

Beryllium: Properties and Applications

Laura Coyle

I. Introduction

Beryllium is a lightweight, stiff, high thermal conductivity material which is useful in many opto-mechanical applications. Much work has been done to achieve high purity, isotropic beryllium blanks and foils. It can be challenging to work with as it can be very brittle, difficult to machine and is toxic to humans. However, in some situations, especially cryogenics, the benefits far outweigh the logistical difficulties. It has structural applications in particle physics experiments and optical applications in space telescopes, among others.

II. General Properties

Beryllium has an atomic number of 4 and is an alkaline earth metal (Group 2 of the periodic table). It is a silver metallic solid or foil with a hexagonal crystal structure. It is only naturally found in combination with other elements in minerals. Table 1 lists important material properties for pure beryllium. Beryllium is available in a few common grades, including O-30, an optical grade beryllium, and S-200, commonly used as a structural material.



Figure 1. Beryllium – raw and machined

Table 1. Material Properties for beryllium

Density	1.85 g/cm ³
Young's Modulus	276-303 GPa
Yield Strength	207 MPa (O-30) 241-296 MPa (I-200)
Thermal Conductivity	220 W/m K
Coefficient of Thermal Expansion	11.5 ppm/°C
Poisson's Ratio	0.08
Hardness	80-100 (Rockwell)
Melting Point	1287 °C

Beryllium has a number of properties which make it a widely useful material. It is resistant to corrosion as it forms a thin layer of beryllium oxide on its surface which protects the material below. Beryllium has a very high specific stiffness, calculated by the ratio of Young's Modulus to material density. It has one of the highest melting points of any light metal and has a very high thermal conductivity (30% larger than aluminum), making it a useful material for heat dissipation. The high thermal conductivity in combination with a low CTE make beryllium dimensionally stable under a large range of thermal loading. Beryllium has mechanical damping capabilities and high resonant frequency making it a useful structural material as well. Its yield strength of about 250 MPa is comparable to aluminum's 240 MPa though less than stainless steel's 1.28 GPa. The stress-strain curve for Beryllium is shown in Figure 2.

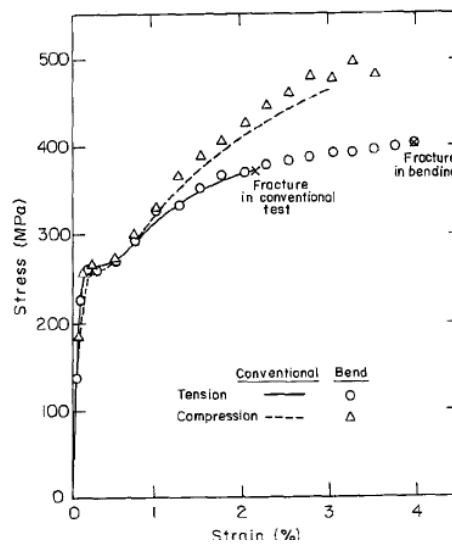


Figure 2. Uniaxial stress-strain curve for Beryllium under conventional and bending tests

Beryllium has a high x-ray transparency and is often used to make filters and windows for radiation and particle physics experiments.

III. Manufacturing Beryllium Optics

In order to achieve the desired mechanical properties, beryllium components are produced using powered metallurgical techniques. To lower the cost of fabrication, blanks are produced with near-net shapes using a fabrication process called Hot Isostatic Pressing. This process has been in use since the 1980's and can produce lightweighted mirrors with good dimensional stability, which are desirable for space applications. This method is also preferred since beryllium is difficult to machine by traditional techniques.

In traditional uniaxial die pressing, a mechanical punch is used to compress powdered metal to its final density. The simplest geometry is a cylinder, with other small variations possible. The limitation on shape is often the ability to remove the part from the die. Undercuts, right angle holes, and threads cannot be directly formed using this process. In addition to the shape restrictions, friction between the powder and the die walls as the powder is compressed results in non-uniformities. It also prevents 100% theoretical density from being achieved.

In Hot Isostatic Pressing (HIP) pressure is applied to the powder hydrostatically using a hot gas rather than mechanically. Complex mirror shapes are produced using mandrels or molds, often made from copper. The beryllium powder is packed inside the mold and enclosed in a steel can. The powder is outgassed to remove oxygen, nitrogen, and water vapor that can interfere with the diffusion process, then the container is sealed. The beryllium particles are consolidated into a solid using diffusion bonding between the grains at high temperature and pressure. The HIP press can achieve temperatures of 2000 °C and pressures of 1000-2000 atmospheres. After the beryllium sets, nitric acid is leached into the container and the mold is dissolved, leaving only the beryllium mirror. Due to destruction of molds and the hazard disposal of the nitric acid, this process is most suited to custom optics rather than mass production. Custom mandrels can create very complex shapes including light weighting ribs and even mounting interfaces which can reduce the weight and cost of the final assembly. Mandrels can be reused if they are coated and can be easily separated from the beryllium part without the use of acid, which can decrease the cost of the mirrors by as much as 50%. However, this process cannot be used on mirrors with closed backs or integrated cooling channels which require destruction of the mold.

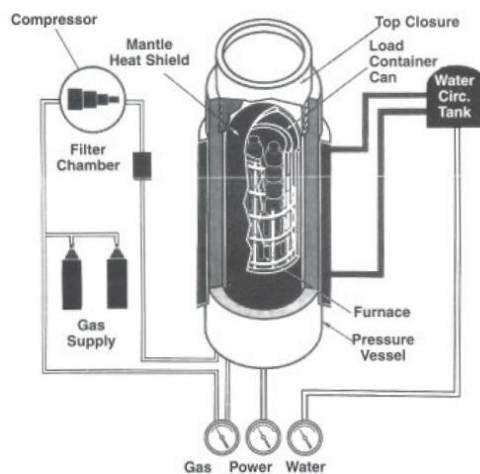


Figure 3. Schematic of HIP system – cylindrical canister for small parts



Figure 4. HIP can for hexagonal blank

HIP improves the dimensional stability of beryllium by making the material more isotropic in bulk, evening out the CTE and Young's modulus in different areas. The hexagonal crystal structure of ground beryllium is fundamentally anisotropic, so beryllium must be processed such that it is compacted in all directions and the grains are less likely to align. Recent advances in manufacturing powdered beryllium have yielded spherical particles (like grade O-30) with much higher isotropy so other techniques like Vacuum Hot Pressing (VHP) can be used to produce high quality blanks. However, HIPed beryllium is still preferred for large optics operating over large temperature ranges.

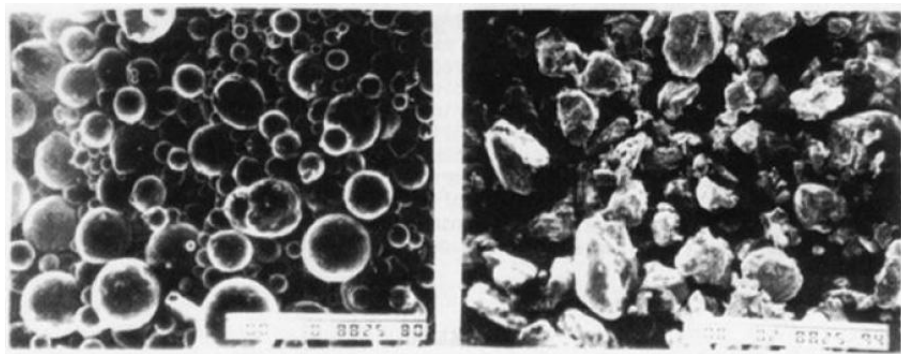


Figure 5. SEM image showing spherical and ground powders

HIPing can improve the yield and microyield strengths of beryllium by as much as 50% over VHPed materials. The powder can be consolidated at lower temperatures which results in smaller grain size and increased strength. This is extremely important for making large optics since the sections can be thinner without compromising strength. Thinner sections also reduce stress from thermal expansion and inertial loading.



Figure 6. Beryllium blank after HIP

IV. Polishing Beryllium Optics

When optics, especially mirrors, are made from beryllium, the optical surfaces must be polished for maximum performance. As many beryllium mirrors are cast at their near-net shape, little grinding if any is needed before the polishing stage. When beryllium is polished, a thin layer of beryllium oxide forms on the surface. Beryllium oxide is harder than most of the overcoats used on conventional glass mirrors and is easily cleaned with acetone.

Since beryllium optics are made from a compressed powder, there is a limitation to the finish that can be achieved by direct polishing. Hardric Laboratories has polished bare 25 x 12.5 cm retroreflector panels to 20 angstrom surface roughness and a surface flatness of a $\lambda/20$ P-V. In smaller mirrors, the finish can be improved.

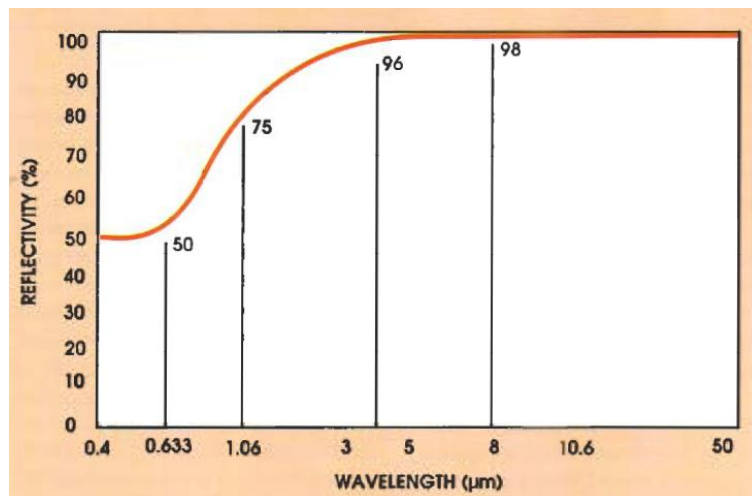


Figure 7. Reflectivity for a bare beryllium mirror (grade S-200)

Bare beryllium achieves high reflectivity in the infrared, but only 50% in the visible, as shown in figure 7. Coatings are used to improve the performance of beryllium optics at visible and UV wavelengths. They are vacuum deposited onto the surface of the mirror and standard choices include aluminum, silver, gold, and enhanced versions of all three. Special coatings for high power lasers have also been developed.

V. Cost of Beryllium optics

Beryllium optics are often used for custom applications, so it can be difficult to determine exact prices. However, there are general guidelines to estimate the cost of a part. It is straightforward to say that cost increases with size, complexity of the shape, and improved surface finish. Small beryllium mirrors (~25 cm) are cost competitive with other metal mirrors, such as aluminum.

Beryllium itself is an expensive material, yet it is not often a major contributor for the final cost of the mirror. The grade chosen and beryllium content can affect the raw material cost by up to 50%. Aluminum-Beryllium is a lower cost alternative but the mixture negatively impacts many of the desired properties of pure beryllium. For fabrication of the mirrors themselves, it is often more cost effective to use near-net shaped HIP rather than machining a blank, especially for larger optics.

Tolerances on the final optical surface are the significant cost driver. For most practical applications, a surface roughness RMS of 20 angstroms can be achieved for reasonable cost. It is possible to achieve 10 angstroms RMS or better at increased cost. Special coatings for operation in the visible and UV also increase the price of an optic.

VI. Applications

Due to its low absorption in the X-ray regime, one of the oldest and most common uses of beryllium is in radiation windows for x-ray tubes. This application requires very high purity and cleanliness to avoid imaging artifacts. The low absorption of beryllium also minimizes heating effects in the apparatus.



Figure 8. Beryllium window between a vacuum chamber and an x-ray microscope

Because of its low atomic number, it is also transparent to energetic particles. The beam pipes in many super colliders, including all four experiments in the Large Hadron Collider at CERN, are made from beryllium. Its stiffness can withstand high vacuum, its low CTE can withstand very low temperatures, and its diamagnetism does not interfere with the powerful magnets used to steer and focus the particle beams.



Figure 9. Beryllium beam pipe in supercollider

Its stability at cryogenic temperatures makes it a good choice for space applications. Beryllium was chosen over ULC and SiC as the substrate for the James Webb Space Telescope's primary mirror during the Advanced Mirror Systems Demonstrator Program (AMSD).

Brush Wellman fabricated a 1.4 meter hexagonal mirror blank for AMSD to determine if the beryllium mirror could meet JWST's performance requirements. The 100% dense blank was HIP'ed from O-30 grade beryllium then machined to the required 90% lightweighting required by the program. The ribs averaged 0.5 mm thick and the face plate was 1.7 mm thick. A uniform CTE of 11.4 ppm/°C was measured in the three orthogonal directions. The polishing was contracted to Ball Aerospace & Technologies Corporation, and the final shape was an off-axis parabola with a radius of curvature of 10 meters. The surface figure error was held to less than 50 nm rms and a surface roughness of 40 angstroms at ambient temperature. It was also shown the the figure changed by about 75 nm rms as it underwent a thermal cycle from 300 to 30 K, the operating temperature of the telescope. As such, the test mirror met all the JWST requirements and was approved for the primary, secondary, and tertiary mirrors.



Figure 10. Assembly of JWST primary mirror segments at Marshall Space Flight Center



Figure 11. Concept drawing for James Webb Space Telescope showing primary and secondary mirrors

VII. References

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