Advances in Near Net Shape Beryllium Manufacturing Technologies

David Saxton, Thomas Parsonage  
Brush Wellman Inc.  
17876 St. Clair Avenue, Cleveland, Ohio 44110

Abstract

Beryllium has been used as an optical substrate material for the past 40 years, for applications ranging from small commercial scanning systems, to large 1.2 meter (M) diameter astronomical telescopes like the VLT (Very Large Telescope). The main reasons for its use has been the need for lightweight optics, aerial densities less than 25 kg/m², high specific stiffness, 7 times glassy materials, high thermal diffusivity, and a moderate coefficient of thermal expansion (CTE).

The main reason it has not been used more widely in these type of applications has been a perceived high cost, perceived long lead times, and perceived anisotropic properties. To address these issues, Brush Wellman Inc. is in the process of completing the development of a number of Near Net Shape manufacturing technologies utilizing a new isotropic grade of beryllium called O-30.

This paper will discuss the state of those technologies: Vacuum Hot Press Bonding (VHP), Near Net Shape Forming (NNS) with re-useable mandrels, and the development of the O-30 material. The paper will also attempt to show how these new manufacturing technologies addresses the perception that beryllium is an expensive, long lead material.

Keywords: O-30, Vacuum Hot Pressed Bonding, Hot Isostatic Pressing (HIP), Re-useable mandrels, Beryllium, Isotropy

1. Introduction

Beryllium is produced by a powder metallurgy technology. Traditionally the preferred method for producing beryllium powders has been by mechanical grinding methods, such as impact or attrition grinding. This process result in powders that reflect the crystallographic nature of the beryllium crystal, which is close packed hexagonal, similar to titanium and silicon carbide. This preferred orientation has tended to produce flat plate like particles. Which during the consolidation of these traditional powders, I-70, I220, and S-200, by either VHP or HIP processes, has tended to slightly align the particles in this preferred orientation, leading to some small degree of anisotropy in the mechanical and thermal properties of the beryllium. This preferred orientation of these mechanically produced powders also tended to limit the ability of beryllium to achieve a high degree of predictable net or near net shape consolidation of shapes.

While for many precision optical applications this slight preferred orientation has not adversely affected the performance of the system, the ideal beryllium would be completely isotropic. To address the needs of increasingly higher performance systems, Brush Wellman Inc. has completed the development of a new isotropic grade of beryllium called O-30. This new optical grade of beryllium is totally isotropic in its properties due to its spherical shape. This spherical shape also allows the beryllium to be consolidated using net or near net shape technologies with a higher degree of predictability.

2. O-30 Optical Material Process

In order to produce a truly isotropic grade of beryllium, Brush Wellman Inc. in the late 1980’s and early 1990’s embarked upon a program to develop inert gas atomization of beryllium and aluminum beryllium (AlBeMet®). This process is mechanically simple and has been used to produce large quantities of other reactive metals like magnesium and aluminum. The process involves vacuum melting of solid high purity beryllium and then pouring this thru a small orifice. This molten stream is then impinged with a high velocity gas stream, breaking the molten stream into fine droplets that under atmospheric cooling turn into fine spheres. The production unit that is currently installed at Brush Wellman Inc. is capable of producing over 500 kgs of material per week (Figure 1).
2.1 Powder characteristics

The powder produced by gas atomization is spherical as shown in Figure 2. The microstructure of the powder particle is polycrystalline. The powder has been subjected to typical consolidation process temperatures like VHP and HIP, and there was found to be no grain growth associated with these processes. Therefore the powder remains spherical in nature and isotropic. One of the important features of the powder, its spherical nature, is demonstrated by the fact that the powder has a high flow rate, 5 grams per second, versus the traditional optical powders like I-70 and I220, which have virtually no measurable flow rate. This high flow rate allows a high packing density of greater than 64% of theoretical. This is significant in terms of the ability to load in HIP cans to thin cross sections/complex shapes, and to better predict the final shape after consolidation by either VHP or HIP processes. This also allows Brush Wellman Inc. to model the deformation process during consolidation in order to minimize distortion and predict final shape. The result of this should reduce the amount of beryllium material used in the process and reduce the final amount of material to be removed during the final machining process of the component. This will reduce the overall cost and schedule of the component.

![SEM Photomicrograph of Sperical Powder and Impact Ground Powder - 100X](image)

2.2 Mechanical and thermal properties of O-30 Powder

The mechanical and thermal properties of spherical grade O-30 powder after consolidation has properties that meet or exceed the properties of mechanically produced optical powders such as I-70 (2). The tensile testing was performed in accordance with ASTM E8 at room temperature, 23°C. The isotropy of the mechanical and thermal properties is evident in the data, with variability on the order of less than 1% in any direction (see Table 1).
Typical Mechanical / Thermal Properties O-30 VS I-70 Beryllium

<table>
<thead>
<tr>
<th>Grade</th>
<th>Ultimate Tensile MPa</th>
<th>Yield Strength MPa</th>
<th>Micro-Yield Strength MPa</th>
<th>Elongation %</th>
<th>CTE in/in/°C 0-65°C</th>
<th>Thermal Conductivity W/m-k 25°C / -166°C</th>
<th>Grain Size μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-30 (HIP) L</td>
<td>410</td>
<td>300</td>
<td>35</td>
<td>3</td>
<td>11.38</td>
<td>215 / 365</td>
<td>7</td>
</tr>
<tr>
<td>T</td>
<td>405</td>
<td>295</td>
<td>35</td>
<td>2.9</td>
<td>11.38</td>
<td>215 / 365</td>
<td>7</td>
</tr>
<tr>
<td>O-30 (VHP) L</td>
<td>300</td>
<td>200</td>
<td>20</td>
<td>2.6</td>
<td>11.4</td>
<td>210 / NA</td>
<td>13</td>
</tr>
<tr>
<td>T</td>
<td>295</td>
<td>198</td>
<td>21</td>
<td>2.5</td>
<td>11.4</td>
<td>210 / NA</td>
<td>13</td>
</tr>
<tr>
<td>I-70 (HIP) L</td>
<td>445</td>
<td>300</td>
<td>35</td>
<td>5</td>
<td>11.4</td>
<td>215 / 365</td>
<td>7</td>
</tr>
<tr>
<td>T</td>
<td>440</td>
<td>296</td>
<td>35</td>
<td>6</td>
<td>11.3</td>
<td>215 / 365</td>
<td>7</td>
</tr>
<tr>
<td>I-70 (VHP) L</td>
<td>240</td>
<td>175</td>
<td>17</td>
<td>2</td>
<td>11.25</td>
<td>210 / NA</td>
<td>15</td>
</tr>
<tr>
<td>T</td>
<td>265</td>
<td>210</td>
<td>22</td>
<td>2</td>
<td>11.42</td>
<td>210 / NA</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 1

2.3 Cryogenic performance

In the last few years Brush Wellman Inc., in conjunction with Rome Labs, Marshall Space Flight Center and other’s, have characterized the cryogenic performance of O-30 beryllium optical grade material (3). This work resulted in establishing a process for tailoring the beryllium particle size, cleaning the powders prior to consolidation, and consolidation processes that would yield improved cryogenic performance of bare beryllium optics. This was demonstrated by measuring the surface figure and optical scatter at various wavelengths of light, from 0.6238 to 10.6μm (see Table 2).

Optical Characterization of O-30 Beryllium

<table>
<thead>
<tr>
<th>Grade / Specimen</th>
<th>Initial P-V @ 298°K</th>
<th>Initial RMS @ 298°K</th>
<th>Post Cold Test @ 30K P-V</th>
<th>Post Cold Test @ 30K RMS</th>
<th>Scatter @ 298K 3° From Specular @ 10.6μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-30 / 150mm dia flat Surface 30-40Å</td>
<td>0.1680</td>
<td>0.0257</td>
<td>0.1632</td>
<td>0.0163</td>
<td>2.7 x 10⁴</td>
</tr>
</tbody>
</table>

Table 2

3. Net / Near Net Shape Technology

During the 1980’s considerable work was performed in developing a Near or Net Shape (NNS) technology for beryllium, utilizing leachable mandrel technology. This work was performed by numerous companies, Brush Wellman, Inc., Perkin Elmer / Hughes Danbury Optical Systems, and OCA Applied Optics (4 & 5). The main mandrel material in all of these processes was copper tooling machined to final dimensions of the lightweight cell structure. The other mandrel material that was used during the development phase of the Beryllium Surveillance Mirror contract (2), was Monel. This process, HIP with leachable mandrels, was demonstrated to be capable of producing up to 1 meter diameter mirror blanks, with either open or closed cell back structures (Figure 3). The main issues with this approach has been; the time and cost to produce precision machined mandrels that can only be used once; predicting dimensional shrinkage of the blank during the HIP process; and potential thermal mismatch of the mandrel to the beryllium during the cool down cycle of the HIP process. The remaining issue has been the limited size of commercial available HIP units to produce large mirror blanks, greater than 1.5 meters in diameter.
To address those issues, Brush Wellman Inc. has embarked upon a program to develop two NNS technologies; reusable mandrel technology and vacuum (VHP) / Hot Isostatic Pressing (HIP) bonding. Both of these technologies utilize spherical O-30 powder. This spherical powder provides, in combination with the consolidation processes, the following benefits over the 1980’s materials technology:

- Higher powder flow rates for improved packing densities – 65% Vs 53%
- Isotropy of properties after consolidation by either HIP or VHP technology
- Improved predictability of final dimensions / shape by modeling the compaction process
- Ability to produce thinner walls and greater aspect ratio’s – as low as 0.5mm walls
- Ability to produce mirror blanks as large as 2 meters in diameter without new facilities
- Reduced cost, 30%, and overall lead times, compared to machined solid mirror blanks

3.1 Mandrel Technology

3.1.1 – Leachable Mandrel Technology
Brush Wellman Inc. has continued the prior work on leachable mandrel technology and recently has produced a 0.5 meter diameter mirror blank as a demonstrator, under a IRAD mirror program with Ball Aerospace, utilizing the isotropic optical grade of O-30 powder (Figure 4).
This mirror blank was produced by utilizing both leachable mandrels and HIP bonding technology. The mandrel material used was the standard copper technology. The HIP bonding technology utilized solid to powder bonding technology. The mirror blank was comprised of solid O-30 beryllium webs, 0.5mm thick between leachable copper mandrels, inter-spaced with O-30 beryllium powder. The face sheet and outside exterior walls were made up of O-30 powder. This was put into a HIP can made of inexpensive mild steel and HIP'ed at < 1000°C. The resultant HIP'ed mirror blank was 100% dense and the mirror blank was stress relieved at the standard beryllium stress relief temperature of 780°C for 3 hours. The final mirror dimensions were then machined using conventional machining technology. The webs of this mirror blank were 0.5mm thick and the overall aerial density was < 10 kgs/m². The face sheet was 3mm thick. All of the cell interfaces where achieved by powder to solid bonding technology, during the HIP process.

### 3.1.2 Reuseable Mandrel Technology

Brush Wellman Inc. has continued previous work on developing the technology to re-use mandrels to make open back lightweighted mirror substrates. We produced triangular mandrels out 316L stainless steel, Figure 5. The use of the 316L stainless was chosen due to its closer coefficient of thermal expansion (CTE) match with beryllium. Each of these mandrels were coated with 3 coatings by the use of plasma spraying technology. These coated mandrels were assembled on to base plates made out of the 316L stainless steel. In between each mandrel 0.9mm thick solid beryllium webs were placed and the entire assembly was loaded into a HIP can made of mild steel. This assembly then was covered in spherical O-30 beryllium powder to produce the faceplate and the outer diameter of the mirror substrate. This “assembly” was then HIP’ed at 830°C and at a pressure of 105Mpa. Figure 6. The HIP process was successful, but the mandrels did not release from the beryllium without the use of mechanical methods. We will investigate this process further to solve the following issues:

- Interlocking of the mandrels to the beryllium due to micro-mechanical forces – increase draft angles and / or improve surface finish of the coatings
- produce HIP can to tighter tolerances to prevent powder flow into gaps during vibration of powder bed
- investigate leachable coatings on re-useable mandrels

### 3.1.3 Vacuum Hot Pressing Bonding Technology

Brush Wellman Inc. has developed a technology called Vacuum Hot Press Bonding to address the issue of producing beryllium substrates using O-30 powder, in diameters larger than the current limit of existing HIP facilities, 1.4 meters. Brush Wellman Inc. currently has an installed capacity to vacuum hot press beryllium substrates as large as 2 meters in diameter. We have vacuum hot pressed structural grades of beryllium in sizes as large as 1.9 meters in diameter for applications such as the Space Shuttle umbilical doors. This technology would allow the production of mirror substrates as large as needed for applications like the NGST, 3 meters x 2.4 meters, without the need for a large, expensive, long lead time HIP facility construction.
To demonstrate this technology we produced a series of 8.25 cm diameter x 1.27 cm thick blanks produced from O-30 beryllium powder by HIP. We then split these blanks in half at a 30° angle using a wire EDM machine. We then loaded these into a die made of graphite. We then applied uniaxial pressure from the top and bottom at a temperature of <1100°C in the vacuum hot press furnace. This process of vacuum hot press bonding provides a metallurgical joint by means of molecular bonding at the grain boundary interfaces, similar to diffusion bonding. All of the 12 coupons were successfully bonded during the process. After the hot press cycle was complete 3 of the bonded samples were cut up into tensile bars to evaluate the mechanical strength of the joint, Table 3.

<table>
<thead>
<tr>
<th>Property</th>
<th>Average of 12 specimens</th>
<th>Input Material – HIP’ed O-30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Hot Press Temperature</td>
<td>&lt; 1050°C</td>
<td>HIP Temperature 830°C</td>
</tr>
<tr>
<td>Micro - Yield Strength - Mpa</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>Ultimate Tensile Strength - Mpa</td>
<td>361</td>
<td>420</td>
</tr>
<tr>
<td>Yield Strength - Mpa</td>
<td>257</td>
<td>317</td>
</tr>
<tr>
<td>Elongation %</td>
<td>2.6</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 3

The vacuum hot press bonding process was successful in producing joints with strength almost equivalent to the parent material, no voids, and a bond line that was difficult to see from a metallurgical view.

These specimens were then sent to SVG Tinsley Laboratories and Raytheon Optical Systems for polishing to determine the potential affects of the metallurgical bond line on the polishing process. The specimens were polished to a surface roughness on average of 31 RMS in order to achieve an interferometric photo of the optical surface at ambient temperatures. Particular attention was paid to the area of the bond line both from a visual inspection and interferometric view. All of the testing was done at ambient temperature, Figure 7 & 8. Neither source found any evidence or effect of the bond line on both the optical processing and the optical testing. These samples are currently being tested at cryogenic temperatures to evaluate the potential effects of the bond line on the optical quality of the substrate. Particular attention will be paid to the optical surface as the substrate is thermally cycled from ambient to 40°K and back to ambient, looking to see if the bond line induces any hysteresis or other thermal effects.

![Figure 7 - VHP Bonded Coupon - Tinsley](image1)

![Figure 8 - VHP Bonded Coupon - Tinsley](image2)

Brush Wellman Inc. has taken the experience gained from the 12 development coupons referred to above and has produced a 0.5M diameter spherical mirror substrate under a contract from MSFC. This 0.5M diameter substrate blank was produced by HIP’ing O-30 isotropic beryllium powder into a solid blank. This blank was then lightweighted by conventional CNC machining to produce a demonstration mirror substrate with open cell structures. The mirror blank was then cut in half at a <60° angle to produce the two bonding surfaces, Figure 9.

MAO-031-0
This blank was then put into a graphite die, with a top and bottom pressure tool, and vacuum hot pressed bonded together at 1050°C, with uniaxial pressure being applied from the top and bottom tool. The bonding was successful with full molecular bonding across the entire interface between the two halves. The part was then taken out of the die and finish machined to the final lightweighting and radius of curvature on the optical face, 20M radius of curvature. The bond line held up under the pressure and loads of the machining processes, both the additional lightweighting and machining across the face of the mirror. The part was then dye penetrate inspected and no indications were found. The part was then stress relieved to remove the residual stress induced in machining, Figure 10. The blank is currently at Raytheon Systems for optical fabrication to the following requirements established by MSFC. These requirements were set up to make sure that when MSFC subjects the part to cryo testing for evaluating the figure and the bond line affects, the optical surface will be good enough to obtain a fringe pattern at both the ambient and cryo temperatures.

O-30 Substrate – After VHP Bonding
4.0 Cryo Testing of O-30 Beryllium Substrate

Under the SBMD mirror program Ball Aerospace and Marshall Space Flight Center (MSFC) have recently completed the initial cryo testing in the Marshall XRCF cryo facility a 50cm diameter ultra-lightweight beryllium mirror, Figure 11. That mirror was produced by Hip'ing O-30 isotropic powder. The mirror weighed 9.8 Kgs/m². It has a face sheet thickness on the order of 4mm and cell walls approximately 0.5mm thick. The radius of curvature at ambient temperature was 20.034mm and at cryo it was 20.005mm +/- 3mm. They were able to change the ROC over 5mm by pushing with the ambient actuators on the tripod at 6 separate points, Figure 12. The ambient figure as measured at SVG Tinsley was <0.12 wave p-v, with a mid spatial figure of <0.01 to 0.02 p-v, Figure 13. During the testing down to 40⁰K and back to 300⁰K they did not see any print thru of the web structure to the front face, indicating a uniform grain structure and CTE in the material. They did see the effects of the gravity sag on the mirror during the cryo testing at MSFC, Figure 14. They also did not see any hysteresis during the temperature cycling from ambient to 40⁰K and back to ambient.

SBMD – O30 Mirror

![Figure 11](image)

Phase Map of Ambient SBMD @ SVG Tinsley

(0.012 waves rms)

Combined Phase Map of 6 Avg. Orientations

(0.020 waves rms)

![Figure 12 – Ball Aerospace Phase Map](image)

![Figure 13 – Ball Aerospace Phase Map](image)
5.0 Conclusions

We have demonstrated that with the new net shape technologies and the use of new improved optical grade beryllium powder, O-30, we can achieve the following in beryllium:

- Produce beryllium blanks as large as 2 Meters in diameter in existing facilities
- Achieve aerial densities of less than 10 Kgs/m² without print thru after polishing or thermal testing
- Achieve surface roughness that meets or exceeds the requirements of applications like NGST
- Improve cryo stability of beryllium optics by utilizing spherical O-30 powder
- Produce webs as thin as 0.5mm by the use of HIP bonding solid to powder technology

6.0 Health and Safety

Handling 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 Brush Wellman Inc., Beryllium Products Group, A/C 419-862-4173.

Acknowledgements

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