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Stability and Precision:

Machining the James Webb Telescope's Mirror

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James Webb
Space Telescope

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Stability and PRECISION

Operator pauses for an in-process check during rough milling of the mirror surface, which is performed using circular interpolation and carbide end mills.

What it takes to machine mirror segments for the next-generation space telescope

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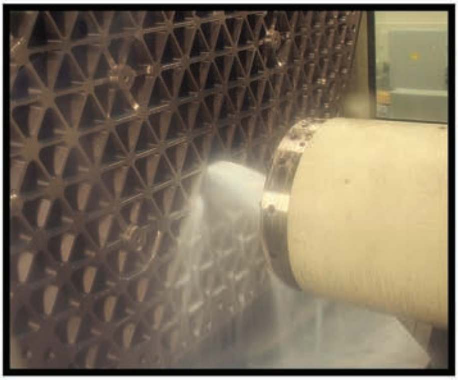
Contributing Editor

What is the shape of the Universe? How did it build up its present elemental and chemical composition? How do galaxies evolve? How do stars and planetary systems form and interact?

Answers to these and other fundamental questions continue to elude astronomers. But scientists at the National Aeronautics and Space Administration (NASA) hope a new space-based telescope can shed light on the origins and nature of the Universe by allowing them to look deeper into space—and thus farther back in time—than ever before.

The heart of the James Webb Space Telescope (JWST) will be a mirror with a clear aperture of 25 m^2. It will be 2.5× larger than the mirror of the Hubble Space Telescope, and is expected to be able to resolve objects 10–100× fainter than Hubble can see.



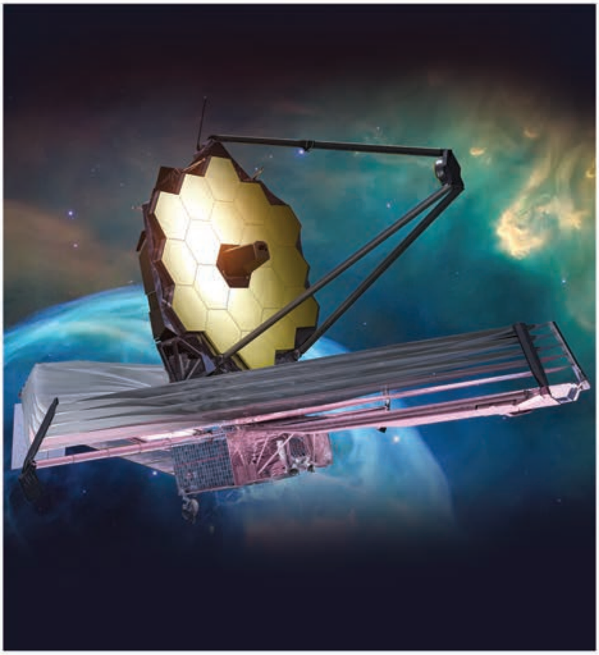
A view into the machine during milling on the back side of the mirror, which features 600 pockets and rib thicknesses as small as 0.020."

The mirror will be made up of 18 beryllium segments, each roughly 1.5 m across. This is the story of how Axsys Technologies Inc. (Rocky Hill, CT), working for Ball Aerospace, which is a subcontractor to Northrop Grumman, the prime on the project, developed machining processes for those mirror segments.

Axsys was awarded the job in September 2003, and is scheduled to start delivering segments in early 2006. The final segment is set for delivery to polishing by the second quarter of 2007.

The company built a new $1.2 million, 20,000 ft² (1860 m²) climate-controlled facility in Cullman, AL, to house mirror production. And, after a lengthy selection process, it chose Mitsui Seiki USA Inc. (Franklin Lakes, NJ) to supply machine technology for the project.

"The process we went through to select the machines was one that we developed over quite a few years," recalls General Manager Martyn Acreman. "We formed a team with representatives from the skilled machinists, purchasing, engineering, quality, and maintenance. We developed a matrix of various capabilities, and we were able to separate out a short list of equipment that we thought would meet our needs. Obviously, price and delivery were factors, but the main factor was machine capability, especially volumetric accuracy."



Beryllium is a unique material in many respects. It's very stable across a wide range of temperatures, and has a very low coefficient of thermal expansion. It's lightweight and stiff, and has isotropic mechanical and physical properties. "That's very desirable in an optical material," Acreman says. "You don't want an optic expanding in one direction and not in another direction. It would distort what the object is trying to do."

But the material also has a few drawbacks. It's very expensive—billets for the mirror segments cost more than $500,000. And it's very difficult to machine safely. "There is a toxicity issue, and there's an issue with a chronic lung disease caused by inhaling airborne beryllium particles," Acreman explains. "We have all kinds of techniques that we've developed over many years to control those issues." For example, machines are fully enclosed, and other measures are taken to minimize airborne beryllium particles.

According to Acreman, the OSHA standard for airborne beryllium is two µg/m³. "Today we work to a standard called ALARA—As Low As Reasonably Achievable," he says. "We take more than 1000 air samples a year, and those thousand air samples are reading, as an average, below 0.1 µg/m³. That's 1/20th of the OSHA standard."

Maintaining the required tolerances while removing about 95% of the billet weight **is quite a manufacturing challenge.**

Manufacturing Engineer Brady Rodgers notes that maintaining the required tolerances while removing about 95% of the billet weight is also a manufacturing challenge. "This is the largest lightweight beryllium optic that has ever been made," he says. "The Advanced Mirror System Demonstrator [AMSD] was practically a full-scale mockup of the actual JWST mirror segments. It was a 1-m beryllium optic which, at the time of manufacture, was the largest in history. That billet started off at something around 700 lb [315 kg], and its ship weight was about 28 lb [12.5 kg].

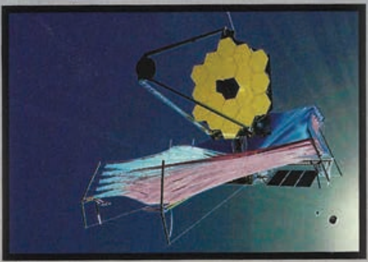
"It's been quite a challenge removing that much material from a beryllium billet and holding its stability and geometry very, very closely."

Each segment features multiple pads on the back side that enable mounting on a backplane, as well as six locators on the periphery that will attach to an actuator to allow individual focusing of each mirror segment. "We're talking about a very, very small movement here—millionths of an inch—so the mirror itself has to be very, very close to perfect before it's launched into orbit," Rodgers says.

Axsys begins work on the segments by importing a solid model of

About the JWST

Scheduled for launch in August 2011 and named after NASA's second administrator, the James Webb Space Telescope is designed to study the earliest galaxies and some of the first stars formed after the Big Bang. Scientists will use the telescope to search for information about the birth and evolution of galaxies, the size and shape of the universe, and other fundamental astronomical questions.



Artist's rendering depicts the JWST deployed in its orbit 940,000 miles from Earth.

According to NASA, JWST is optimized for infrared detection to enable it to see the very first stars and galaxies to form in the early Universe. Because the Universe is expanding, the farther we look, the faster objects are moving away from us, creating what astronomers call red shift. Red shift means that the light is shifted more and more to redder wavelengths, sometimes even into the near and mid-infrared part of the spectrum. Therefore, studying the early Universe requires a telescope and instruments optimized for this light.

JWST's 6.5-m diam mirror is 2.5× larger than that of the Hubble Space Telescope, weighs only about a third as much, and will have about 10× the light-gathering capability. Both the mirror and a sunshield the size of a tennis court will fold up for transport, then unfold when JWST is in its designated orbit 940,000 miles (1.5 million km) from Earth. The telescope's mission is planned to last from five to 10 years.

A key element in NASA's Origins program, JWST's program cost is expected to top $3 billion. For more information on the telescope, visit NASA's JWST website at www.jwst.nasa.gov.■

each part supplied by its customer, Ball Aerospace. NC programmer Bruce Ponder uses the solid model to create toolpaths using Unigraphics NX-3 CAD/CAM software.

"We export the program in G-code to a DNC system or a hard drive area that they can access at the machine. Operators tag a file and then upload it to the machine itself," Ponder explains.

Axsys personnel use a Zeiss Prismo CMM on the shop floor to check parts at several points during and after processing.

"We also use Vericut NC verification software from CGTech to verify the program before it goes to the machine," he adds. "It allows you to see everything working in simulation, and that way we can find any deviations in the toolpath and correct them before the program ever goes to the machine."

Machining begins when a 750-lb (338-kg) beryllium billet supplied by Brush Wellman (Cleveland) is fixtured vertically onto an angle plate on the machine pallet. The six-sided billet is 4" (100-mm) thick, 54" (1.4 m) across, and 62" (1.6 m) from point to point.

"On the first pass, we're reducing thickness on the back side of the plate," explains Lead Man Tony Neal. "We do that because we have to do a clean-up cut on the billet to get rough edges off. We do a clean-up pass, then turn it around and refixture it. It stays there for about two months for pocket machining."

The back side of each mirror segment features 600 pockets, each about 2½" (63 mm) square. Other features

About the Machines

The HMCs Mitsui Seiki built to machine JWST mirror segments combine a massive structure with the ability to position to within a few microns anywhere in the machining envelope.

Based on Mitsui's HS6A HMC, Axsys' machines were modified to fit the task at hand. For example, they use a slightly shorter *Z* axis travel—980 mm, versus the standard 1000 mm—to accommodate the oversized pallet needed for Axsys' fixtures. *X* and *Y*-axis travels are 2000 and 1500 mm, respectively. Other features include 60-tool ATCs and a laser-based tool monitoring system.

Eight modified Mitsui Seiki HS6A HMCs for the JWST mirror project are capable of volumetric positioning accuracy within a few microns over their 2000 × 1500 × 980-mm (*X-Y-Z*) machining envelope.

"These are very large, heavy machines, so the components are substantial," says Scott Walker, president, Mitsui Seiki USA Inc. (Franklin Lakes, NJ). "The column weighs 11 tons, the bed is 20 tons.

"However, the machines also needed to position and travel in a very specific manner," he continues. "Axsys was trying to have consistent cutting, because machining generates a lot of stress on the part and they're taking a lot of material out. So the cutting conditions, the toolpath, and how the servomotors control the toolpath to provide consistency of machining load are keys to successful cutting of the mirror."

At Axsys, machines are mounted on concrete pads 39" (1-m) thick. Each pad is surrounded by a bed of sand to isolate the machine from surrounding equipment, and each machine is anchored to its pad using 27 anchor plates with four anchor bolts per plate—108 bolts.

Mitsui Seiki built a total of eight machines for the JWST mirror project, and Walker says each is well within agreed-upon specifications.■

Production Stats

- The JWST Mirror — the heart of the telescope — is made up of 18 beryllium segments, each 1.5 m wide
- Each mirror billet weighed 700 lbs. when loaded into one of the 8 Mitsui Seiki HMCs and 28 lbs. when machining was complete
- Each mirror structure required 18 weeks of machining time
- There are 8 different rib thicknesses on the 600-pocket side of the mirror structure ranging from 0.021 inch to 0.2 inch
- Tolerances for mirror finishing are + 0.0002 inch / - 0.00 inches
- True position is 0.001 inch from the inside to the outside of the hubs
- True position is 0.005 inch all the way around the 48-inch bolt hole circle
- The mirror surface has a specified thickness of 0.098 inch +/- 0.003 inch
- Tolerances on the 32, 0.250 inch diameter holes on the edge is + 0.0002 inch / - 0.00 inch

on the back of the mirror include locator hubs, and mounting pads around the perimeter. "There are a total of 22 pads on the pocket side," Neal says. "And there are 250 holes in the center of each web intersection point to reduce weight."

After pocket milling on the back side, the billet weighs about 275 lb (124 kg). The segment is heat-treated by Axsys to relieve machining stresses, then the mirror side is roughed before another stress-relief heat treatment. "Roughing is a circular cut that starts in the center and works its way out, and removes another 50–60 lb [22–27 kg] of material, Neal says.

The next operation is finish milling of the pocket side—another ten weeks of machine time. Wall thickness at this point is 0.040" (1 mm). After this, the segment is electrochemically etched and deburred several times before machining to finished dimensions.

Each segment requires 18 weeks of machine time, *two weeks for heat treatment, and several days for inspection.*

Finish milling of the mirror side, pocket side, and locator hubs is next. "There are eight different rib thicknesses on the pocket side, ranging from 0.021 to 0.2" [0.53–5 mm] near the locator hubs," Neal explains. "Tolerances for mirror finishing are +0.0002/-0.00" [+5/-0 µm], and true position is 0.001" [0.025 mm] from the inside to the outside of the hubs and 0.005" [0.127 mm] all the way around a 48" [1.2-m] bolt circle. The mirror surface itself has a specified thickness of 0.098" [2.48 mm] ±0.003" [0.076 mm].

"The segment is placed horizontally for the last machining operation in this building," Neill says. "There are 32, 0.250" [6.35-mm] diam holes on the edge. "Tolerance is +0.0002/-0.00"."

According to Neal, the holes are for tooling balls used to maintain a profile of the mirror surface during polishing. "It gives them a chance to check before they start polishing, because once they start they can't go back to the pocket side to check anything," he explains. "They have to check everything from the mirror side, so they use these tooling balls to control the profile."

All told, each segment requires 18 weeks of machine time, two weeks for heat treatment, and at least a week for inspection. "Inspection programs take a long time to run and inspect each individual feature," Neal says. "Parts are inspected at each step in the process,

A technician mounts a fiducial (reference point) on the AMSD mirror segment, a technology demonstrator nearly as large as the JWST flight mirror segments.

whether it's a machining operation, heat treatment, or deburring. They're inspected dimensionally and to check for residual stresses."

Polishing removes at least 0.0005–0.001" *off the mirror surface thickness.*

On the pocket side, the Zeiss Prismo CMM checks the depth of each pocket and rib thicknesses. After mirror roughing, the CMM checks every 2" (51 mm) across the mirror surface; after finishing, it checks a 1/2" (12.7-mm) grid pattern. Segments also are dye-penetrant inspected to look for cracks at least twice during the machining process.

Finally, a wire EDM machine removes the excess material from the segment periphery. "It cuts a wide strip on the outside of the mirror ranging from 1/2 to 1" [12.7–25.4-mm] thick depending on what type of mirror segment it is," Neal explains. "There are three different segments—A, B, and C—and they're slightly different sizes."

Neal says segments will be polished by Tinsley Laboratories Inc. (Richmond, CA) using computer controlled polishing machines. "For polishing, Tinsley has to take at least 0.0005–0.001" [0.013–0.025 mm] off the mirror surface thickness," he explains. "The amount they take off depends on how close we come to holding the profile."■