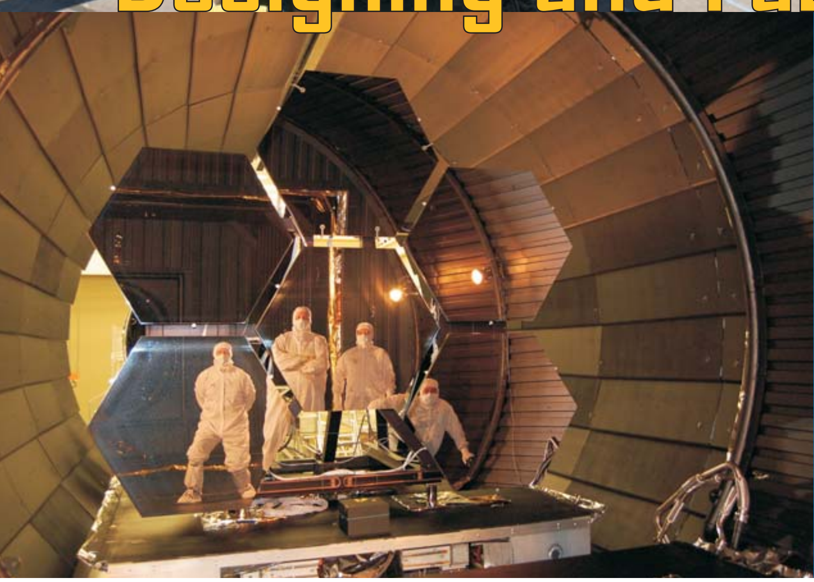
MATERION

Designing and Fabricating Beryllium

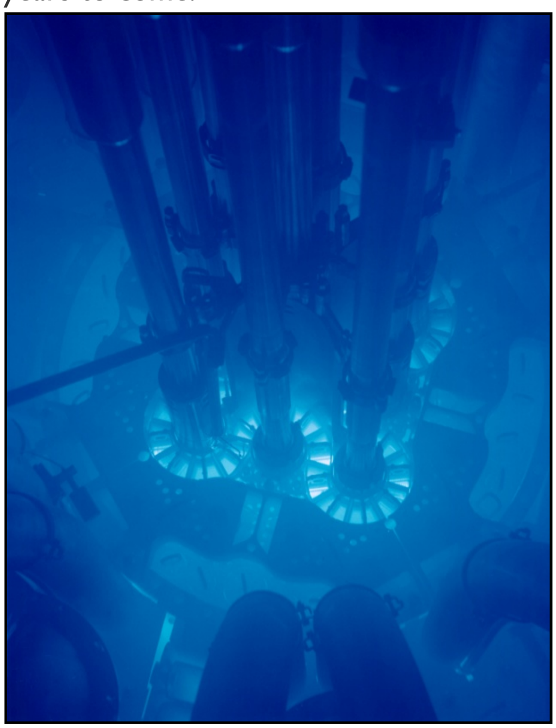


BERYLLIUM & COMPOSITES

Engineers will find beryllium to be one of the lightest metals known with a unique combination of properties not found in any other material. Strength-to-weight and stiffness-to-weight ratios of beryllium are outstanding. Its high specific heat and excellent thermal conductivity allows the material to sustain crucial properties at both elevated and cryogenic temperatures. Materion Beryllium & Composites pioneered the development of beryllium and its derivative materials are recognized throughout the world as the leader in this technology.

Today, beryllium is used in a wide variety of leading edge applications; including military aircraft, aerospace, medical, and commercial markets. Materion Natural Resources Inc. mines its own ore (bertrandite) and processes it at our Delta, Utah mill. Our bertrandite reserves assure a reliable source of supply of beryllium beyond the 21st century. Beryllium hydroxide, an intermediate product, is converted within Materion Beryllium & Composites into beryllium metal and derivative products.

Substantial investments are being made at Materion Corporation's facilities to bring state-of-the-art equipment to refine and convert our ore into high quality beryllium products. A new state-of-the-art facility in Elmore, Ohio, has been built to supply the beryllium needed for many years to come.



Because of its excellent thermal and nuclear properties, beryllium is widely used in nuclear test reactors like the Advanced Test Reactor at INL. Photo Courtesy of Idaho National Lab.

As the world's primary manufacturer of beryllium metal, we are constantly working towards improvement in quality and dependability of our materials. We are committed to working with our customers in supporting and developing designs that are cost efficient and meet the critical requirements of the applications.

Our company developed the methods of making high quality beryllium powder and subsequent consolidation by Vacuum Hot Pressing (VHP), extrusion, Hot Isostatic Pressing (HIP), and Cold Isostatic Pressing (CIP). The HIP and CIP methods of consolidation produce near net shape parts, thereby, reducing the amount of machining required to manufacture a finished part.

Materion Corporation's Beryllium & Composites Elmore facility fabricated primary mirror segments for the James Webb Space Telescope, successor to the Hubble Telescope and the largest telescope ever launched into space. Optical grade beryllium was selected for its ability to operate at cryogenic temperatures, around -268°C.

There are various grades (i.e. material specifications) available in the various methods of consolidation. Physical and mechanical properties are dependent on the grade and consolidation method of choice. Materion Corporation's Beryllium & Composites team of engineers and skilled personnel are available for support to our customers. Materion Beryllium & Composites provides support early on in the design process to maximize the yield of material used to minimize costs.

"It should be noted that JWST would likely not be possible without the development of O-30 beryllium," Based on research performed while at the University of Arizona, Dave Baiocchi, RAND Corporation and H. Philip Stahl, NASA Marshall Space Flight Center."

Based on research performed at the University of Arizona, Dave Baiocchi, RAND Corporation and H. Philip Stahl, NASA Marshall Space Flight Center said, "It should be noted that JWST would likely not be possible without the development of O-30 beryllium. Materion Beryllium & Composites, along, with the U.S. Air Force, started developing optical grade beryllium 23 years before JWST's currently schedule launch. "Enabling Future Space Telescopes: Mirror Technology Review and Development Roadmap.

Beryllium & Composites is committed to on-time delivery of defect-free metallic beryllium and beryllium oxide powder products and are

also strongly committed to productivity improvement and cost control programs that will make our products even more competitive with conventional engineering materials. Different grades of beryllium include hot-pressed and hot-isostatically pressed beryllium, each engineered for outstanding performance in a specific range of structural, instrument, optical or nuclear applications. Beryllium can be machined into shapes specified by our customers. We also produce beryllium plate, sheet, foil, and deep-drawn blanks in-house.

PHYSICAL PROPERTIES

Low Density

Beryllium is one of the lightest structural metals known. Its density of 0.067 lbs/in^3 (1.85 g/cm^3) is two-thirds that of aluminum. Beryllium's light weight, coupled with its high stiffness and strength, make it ideal for applications requiring a favorable weight-to-stiffness ratio.

Atomic Number	4	Reflectivity: Optical reflectivity 50%, ultraviolet reflectivity 55%, infrared (10.6 µm) reflectivity 98%.
Atomic Weight	9.01	
Latent Heat of Fusion	488 BTU/Lb (1133 Kj/kg)	
Specific Gravity	1.85 g/cm^3	Sonic Velocity: Velocity of sound in beryllium is 41,300 ft/second (12,588m/sec) 2.5 times that of steel.
Melting Point	2345°F (1285°C)	
Electrical Conductivity	40.7% of IACS (0.24 mhos/cm)	X-ray Transparency: Due to its low atomic number, beryllium transmits x-rays 17 times better than an equivalent thickness of aluminum. Beryllium x-ray windows allow the most efficient use of generation radiation in medical and analytical applications.
Magnetic Characteristics	Beryllium is diamagnetic, -1.0 x 10^{-6} cgs units	

Thermal Properties

Beryllium has a specific heat at room temperature of 0.046 BTU/lb°F (1925j/Kg·K), the highest heat capacity of all metals. This means for any given weight and temperature change, beryllium has the ability to absorb more heat than any other metal. This superiority is maintained up to its melting point of 2352°F (1289°C). Beryllium also has the best heat dissipation characteristics among metals on an equal basis with a thermal conductivity at room temperature of 125 BTU-ft/ft^2 hr °F 216 W/m.K. The material's coefficient of thermal expansion is 6.4 x 10^{-6}/°F (11.5x10^{-6}/C). This value is comparable to those for stainless steel, nickel alloys and cobalt alloys. Thermal expansion as a function of temperature for two grades of beryllium across the temperature range of 100K to 450K. The thermal diffusivity of beryllium, 2.28 ft^2/h (0.21 mz/h), assures rapid temperature equalization which tends to eliminate or greatly reduce distortion which might otherwise occur as a result of thermal gradients.

THERMAL PROPERTIES COMPARISON AT ROOM TEMPERATURE

	Specific Heat		Melting Point		Thermal Conductivity		Coefficient of Linear Expansion	
Metal	BTU / Lb °F	J / Kg (K)	°F	(°C)	BTU-ft / Hr ft^2 °F	W / m ·K	[x10^{-6}/in/in/°F]	(x10^{-6}/cm/cm/°C)
Beryllium	0.46	(1925)	2345	(1285)	125	(216)	6.3	(11.4)
Aluminum	0.22	(920)	1220	(660)	128	(221)	13.1	(23.6)
Steel	0.12	(502)	2800	(1538)	27	(47)	8.3	(14.9)
Copper	0.09	(337)	1980	(1082)	226	(391)	9.8	(17.6)
2124 T6-30% v/o SiC	0.19	(795)	1220	(660)	72	(125)	7.5	(13.5)
2024 T6-25% V/O F-9	0.20	(837)	1220	(660)	89	(154)	9.1	(16.4)

Figure 1 - RELATIVE DENSITY OF LIGHT WEIGHT MATERIALS

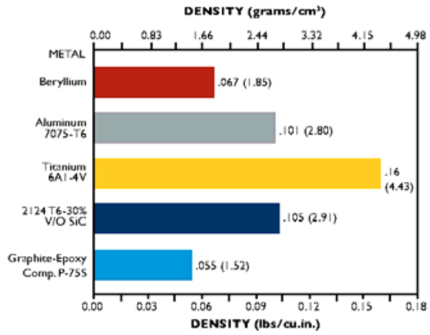


Figure 2 - WEIGHT OF MATERIALS FOR EQUAL HEAT ABSORPTION

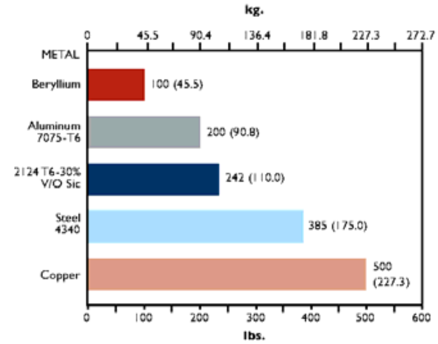


Figure 3 - SPECIFIC HEAT COMPARISON

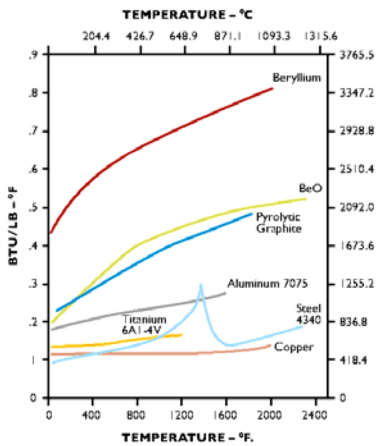
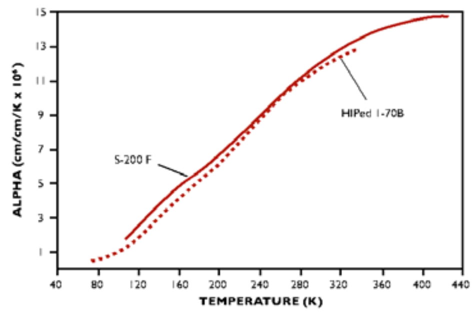


Figure 4 - COEFFICIENT of THERMAL EXPANSION vs TEMPERATURE



Nuclear Properties

The nuclear properties of beryllium, combined with its low density, are attractive characteristics for neutron reflectors and moderators in the design of reactors. Beryllium's high scattering cross-section makes it effective in slowing neutron speed to a level required for efficient reactor operations. This ability classifies beryllium as one of the few good solid moderators available. Its major application, however, is as a reflector. In this capacity, beryllium acts to scatter leaked neutrons back into the reactor core. Neutrons are conserved because of beryllium's low thermal neutron capture cross-section. Furthermore, beryllium acts to increase neutron flux density through the Be^9 (n, 2n) Be^8 reaction.

Mechanical Properties

Strength

The mechanical properties of beryllium vary with the production method used. Ultimate tensile strengths range from 50 Ksi (345 MPa) for hot-pressed block to 75 Ksi (517 MPa) for HIP block. At elevated temperatures up to 1500°F (816°C), beryllium retains useful strength, while other structural metals such as aluminum and magnesium have exceeded their melting point. The specific strength of beryllium (tensile strength/density) ranges from 11.5 to 10.5 in (2.92 x 10^4m) for cross-rolled sheet, to 7.0 x 10^5 in. (1.98 x 10^4m) for hot-pressed block. At both room and elevated temperatures, the specific strength for wrought beryllium is greater than other structural metals.

Figure 5 - SPECIFIC STRENGTH COMPARISION

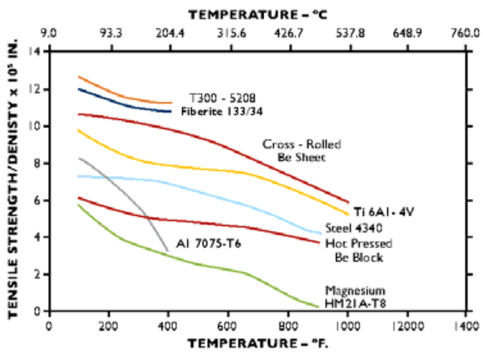


Figure 6 - YOUNG'S MODULUS

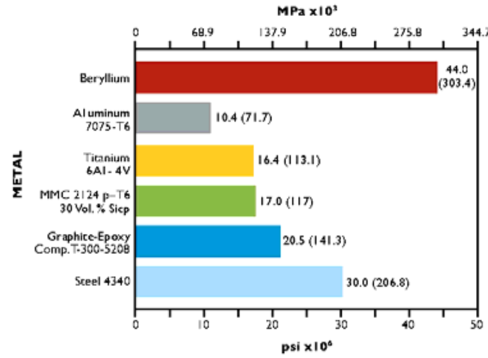


Figure 7 - SPECIFIC MODULUS COMPARISION

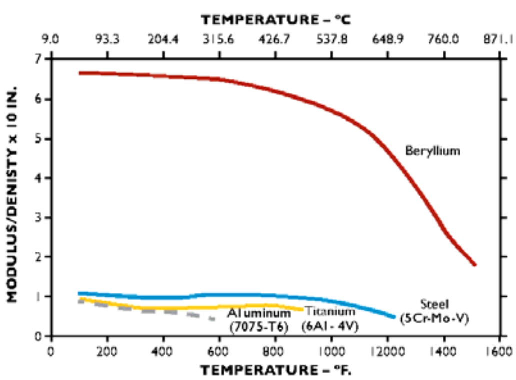
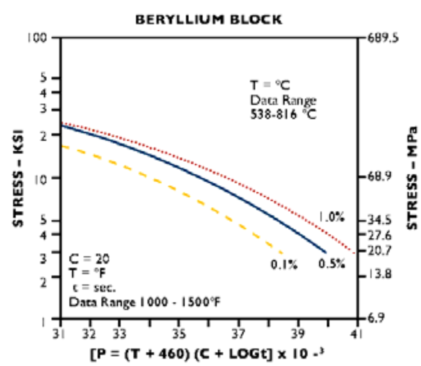


Figure 8 - LARSON-MILLER PARAMETER



Rigidity

One of beryllium's most outstanding features is its high elastic modulus and the resultant stiffness-to-density ratio. Compared to other metals on this basis, beryllium is superior by a factor of seven from room temperature to 1200°F (649°C). Beryllium has a modulus of elasticity of 44.0 x 10^6 PSI (2.03 x 105) MPa, four times that of aluminum, 2-1/2 times that of titanium, twice that of SiC reinforced aluminum and various grades of graphite epoxy.

For lightweight applications requiring a high specific modulus of elasticity, beryllium is unsurpassed.

Creep

Through the use of the Larson-Miller parameter, the time and temperature to produce 0.1%, 0.5% and 1.0% plastic creep at any given stress can be obtained. Creep properties should be given serious consideration if high operational stresses are to be maintained at temperatures above 1000°F (538°C).

Figure 9 - LARSON-MILLER PARAMETER

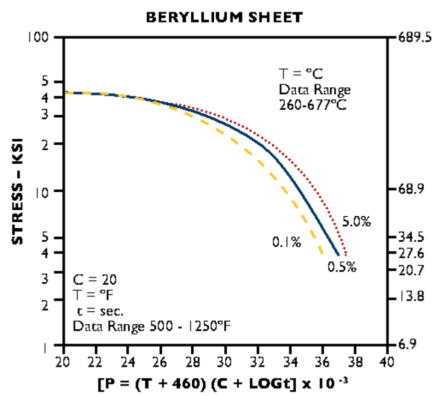


Figure 10 - MICROCREEP vs TIME for the 6445-lb/in² LOADING

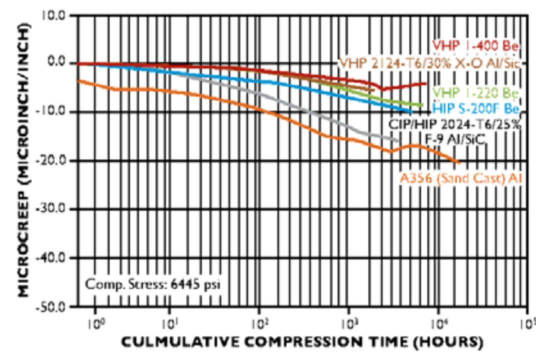


Figure 11 - NOTCHED STRENGTH vs TEMPARTURE for BE BLOCK

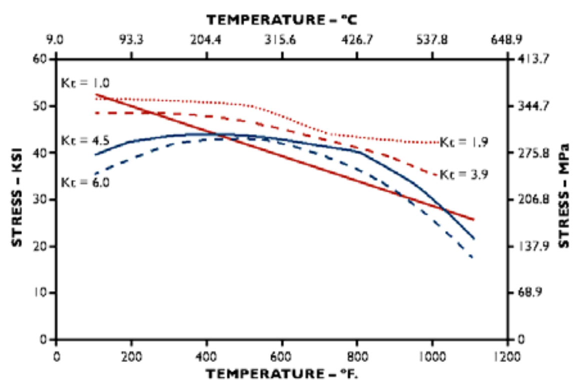
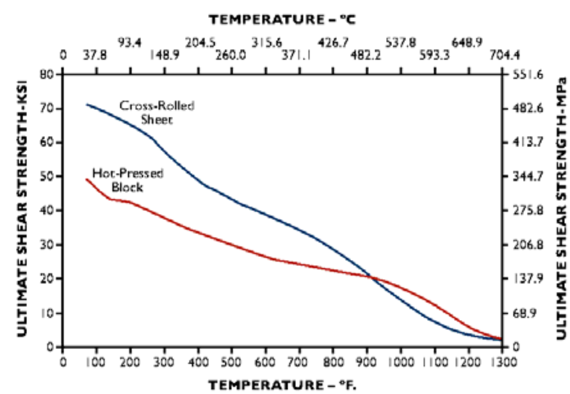


Figure 12 - ULTIMATE SHEAR STRENGTH OF BERYLLIUM



Notched Properties

Notch strengthening occurs in beryllium at temperatures around 400°F (204.4°C) over a wide range of stress concentration factors. In fact, S-200F, with a notched ratio of 1.21 at 400°C (204.4°C), has a notched tensile strength that is greater than the un-notched strength. Also at room temperature, the notched strength ratio of S-200F is approximately one (1.0) and, therefore, does not exhibit any notch sensitivity.

Shear Strength

The shear strength characteristics of beryllium in both hot-pressed and sheet form are unusual. The relationship between shear strength and tensile strength is greater than most materials at low temperatures, but at temperatures greater than 900°F (482°C, the ratio is lower than expected) these tests are conducted using tear-type specimens. The shear modulus for beryllium is typically 19.6 $\pm$ .07 Msi (137 GPa) for both the longitudinal and transverse directions. The average shear rupture modulus for S-200F is 44.8 $\pm$ 1.2 Ksi (309 MPa).

Figure 13 - AXIAL S-N CURVE FOR HOT-PRESSED Be BLOCK

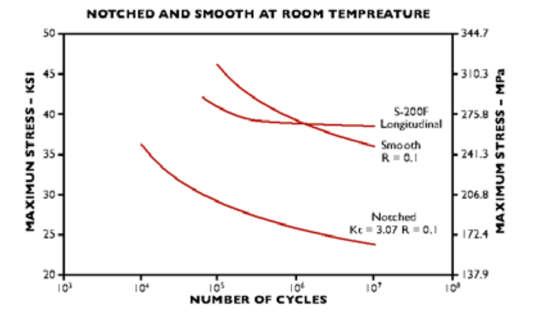


Figure 14 - AXIAL FATIGUE STRENGTH COMPRISON

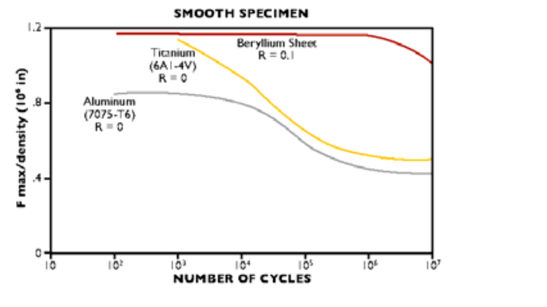


Figure 15 - FATIGUE STRENGTH TO DENSITY RATIO OF NOTCHED MATERIAL

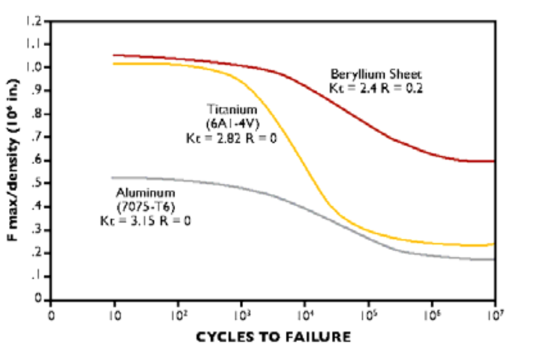
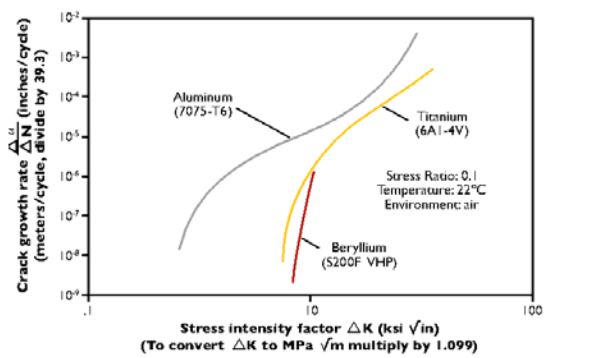


Figure 16 - FATIGUE CRACK GROWTH RATE



Comprehensive Yield Strength

The comprehensive yield strength (0.2% offset) at room temperature of beryllium is typically 10% higher than the tensile yield strength. At 400°F (204.4°C), the comprehensive yield strength is equal to the tensile yield strength. This is a unique property of beryllium and is demonstrated by S-200F where the room temperature tensile yield strength is 37 Ksi (255 MPa) and the compressive yield is 41 Ksi (283 MPa).

Fracture Toughness

A growing interest in beryllium as a structural material has been accompanied by an increasing interest in the toughness of this material.

When the more common vacuum hot-pressed structural grades of beryllium, S-65 and S-200F, are tested, a K_{IC} value of 9-12 Ksi $in^{1/2}$ (10.65-12.3 MPa-$m^{1/2}$) at room temperature can be expected.

Material Selection Guide

Properties of Milled Products

Beryllium Powder

The production of beryllium powder begins at Materion Beryllium & Composites with the extraction of the metal from the ore through a series of chemical operations. Primary beryllium is produced as "pebble" by the magnesium reduction of anhydrous beryllium fluoride.

The pebbles are vacuum remitted to remove reduction slag and cast into ingots. In the cast form, the metal is very difficult to machine and mechanical properties are poor. For these reasons, virtually all beryllium enters service as a powder metallurgy-derived product. Powder is prepared by chipping the ingots and mechanically grinding the chips to the appropriate particle size distribution for consolidation into essentially full density billets by powder metallurgy techniques. The mechanical grinding systems used to manufacture beryllium powder of a given particle size distribution has been shown to have an effect upon the characteristics of the fully dense body prepared with the powder. This is most notable in the level of minimum tensile elongation which can be generated in any direction at room temperature. This is true because of the anisotropy of the basic beryllium crystal with room temperature slip capability limited to a single direction coupled with basal plane cleavage as a major fracture mode. Most grinding procedures for beryllium result in a powder with a high fraction of particles with a flat plate configuration which tends to orient in powder handling and consolidation operations.

Impact grinding is a procedure for grinding chips to powder involving the impact of beryllium chip propelled by a high pressure gas against a beryllium target. The consolidated beryllium manufactured from this type of powder may exhibit among other characteristics, high elongation so that a minimum of more than 1% at room temperature may be guaranteed.

Grades of Vacuum Hot-Pressed Beryllium

	S-65	S-200F
Chemical Composition		
Be, Min%	99.0	98.5
BeO, max%	1.0	1.5
Al, max ppm	600	1000
C, max ppm	1000	1500
Fe, max ppm	800	1300
Mg, max ppm	600	800
Si, max ppm	600	600
Other, each max ppm	400	400
	BeO specified is minimum in this instance	
Tensile Properties		
Ftu, psi min	42,000	47,000
(MPa min)	(290)	(324)
Fty, psi min	30,000	35,000
(MPa min) (0.2% offset)	(207)	(241)
Elongation, % min	3%	2%
Microyield, psi min (MPa min)	--	4,000
		(27)
		Typical
Standard Sizes*		
Inches	32 dia x 30 lg	32 dia x 45 lg
(cm)	(81x76)	(81x114)
*Pressing (billet) sizes can range from 7" (18cm) and 6" (15cm) to 66" (168cm) in length, depending upon grade and chemistry.		

Hot Pressed Block

The most common form of beryllium is vacuum hot-pressed block. The hot pressing operation, consisting of the application of heat and pressure to beryllium powder contained in a suitable die, results in a uniform, fully dense, fine-grained beryllium which has been thoroughly out-gassed by the use of vacuum during the operation.

Through variation in chemical composition, particle size distribution, and temperature it is possible to produce a variety of beryllium grades with differing characteristics for many divergent applications.

Structural Grades

The specification numbers which identify the structural grades of beryllium vacuum hot-pressed block are S-65 and S-200F.

S-65 is a premium material which is guaranteed to exhibit a minimum of 3% tensile elongation at room temperature in a test direction. This stain capacity is obtained through the use of impact grinding during powder manufacture and by holding the micro-alloying elements, iron and aluminum, to the proper ratios. S-65 is utilized in the winder frames, umbilical doors and navigational base of the space shuttles.

S-65 is lower in oxide content at 1.0% maximum than other grades. While it has a higher guaranteed minimum room tensile elongation, it is lower in strength than our standard purity structural grade, S-200F. Grade S-200F is most frequently used for parts machined from hot-pressed block. Typical data for this material is given in accompanying charts. S-200F is a versatile material, and it has become a successful entity in a wide variety of applications such as inertial guidance systems, missile interstages, optical substrates, spacecraft structures and small rocket nozzles.

Nuclear Applications

For situations where weight or volume are a consideration, or a high neutron flux is desired, beryllium is very useful both as a moderator and reflector of neutrons. There is considerable interest in using beryllium as the neutron multiplier for solid blanket fusion reactor designs because it enhances the breeding process by providing additional neutrons. This increases the overall reactor efficiency and decreases the hazardous waste production several fold. In fact, beryllium is transparent to most forms of radiation and absorbs a smaller percentage than conventional materials. Beryllium maintains this advantage at elevated temperatures, thereby increasing its usefulness in fusion energy applications over the conventional graphite materials.

Materion Beryllium & Composites S-65 grade is the reference grade of beryllium for the International Thermonuclear Experimental Reactor (ITER), a fusion energy program, because it has superior resistance to cracking under high heat flux thermal cycling.

Instrument Grades

I-220H is instrument grade beryllium. It is a hot isostatically pressed beryllium that has been developed for applications where a high micro-yield strength i.e., the stress required to produce the first microinch of permanent strain (also known as the precision elastic limit or PEL) is required.

I-220H is manufactured using impact ground powder consolidated by an isostatic process (hot isostatic pressing or HIP).

Optical Grades

The specification numbers which identify optical grades of beryllium are I-70H, I-220H and S-200F. A hot isostatically pressed optical grade of I-70H was developed to provide an improvement over the standard grade for bare polished beryllium optics.

At 0.5 wt% maximum BeO, it is the lowest oxide beryllium which has even been marketed. It is manufacturing by controlling impact ground powder into an isostatic process (HIP), yielding a more isotropic material than any previously available optical grade of beryllium.

Grades S-200FH and I-220H beryllium, with guaranteed minimum micro-yield strengths, are used where the optical surface is a hard polished electroless nickel. Mirrors of this type are used in the visible and infrared wave lengths of light or any system that may require high resistance to plastic deformation due to severe G-loads or other working stresses.

Grades S-200F has been used successfully as an optical substrate and support bench in many astronomical telescopes, in fire control and FLIR systems, and in earth resources ad weather satellites. In most applications the optical surface of S-200F is a hard polished coating of electroless nickel, 24 micrometers to 150 micrometers thick. electroless nickel is harder than bare beryllium and more easily polished to a fine surface finish.

Wrought Forms of Beryllium

Wrought forms of beryllium are usually produced from vacuum hot- pressed blocks by conventional working techniques carries out either in warm or hot working temperature ranges. Wrought products exhibit improved strength and tensile elongation relative to the hot-pressed block on the direction of metal working, but lower properties particularly tensile elongation) transverse to the direction of working. This is due to the crystallographic orientation resulting from the working operations. Multi-directional working schedules are frequently used to alleviate this effect.

Beryllium Foil

By convention, beryllium foil is flat stock with a thickness of 0.020 inch (0.508 mm) or less. The foil is manufactured by rolling the material at elevated temperature in steel cans. As beryllium cannot be successfully rolled at room temperature, a cold-rolled surface is not available.

Because of its low absorption of radiation, beryllium foil is used in windows that transmit different wavelengths of radiation, both in detector and source applications.

Due to the nature of these applications, it is only available in two high purity grades, PF-60 and IF-1. IF-1 is the highest purity material and is available as a standard product in thicknesses between 0.0003 (0.008 mm) and 0.020 (0.508 mm) inches. PF-60 is available at gauges from 0.0003 (0.008 mm) and 0.125 (3.175 mm) inches.

Beryllium Plate and Sheet

By convention, beryllium rolled stock with a gauge between 0.020 (0.508 mm) and 0.250 (6.35 mm) inches is known as sheet, while thicker gauge material is referred to as a plate. The specification numbers are SR-200 for sheet and PR-200 for plate. The chemical composition of both of these products conforms to that previously listed for S-200F vacuum hot-pressed block. These rolled products are manufactured by warm rolling billets of vacuum hot-pressed block encased in steel. The crystallographic orientation and thus the properties of the sheet are balanced by cross rolling (i.e. rotation of the rolling direction 90°) during the reduction schedule.

Tensile Properties

The relationship of shear strength to tensile strength is higher than foremost materials in the lower part of the temperature range and is lower than expected at temperatures exceeding 900°F (482°C). The shear tests were conducted using a tear-type specimen. Compression stress-strain curves indicate that the compressive yield strength is at least equal to the tensile strength based on a limited number of tests.

When a structural member is designed to span a given distance or over a given area, weight saving is usually limited to reducing the thickness of the component. Resistance to deflection or buckling is then the primary consideration and rigidity, not strength, is often the controlling design parameter. Weight comparisons in typical design causes are helpful in evaluating the structural efficiency of beryllium sheet for this type of application.

It is shown that beryllium is superior to H-11 tool steel, beta III titanium, HM21A-58 magnesium and 15-7PH stainless steel. This superiority is maintained form the lowest intensities up to 50,000 pounds per inch width (8.95×10^{-5} kg/m width). An H-11 tool panel, for instance, with a buckling resistance equal to a beryllium panel, will weigh five times as much if the buckling load is less than 4,000 lb/in of width (7.16×10^{-4} kg/m width.) Beryllium sheet exhibits post-buckling behavior similar to that of other metals.

Near Net Shapes

Despite a combination of physical, mechanical and thermal properties that is unequalled by any other material, beryllium's use has been limited until recently by its availability in primarily one single form, vacuum hot-pressed block. This form involves high costs in both producing the material and in fabricating machined components, making beryllium a less cost effective engineering material.

Materion Beryllium & Composites has solved with problem with the development of production facilities to produces near net shapes. The use of hot isostatic pressing (HIP) and cold isostatic pressing (CIP), along with the conventional cold pressing technology, has brought beryllium within reach of a wider range of applications.

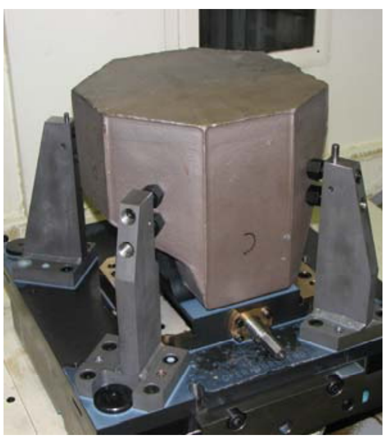
Hot isostatic Pressed Grades

The specification numbers which identify the grades that are available by hot isostatic pressing (HIP) are S-200FH, S-65H and I-220H.

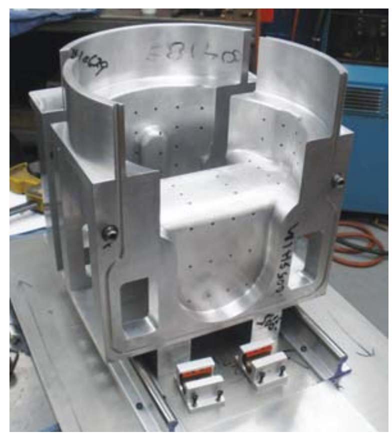
The S-200FH grade utilizes impact ground powder that is consolidated in a sheet metal can formed into the shape of the final part. In production, the can is degassed, sealed, and HIP'd, typically at 1000°C and 15,000 psi (103 MPa). This process conserves material (powder) and reduces the total finish machining time.

The S-200FH material is more isotropic, has higher density (99.8% of theoretical) and higher mechanical properties than the traditional vacuum hot-pressed material. It is useful for structural applications or those requiring low weight, high mechanical strength and a high fatigue endurance limit.

Grade I-220H is a high strength, moderate ductility material useful for structural, instrument and optical applications and those requiring high resistance to plastic deformation at low stress levels. It offers the best combination of high tensile strength, ductility and micro-yield strength of any grade of beryllium. Its microyield strength (amount of stress required to produce one micro inch of permanent strain) is typically 14 ksi.


Hot Isostatic Pressing


Cold Isostatic Pressing/Sintering


Seamless Iterative Process

S-65H has a lower impurity content which is more compatible with nuclear energy applications. It is recommended for applications which need high ductility at elevated temperatures.

Cold Isostatic Pressed Grades Specification number S-200FC identifies the only grade currently available by cold isostatic pressing (CIP).

This grade utilizes impact ground powders that are consolidated in a flexible rubber bag that approximates the final shape of the part. The powder is loaded into the bag and is degassed, sealed and CIP'ed at typically 60,000 psi (414 MPa) at room temperature. The part is then sintered to final density, 99+%, and, if required, may be hot formed to final shape. Typical properties of S-200FC beryllium are 46 ksi (319 MPa) UTS, 33 ksi (231 MPa), yield strength, and 3% elongation.

This process is useful for applications requiring lesser properties than those obtained by HIP. The tooling is reusable, making it advantageous for parts required in the hundreds. Typical applications for these grades are optics for fire control systems in tans and aircraft, as well as instrument applications such as inertial measurement units.

Seamless Iterative Process involves using net shaping technology and mold design iterations to minimize consumption by making rough blanks and finishing to designer's print lessens material costs by performing needed mold changes without compromising quality or schedules in the supply chain.

EXTRUSIONS

Extrusion is a conventional approach to the creation of thick-walled beryllium tubes and shapes. For specific supplications, extrusion provides consistent mechanical properties, dimensions and tolerances. Sections are made to dimensions that are well within commercial tolerances, and mechanical properties are superior to those of hot-pressed block in the direction of metal flow. Directional properties are produced in varying degrees as a function of crystallographic orientation.

The input billets for extrusions are usually machined from hot pressed block. The billets are jacketed in mild steel cans with shaped nose plugs and are extruded through a steel die in temperature ranges between 1650°F (899°C) and 1950°F (1066°C). The jackets are later removed by chemical means.

Rod, tubing and structural sections are the most common extruded shapes. Rod is available in sizes from 0.375" to (0.953 cm) to 5.75" (14.605 cm) diameter; tubing from 0.25" (635 mm) OD by 0.020" (0.015 mm) wall thickness to 4.0" (101.6 mm) wall thickness to 4.0" (101.6 mm) OD by 0.250" (635 mm) wall thickness.

Current applications of extruded shapes include boom arms for solar array panels, satellite truss supports, draw stock for wire, fuel element cladding and input for co-extrusions with dissimilar metals, to name a few. Mechanical properties and chemistry are tailored to the specific application. Beryllium extrusions have been typically made from the standard structural grade, S-200.

Materion Beryllium & Composites has a 3,000 ton (2,720 tonne) extrusion press at its Elmore, Ohio facility. That capability, plus those of the independent extruders, gives the design engineer a wide range of products from which to choose in solving his weight and stiffness.

ELECTRONIC GRADES

Cross-rolled SR-200 beryllium sheet is utilized as a combination heat sink and structural support in military electronic and avionic systems.

Constraining cores made from this material are attached to surface mounted (SMT) printed circuit boards to alleviate the mechanical stress on the solder joints of leadless and leaded ceramic chip carriers (LCCCs).The high thermal conductivity of beryllium is needed to dissipate the heat generated by the combination of large scale integration and high switching speeds.

The applications also requires a coefficient of thermal expansion (CTE) that is a good match to the alumina and polyimide glass substrates used in the system.

The major appeal of beryllium, however, is its low density. Since about seven pounds of payload or fuel can be added for every pound saved in the electronics systems of space and airborne vehicle, this is a matter of prime importance. Compared to other core plate materials, beryllium weight s about one-fifth as much as copper clad molybdenum and one-fourth as much as copper clad invar.

In addition to its light weight and desirable thermal properties, beryllium possesses high specific stiffness, high modulus of elasticity, and minimal interaction with magnetic fields.

Dimensional stability is an important attribute in constraining core plates because any tendency of the material to vibrate, flex or bend would be used as traumatic to the PCB as expansion/contraction. In terms of specific modulus, beryllium far outperforms the other candidates.

Beryllium not only dissipates heat, but readily absorbs it when necessary. The specific heat of beryllium is four times that of Cu Invar/Cu and six times that of Cu/Mo/Cu.

Fabrication Processes

Machining Beryllium

Generally, beryllium is easily machined to intricate forms, maintaining excellent surface finishes and close tolerances. Machining practices for beryllium parallel those of cast iron. Generally, tool design for cast iron will be applicable. Beryllium has a machinability factor of 55% using 1113 steel as 100%. It is a comparatively soft material (Rb 80-90) but abrasive, producing a discontinuous chip. Generally, Grade 2 general purpose carbide for cast iron and non-ferrous metals is selected as the cutting tool material. Selective specific grades in the class, such as Valentine VC-2 or equivalent, will give excellent results.

Care should be taken to secure clean, uncontaminated beryllium chips when removing substantial quantities of metal for economic reasons because of the high value of such clean chips. Contamination of chips results in the necessity of expensive reclamation procedures before such metal can be reintroduced into the manufacturing stream. For this reason, beryllium is machined dry whenever practical. Beryllium should not be machined until it is certain that the required limits on airborne beryllium will be observed. For detailed information on the requirements, consult Materion Corporation.

Beryllium is quite susceptible to surface damage as a result of machining operations. This damage may be seen by careful sectioning of machined material and observation of the disturbed surface layers, twins and, actually cracking, in severe cases. The damaged layer may be of varying depth and dependent upon the severity of machining operation, condition of tooling cutting edges, etc. Generally, with good practice, it does not exceed 0.002" (0.015 mm) in depth, but may reach 0.008"-0.010" (0.203-0.254 mm) in severe cases. The result of such damage, if not removed, is a dramatic decrease in the fracture strength and elongation characteristics of the metal. Yield strength may not be affected. Machine damage is controlled by adherence to accepted machining practice followed by etching to remove 0.002"-0.004" (0.051–0.102 mm) per side or by heat treatments designed to anneal out the disturbed layer and twins.

In summary, beryllium can be readily and successfully machined into intricate and very precise tolerance components using standard metal cutting and finishing techniques, with slight adaptations.

Drilling of Wrought Products

The key to successful drilling of wrought products involves control of the feed rate and selection of drill points which minimize tool pressure. Improper control of any factor in this process can result in laminar breakout or declamation within the product. To prevent the occurrence of such a problem, Materion Beryllium & Composites recommends the use of a drill that utilizes an automatic torque-sensing device which varies the speed and feed in order to maintain the cutting force within safe limits for both the drill and the beryllium. A straight two-fluted modified master drill is recommended and commercially available.

Sheet Cutting

Straight cuts are made in sheet by an abrasive sawing technique. This operation is performed wet using a resin-bonded, semi-friable aluminum oxide wheel rotating to give a surface speed of 7,000 to 9,000 fpm (35.6 to 45.7 meters per second.) Materion Corporation recommends using a wheel with an abrasive grain size of 80 grit and a relatively soft "L" bond grade.

Chemical Milling

Chemical milling techniques have been successfully used in the fabrication of parts made from beryllium block, sheet extrusion and forgings. Metal removal may be over the entire surface or it may be restricted to selected areas by masking.

The important steps in chemical milling operations are: clean, mask, scribe and strip mask before milling; milling and mask removal after milling. Material removal rates vary from 0.001" (0.025 mm) to 0.002" (0.051 mm) per minute. Tolerances on the final part are very close to those of the original and can be held at +/-0.005" (+-0.127 mm) for material removal of approximately 0.100" (2.54 mm). Tolerances can be expected to vary in complex configurations. Surface finishes are generally rougher after chemical milling and depend, to a great extent, on starting material surface quality.

Electrochemical Machining

Successful trepanning, contouring and drilling of complex beryllium parts have been carried out using electrochemical machining. This process is attractive because it produces a relatively small degree of surface damage. For beryllium, NaCl and $NaNO_3$ are two electrolytes which have been reported to work successfully.

Electric Discharge Machine (EDM)

EDM is very effective on beryllium and is used to machine intricate and irregular forms at good production rates. The process is generally carried out using brass or graphite cathode tools, which enhance metal removal rates, and dielectric oil that acts as a coolant.

This method is very practical for the machining of complex shapes of beryllium. Beryllium can also be cut successfully to precise tolerances by using a wire EDM machine.

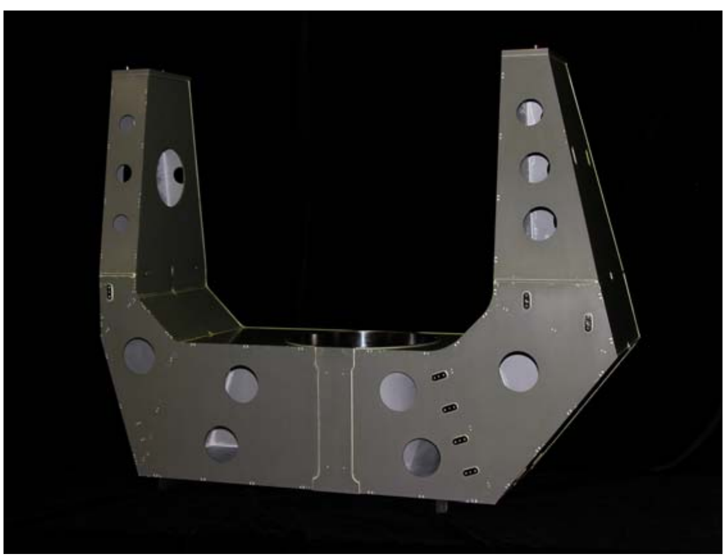
Joining

Adhesive Bonding

Adhesive bonding is a very desirable way to join beryllium to itself and other metals. The method of joining permits the utilization of the desirable mechanical and physical properties of the metal, while minimizing notch sensitivity.

Depending on the application of the part to be joined, specific adhesives ranging from the low temperature to the high temperature are available. Of all the steps involved in producing a good bonded joint, surface preparation is by far the most important.

Once the adherents have been acid-cleaned and neutralized, the adhesive is applied. The joint is then exposed to heat and pressure, characteristic for each specific adhesive, for about one hour. If, for any reason, the parts must be taken apart, the adhesive must be removed and the procedure repeated with a clean surface.



Brazing

Brazing is another means of joining beryllium to itself and other metals. There are several brazing techniques in use, the choice depending on the specific application of the beryllium part. Typically, a silver base, zinc base or aluminum base alloy is used providing the designer varied strength and thermal capabilities. Brazing is considered to be the most reliable method of metallurgically joining beryllium.

Above, is the SBSS yoke final brazed assembly that was designed and fabricated by WessDel Inc.

Other Joining Methods

Electron beam welding is successfully carried out, particularly in instrumentation assemblies where severe structural requirements are not present.

Diffusion bonding can be carried out with beryllium and has been used for assemblies. Such techniques are usually held proprietary by the fabricator.

The technique of furnace brazing has been used successfully with beryllium using a silver braze alloy with 0.50% lithium content. This technique involves replacing the braze alloy between two halves of the assembly. The joint is then subjected to static loads at high temperatures. The brazing is done in a vacuum to prevent oxidation of the beryllium at the elevated temperature.

Coatings

An extensive amount of work is being carried out to develop coatings and protective systems for beryllium operating in hostile environments. Coatings are also used to develop surfaces on beryllium which have characteristics other than that of beryllium itself. A few of these coatings are described below.

Passivation

A beryllium surface exposed to chromate solutions will become passive and relatively stable. Adherence of strain gauges to such a surface or deposition and adherence of electroplated metal is extremely difficult. Berylcoat D is marketed by Materion as one treatment of this type which will aid in the prevention of "on the shelf" corrosion problems with the precise instrumentation. No measurable change in dimension or appearance results with the use of the treatment.

Strength of Adhesive Bonded Beryllium Joints			
Adhesive System	Average Strength		Type/Test
EA-9309-BR127 Primer	4700 psi	(32.4 MPa)	Lap Shear
HT-424-BR127 Primer	2500 psi	(17.2 MPa)	Lap Shear
FM-123-BR127 Primer	3500 psi	(24.1 MPa)	Lap Shear
FM-123-BR127 Primer	55 lb/in	(985 kg/m)	Honeycomb Peel
EA-934-BR127 Primer	75 Shore D		Hardness
Epoxy Np. 206 – Grade A	3500 psi	(24.1 MPa)	Lap Shear
BR127 Primer	K40 lb/in	(716 kg/m)	90° Peel

Strength of Beryllium Joints		
Braze Alloy Composition	Average Shear Strength, Ksi (MPa)	
Silver – Lithium (0.2%)	30.0	(206.8)
Silver – Copper (28)	35.0	(241.3)
Easy – F10 (50 Ag, 15.5 Cu, 16.5 Zn, 18 Cd)	44.0	(303.4)
Aluminum-Silicon (12%)	15.0	(103.4)

Anodizing

Chromic black or "black" iodization of beryllium is employed extensively to provide corrosion protection to beryllium surfaces, to increase emissivity and to depress light reflectivity in optical systems. As deposited, the anodized coating is electrically conductive, but after proper curing, is non-conductive. Excellent resistance to salt spray and high temperature oxidation has been reported for anodized beryllium.

The surface finish of an anodized beryllium part is the same as that of the part prior to anodizing. In other words, it can be either highly reflective or matte in nature.

Plating

A number of metals have been electroplated on beryllium. Electroless and electrolytic nickel plating have been used extensively with beryllium, especially in the optics field where the nickel plate is utilized in developing the optical figure and final polish of beryllium mirrors.

Chromate Conversion Coating

Enhanced resistance of salt spray and high temperature oxidation are provided to beryllium by chromate conversion coating developed for aluminum (e.g. Iridite Allodyne). These coatings are formulated and applied following the instructions for use on aluminum.

Corrosion Resistance

Beryllium, much like aluminum, develops an adherent, protective oxide coating in air. Due to this coating, corrosion and oxidation in air is minimal up to temperatures of about 1400°F (760°C).

However, in other environments, the protection is not adequate and care must be exercised to avoid corrosion. Beryllium that is clean and free of surface contamination has good corrosion resistance in low temperature, high purity water. However, beryllium is highly susceptible to localized pitting when in contact with the chloride and sulfate ions contained in ordinary water. Therefore, exposure to tap water should be kept at a minimum and always followed by a rinse with deionized water, followed by drying to insure against damage. Sea water is very corrosive to beryllium. The handling of beryllium parts with a finished surface should also be done with care. A fingerprint left on the surface will disrupt the effectiveness of the final etch or coatings. When corrosive conditions are anticipated, the use of a protective coating is advised.

Because of the critical nature of most of the applications we review, our engineers are accustomed to working closely with design engineers at the product development stage. If you have a candidate application in mind, call our customer service numbers at our Elmore plant.

AVAILABILITY

Beryllium's unique blend of engineering properties – stiffness, high strength, low density, heat resistance and reflectivity – has opened the doors to countless new applications in recent years. If your design requirements fit any of these parameters, investigate the possibility of using beryllium or one of its related materials. The Sales and Engineering staff at Materion Beryllium & Composites will be glad to assist you in this effort.

Product Availability

Beryllium Products	Production Processes	Available Forms	Material Specifications
Standard Mill Products	Vacuum Casting	Ingot, Lump & Chips	B-26-D
	Vacuum Hot Pressing & Machining	Block, Billet, Rod, Bar & Tube	S-200F, S-65
	Rolling	Foil Discs & Rectangular Sheet & Plate	SR-200, PS200, PF-60, IS-50M
	Hot Isostatic Pressing	Near Net Shapes	S-200FH, I-22H, S-65H, I-70H, O-30H
Non-standard Mill Products	Hot Isostatic Pressing	Near Net Shapes	S-200FH, O-30H, S-65H, I-70H & I-220H
	Cold Isostatic Pressing	Near Net Pressing	S-200FC & S-65

Health and Safety

Handling beryllium in solid form poses no special health risk. Like many industrial materials, beryllium-containing materials may pose a health risk if recommended safe handling practices are not followed. Inhalation of airborne beryllium may cause a serious lung disorder in susceptible individuals. The Occupational Safety and Health Administration (OSHA) has set mandatory limits on occupational respiratory exposures. Read and follow the guidance in the Material Safety Data Sheet (MSDS) before working with this material. For additional information on safe handling practices or technical data on beryllium, contact Materion Corporation.

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