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BERYLLIUM MIRRORS FOR SPACE TELESCOPES

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BERYLLIUM OPTICS ENABLE ADVANCED SPACE TELESCOPES

Beryllium won a lengthy competition as the material of choice for the mirrors on the James Webb Space Telescope, set to launch in 2018.

Don Hashiguchi, FASM*
Materion Corp.
Elmore, Ohio

James Marder, FASM*
Thermacore Inc.
Rostraver, Pa.

Roger Paquin*
Advanced Materials
Consultant
Grantham, N.H.

*Member of ASM International

Launching objects into earth's orbit is enormously expensive, so every pound removed saves significant cost. When considering materials for the James Webb Space Telescope (JWST), a lengthy competition took place to determine the best choices and beryllium was ultimately specified for the mirrors. This article documents the developmental history leading up to that decision. It took decades of improvements to make Be—in particular O-30 atomized powder/hot isostatically pressed (HIP'd) components—homogeneous, isotropic, polishable, thermally and dimensionally stable, and above all, predictable.

BERYLLIUM PROPERTIES: IDEAL FOR SPACE

The most obvious requirements for space optics include low mass, high stiffness, predictable contraction when cooled to cryogenic temperatures, and the ability to be polished to a highly reflective surface. These characteristics were recognized and discussed as design parameters as early as 1966 by Barnes[1], while limitations of the available vacuum hot pressed (VHP) Be were also detailed. A decade later, after numerous telescopes with Be mirrors were already in orbit, hot isostatic pressing was advocated for Be optics and an evaluation of HIP'd Be material in comparison with VHP'd Be from the same powder was published[2]. The new material was found to be superior and therefore meets the specifications for infrared mirrors.

Low thermal expansion glass, such as the ULE fused silica (Corning's Code 7972 Ultra Low Expansion Glass) selected for the Hubble Space Telescope primary mirror, meets several of the material criteria very reliably—but not as well as O-30 Be, which was developed specifically for satellite mirrors. Table 1 compares the important properties of O-30 Be, ULE, aluminum, and magnesium.

In order to minimize mass, using a low density material is an obvious first step: The density of ULE is slightly less than that of Al. However, conventional mirror materials such as ULE and Al are much heavier than Be, which is 31% lighter than Al and 18% lighter than ULE. Magnesium is 6% lighter than Be. Yet another factor is stiffness, or modulus of elasticity, which is equally important because it measures how well a material resists deformation under load. Beryllium is 400% stiffer than both Al and ULE and 670% stiffer than Mg. Specific stiffness—the ratio of modulus to density—determines the engineering efficiency of a material, and it is clear that Be is more than five times better than the other materials in this regard.

Specific stiffness measures how well a structure maintains its shape in the face of forces such as gravity, launch, or maneuvering g's. After a mirror is polished to its desired shape—or *optical figure*—on earth at 1 g, it changes figure in the 0-g orbital environment. This "gravity release" causes only a slight figure change, but with very lightweight mirrors these changes, measured in fractions of wavelengths of light, can be enough to substantially distort the image. Grinding and polishing the mirror on earth to what will become the correct figure in space is called *null figuring,* which is much easier with a material featuring a high specific stiffness because the distortions are so much smaller. Surprisingly, steel, Al, Ni alloys, and Ti alloys all have similar ratios to Mg and ULE, while the specific stiffness of Be surpasses all of these, as shown in Table 1.

Historically, Be was not considered an ideal optical material[1]. However, due to its significant weight and stiffness advantages, a concentrated development effort worked to overcome its limitations. During the 1980s, the Strategic Defense Initiative emphasized the need for extremely lightweight, high performance surveillance satellites. It was during the "Star Wars" initiative that the shortcomings of Be as a mirror material were generally recognized and possible solutions imagined. Designers of satellite mirrors and structures constantly thought about how to save even a single pound. Beryllium affords these designers the opportunity to potentially save hundreds of pounds.

BERYLLIUM SPACE TELESCOPE HISTORY

The reflecting mirrors that act as the compound eyes of the James Webb Space Telescope are among the most precise and complex space optics ever fabricated. Essential to the telescope's performance are the characteristics of 18 adjustable segments that make up the 6.5-m primary reflector. Specifying Be broke new ground in high performance space optical materials development, and was a significant departure from the glass Hubble Space Telescope primary mirror that preceded the JWST. However, even during the 1970s, many space telescopes featured Be optics. These early mirrors cleared the path to the improved polishability and stability of the JWST.

TABLE 1–ROOM TEMPERATURE PROPERTIES OF MIRROR MATERIALS

Property	Symbol	Units	O-30 Be	ULE	6061 Al	Mg
Density	ρ	g/cm^3	1.85	2.21	2.70	1.74
Modulus	E	GPa	303	68	68	45
Specific stiffness	E/ρ	$10^6 m^2/s^2$	163	30	25	26
Coeff. of thermal expansion	α	$10^{-6}/K$	11.4	0.03	22.5	24.8
Thermal conductivity	k	W/m•K	208	1.3	167	156

Space telescopes serve many purposes, ranging from weather and astronomical exploration to communications and a variety of scientific and military applications. Increasing demand for higher resolution, lighter weight, and greater dimensional stability has driven the choice of many systems to Be, but with increased emphasis on dimensional stability and polishability.

Beryllium use for light, stiff, low moment of inertia applications during and after WWII show that it could be the right material for mirrors and structures in the new field of space technology. One of the earliest applications of Be mirrors in space was the Multi-Spectral Scanner for the Landsat earth imaging satellite in which the S-200E grade was used. The earliest applications were electroless nickel plated because uncoated S-200E could not be polished to the required finish. The first of these Landsat satellites was launched in 1972. Later versions include the Thematic Mapper instrument, which used S-200F, an improved version of S-200E. An SEM micrograph of the powder and an optical micrograph of consolidated S-200F are shown in Figs. 1 and 2, featuring an oxide content of approximately 1% BeO.

Another early space optical application was VISSR, the Visible Infrared Spin Scan Radiometer on the GOES, Geostationary Operational Environmental Satellite[3]. The scan mirror was particularly critical in this application, and any bending as the mirror reversed direction would have distorted the image. The extremely low moment of inertia Be scan mirror provided the required image stability, whereas conventional materials could not. The three mirrors for the early VISSR telescopes were plated with electroless nickel for polishability[4]. The first of these satellites was launched in 1974 and GOES satellites are still produced and launched. The VISSR instrument was replaced by a multispectral scanner that continues to use lightweight Be mirrors, with improved Be grades specified as they became available.

One of the first space telescopes to use an engineered grade of Be was IRAS, the InfraRed Astronomical Satellite, launched in 1983. It had a 60-cm primary mirror of I-70A Be and was polished bare, without a Ni coating. IRAS was one of the first athermalized telescopes where all components, including the mirrors and structure, were made of Be. This ensured that the entire assembly contracted uniformly to the 10K operating temperature. The coefficient of thermal expansion of Be at that temperature is virtually zero, which guarantees dimensional stability with any minor temperature variations. The IRAS primary mirror did, however, exhibit significant thermal figure distortion at the cryogenic temperature, but that distortion only minimally affected measurements at the shortest wavelength of 12μm. At longer wavelengths, the telescope was diffraction limited.

The successor to IRAS was the Shuttle InfraRed Telescope Facility, SIRTF, now designated Spitzer Space Telescope, one of NASA's four great

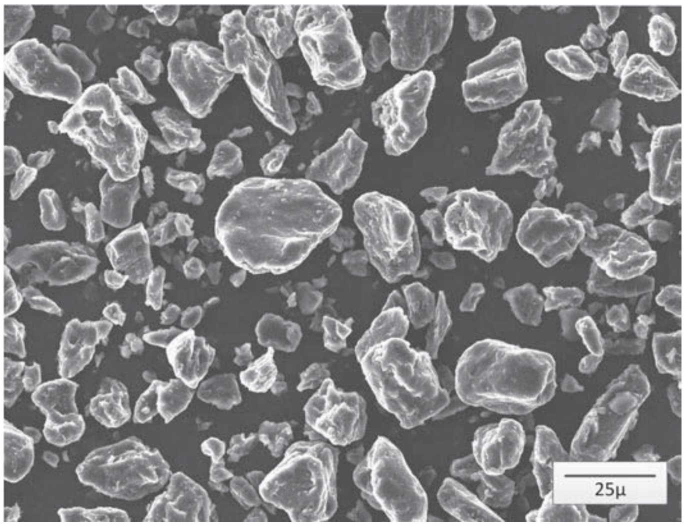


Fig. 1 — 500× SEM photomicrograph of S-200F grade blocky shaped beryllium powder produced by impact grinding. All images courtesy of Materion except 5 and 6.

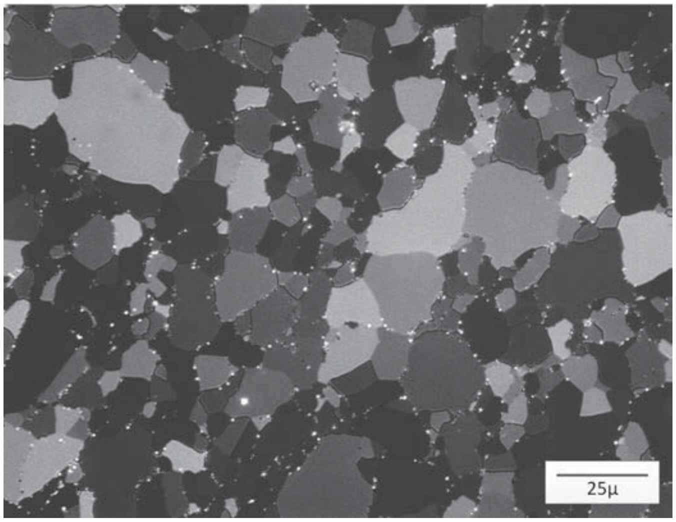


Fig. 2 — Polarized light photomicrograph of S-200F grade beryllium.

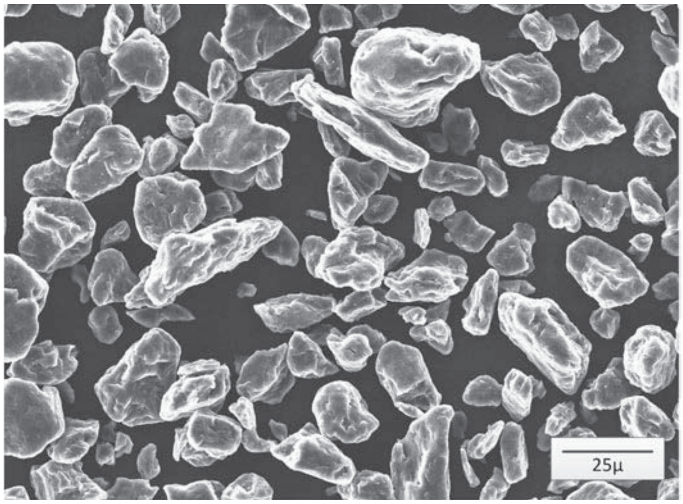


Fig. 3 — SEM photomicrograph of I-70 grade beryllium powder produced to a higher purity in comparison to S-200F grade that improved the ability to produce a polished mirror surface. Powder is produced by impact grinding.

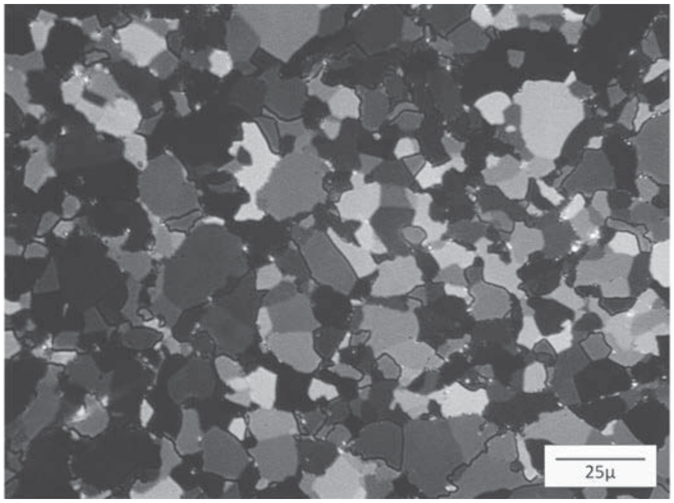


Fig. 4 — Polarized light photomicrograph of I-70H grade of beryllium consolidated by HIP. Higher purity input powder in comparison to S-200F is illustrated by fewer white oxide particles.

observatories. With its 85-cm diameter, bare polished primary mirror made of HIP consolidated I-70 Be (I-70H), this all-Be telescope operates at 5.5K. An SEM and associated light micrograph of I-70H are shown in Figs. 3 and 4. The telescope shown in Fig. 5 is the prototype being tested at Jet Propulsion Laboratory[5]. The excellent surface finish and optical figure obtained, as well as the insignificant thermal dimensional instability observed when tested at 10K, were a direct result of the improved material quality achieved by the HIP process. Because the optical figure of the primary mirror was tested at cryogenic temperatures, the correction to the small figure error was polished into the surface in a process called cryo null figuring. While neither the scatter nor optical figure of this telescope would be acceptable for a diffraction limited visible wavelength system, it exceeded specifications for the mid and far infrared wavelengths being observed.

The low oxide content and residual inhomogeneity found in I-70H (0.7% BeO) needed to be reduced even further before Be could become a viable candidate for JWST mirrors, because they operate at much shorter wavelengths. The next step—development of spherical Be powder consolidated by HIP—provided the ultimate material for the JWST mirrors. Four mirrors are used in the JWST, including the 18 segment 6.5-m primary, 738-mm secondary, 738 x 517-mm tertiary, and a 172.5-mm fast steering mirror to stabilize the image. All mirrors are gold-coated for enhanced infrared reflectance. Figure 6 shows the finished mirrors and the complete JWST[6].

Each of the 18 primary mirror segments (plus spares) measures 1.3 m and weighs approximately 40 kg (88 lb). Segments were polished to a surface figure accuracy of 24.2 nm rms and include

Fig. 5 — Prototype SIRTF telescope undergoing random vibration testing[5].

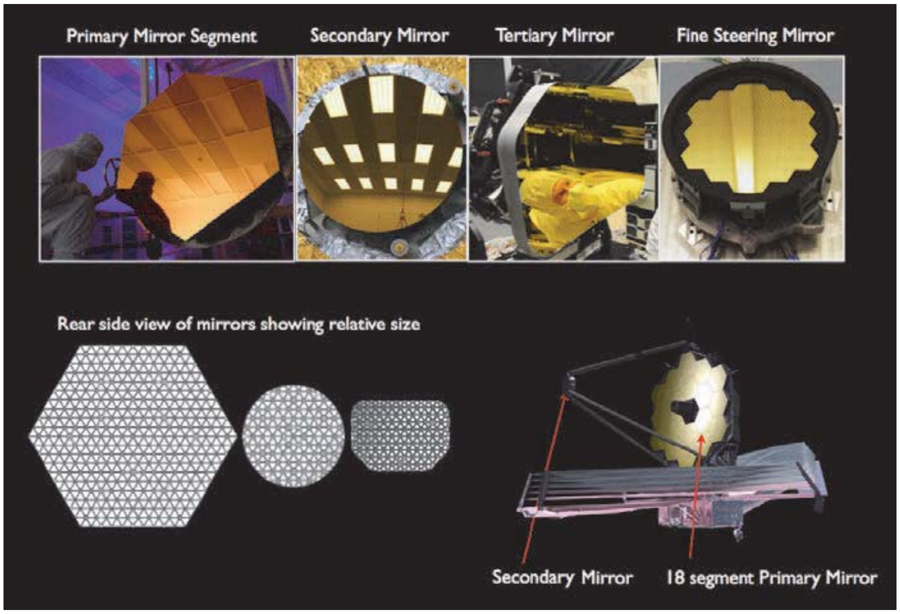


Fig. 6 — James Webb Space Telescope and its mirrors[6]. Bottom right shows an artist's conception of the telescope optics with 18 primary mirror segments. On the bottom row are the three different mirror segments as seen from the rear showing the honeycomb structure that makes them both light and stiff.

a vacuum deposited gold coating, 1000 Å thick. The convex secondary mirror, though much more difficult to polish and measure, has a similar figure accuracy.

BERYLLIUM POWDER: HISTORICAL DEVELOPMENT

Beryllium processing traditionally starts with vacuum melting and casting as part of the refining process. Vacuum melting removes residual magnesium and oxides that might be carried over from the reduction of beryllium hydroxide into metallic Be. Newly refined as well as recycled Be are input to the vacuum casting step. Statically cast beryllium features a typical ingot structure, with large columnar grains growing inward from the ingot wall and residual porosity toward the center. This results in property anisotropy, difficulty in machining, and overall poor properties. However, machining the ingot into chips prior to powder processing helps improve properties.

Powder metallurgy was used in the late 1940s to produce fine grained, nearly random-structured material. The more random grain and crystal orientation improves isotropy, particularly the coefficient of thermal expansion, while the finer grain size also improves mechanical properties. In the 1940s and 50s, beryllium powder was produced by two different processes—ball and attrition milling. Ball milling uses a rotating canister filled with chips and grinding media generally made of hardened steel. Beryllium was crushed and sheared into fine powder flakes, but this was a costly batch operation and resulted in iron contamination from the grinding media. Attrition milling was a continuous process in which beryllium chip was fed into a device similar to old flour mills. The chip passed between rotating and stationary beryllium plates and was sheared into powder particles. The weakest orientation of the Be crystal is the basal plane and this process produced powder particles with a slight flake-like structure by fracture on the basal plane.

Impact grinding to produce beryllium powder was introduced as a production process in the late 1970s and uses high velocity gas to propel Be chips against a Be target. The air is dried, and then cools as it expands from the nozzle. The impact shatters the chips into powder particles, which exhibit a blockier shape than ball or attrition milled powder. This process was also semi-continuous because oversized powder particles could be separated by air elutriation and fed back into the impact stream. This process improvement reduced iron and oxygen contamination, and produced a powder shape less related to the crystal structure than other processes. This was important during vibratory loading of containers in preparation for consolidation into a solid. The flat surfaces of flakes are all basal planes. When flakes are loaded into a press to consolidate them, they can stack up like a deck of cards or sheets of mica, with large regions having the same crystal orientation. Each of these regions behaves differently than adjoining regions with different orientations. When the solid, polished mirror cools, the difference between regions gives the surface an orange-peel appearance, which means that each region is reflecting a beam of light at a slightly different angle, scattering the beam rather than reflecting it in one uniform direction. Each time the mirror is warmed and cooled, these regions actually deform one another slightly. Scattering is unpredictable and changes on each cooling cycle. Therefore, additional polishing is not a solution.

The process that made the most sense for making powder was inert gas atomization, developed in the late 1980s for beryllium. A stream of liquid metal is blasted into small droplets by a stream of gas in a two-story chamber, resulting in spherical particles. Helium, argon, and ultimately nitrogen were all used as atomization gases. An SEM micrograph of atomized Be powder is shown in Fig. 7.

Spherical particles pack together with no relation to crystal orientation. Because each particle is randomly oriented, no large regions can develop. Properties level themselves out, leading to an essentially uniform surface. In conjunction with HIP consolidation, this results in a predictable mirror with equal thermal contraction in all directions. In addition, oxide particles degrade the performance of a mirror because each oxide particle acts as a separate scattering source. Therefore, lower oxide translates into improved optical performance. The solid optical blanks made from the atomized optical grade of beryllium powder, O-30, have less than 0.35% beryllium oxide. Recall that I-70A and S-200F have 0.7% and 1% oxide respectively. Atomized powder is therefore an excellent choice for a mirror material[7].

Once the powder is made, it is compacted into a solid. Historically, powder was vacuum hot pressed into solid cylinders ranging from roughly 8 to 72 inches in diameter. Aerospace components requiring the highest level of stiffness to density were made from these cylinders. For example, the Space Shuttle umbilical doors were machined from large-diameter hot pressed cylinders, as were the window frame, brakes, and navigation base. The Advanced Inertial Reference Spheres (AIRS) of the Peacekeeper ICBM (intercontinental ballistic missile) were likewise machined from vacuum hot pressed beryllium. This hot pressing method leaves less than 0.5% voids, but does not totally eliminate them. For the JWST Telescope, all voids had to be eliminated, leading to use of hot isostatic pressing (HIP)[2].

Although HIP was developed by Battelle at its Columbus, Ohio, headquarters in the 1940s for cladding nuclear reactor fuel rods, its uses have greatly expanded to include casting densification, powder consolidation, and diffusion bonding. In HIP, powder is poured into a metal can that is evacuated and sealed. This is then placed into the HIP unit, which is pressurized with argon and heated. A typical pressure compressing the can and its contents is 15,000 to 30,000 psi and temperatures to 2000°C can be applied. The solid that emerges after the can is removed is completely free of voids. Another advantage of HIP is that the pressure is applied in all directions so it maintains the non-directionality of the final product better than uniaxial vacuum hot pressing. The microstructure of consolidated O-30 is shown in Fig. 8.

Technologists who worked on mirrors in the 1960s reported that beryllium atomization trials were unsuccessful. In particular, very high oxide levels resulted. Much effort was spent making certain that the new atomizer was airtight to control the oxygen level. HIP'ing beryllium powder had also been tried, but failed because voids were formed when

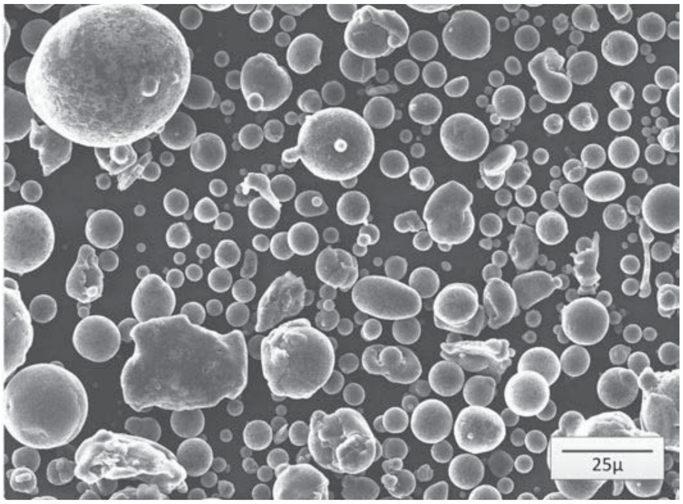


Fig. 7 — SEM photomicrograph of inert gas atomized O-30 grade Be powder.

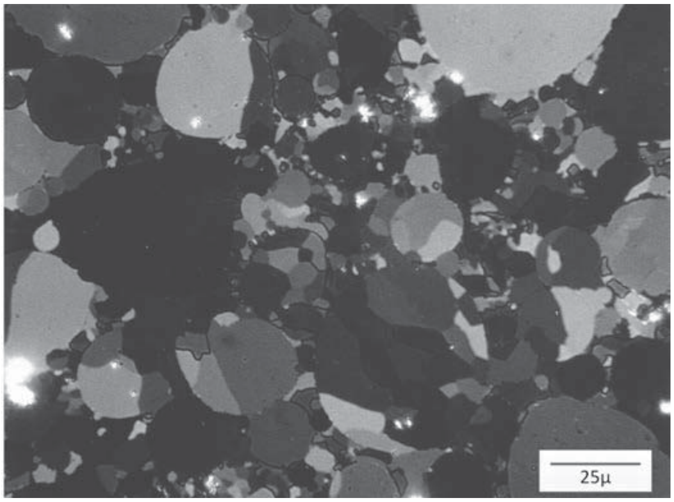
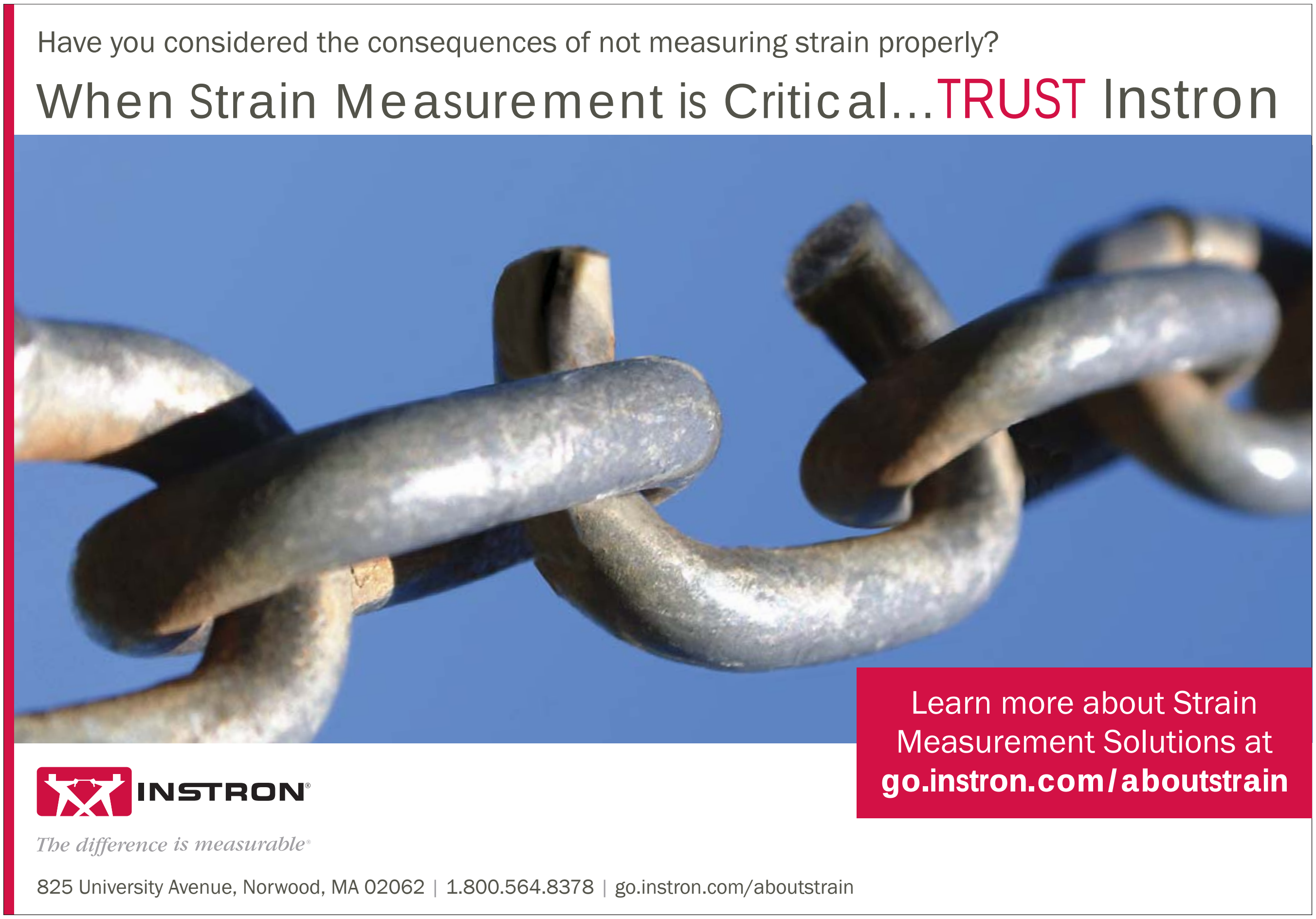


Fig. 8 — Polarized light photomicrograph of O-30 H grade beryllium consolidated by HIP from inert gas atomized beryllium powder. Spherical prior particle boundaries containing multiple grains per particle are evident.



the solid mirror blanks were heat treated, which was referred to as "HIP disease." When O-30 was developed, it was recognized that water molecules entrained on the surface of powder particles were the cause of HIP disease, now called "thermally induced porosity." The process was further developed to eliminate the water molecules and therefore the disease.

The James Webb Space Telescope is scheduled for launch in 2018. It is expected to provide as dramatic an improvement over the Hubble as the Hubble did over previous observatories. The evolution of beryllium as the optical material will provide a substantial contribution to the success of the new telescope.~**AM&P**

For more information: James Marder is vice president of materials and process development, Thermacore Inc., 440 Jonathan Willey Rd., Belle Vernon, PA 15012, 724.379.1490, j.m.marder@thermacore.com, www.thermacore.com.

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References

1. W.P. Barnes, Jr., Considerations in the Use of Beryllium for Mirrors, *Applied Optics*, Vol 5, No. 12, p 1883, 1966.
2. E.W. Gossett, Jr., et al., Evaluation of Hot Isostatic Beryllium for Low Scatter Cryogenic Optics, *Proc. SPIE*, *Space Optical Materials and Space Qualification of Optics,* Vol 50, p 1118, 1989.
3. Gunter's Space Page, GOES 4, 5, 6, G, 7, http://space.skyrocket.de/doc_sdat/goes-d.htm.
4. J.C. Campbell, Metal Optics for a Visible Infrared Spin-Scan Radiometer, *Proc. SPIE*, *Design, Manufacture and Application of Metal Optics,* Vol 97, p 0065, 1976.
5. J.L. Fanson, et al., The Space Infrared Telescope Facility, *Proc. SPIE*, *Space Telescopes and Instruments V*, p 3356, 1998.
6. Explore James Webb Space Telescope, NASA website, www.jwst.nasa.gov.
7. D. Hashiguchi and J.M. Marder, Spherical Beryllium Powder, WL-TR-91-8017, Wright Laboratory, Air Force Systems Command, Wright Patterson AFB, 1991.
8. D.A. Gildner and J.M. Marder, Creation of Aspheric Beryllium Optical Surfaces Directly in the Hot Isostatic Pressing Consolidation Process, *Proc. SPIE, Reflective and Refractive Optical Materials for Earth and Space Applications,* p 1485, 1991.