

## HIP Beryllium Achieves Full Commercial Status

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### ABSTRACT

The following paper by H D Hanes and A J Stonehouse of Materion Beryllium & Composites, Elmore, Ohio, describes the company's experience in producing beryllium components by two basic processes. The first of these is direct HIPing of powder in a container. The alternate approach is containerless HIPing, where the parts are cold pressed (die or isopressed), vacuum sintered, and then HIPed. The relative economics of conventional versus HIP processing of several production parts is compared.

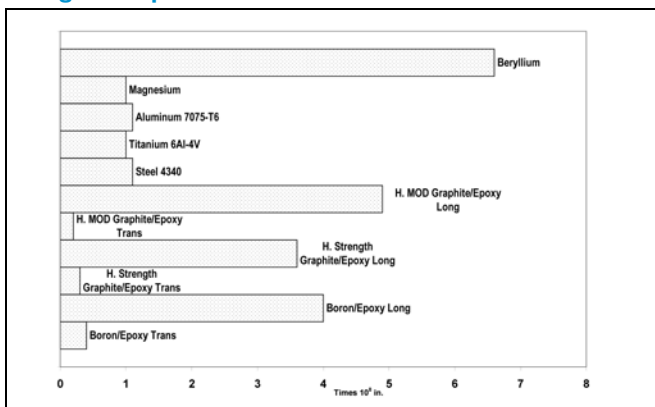
**Keywords: HIP processing, HIPing, Hot Isostatic Press, Beryllium, cold pressed (die or isopressed), CP, CIP Sinter, Vacuum Hot Press, NNS, Near Net Shape**

Beryllium provides designers with a unique combination of properties. It is one of the lightest structural metals known. It has an outstanding stiffness-to-density ratio as illustrated in Fig. 1, a good strength-to density ratio, high specific heat, excellent thermal conductivity, and the ability to retain useful properties at high temperatures.

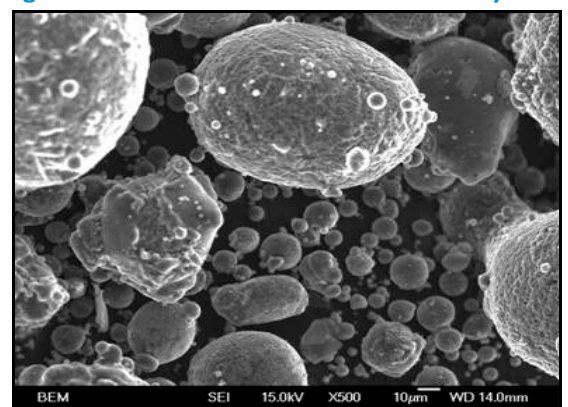
These characteristics have made beryllium a preferred engineering material for structural applications where light weight, high strength, and high stiffness are required. Examples are windshield frames and umbilical doors for the Space Shuttle Orbiter; spacecraft, missile, and aircraft guidance systems; instruments; scanning mirrors; and other applications space telescopes; where performance requirements result in beryllium being the most cost effective design approach. Cost constraints have prevented beryllium parts from being designed into less demanding products, even when the properties of beryllium would greatly improve product performance. Beryllium is an expensive engineering material and beryllium parts are expensive to produce by conventional low-material-yield methods.

Virtually all beryllium is a PM product entering service at nearly full density (99+% of theoretical density). The PM approach is utilized because this is the only way in which fine-grained (5-15  $\mu\text{m}$ ) microstructures, as shown in Fig. 2, exhibiting favorable strength, ductility, and machining characteristics, have been successfully generated. Extrusions, rolled products and forgings are available, but these are obtained by the hot and warm working of PM billets. Vacuum hot pressing has been the primary consolidation procedure for beryllium powders using large graphite and IN-100 dies. Vacuum hot pressings up to 72 in. (1830 mm) diameter by 24 in. (610 mm) high weighing about 6000 pounds (2730 kg) have been produced along with a large inventory of smaller sizes some of which utilize an L; D ratio as high as 6:1. The product, however, has nearly always been a right circular cylinder or cylinders with simple tapered sides

**Figure 1 Specific Modulus of Structural Materials**



**Figure 2 Microstructure of direct HIPed beryllium**



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From which the final hardware is which machined. While beryllium with simple tapered the final hardware is a readily machinable material capable of holding very close tolerances in precision components such as inertial guidance components, the large volume of material that must be removed makes machining operations time consuming and costly even when automated machine tools such as C\_ NC'\_ machines are used. Machining complex parts from a solid is also a high risk operation. Operator or programmer errors may result in substantially increasing cost.

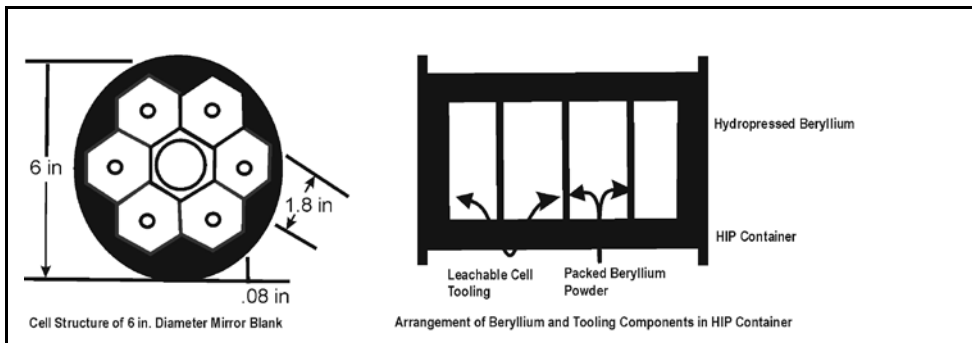
A substantial cost factor in the conventional approach to manufacturing beryllium parts is the low yield of input material in the finished component. In some cases, tip to 90% of the input hot-pressed block must be converted to machine chips to achieve the final part geometry. Typically, about two-thirds of the input weight is converted to solid scrap or chips to manufacture beryllium components. Beryllium is conserved by recycling all chips and scrap, thus considerably reducing costs relative to those that would otherwise be generated.

### NEAR NET SHAPE HIPING OF BERYLLIUM

In order to reduce the cost of producing beryllium components, particularly as they become increasingly complex, Materion Corporation's Beryllium & Composites has been studying techniques for the near-net-shape manufacture of beryllium blanks by isostatic processing and has installed a 30 inch (760 mm) x 65 inch (1650 mm) HIP unit.

The direct HIP and CIP/HIP of beryllium powder has a long history. In the early 1960's, Battelle-Columbus Laboratories successfully produced near-net-shape parts by consolidating beryllium powders. This was the first demonstration of the ability to form near-net-shape parts by HIPing. In the same time frame, it was recognized by Battelle workers that HIP processing resulted in a more nearly random crystallographic texture than other beryllium powder consolidation procedures (1). Since that time, Battelle and other laboratories have demonstrated that HIPing is, indeed, a practical process for producing high quality, near-net-shape beryllium parts.

At the Fourth International Conference on Beryllium, sponsored by The Metal Society of the Royal Society, London, held in 1977, several papers on the HIPing of beryllium were presented including one describing a manufacturing process for beryllium bar. In order to reduce the cost of stock in production at, the Royal Ordnance Factory, Cardiff (2) and a paper describing the fabrication of beryllium mirrors with accurately spaced cell cavities formed by HIPing beryllium powder around copper tooling later removed by chemical etching (3) as shown schematically in Fig. 3.



**Fig 3 Procedure for fabricating beryllium mirrors at Battelle-Columbus Labs as described by Mueller (1).**

**Fig 4 Beryllium & Composites 0 inch (760 mm) HIP unit.**

The specific advantages of HIPing beryllium powder as compared to vacuum hot pressing have been shown by work at Materion's Beryllium & Composites and elsewhere to be as follows:

- (1) Production of complex shapes to near-net shape.
- (2) Production of material at full density.
- (3) Production of material with equivalent or improved mechanical properties.
- (4) Production of material with more nearly random crystallographic texture.
- (5) Shortened pressing cycle times giving increased productivity with adequately sized equipment.

These advantages translate quickly in each case to either a substantial economic advantage or a technical-quality gain indicating a commercial justification for the use of IIP in beryllium component manufacture. Accordingly, Materion Corporation's Beryllium & Composites has installed a state-of-the-art HIPing facility at the Elmore, OH manufacturing facility.

MAAB-003

### COMMERCIAL BERYLLIUM HIP FACILITY

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The HIP unit at Materion Beryllium & Composites' Elmore plant shown in Fig. 4 was supplied by Autoclave Engineers and became operational in late 1985. The HIP system is capable of processing materials at temperatures up to 1250C and 15,000 psi (103 MPa) argon pressure. The maximum load size which can be accommodated is 30 in. (760 mm) diameter by 65 in. (1650 mm) long.

The pressure vessel is monolithic steel forging of ASME Grade SA-723 steel. The top cover is retained by a resilient spring-type thread and has an automatic opening cover, which is supported and retained by a shoulder inside the bottom of the pressure vessel's bore.

The furnace assembly consists of a base module, an external thermal barrier, and an internal convection liner that doubles as work piece loading furniture. The base module contains a molybdenum support structure, three zones of molybdenum sheet heating elements, a molybdenum fan for forcing convection flow, and connections to plug into the bottom cover when the furnace is loaded into the pressure vessel. There are provisions for thermocouples during hold times are typically  $\pm 10C$  or better throughout the entire workload volume. Computer controls as shown in Fig. 5 are used for all system functions. All electrical relays and gas valves are controlled directly by a Texas Instruments PM-550 programmable control system. Fully automatic HIP cycles are facilitated by using an IBM personal computer in a supervisory function over the programmable controller. Parameters for pressurization, heating, hold conditions, and cool down are entered by the operator into a cycle recipe and loaded into the computer's memory prior to the HIP cycle. Once the automatic cycle is started, the operator monitors its progress and makes minor control adjustments if needed. Typical HIP cycle times are 12-14 hours, depending on furnace loading.



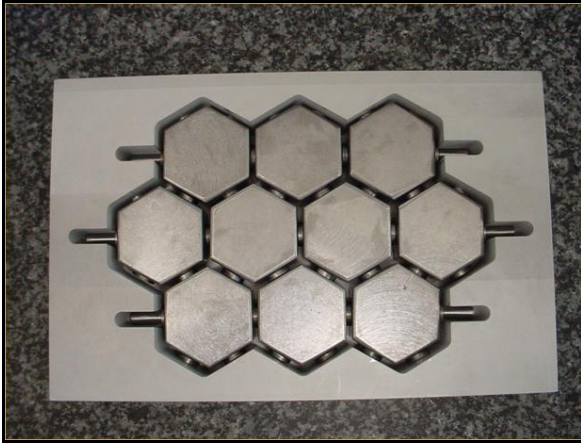
Fig 5 Control Console for Beryllium & Composites' HIP unit



Fig 6 Partially machined HIPed blank

Direct HIPing of Beryllium. The direct HIPing of beryllium powder using steel cans is one procedure which is being used to produce beryllium components. Generally, this approach is limited to large blanks with a relatively simple configuration. An exception to this generalization is the case where complex, light weighted optical mirrors are produced by direct HIPing of beryllium powder around copper internal tooling in a steel can.

A partially machined HIPed blank is shown in Fig. 6. In Fig 7, are HIP'd Honeycomb monolithic mirror blanks. The rectangular blanks with central through openings are shown in Fig. 8. This direct-HIPed blank weighing 84 lbs (38 kg) is used to produce the sensor support structure for the helicopter mast mounted sight shown in Fig. 9. Substantial, further light weighting of this blank is planned as the production run proceeds.

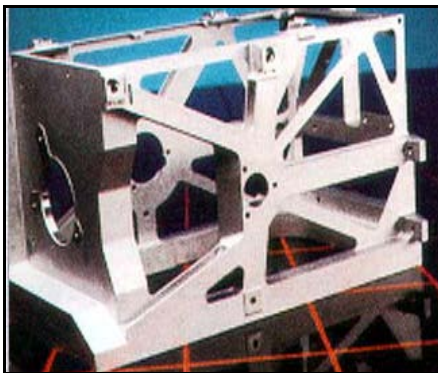


**Fig 7 Honeycomb monolithic mirror blank**



**Fig 8 Direct HIPed beryllium blanks for mast mounted helicopter sight sensor supports**

The relative high shrinkage factors associated with the consolidation of beryllium powder from about 55% of theoretical density to full density during HIPing make this procedure susceptible to a variety of problems including can buckling and weld failures as well as dimensional control. Nevertheless, large simple shapes are being produced in this manner with substantial economic advantage over vacuum hot pressing. This approach also allows increased versatility in pressed blank sizes as the inventory of hot pressing dies is limited due to the high cost and long delivery times of large graphite stock.



**Fig 9 Finished beryllium sensor support for mast-mounted helicopter sight.**



**Fig 10 CIP-Sinter-HIP beryllium guidance component blank.**

Out gassing of the beryllium powder prior to sealing the HIP can is particularly important in direct HIPing as none of the gases usually evolved are soluble in beryllium. If this out gassing at elevated temperature is not properly carried out, subsequent stress-relief or joining operations can lead to substantial thermally-induced porosity and dimensional changes as the micro-bubbles of trapped high-pressure gas expand.

Containerless HIPing of Beryllium. As with other materials, container less HIPing of beryllium, where the preform has no open porosity and thus does not need an enclosing can for HIP consolidation, is of great economic advantage. Cold isostatic pressing or even axial cold pressing followed by vacuum sintering is being used to produce beryllium preforms with closed porosity and complex geometry. These preforms then can be given a HIP cycle achieving full densification and excellent shape retention. An example of an inertial guidance component preform fabricated by the CIP/sinter sequence is shown in Fig. 10. Beryllium components fabricated for a belt limiter in the Joint European Torus at Cullam, England, using an axial cold press, vacuum sinter, container less HIP sequence are shown in Fig. 11.

## PROPERTIES OF HIPED BERYLLIUM

The mechanical properties of direct-HIPed beryllium are fully equivalent or superior to vacuum hot-pressed beryllium in all respects. The strength level of beryllium is a function of grain size following the Hall-Petch relation (4, 5). The grain size of beryllium is primarily established by the particle size distribution of the powder prior to its consolidation into a dense, polycrystalline body. The final grain size, however, is affected by recrystallization and grain growth in the consolidation procedure dependent upon the temperature time envelope used.

The high consolidation pressure available in a HIP cycle allows lower temperatures and shorter times to be used in direct-HIP consolidation of beryllium as compared to vacuum hot pressing. The net effect is that finer-grained and thus stronger bodies may be manufactured by direct HIP as compared to vacuum hot pressing with a given powder input. This is illustrated by the comparative data for direct-HIPed and vacuum-hot pressed S-200F shown in Table I. The tensile elongations are generally equivalent with the two procedures unless the HIP temperature is sufficiently low that the powder remains in a highly cold-worked condition, in which case, low elongations may be recorded.

**Table I Room temperature tensile properties of direct-HIPed S-200F beryllium as compared to vacuum hot pressed S200F.**

	Sample Orientation	Ultimate Strength		Yield Strength		% Elongation
		(1000 psi)	(MPa)	(1000 psi)	(MPa)	
Tube, 12" OD x 9.5" ID x 10" long	L	72.2	497.8	49.1	338.5	5.0
	T	71.7	494.4	49.3	339.9	4.6
Rectangle, 16.3" x 8.75" x 4.7"	L	65.0	448.2	47.0	324.1	2.8
	T	67.0	462.0	48.6	335.1	3.0
Vacuum Hot Pressed (VHP) S200F	L	58.0	399.9	39.0	268.9	2.8
	T	60.0	413.7	39.0	268.9	4.7
Specification Guaranteed Min VHP		47.0	324.0	35.0	241.3	2.0

CP and CIP-Sinter-HIP Beryllium. The ultimate and yield strengths of beryllium consolidated by either axial cold pressing or CIP followed by vacuum sintering to close porosity and HIPing to full density will be slightly lower than the values shown for vacuum hot pressings of the same powder as illustrated in Table 2. This difference arises as the result of grain growth occurring in the vacuum sintering operation which is carried out without applied mechanical pressure at a temperature higher than that employed for vacuum hot pressing. The subsequent container less-HIP operation carried out at a lower temperature has no effect upon the final strength beyond the elimination of porosity.

## CRYSTALLOGRAPHIC ISOTROPY OF ISOSTATICALLY CONSOLIDATED BERYLLIUM

Isostatically consolidated beryllium, either direct HIPed or CIP-Sinter-HIPed, has the most nearly random crystallographic texture of any polycrystalline beryllium. The crystal structure of beryllium is close-packed hexagonal with properties that differ along the two principal crystal axes. Slip can occur at room temperature only in a direction contained by the basal plane (0002). In addition, the coefficient of thermal expansion is about 27% greater in the a-axis direction than in the c-axis direction. A random texture is, therefore, extremely important to achieve ductility in all directions. It is also particularly important in the fabrication of cryogenically cooled, precision optical mirrors where uniform thermal expansion is required. Metal working procedures such as rolling and extrusion result in a high degree of preferred orientation in beryllium in which the basal planes align in the direction of working.

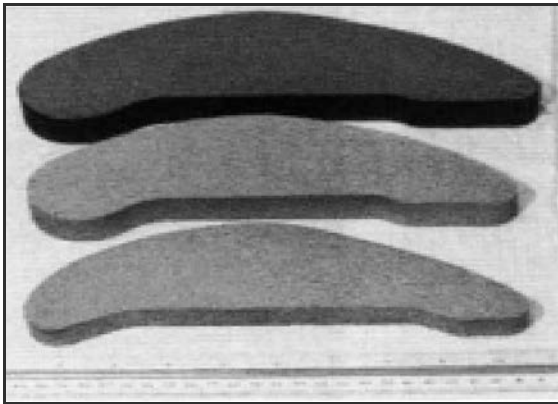
**Table 2 Tensile properties of cold pressed-vacuum sintered HIPed S-65B beryllium as compared to Vacuum Hot Pressed material.**

	Ultimate Strength		Yield Strength		% Elongation
	(1000 psi)	(MPa)	(1000 psi)	(MPa)	
CP-S-HIP	49.6	342.0	30.6	211.0	5.2
Vacuum Hot Pressed	65.	453.7	39.6	273.0	5.4

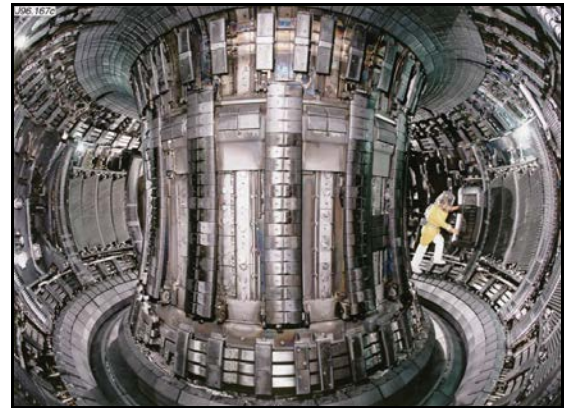
Values average of six tests taken at room temperature in direction transverse to pressure application in each case.

A principal factor in the texture of consolidated beryllium bodies is the morphology of the powder particles. Attritional beryllium powders as illustrated in Fig. 12 are basically plates arising from basal plane cleavage of larger particles during mechanical grinding. These plates are difficult to keep randomly oriented during die loading or compact loading operations giving rise to the classic textures of beryllium billets. Impact grinding provides a more equiaxed particle as shown in Fig. 13 which can be maintained in a random orientation more readily in loading operations than the classic attritioned powders. Today, the favored commercial grades of beryllium are manufactured from beryllium prepared by impact grinding.

A small amount of oriented mechanical working apparently does occur in the hot isostatic pressing procedures both at room temperature and in vacuum hot pressing. Thus, the most nearly random material is prepared using impact ground powder consolidated by either direct-HIP or CIP Sinter-HIP procedures.



**Fig 11 HIPed beryllium tiles for JET (Fusion Reactor)**



**JET Fusion Reactor**

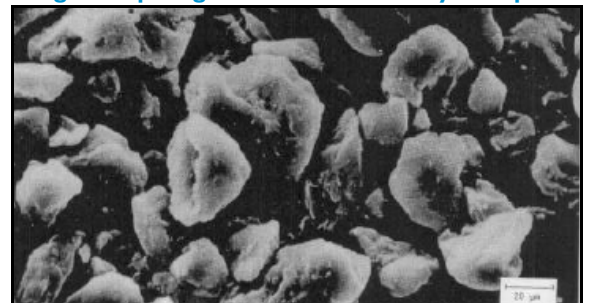
**ECONOMICS OF NEAR NET SHAPE BERYLLIUM**

The high cost of beryllium makes the use of near-net-shape processing very attractive from an economic standpoint. While all beryllium is carefully recovered and recycled, these procedures add appreciable costs that would not be generated were such recycling unnecessary. The impact of the savings which can be realized by the use of direct HIP of relatively large components is illustrated by the examples shown in Table 3. Each of the shapes included in this table is either in production at the present time or will be in the near future. With direct HIP, the cost savings relative to machining from vacuum hot pressed block increase with the relative size of the component. The savings that can be realized with any given component is, of course, materially affected by the degree of shaping which can be achieved relative to the final part configuration.

**Fig 12 Attritioned -325 mesh beryllium powder.**



**Fig 13 Impact ground -325 mesh beryllium powder.**



The use of container less HIP with vacuum sintered, cold-pressed, or CIPed preforms results in equally or more dramatic cost savings where these procedures may be used. This advantage comes from the additional savings of

eliminating the can fabrication and out gassing sequences on individual pieces and substituting the pressing and multiple vacuum sintering operations. Usually a large number of pieces may be HIPed at the same time further decreasing costs. The cost of the JET belt limiter components referred to earlier, for example, manufactured by a cold press-vacuum sinter-HIP sequence was only 45% of what the cost would have been if these parts had been machined from vacuum hot pressed block.

**Table 3. Comparative economics of vacuum hot pressing and direct HIPing of beryllium components.**

Shape	Vacuum Hot Pressing			Direct HIP					Cost Savings by HIP
	Input Weight		Blank Weight	Input Weight		Blank Weight			
	Lbs	Kg		Lbs	Kg	Lbs	Kg	Lbs	
"A"	183	83.2	68	30.9	89	40.5	48	21.8	42%
"B"	67	30.5	28	12.7	30	13.6	25	11.4	31%
"C"	37	16.8	16	7.3	17	7.7	11	5.0	27%
"D"	17.5	8.0	5	2.3	8	3.6	5	2.3	18%

Note:

Handling Aluminum-Beryllium materials 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 materials, contact Materion Beryllium & Composites.