Cost Effective Aluminum Beryllium Mirrors for Critical Optics Applications

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ABSTRACT

The unique performance of aluminum-beryllium frequently makes it an ideal material for manufacturing precision optical-grade metal mirrors. Traditional methods of manufacture utilize hot-pressed powder block in billet form which is subsequently machined to final dimensions. Complex component geometries such as lightweighted, non-plano mirrors require extensive tool path programming, fixturing, and CNC machining time and result in a high buy-to-fly ratio (the ratio of the mass of raw material purchased to the mass of the finished part). This increases the cost of the mirror structure as a significant percentage of the procurement cost is consumed in the form of machining, tooling, and scrap material that do not add value to the final part. Inrad Optics, Inc. and IBC Advanced Alloys Corp. undertook a joint study to evaluate the suitability of investment-cast Beralcast® 191 and 363 aluminum-beryllium as a precision mirror substrate material. Net shape investment castings of the desired geometry minimizes machining to just cleanup stock, thereby reducing the recurring procurement cost while still maintaining performance. The thermal stability of two mirrors, (one each of Beralcast® 191 and Beralcast® 363), was characterized from -40°F to +150°F. A representative pocketed mirror was developed, including the creation of a relevant geometry and production of a cast component to validate the approach. Information from the demonstration unit was used as a basis for a comparative cost study of the representative mirror produced in Beralcast® and one machined from a billet of AlBeMet® 162 (AlBeMet® is a registered trademark of Materion Corporation). The technical and financial results of these studies will be discussed in detail.

Keywords: Aluminum-Beryllium, Mirrors, HIP'd, Investment-Cast, Beralcast®, Mirror Substrate, Precision Optics, Thermal Stability, AlBeMet®

1. INTRODUCTION

The most demanding precision metal optical applications require materials that are light weight, strong, rigid and stable[1]. In the metal optics industry today, two of the highest performing materials being used that meet these requirements are beryllium and aluminum-beryllium alloys. In particular, due to its excellent mechanical and thermal characteristics and lower cost as compared to beryllium, AlBeMet® (a registered trademark of Materion®Corp.) has been a long standing solution for metallic mirror substrates.

A potential alternative to AlBeMet® is Beralcast® 191 or 363, two alloys specifically designed for net-shape investment casting of complex structures. 363 was developed as a structural alloy with mechanical performance on par with traditional aerospace alloys. Mechanical and thermal characteristics of Beralcast® 191 and 363alloys are similar to AlBeMet®. A summary of common aluminum alloys, AlBeMet® and Beralcast® are shown in Table 1.

Material	Mechanical Properties				Thermal Properties			
	Young's Modulus (Msi)	Poisson's Ratio	Material Density (g/cm3)	Specific Stiffness (E/ρ)	CTE (ppm/C)	Conductivity (W/m-K)	Specific Heat (J/kg-K)	Thermal Diffusivity
	E	ν	ρ	M	α	κ	Cp	α/κ
Aluminum 2024T6	10.5	0.024	2.77	3.8	22.9	151	875	0.152
Aluminum 6061T6	10	0.024	2.7	3.7	23.6	180	896	0.131
AlBeMet 162	28	0.017	2.1	13.3	13.9	210	1506	0.066
Beralcast 363	29.3	0.2	2.16	13.6	14.2	105.5	1250	0.135
Beralcast 191	29.3	0.2	2.16	13.6	13.2	180	1423.5	0.073

Table 1: Physical properties of selected alloys[2,3,4]

AlBeMet® is produced from powdered metallic materials that are HIP consolidated under high pressures and temperatures to generate a blank or billet that can be utilized as input stock for machining to a desired final shape. Beryllium content is between 60% and 70% wt., with the primary balance being aluminum. Due to the fine size of the input material there is a fairly uniform distribution of small particulate beryllium phase in the consolidated product. Potential processing defects include clumping or settling of powders prior to the HIP process, lack of full consolidation yielding micro-porosity, and foreign contamination. In addition, the high oxidation potential of the aluminum and beryllium powders require stringent handling procedures to assure that the oxides on the high surface-to-volume ratio powders are minimized.

The proprietary casting processes used by IBC to produce Beralcast results in homogenous microstructures. The two-phase composite microstructure consists of beryllium dendrites surrounded by an aluminum second phase that is evenly distributed throughout the cross-section. The expected statistical range of the microstructural features has been accommodated in the performance data and is correlated to the radiographic inspection plates used during the normal course of production. Potential defects include shrinkage, foreign contamination, and phase segregation.

The current method of producing stable optical quality substrates from AlBeMet® is to begin with a billet size which approximates the maximum volume that can contain the finished piece. Conventional CNC machining is employed generate an optical processing ready mirror blank. The best utilization of material is achieved when the optic to be produced is of flat constant thickness geometry. Light-weighting, large curvatures, stand-offs and mounting structures all reduce the yield from the original billet, and the resultant chips and waste stream are ultimately unusable residual material. Additionally the beryllium content of the AlBeMet® makes the machining process both machine and labor intensive raising costs.

Beralcast® alloys can be cast to near net shape requiring only minor machining to prepare the optical substrate for final optical processing. Given that the mechanical and thermal properties of Beralcast® alloys in casting form are similar to AlBeMet® billets, and the fact that Beralcast® can be produced to near net shape, there is a potential opportunity in the form of reduced cost to use Beralcast® as an optical substrate material.

In a collaborative effort to address this potential market need for a lower cost solution to machining billets of AlBeMet® for optical structures, IBC Advanced Alloys Corp and Inrad Optics Inc. entered into a memorandum of understanding (MOU) in October of 2012. The MOU enables IBC and Inrad Optics to evaluate the technical and commercial viability of IBC's proprietary Beralcast® alloys as a cost effective alternative optical substrate material.

Inrad Optics is a vertically-integrated photonics manufacturer offering crystal-based optical components and devices, custom optical components from both glass and metal and precision optical and opto-mechanical assemblies. Its components and photonic devices are used in a wide variety of defense, aerospace, laser, medical, process control and metrology applications. Within its metal optics fabrication facility in Sarasota, Florida, Inrad Optics maintains the capability to CNC machine beryllium based optical substrates, as well as grinding, polishing, and diamond turning. An integral element of its success is the state of the art electroless nickel plating lab and electrolytic gold plating processes. All optical processing of the materials in this study were performed at the Inrad Optics metal optics facility in Florida.

IBC Advanced Alloys is a specialty alloy and products provider to the aerospace, optics, and commercial industries. Their Engineered Materials Corp. division in Wilmington, MA has optimized and produces the Beralcast® family of beryllium-aluminum alloys based on a proprietary vacuum casting metallurgy, which was developed in the mid 1990's as a cost effective solution for optical support structures in defense related applications. IBC's Wilmington facility is a dedicated state-of-the-art beryllium-aluminum casting facility that began operation in 2007.

2. COST COMPARISON OF ALBEMET® BILLET VS BERALCAST® CASTING

The intent of this study is to determine the cost advantage of utilizing a near net shape casting rather than direct machining of billet stock to generate optical processing ready mirror substrates. By using a casting, only light machining is required to finish the substrate prior to final optical processing, after which all processing steps are equivalent with either material approach. This leads to a direct reduction in cost due to the elimination of material waste and reduction in required machining. However, there are casting specific non-recurring engineering (NRE) and non-recurring tooling (NRT) costs that differ from machining billet stock. These differences are explained in cost study below.

For this cost comparison, a representative geometry was chosen with machining intensive mechanical features including light weighting pockets, mounting flexures and a concave, canted, off-axis parabolic optical surface. A mechanical drawing of this geometry is shown in figures 1, 2 and 3.

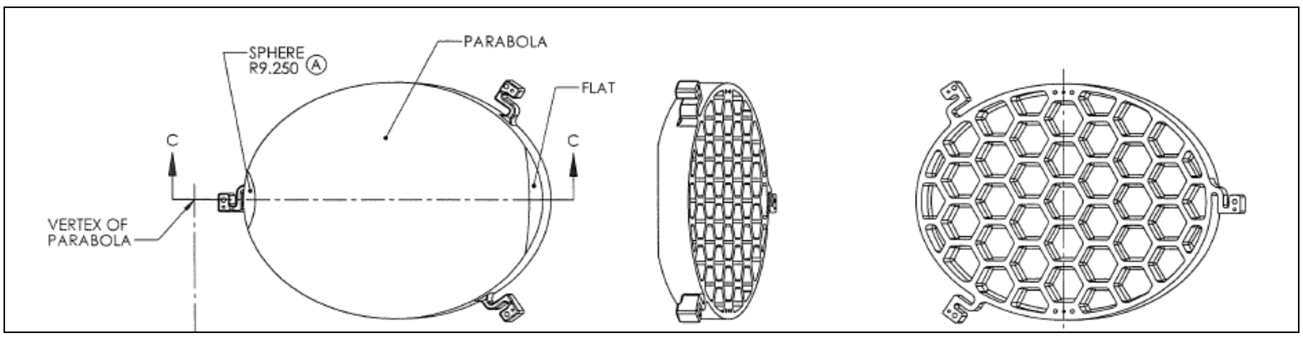

Figure 1: Representative Complex Geometry for Cost Comparison Study

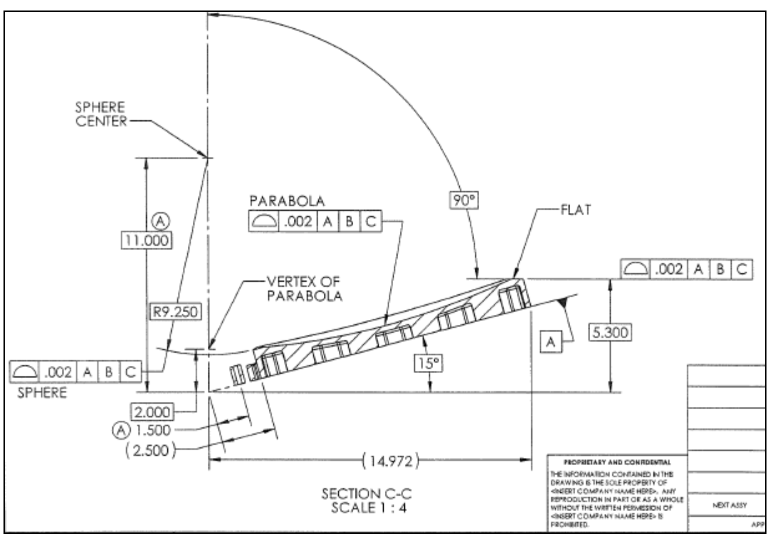

Figure 2: Representative Complex Geometry – Side View

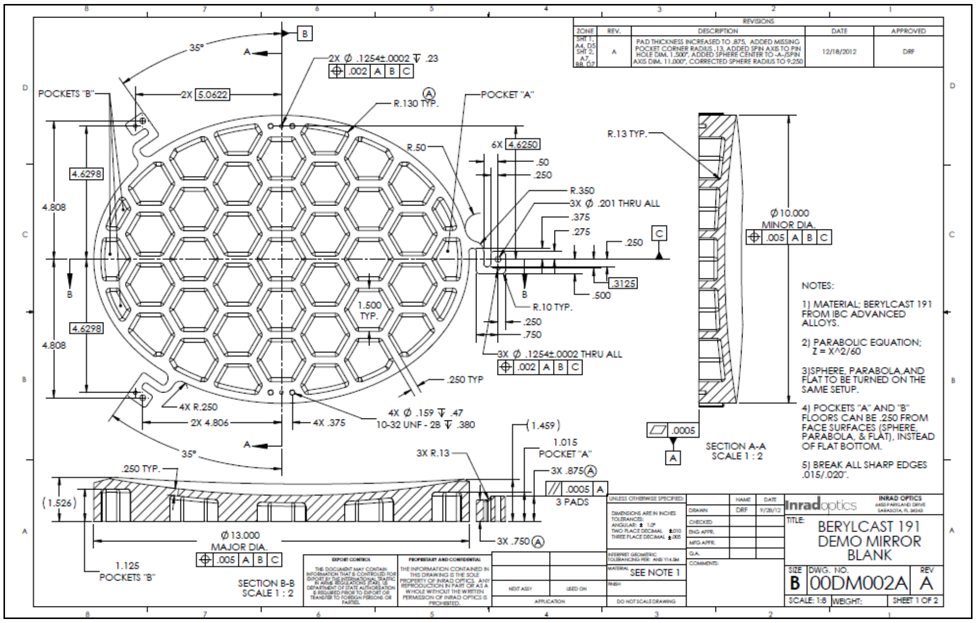

Figure 3: Representative Complex Geometry - Mechanical

Machining this geometry from a billet of AlBeMet® typically begins with a disk or slab of raw material with dimensions such that the outline of the component would fit within (Figure 4). For the representative component, a billet stock would be approximately 13.25" x 10.25" x 2.20", yielding a volume of 298.79 in^3, or equivalent weight of approximately 23.9 lbs of AlBeMet®. This represents a raw material cost in AlBeMet® of approximately $11,500.00 for quantity 1.

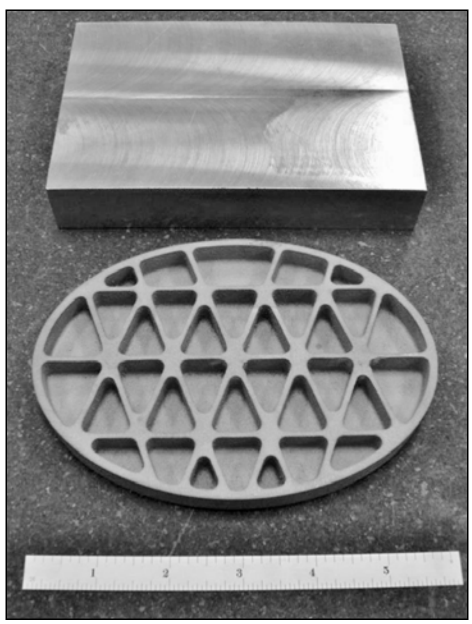

Figure 4: Stock blank required to machine from billet

The casting of Beralcast® begins at the foundry with a consumable invest that is produced either from a wax injection tool or a rapid prototype process (i.e. stereolithography, 3D printing, etc.) The invest is an exact replication of the geometry to be produced, with the inclusion of machining stock on critical surfaces, stock to fill small holes to be drilled, machining hold down features, inspection datums, and a shrinkage factor applied to the entire geometry. Gating runners and metal pouring geometry are wax welded to the invest(s) . The wax assembly is then dip coated in ceramic slurry and has ceramic media applied to the wet surface. After the coat is dried the shell coating process is repeated until an adequate buildup thickness is obtained. The shell is de-waxed and fired in simultaneous operations which removes the invest completely from the shell and fuses the ceramic to produce a robust mold. The metal is melted from a raw elemental stock within a vacuum furnace in order to maximize the quality of the produced part, and is subsequently poured into the evacuated mold cavity. The metal is allowed to solidify and cool. After the shell and gating system is removed, the casting is then subjected to HIP processing. The casting process is controlled and is produced to AMS 7918, “Beryllium Aluminum Alloy Investment Castings.” This is done to assure a homogeneous casting.

At this point the blank is ready for final machining of the critical surfaces. The machine stock applied is a function of the casting variability, and the minimum material to adequately machine the surfaces. For the geometry identified, 0.045” machine stock was applied to the optical surfaces and the pockets would remain as-cast with their inherent variability. The bottom face of the stiffeners and machining tabs had 0.030” of stock applied (machine stock can be identified as the blue surfaces in Figures 5, 6 below.) Drilling and tapping operations for small holes and required load-bearing threads will be required. The significant reduction in required machining yields savings from less machining and programming hours, improved buy-to-fly (can be as low as 1.1 to 1) for a premium material, and potentially a reduced tooling package (geometry dependent.)

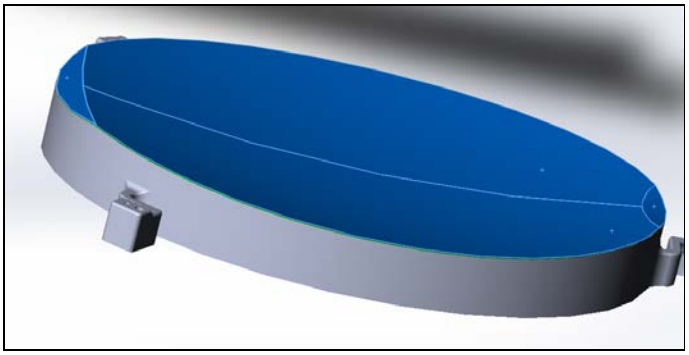

Figure 5: Casting blank with machine stock highlighted – optical surface

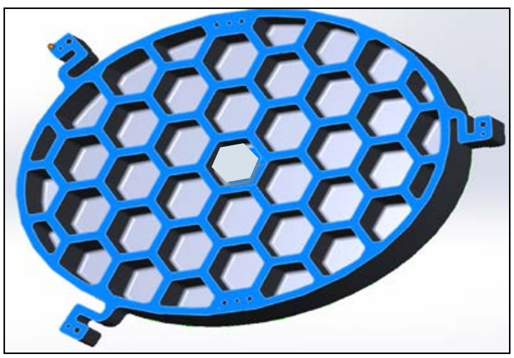

Figure 6: Casting blank with machine stock highlighted - light weighted surface

For the casting process, the material is included in the casting price to produce this near net shape blank. The cost for the casting to produce the mirror blank at quantity 1 is $3,150.00. There is however initial non-recurring tooling and non-recurring engineering (NRT, NRE) requirements to produce this investment of $16,000.00. For this cost analysis, the investment NRE and NRT is amortized per piece as quantities increase.

After the procurement of the raw material or the casting mirror blank, machining cost is incurred proportional to the number of machine hours required to finish the optic from billet or the cast blank. Machining NRE/NRT is equivalent for either the cast or billet process. For the sake of this comparison, therefore, CNC machining NRE/NRT will be neglected. All final optical processing is also equivalent and therefore will be omitted in the cost analysis. A summary of comparative costs is shown in figures 7 and 8.

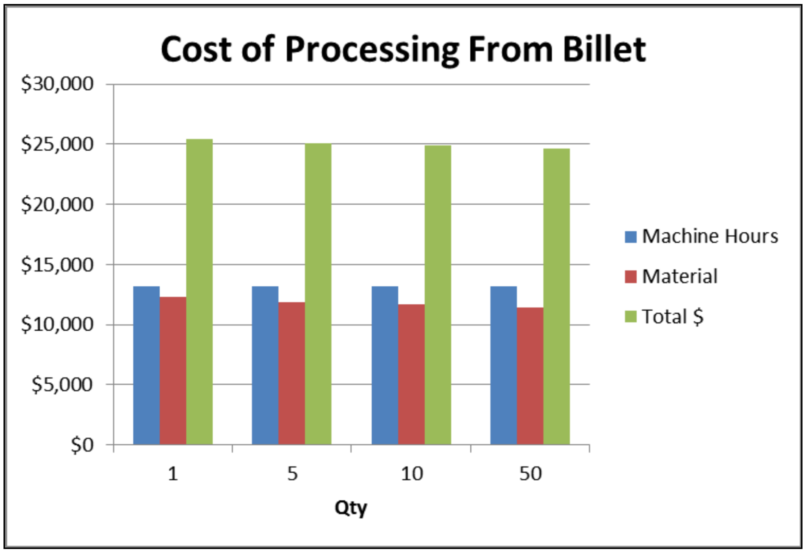

Figure 7: Cost of Materials and Processing from AlBeMet® Billet

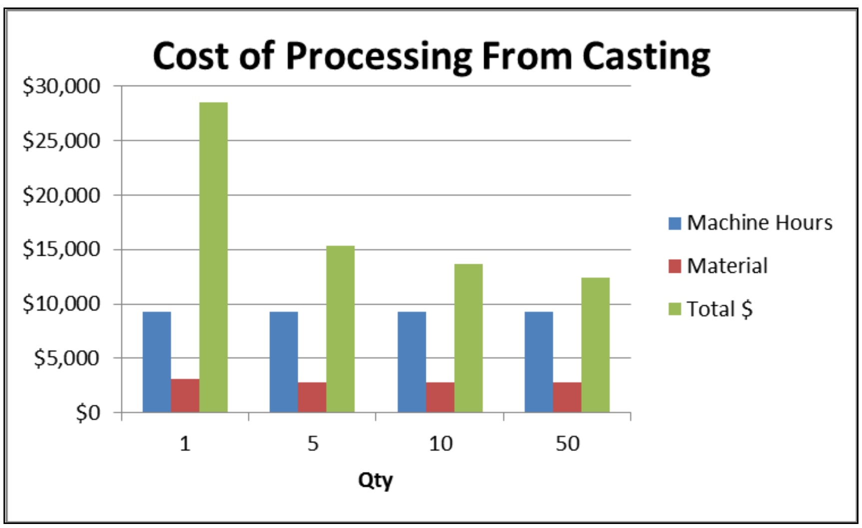

Figure 8: Cost of Materials and Processing from Beralcast® Casting

Figures 7 and 8 illustrate a compelling argument toward further investigation of the viability of casting versus billet processing for optical substrates. Note that the overall cost of processing from a casting, while slightly higher for quantity 1, reduces as quantities increase. Contrasting this, the overall cost of processing from a billet of raw material begins slightly lower for quantity 1, but with negligible reduction in cost as quantities increase. This is due to the cost of raw material associated with billet processing. Figure 9 illustrates the break-even point at which the cost of the casting NRE/NRT is absorbed. In other words, the cost of the casting investment NRE/NRT divided by the quantity ordered becomes less than the cost of the raw material and machining cost of the billet at quantity 2 or more.

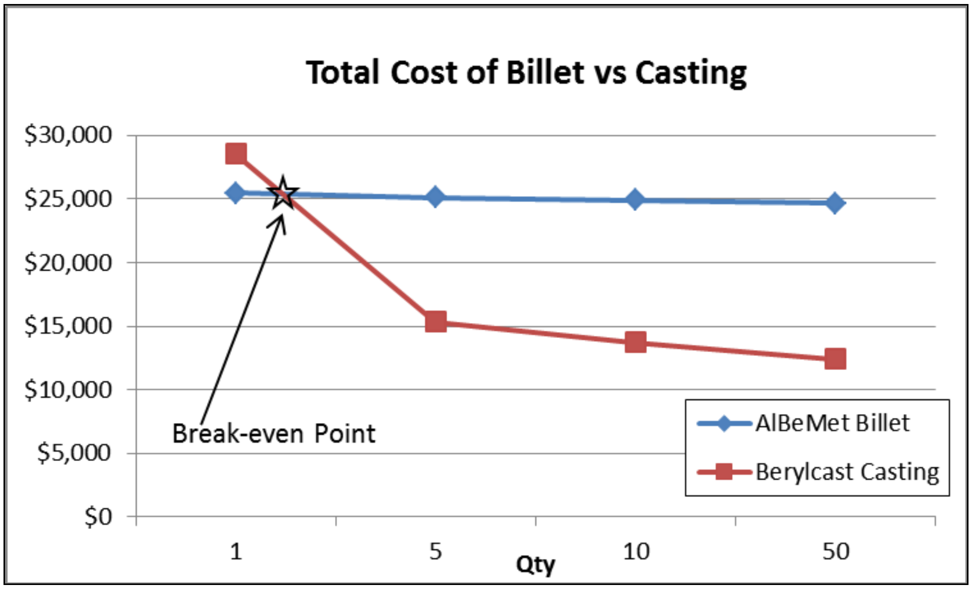

Figure 9: Break-even Point for Casting NRE/NRT

The initial cost analysis of producing a representative complex geometry optical component from a casting of Beralcast® 191 versus from a billet of AlBeMet® shows that there are compelling reasons to move forward with thermal and optical studies of the processed material. The cost of raw material is reduced in the cast part due to the fact that cast shape approximates the final optic and therefore the loss of material in the form of waste is significantly reduced. In addition, the machining hours required to finish the component (mechanically) are reduced due to the fact that only a small amount of stock removal is required. Finally, the break-even point for absorbing the initial investment NRE/NRT occurs at quantity of 2 units, after which the cost per unit reduces dramatically for this geometry.

3. PRELIMINARY THERMAL STUDY

Initial thermal testing was conducted on a cast plano light-weighted Beralcast® 363 mirror blank (see Figure 10 below.) It was surface ground, nickel plated, polished and thermal cycled to provide a general indication of thermal stability when nickel plating the optic is required (the off-axis parabolic geometry in figures 1, 2, 3, requires diamond turning and post polishing to achieve the optical specifications required). The optic was characterized interferometrically from -45°F to +165°F and at ambient. The results showed a 0.060 wave RMS wavefront error at ambient, 0.407 wave RMS wavefront error at +165°F, and 0.659 RMS wavefront error at -45°F.

While not of sufficient thermal stability for a precision optic, these preliminary results prove encouraging. This mirror blank was produced from Beralcast® 363 without HIP processing. Because HIP processing reduces microporosity and increases homogeneity, it is believed that HIP'd Beralcast® 363 or 191 will perform better, possibly resulting in a tolerable wavefront error over temperature excursions of the magnitude tested here.

Figure 10: Light-weighted Beralcast® 363 mirror

In order to test the hypothesis that HIP'd Beralcast® 363 or 191 may be considered an alternative to HIP'd AlBeMet® in an optical application, Inrad Optics has designed the simple plano geometry mirror substrate illustrated in Figure 11. This mirror will be measured interferometrically at temperature and compared to a mirror of similar design fabricated from AlBeMet®. This project is on-going.

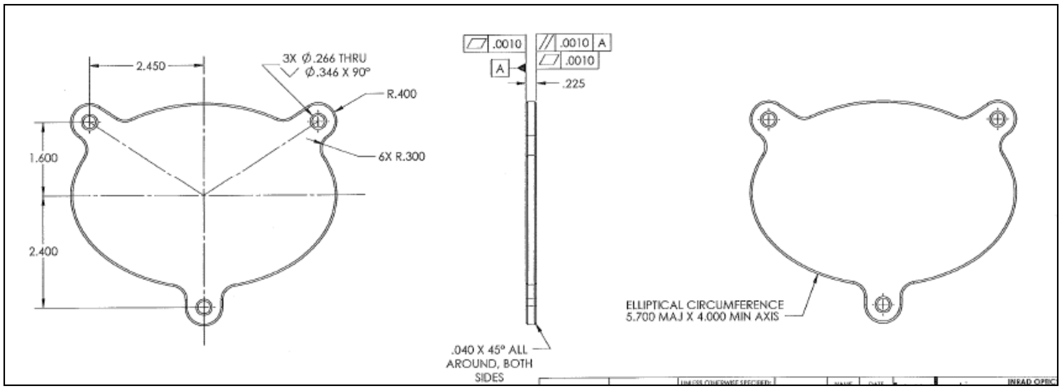

Figure 11: Simple mirror blank

4. CONCLUSION

Many light weight, high performance optical applications require the use of strong, rigid, thermally stable materials such as beryllium or AlBeMet®. However, a limitation to using these materials is cost. The cost is driven by material, labor and machining.

IBC Advanced Alloys and Inrad Optics have teamed to investigate the potential of using Beralcast® 191 and 363 alloys which are specifically designed for net-shape investment casting of complex structures. In this paper, a cost analysis was performed to compare producing a complex geometry substrate from both AlBeMet® billet and Beralcast® casting. The results of the cost analysis proved encouraging with Beralcast® producing a significant reduction in total cost after the realization of the 2nd unit produced.

The potential fiscal benefits of using cast materials over billets motivated further technical exploration. A preliminary thermal analysis was performed on a simple non-HIP'd light-weighted casting. The mirror substrate was optically processed, then subjected to thermal excursions of the magnitude commonly seen in demanding applications. The results showed a wavefront error total deformation of < 0.6 waves RMS over a 200° F temperature delta.

This result is sufficiently encouraging to continue the analysis with HIP'd materials which involves producing a simple mirror substrate from HIP'd Beralcast® and compare its performance to an equivalent mirror produced from AlBeMet® This project is on-going.

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