinders, jig borers and external thread grinders. The company's factory in Kawajima, Japan, is built on 1,700 piles driven 120' into the ground to reach bedrock. Concrete in the factory floor is a minimum of 1m deep, and 1.2m deep in construction bays. "The surfaces our machines are built on are separated from the main factory floor so any potential vibration from outside sources does not affect machine construction," said Scott Walker, president of Mitsui Seiki U.S.A. Inc., Franklin Lakes, N.J., during a tour of the Mitsui Seiki plant. "This ensures there are no seismic deformations when we build and test machines."

That's just one of the features that distinguishes the ultraprecise machine tool manufacturing process. Others include nearly total thermal stability during manufacturing, hand scraping and fitting of way surfaces, and a repetitive process of assembly, measurement, disassembly and rescraping until a nearly perfect fit of machine components is achieved.

Naturally, none of this comes cheap. Mitsui Seiki and other ultraprecise machine tool builders, such as Dixi Machines SA (a Swiss-based unit of Mori Seiki) and Yasda Precision Tools K.K., Okayama, Japan, sell some of the most expensive machine tools in the world. For example, a commodity-grade horizontal machining center might cost about $175,000, while the same size midrange HMC might cost about $600,000, according to Walker. A same-size Mitsui Seiki HMC would cost about $800,000. "Machine tool price is directly proportional to machine tool accuracy," he said.

Fitter-scraper at work. Fitter-scrapers can achieve accuracies that machines can't in building ultraprecise machine tools. It takes 5 to 7 years to fully train a new fitter-scrapper at Mitsui Seiki.

All images: A. Rooks

Volumetric Accuracy

That high price provides the highest possible volumetric accuracy, a measurement of how a spindle moves inside the 3-D operating "cube" of a machine tool to achieve a specific dimensional positioning capability within that cube, Walker said. The cube defines the effective cutting reach of the machine tool, and imperfections in the machine tool's construction can lead to nonuniform accuracy at different points within that cube. The goal of an ultraprecise machine tool is to eliminate as many of these imperfections as possible, thus increasing volumetric accuracy. This is especially important when 5-axis machining, which features more complex movement than 3-axis machining. "Many people talk about repeatability and positioning, but that's only a small piece of the volumetric accuracy puzzle," said Walker.

Ultraprecise machine tools provide the highest volumetric accuracy, but are not appropriate for most applications. "There is nothing wrong with commodity machines," said Walker. "They are a good fit for low-cost, high-production operations, such as manufacturing brake drums." Commodity machines, which account for about 75 percent of all machine tools sold worldwide, can deliver true positioning within about 100 microns in the machining cube, according to Walker. Ultraprecise machines can deliver true positioning within 12 microns and account for about 5 percent of all machines sold, he said.

An ultraprecise machine achieves the machining trifecta: high volumetric accuracy, thermal stability and structural robustness, said Walker. "These are literally hand-built, custom machines. They are designed to be extremely thermally stable. When you heat a square meter of cast iron 1° F, it grows 25 microns, so when building an ultraprecise machine you must be able to control thermally for less than half of that when the machine is warmed up and running."

Structural robustness guarantees that after machining, an ultraprecise machine tool will return to exactly

Five-axis technology extends machine capabilities

Five-axis machining is changing the way all machine shops and manufacturers produce parts, but the technology's impact in the ultraprecise machine market is critical, according to Scott Walker of Mitsui Seiki U.S.A. Inc. "In all 5-axis applications, the benefits for machine shops and manufacturers include reduced setups and better repeatability. In ultraprecise machines, 5-axis is the key in high-performance output. High tolerances are difficult to achieve unless the high-precision machine geometry is built into the machine platform."

New 5-axis developments are leading to higher productivity by increasing table speeds and introducing multifunctionality to the platform, said Walker. This will increase manufacturers' throughput. He added that 5-axis machines currently represent about 80 percent of Mitsui Seiki's order volume.

Mitsui Seiki's most recent 5-axis vertical machining center is the Vertex 550-5X. The machine's casting design provides an ultrarigid machine structure, according to the company. The gear drive system for the A and C rotary axes provides high-speed radial performance (A rotates at 30 rpm; C rotates at 50 rpm) and overall drive system stiffness. The trunnion tilt axis, A, has a dual-side support construction bolstering rigidity. The linear axes move the spindle only. The motion of the workpiece is by the rotary axes only, offering improved control of machine dynamics.

—A. Rooks

Mitsui Seiki expands Kawajima factory

Tadauki Abe, president, Mitsui Seiki Kogyo.

With the world market for machine tools growing rapidly, Mitsui Seiki Kogyo Co. Ltd. is expanding its production capacity. This decision was not taken lightly because constructing work areas for building ultraprecise machines is costly. The company is creating two additional bays that will add a total of 12,000 sq. ft. for the manufacture of smaller, low-profile machine tools, allowing larger machines to be built in the main workshop. In June 2008, the company plans to expand further, with two more bays totaling 50,000 sq. ft.

According to Tadauki Abe, president of Mitsui Seiki Kogyo, manufacturing growth in Asia, the U.S. and Europe is fueling Mitsui Seiki's growth. Mitsui Seiki ships about 20 to 30 machines per month, depending on the product mix, and aims to increase that output to 45 to 55 machines per month after the two expansion projects.

"The annual global requirement for machines increased 100 percent between 1990 and 2000, moving from $30 billion to roughly $60 billion," said Abe. "The additional requirement for high-quality parts made from hard materials is driving sales for Mitsui Seiki. Producers of aerospace parts are looking to reduce costs by making parts in one setup, and our 5-axis machines are well suited for that process."

Abe also noted that the aerospace industry is moving to manufacture more parts from titanium, as well as carbon fiber and other composite materials, all of which are good candidates for machining on ultraprecise machines.

—A. Rooks

the same position it started in. "When a cutting tool tip touches a workpiece, the machine will bend; you can't get away from that," said Walker. "What you want is for the machine to bend to a position while it is machining and bend back to the same position it started in. The next time that tool engages, the machine should bend to exactly that same position. That's robustness. That's stiffness."

Manufacturing Discipline

The demanding nature of building ultraprecise machine tools requires several extraordinary considerations, including workshop temperature control, materials and component size.

At the Kawajima plant, temperature is maintained at 20° C, ±0.5°, and humidity at 55 percent, ±0.5 percent, floor to ceiling. To accomplish this, the shop's air is fully exchanged every 2½ minutes. Recirculators capture air on the shop floor. The air is compressed, cooled, expanded and diffused from the top of the plant. The air is maintained at a slight positive pressure, so when doors are opened, air goes out but does not come in. "It is essentially a thermal bath for all the components so that as machines are built, the components do not expand or contract," said Walker.

The factory's precision measurement area has more exacting temperature control, maintaining a temperature of 20° C, ±0.1°. Mitsui Seiki spends $75,000 per month to operate the temperature control system.

For machine bases, Mitsui Seiki uses high-nickel cast iron. "Nickel is a good heat sink; it absorbs heat and doesn't let it go quickly," said Walker. Also, Mitsui Seiki uses SCM 415 (JIS standard) tool steel containing chrome and molybdenum to create ways because it is a tough, thermally stable material with predictable bend characteristics. "Commodity machine builders typically have cast iron beds with built-in cast iron ways," said Walker. "Using tool steel, we hand-scrape the way surface to take the pitch, yaw and roll out of the surface. The way surface retains a crown because when it is loaded with pallets and parts, it will be flat."

Beds for Mitsui Seiki machines are larger than lower-end machines. "For example, when you want an I-beam to support more ceiling weight, you don't make it thicker—you make the 'I' bigger," said Walker. "The same is true for machine tool beds. Our beds are 30 to 50 percent bigger than those in lower-end machines. This robustness creates predictable bending forces while machining that translates into highly accurate machining processes. It also allows the machining of tough materials with extended tool life because of consistent chip loads on the cutting tools."

To achieve high volumetric accuracy, spindles on ultraprecise machine tools must be stiffer than lower-end machine tools. Stiffness is measured by hammer modal analysis, in which frequency and magnitude of excitation in the X and Y axes are measured by putting a test bar in the spindle and striking it with a hammer. Transducers on the machine collect the vibration data.

As a result, spindles on ultraprecise machines must run at slower speeds than other machine tools. "The stiffer the machine, the less the spindle will bend, and the stiffer the spindle, the hotter it gets at higher rpms," said Walker. "That is the tradeoff between speed and spindle stiffness. We build spindles to operate from 12,000 to 15,000 rpm. They are not the fastest, but they are the stiffest."

Spindle stiffness is an important characteristic when cutting all metals, from soft to very hard. "Even when cutting aluminum, if you engage it with a single-point boring tool, there is quite a bit of point load that transmits to the machine and bends it," said Walker. "If you want that bend to be consistent and provide consistent positioning in the cutting process, you need a stiffer spindle."

Hand Scraping

The craft of hand scraping and fitting sliding surfaces distinguishes ultraprecise machines. According to Walker, it takes 5 to 7 years to fully train a new fitter-scraper. "This is a

Aerospace boom fuels machine tool growth

The current aerospace boom, in which both commercial and military aircraft markets are growing rapidly, is a key driver behind the growth of ultraprecise machine tools. Mitsui Seiki Kogyo Co. Ltd. estimates that aerospace OEMs account for about 50 percent of its current sales, Tier 1 aerospace suppliers 20 percent and other nonaerospace machining operations 30 percent. That's a big change from just 4 years ago, when aerospace OEMs accounted for just 20 percent of the company's sales, said Scott Walker of Mitsui Seiki U.S.A. Inc.

Ultraprecise machine tools are ideal for making aerospace parts, said Walker. "Aircraft are designed in a process that is approved by various national licensing boards. After that process is approved, it doesn't change for a long time. Companies producing these parts need machines that are going to operate consistently throughout the lifecycle of the product."

Ultraprecise machine tools typically have much longer operating lives than other machines tools. For example, Mitsui Seiki machines have an average operating life of 75,000 hours, and at 2,200 production hours per year, a machine would last 34 years. At the high end of production, 6,600 hours per year, a machine would last about 11½ years. A commodity machine might last just 20,000 hours, said Walker.

Ultraprecise machine tools allow for more consistent parts production, another key for the aerospace industry. "If you don't have high-end machines, the operator has to stop the machine frequently to measure and take another cut," said Walker. "Customers that buy high-end machines want to produce high-end, precision parts lights out every time they turn the machines on. They don't want to have operators measuring the bore and doing tool offsets."

A machinist manufactures special cutting tools at Aikoku Alpha, Nagoya, Japan.

Mitsui Seiki is engaged in joint R&D efforts with major aerospace manufacturers to share in the development costs of machine tool products, with much of the work focused on difficult-to-machine materials, such as titanium, as well as the carbon-fiber and other composite materials common in new aircraft. "This provides a cost-sharing platform for very specific requirements and locks us into long-term projects on new aircraft," said Walker.

One example of a company using Mitsui Seiki machine tools to make aerospace parts is Aikoku Alpha Corp., Nagoya, Japan. The company also produces cold-formed auto parts, CATIA CAM software and other products.

Since 1997, Aikoku Alpha has been a Tier 1 supplier to The Boeing Co.'s commercial aircraft group. "We are focused on the high value-added parts market," said Masaaki Kanamaru, senior managing director of Aikoku Alpha. "Thirty years ago, we decided to invest in 5-axis machining, and we have become a leader in this area." The company currently operates about 60 5-axis machines, including 20 Mitsui Seiki units.

The company is looking for 5-axis machines with more flexible speed ranges and the ability to machine different materials. "We need a little smaller machine that goes a bit faster," said Kanamaru.

According to Walker, Aikoku Alpha is typical of many aerospace parts manufacturers that are gaining "overflow" work from aerospace OEMs. "They may get, say, a 200-piece titanium parts order that never repeats, and then move onto to a different project with different materials," he said. "I hear this everywhere I go. Some manufacturers may need a faster spindle speed for an aluminum part, but once you increase spindle speed, you lose spindle stiffness, degrading your ability to machine materials like titanium. Once you start increasing 5-axis feeds and speeds, you lose profile accuracy because you have difficulty controlling all that mass accurately. It's part of the tradeoffs in operating ultraprecise machines."

—A. Rooks

very exacting job, so people must have the right personality," he said. "For some, only perfection will do, and we use those fitter-scrapers on our most critical machines."

In hand scraping, the surface of a casting is cut with a chisel-shaped tool. The scraper removes about 1 to 3 microns of material in each pass, making it possible to create any shape. Experienced fitter-scrapers can achieve degrees of flatness, squareness and straightness not possible with machines.

A scraped surface has irregularities, with high and low points. After a first pass, vermillion is painted onto the surface. The fitter-scraper then takes a perfectly flat plate, a rubbing jig, and rubs it over the scraped surface. The vermillion rubs off on protruding areas. The fitter-scraper then trims sections where the vermillion has rubbed off. This process is repeated until the desired flatness is achieved.

Technician measures flatness during machine tool production.

There are several different scrape finishes, including 24-, 36-, 48- and 90-point scrapes. A 90-point scrape is the most precise and most difficult to achieve. This translates into 90 "peaks and valleys" in a 1-sq.-in. surface. The larger number of contact points, the better the degree of contact between the two surfaces and the higher the precision.

After a machine is scraped and fitted, it is assembled and measured. It is then disassembled and rescraped, with the process repeating until the machine meets specification. This process can take anywhere from 80 to 800 man-hours depending on the machine type, said Walker.

He sees several trends affecting ultraprecise machine tools. "Productivity increases have always been the driving force in the purchasing of new capital equipment," Walker said. "But today's global sourcing opportunities require continual cost reductions along with timely deliveries and quality performance. In the manufacturing of expensive components, purchasing more expensive, high-performance machine tools allow for more cost savings opportunities." △