Application and Testing of Additive Manufacturing for Mirrors and Precision Structures

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ABSTRACT:

Additive Manufacturing (aka AM, and 3-D printing) is widely touted in the media as the foundation for the next industrial revolution. Beneath the hype, AM does indeed offer profound advantages in lead-time, dramatically reduced consumption of expensive raw materials, while enabling new and innovative design forms that cannot be produced by other means. CMM Optic and their industry partners have begun to embrace this technology for mirrors and precision structures used in the aerospace, defense, and precision optical instrumentation industries. Aggressively light-weighted, open and closed back test mirror designs, 75-150 mm in size, were first produced by AM from several different materials. Subsequent optical finishing and test experiments have exceeded expectations for density, surface finish, dimensional stability and isotropy of thermal expansion on the optical scale of measurement. Materials currently under examination include aluminum, titanium, beryllium, aluminum beryllium, Inconel 625, stainless steel/bronze, and PEKK polymer.

Design considerations for AM include the ever expanding availability of material choices, advanced CAD topological optimization tools, producible wall thicknesses, build overhang criteria, and powder removal considerations. Manufacturing considerations include scaffolding during build processes, heat treat, thermal cycling, hot isostatic pressing (HIP), diamond point turning (DPT), and optical polishing. Finished test mirror specimen were then subjected to thermal cycles to verify dimensional stability at room temperature and then measured under vacuum at hot and cold temperature excursions using laser interferometry. Both flat and spherical optical reference surfaces were used to differentiate longitudinal and transverse effects.

Keywords: additive manufacturing (AM), 3D-printing, direct metal laser sintering (DMLS), electron beam melting (EBM), binder jetting, dimensional stability, coefficient of thermal expansion (CTE) isotropy, beryllium, aluminum beryllium, metal matrix composites (MMC), metal optics, precision structures, diamond point turning (DPT), laser interferometry, topological optimization, bio-inspired design, hot isostatic pressing (HIP).

INTRODUCTION:

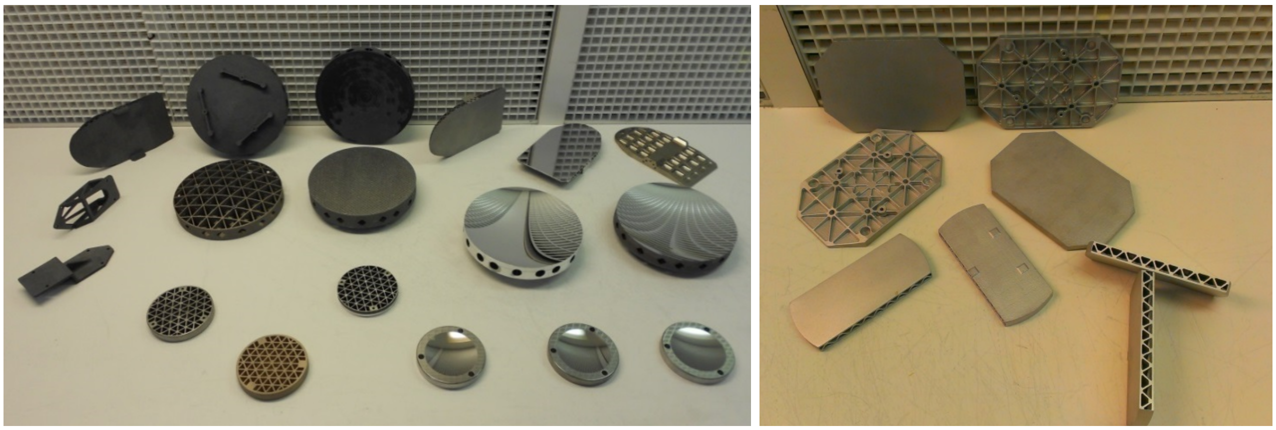


Figure 1: Assorted test mirrors designed and manufactured by CMM Optic to assess the application of additive manufacturing for a wide variety of aerospace and commercial applications for mirrors and ultra-precision structures.

Metallic, ceramic, and glass mirrors for aerospace, defense, and research in astronomy are among the most precise components produced by mankind. Metal mirrors are often made from aluminum and beryllium alloys and metal matrix composite materials such as Al-SiC and Al-Be. Metal mirrors are often chosen over glass or ceramic when strength, toughness, extreme light-weight, integral mounting features, thermal conductivity, specific stiffness, structural damping, and other properties are of interest.

Metallic, ceramic, and glass mirrors, and lenses are typically housed within ultra-precision structures that likewise require excellent dimensional stability and isotropic properties in order to tightly control the registration of optical elements over time and temperature. Examples of such structures include gimbals, optical benches, lens barrels, and metering tube structures common to dynamic optical pointing systems and telescopes.

CMM Optic Structures Group routinely design and/or produce many types of metal and SiC mirrors, ultra-precision structures, and related assemblies thereof. Starting in 2014 we have been exploring the application of the method of additive manufacturing (AM) for a variety of precision components. An overview of our progress in the evolution of design and manufacture of mirrors and precision structures in this exciting technology area is presented herein.

DISCUSSION:

Generally mirrors and precision structures produced by AM can be expected to have more refined features and similar dimensional accuracy as high quality investment castings. Due to the fine and homogeneous material grain structure that results from the limited re-melting of gas atomized spherical powders, AM generated components are likely to be superior in strength and isotropic thermal expansion compared to investment castings and can approach mechanical properties observed in bar and plate materials (ref. 1). In most cases, strength is not a driving criterion for mirrors and precision structures, but dimensional stability and isotropic expansion over temperature are critical.

Primary impetus for development of mirrors and precision structures by additive manufacturing include the following:

Advanced design forms: Semi-closed cellular and lattice structures, and essentially free form topological optimization can be realized with additive manufacturing. New CAD applications are being developed to embrace topological optimization. Blending and layering of different materials as part of AM processes is also emerging.

Product mass reduction: Structural optimization advantages enabled by AM results in significant mass reduction to achieve the same function. Unlike machining, added complexity in favor of mass reduction actually reduces AM cost.

Lead time advantage: 1-2 week turnaround for complex prototypes including set-up, printing, cool down, stress relieving, and machining off of scaffolding is readily achievable by AM. Although bar or plate aluminum is readily available on short notice, bulk beryllium is generally custom ordered based on size requirements and procurement can often take 12-16 weeks or longer. For AM, powders can be maintained in stock, independent of part size and shape.

Raw material cost savings: Expensive alloys machined from bulk materials are commonly whittled away to less than 10% of the input stock. In contrast, Titanium and Beryllium parts produced by AM from powder can result in considerable cost advantages since perhaps only 10% of the material is trimmed away and sold for recycling.

Dimensional homogeneity and stability verses solid bar and investment castings: GD-GIT investigations have directly compared AM test mirrors to similar specimen machined from solid bar stock. AM generated components have been shown to perform favorably compared to bar materials.

Strength verses solid bar and castings: We have not yet focused on strength experiments since this criterion is not typically mission critical for mirrors and precision structures applications. AM generated parts will generally have superior strength compared to castings due to finer grain structure and reduced critical flaw sizes (ref 1). Continuous improvements to AM processes in other aerospace industries such as jet and rocket engine development are resulting in optimization of metallurgical properties approaching those of forged and machined materials.

High volume potential: Current AM technology is most ideal for prototyping and low volume production. Faster processing and larger build volumes are emerging to enable batch processing of complex and moderate sized precision components to improve competitiveness with incumbent production manufacturing technologies.

Progressive machining, heat treating, and thermal cycling remain as critical for additive manufacturing as for conventional subtractive methods to ensure optimal dimensional stability and to incrementally achieve optical precision tolerances required for optical components and related structures.

AM Process	Relative Advantages	Relative Disadvantages
EOS DMLS (direct metal laser sintering)	High fidelity, small hot spot EOS machines widely used Adaptable to many materials. Good strength, metallurgy properties 100% density and good optical test results 0.25 mm walls are feasible High purity is possible	Hot process, inert gas required Scaffolding required, 45° overhang Laser reflection losses Relatively slow, low power High internal stresses can result Readily available machine size is limited to about 200 mm^3 although 400mm^3 capacity is emerging
Arcam EBM (electron beam melting)	Arcam machine widely used Adaptable to many materials Good strength, metallurgy properties Not subject to laser reflectance losses Faster than DMLS, higher power 100% dense and good optical test results. Thin walls are feasible High purity is possible	Hot process, inert gas required Scaffolding is required, 45° overhang Aluminum is not yet well developed. Available machine size is currently limited to about 200 x 200 x 380 mm^3

ExOne Binder Jet	ExOne machines widely used for sand and high density metal powders Cold process. Very fast process Adaptable to many materials Scaffolding not required. Near 100% dense and good optical test results. Available size: 800 x 550 x 400 mm^3	Porous unless re-infiltrated with second material and/ or HIPed. Pyrophoric powders such as aluminum and titanium are not yet developed. Small % entrapped binder artifacts Requires thicker walls than DMLS or EBM due to the fragility of the green form. 1.5-2.5 mm walls typical.

Table I: Primary AM processes and machine builders considered by CMM Optic for application to mirrors and related precision structures

Gas Atomization of Powders is essential to create high quality feed stock for all of the AM processes under consideration by CMM Optic. This process consists of vacuum induction melting of one metal or a mixture of metals (also ceramics and polymers) of interest in a crucible and then using a pressurized inert gas such as Argon to force the liquid metal through a fine spray nozzle that is downward directed. The resulting atomized liquid droplets then rapidly cool into spherical shaped powder having a Gaussian size distribution as they descend under gravity into a collection container. The mean particle size of a given batch can be adjusted by nozzle size and gas pressure. Spherical powder is critical for powder bed AM processes such as DMLS, EBM, and binder jetting to yield optimal compaction and isotropic properties after consolidation. Spherical powder is also favorable for its fluidic response to roller and wiper operations that are used to smooth and level the powder after re-coating to print successive layers in the build. Pure metals, alloyed metals, and metal matrix composites can all be produced by this technology. Gas atomized metal powder also virtually ensures randomized metal grain orientation during sintering operations typical of DMLS, EBM, and binder jetting AM technologies since re-melting is very limited in extent unlike metal casting and welding processes that result in partial or total melting with resulting differential cooling and metal grain re-growth.

Small scale gas atomization also offers the opportunity to produce boutique batches of metal alloys, metal matrix composites, and non-metals such as polymers and ceramics having exceptional purity and focused on unique aerospace and precision instrument applications. As an example, AM aluminum alloy formulations that are better suited for both diamond point turning and bare polishing by computerized methods such as MRF could be developed.

Although many AM technologies were considered as part of this investigation, we narrowed our selection to the processes and machine builders shown in table I above:

2.1 AM Case Study #1: 75 mm Test Mirrors for AM material and process development (see figures 2, 3, 4, 5)

In order to evaluate dominant AM technologies applied to various materials, we defined a universal 75 mm test mirror design with aggressive, open back, isogrid triangular light-weighting. The test mirrors have an F/2.0 concave spherical surface, a flat rim surface and precision machined outside diameter that were finished to optical precision tolerances. In parallel, we manufactured similar mirrors from solid bar material with no light weighting for optical test results comparison. We also utilized multiple suppliers for aluminum AM specimen. A summary of the materials and processes evaluated in the form of 75 mm test mirrors are shown in the table II below:

Material	Process	Substrate Supplier
AlBeMet162 bar	Conventional Machine, no pockets	CMM Optic
AlBeCast 910, 920, 950	SLA AM pattern + investment cast	Materion Corporation
Al 6061-T6 bar	Conventional Machine, no pockets	CMM Optic
AlSi10Mg	EOS DMLS AM	Stratasys Direct, others
Titanium 6Al4V bar	Conventional Machine, no pockets	CMM Optic

Titanium 6Al4V	Arcam EBM AM	University of Louisville
PEKK PEKK carbon reinforced	EOS DLS AM	Oxford Performance Materials
420SS+bronze Inconel 625	ExOne Binder Jetting AM	ExOne Corporation

Table II: AM powder materials and comparison bar materials down-selected by CMM Optic as part of this investigation.

Aluminum beryllium products are not currently produced by AM processes directly but are being produced indirectly by AM generated patterns used for investment casting. This material was chosen for the AM study since it is a viable candidate for near-term direct additive manufacturing as it can be both cast and electron beam welded like other AM materials and is also already gas atomized into spherical powders by Materion. CMM Optic optically processed both bar AlBe material and three different AlBeCast materials contributed by Materion Corp for purposes of this study.

Aluminum alloy AlSi10Mg has similar mechanical properties to wrought aluminum 6061-T6 and was chosen for the AM study since it is well developed for the EOS DMLS process and appears suitable as potential 6061-T6 replacement for aluminum mirrors and related ultra-precision structures. Stratasys Direct contributed 3” test mirror specimen for purposes of the study and also produced numerous other parts under contract among other qualified DMLS suppliers.

Titanium alloy 6Al4V was chosen for the AM study since it is a common opto-mechanical material that is primarily used for optical support structures where high strength, low weight, fracture toughness, and sometimes low thermal conductivity are highly valued. Also, this was an opportunity to assess the relative merits of the electron beam melting (EBM) AM process in comparison to DMLS. The University of Louisville contributed EBM generated test mirror substrates for optical processing and final testing at CMM Optic.

PEKK (polyetherketoneketone) was selected for the AM study since it has merit as alternative to aluminum for some types of opto-mechanical structures. PEKK is half the density of aluminum, is nearly as strong as 6061-T6 aluminum, and has similar CTE. PEKK is readily, and relatively inexpensively, AM processed into very intricate design forms using the EOS polymer laser sintering process. Also, PEKK powder is self-scaffolding and is thus not subject to overhang support criteria such as with DMLS and EBM. This material may be suited for light weight, shock resistant opto-mechanical structures such as lens barrels. Oxford Performance Materials provided several specimen of CMM Optic’ design for purposes of the AM investigation both in unfilled and carbon fiber filled varieties.

420 stainless steel infiltrated with bronze and Inconel 625 were chosen, not for opto-mechanical applications, but as an opportunity to assess the ExOne binder jetting technology for future use on other material systems. Since binder jetting is a cold process, any metal, polymer, or ceramic powder can, in theory, be consolidated into a green state suitable for sintering, infiltration, and HIP. It is also conceivable to produce uniformly porous forms that can be infiltrated to full density and/or over-coated or plated with 100% dense materials. ExOne contributed 420SS/Bronze and both HIPed and un-HIPed Inconel 625 light-weighted 3” test mirrors for finishing and test at CMM Optic.

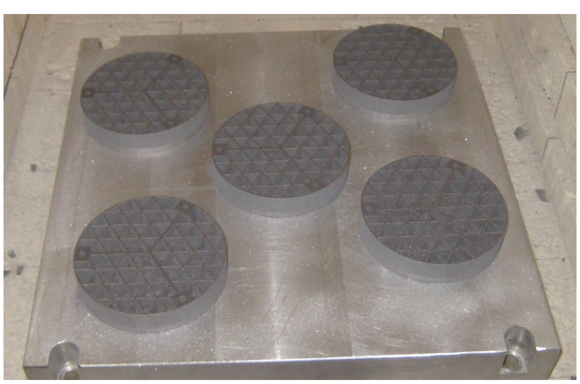


Figure 2: At left is a batch of five light weighted 3” isogrid light-weighted AlSi10Mg test mirror specimen on the build plate of an EOS DMLS AM machine at Stratasys Direct. At middle right is shown a diamond point machined solid aluminum 6061-T6 test mirror next to a similarly processed DMLS generated AlSi10Mg specimen. Surface finish and optical figure results are similar.

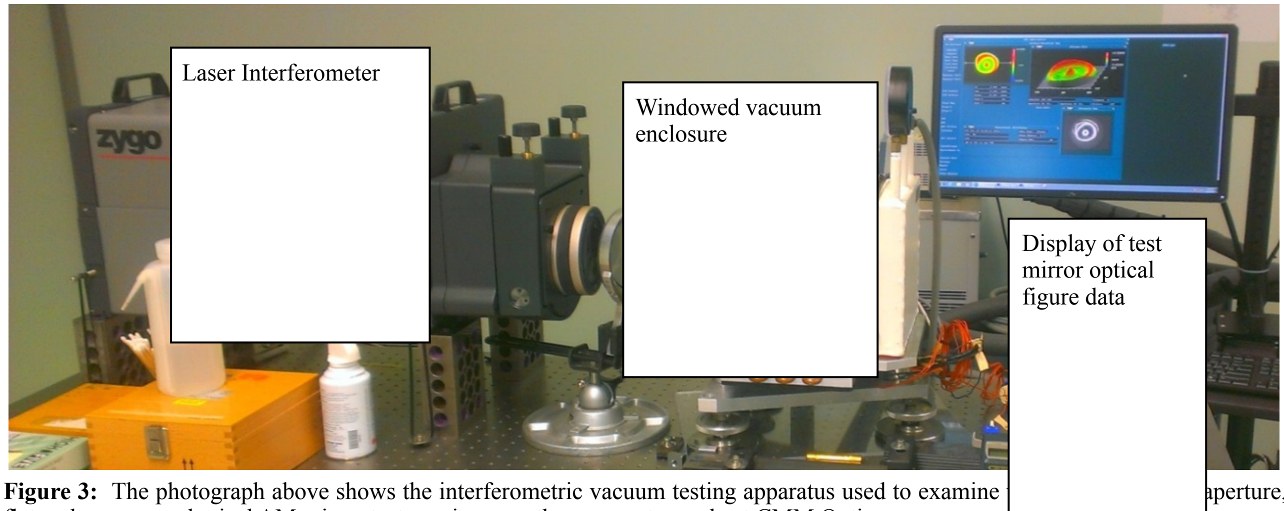
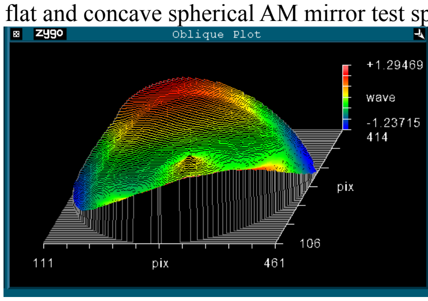
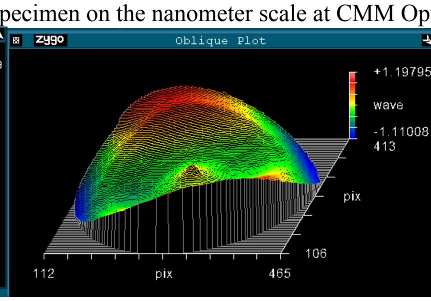


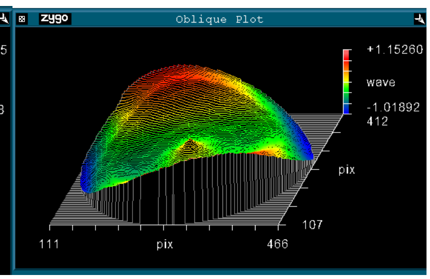
Figure 3: The photograph above shows the interferometric vacuum testing apparatus used to examine aperture, flat and concave spherical AM mirror test specimen on the nanometer scale at CMM Optic.



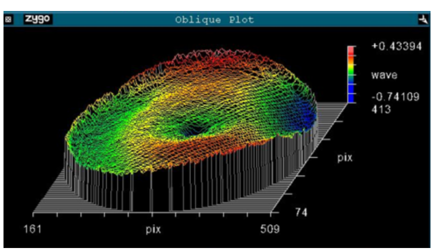
3” DMLS AlSi10Mg cc sphere at 0°F



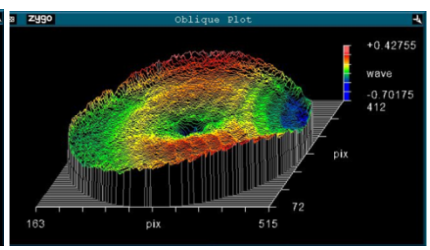
3” DMLS AlSi10Mg cc sphere at 70°F



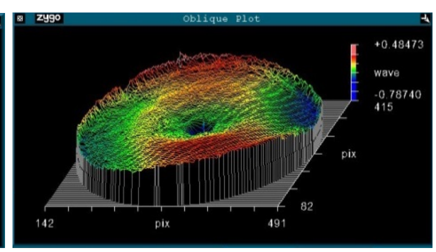
3” DMLS AlSi10Mg cc sphere at 140°F



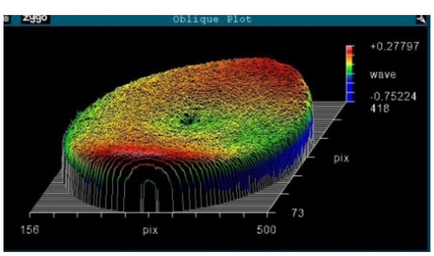
3” EBM Ti6Al4V cc sphere at 0°F



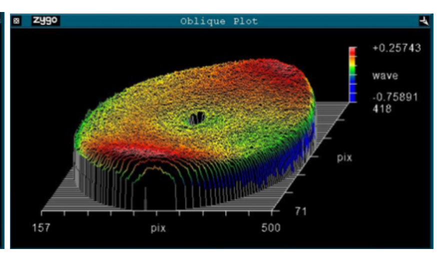
3” EBM Ti6Al4V cc sphere at 70°F



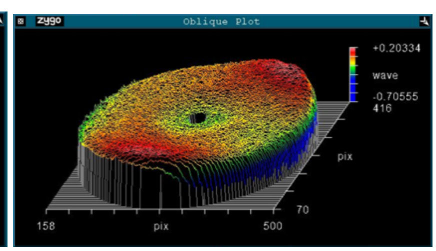
3” Ti6Al4V cc sphere at 140°F



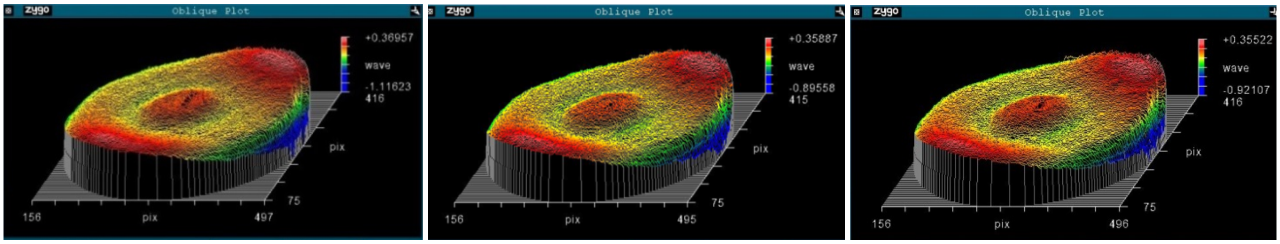
3” BJ 420SS/Brz cc sphere at 0°F



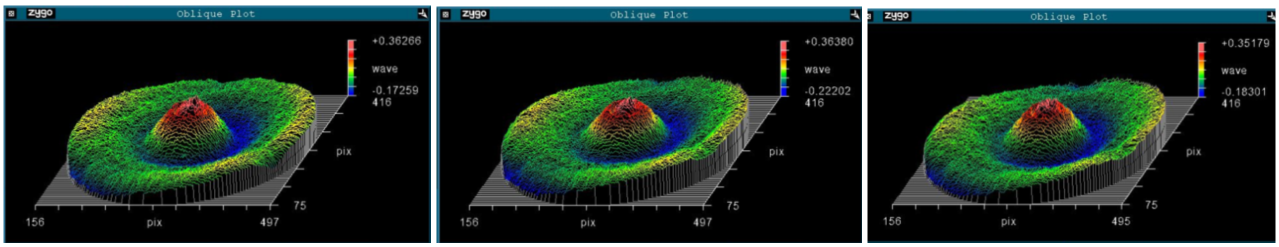
3” BJ 420SS/Brz cc sphere at 70°F



3” BJ 420SS/Brz cc sphere at 140°F

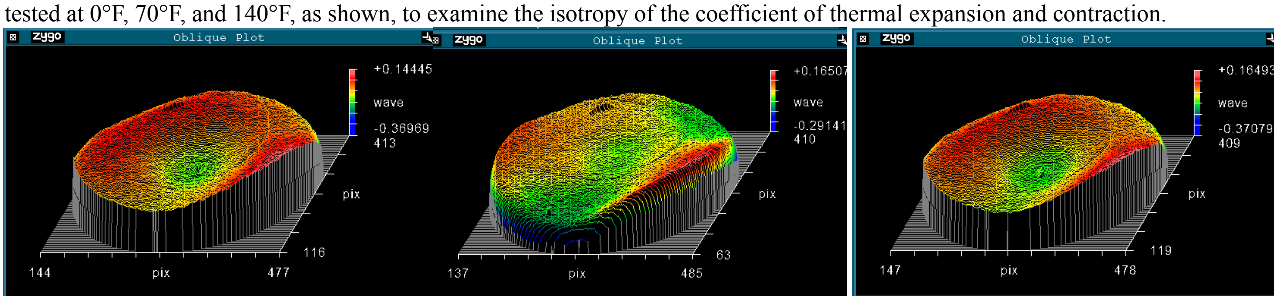


3" BJ/HIP Inconel cc sphere @0°F **3" BJ/HIP Inconel cc sphere @ 70°F 3"** **3" BJ/HIP Inconel cc sphere @ 140°F**

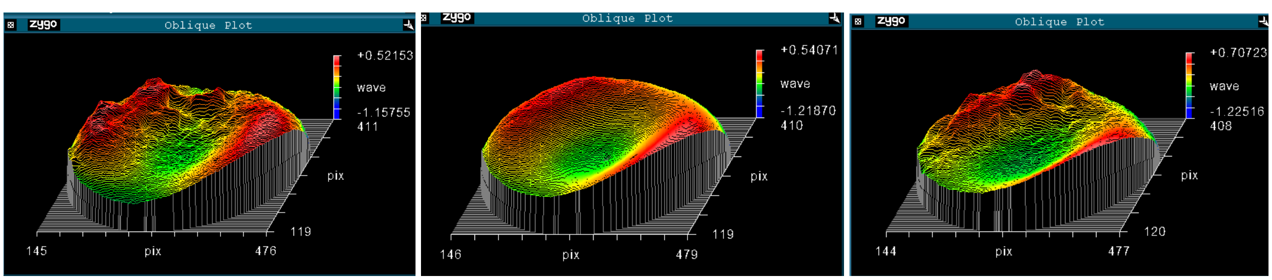


3" BJ/no-HIP Inconel cc sphere at 0°F **3" BJ/no-HIP Inconel cc sphere at 70°F** **3"BJ no-HIP Inconel cc sphere at 140°F**

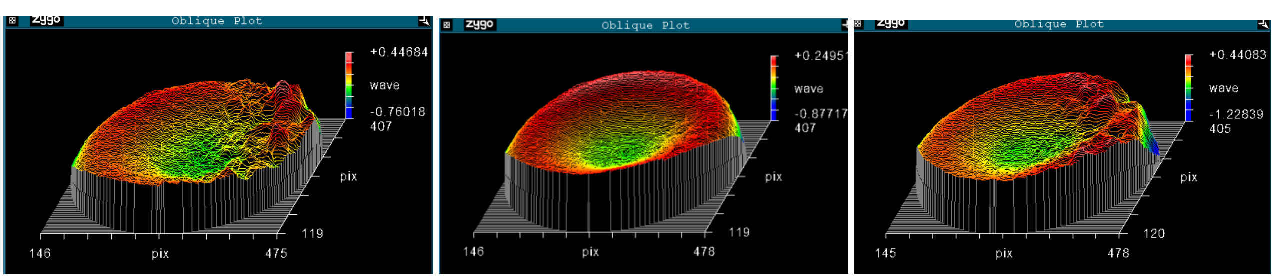
Figure 4: Interferometric measurements over temperature of 3" isogrid light weighted concave spherical test mirrors made from various materials and three different powder bed AM technologies. DMLS denotes direct metal laser sintering. EBM denotes electron beam melting. BJ denotes binder jetting. HIP denotes hot isotstatic pressing. All of the test mirrors exhibited excellent dimensional stability when thermal cycled from -100°F to +325°F and re-tested at room temperature. Then each mirror was vacuum tested at 0°F, 70°F, and 140°F, as shown, to examine the isotropy of the coefficient of thermal expansion and contraction.



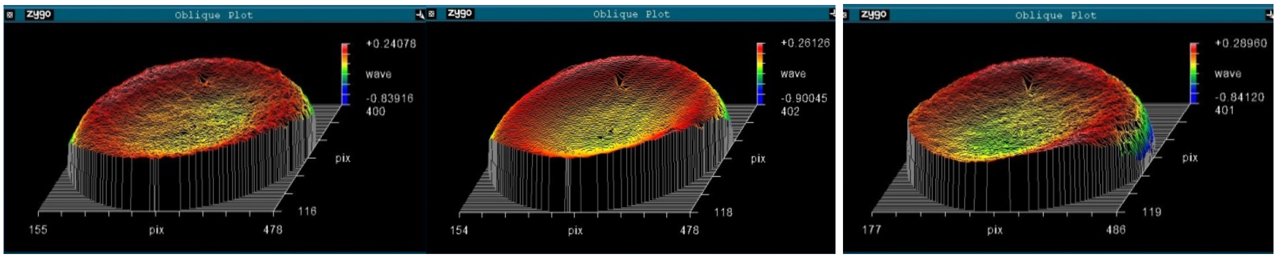
3" AlBeMet162 cc sphere @0°F **3" AlBeMet162 cc sphere @ 70°F 3"** **3" AlBeMet162 cc sphere @ 140°F**



3" AlBeCast-910 cc sphere @0°F **3" AlBeCast-910 cc sphere @ 70°F 3"** **3" AlBeCast-910 cc sphere @ 140°F**



3” AlBeCast-920 cc sphere @0°F **3” AlBeCast-920 cc sphere @ 70°F 3”** **3” AlBeCast-920 cc sphere @ 140°F**



3” AlBeCast-950 cc sphere @0°F **3” AlBeCast-950 cc sphere @ 70°F 3”** **3” AlBeCast-950 cc sphere @ 140°F**

Figure 5: Interferometric measurements over temperature of 3” spherical test mirrors from various aluminum beryllium formulations. The AlBeMet162 specimen was sintered and HIPed from gas atomized spherical powder into bulk material and then post machined with no pocket structure. The AlBeCast-910, -920, -950 are light weighted and were investment cast from AM SLA polymer patterns. As expected, the AlBeMet162 changed very little over temperature attributable to the nature of the gas atomized spherical powder. The AlBeCast-910, -920 test mirrors exhibited little global change in optical figure but both developed local bumps and holes at hot and cold temperature excursions due to anisotropy of the cast microstructure. The AlBeCast-950 specimen remained optically smooth over the entire temperature range. Since AlBeCast is primarily developed for structural applications and not mirrors, the small degree of anisotropy that is seen is probably not consequential for most applications. It is possible that with further work, AlBeCast-950 might be developed for mirror applications. Also, future beryllium and aluminum beryllium AM development, particularly when using gas atomized spherical powder, is expected to replicate results summarized for AlBeMet162 above and the materials discussed in figure 4.

Phase measuring laser interferometry was used to examine the optical figure of various AM test specimen after optical processing and thermal cycling to ensure dimensional stability when measured at room temperature. Each test mirror was then mounted to a heat exchanger within a windowed vacuum enclosure as shown in figure 3. The relatively thick vacuum window was core drilled in the center so a much smaller and much thinner window could be fitted over the hole to minimize the induced spherical aberration when measuring the F/2.0 concave spherical surface. The larger and thicker outer window allowed measurement of the flat rim of the small spherical test mirrors or other flat mirror test specimen up to 100 mm with a small obscuration.

2.2 AM Case Study #2: Aggressive Open back 150 mm aperture mirror design (see figure 6)

CMM Optic designed and manufactured a 150 mm aperture, concave spherical, AlSi10Mg open back light weight mirror design similar to many conventionally machined designs except with several features uniquely enabled by the AM approach (fig. 6). All walls were only 1.25 mm, corner radii were limited to about 0.25mm and each wall section in the isogrid triangular pocket structure was cut through with diamond shaped holes to reduce superfluous mass. The mirror also has three mounting bosses that are grown starting about 2/3 up from the mirror face sheet. In similar fashion it is possible to easily transition to a “T” shape at the tops of each of the ribs to further improve the structural efficiency of the design. The mirror was grown with the mirror side down by first printing a low density scaffold structure to support the dome of the concave optical surface. The through holes in the sides of the pockets were required to be diamond shaped so that an overhang condition of 45° could be sustained while at all times melting powder on top of solidified metal. After conventional machining to remove scaffolding, the optical surface was generated by diamond point machining. Although the optical surface sustained 100% density and respectable optical form and finish, the substrate was prone to significant mechanical stress release that could be readily seen during interferometric testing. The optical figure developed triangular bumps replicating the underlying pocket structure (aka quilting). The mirror figure proved stable after thermal cycling and also held figure when measured over temperature. Since another supplier had successfully produced a more aggressive part of similar design without significant stress release using the same type of aluminum powder, same model EOS DMLS machine, and presumably the same processing parameters, a root cause investigation was undertaken. It was ultimately determined that the laser used for the process was operating below the required power level required by the process, thus resulting in high residual stress.

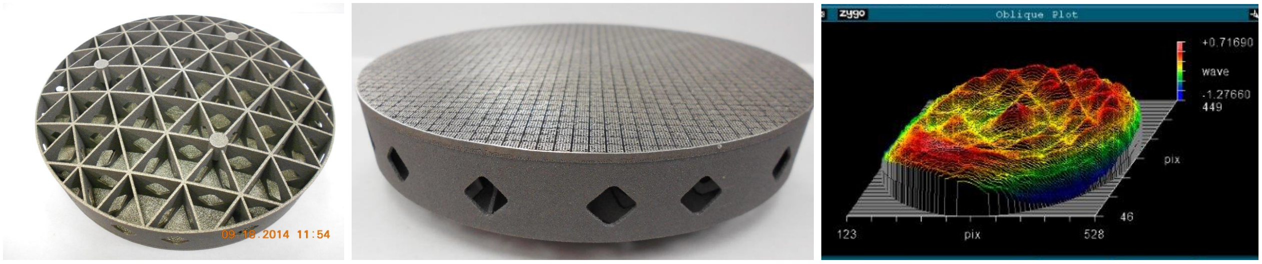
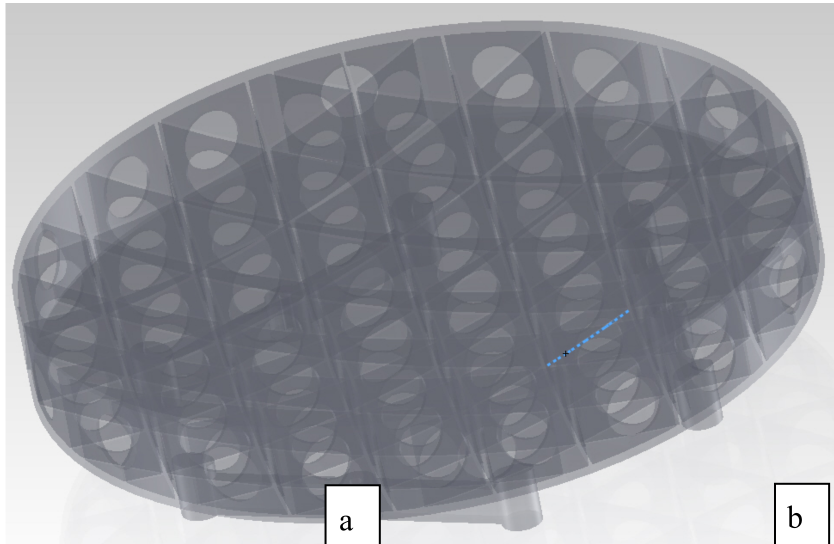


Figure 6: At far left is the back side of a 150 mm aperture light-weight concave spherical mirror designed and optically finished by CMM Optic. All walls are 1.25 mm thick, all corner radii are about 0.25 mm, each pocket wall is holed through, and three mounting bosses are grown about 2/3 up the rib structure from the mirror face sheet. All of the desired features proved to be readily producible in AlSi10Mg by DMLS. At center the low density scaffolding structure that was printed to support the concave dome of the spherical optical surface after substrate removal from the AM build plate can be seen prior to final machining. At the far right an interferometric measurement is made of the finished optical surface. Note the triangular pocket structure that resulted from stress spring-back effects on the optical measurement scale caused from too low applied laser power during DMLS.

2.3 AM Case Study #3: Aggressive closed back 150 mm aperture mirror design (see figure 7)

The 150 mm concave spherical mirror design was further modified to thin all of the walls from 1.25 mm to 0.75 mm thickness, close the back sheet of the mirror and apply circular holes through the center of each of the triangular wall sections. In addition, three tangent flexure bars connected at six points to the back of the mirror were directly printed into the closed back sheet. The selected outside supplier was able to maintain the 45° overhang condition by tilting the substrate by 45° relative to the build plate of the AM machine. The scaffolding was machined away and the part was diamond point machined. The resultant optical surface figure was smooth, <1.0 wave P-V, and the surface roughness averaged 60-80 Angstroms RMS. Also, an attempt at computer polishing using MRF at QED was promising (fig. 7).



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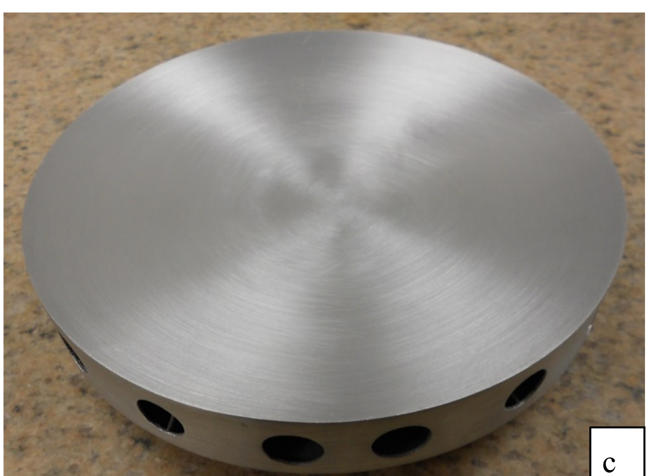

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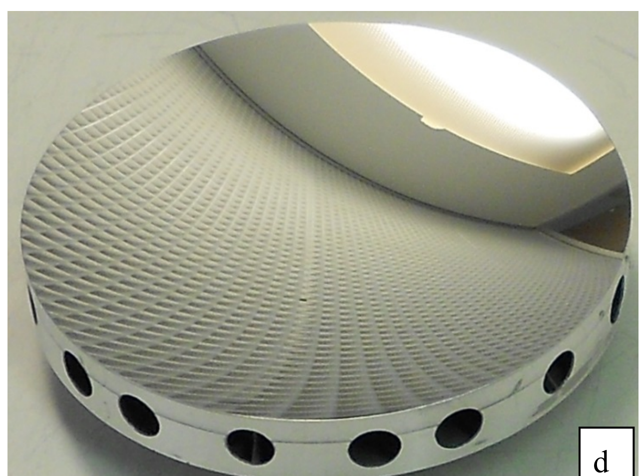

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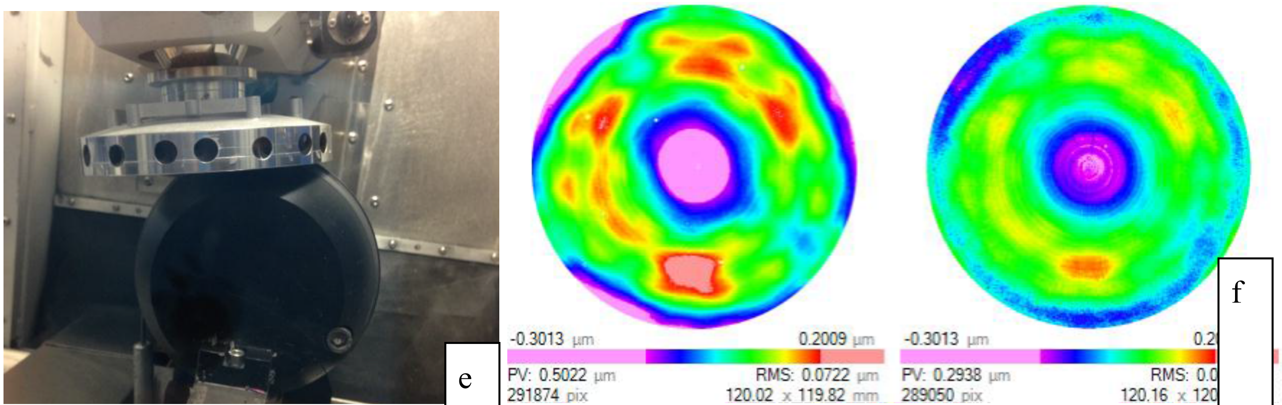

Figure 7: Various stages in the design and m cture of a closed back, aggressively light-weighted aluminum mirror produ y additive manufacturing. a) Semi-transparent n model b) Tilted at 45 degrees with scaffolding after removal from the S build platform. c) after conventional machin remove scaffolding. d) after diamond point machining to about 75 Ang ns RMS uniform and dense optical finish. e) Set QED Technologies MRF computer polishing machine. f) Initial and final ts after one hit using MRF to significantly impro gure, eradicate diamond turning artifacts, and improve the RMS surface finish.

2.4 AM Case Study #4: Flat mirrors for optical scanning and line of sight (LOS) stabilization (see figure 8)

Flat mirrors made from aluminum, beryllium, and silicon carbide are commonly used for high speed scan mirrors and mirrors used on gimbals for line of sight (LOS) stabilization of EO/IR imaging and targeting systems. Typically these mirrors must remain optically flat when influenced by operating accelerations and must be light-weight and low inertia to minimize the mass and power requirements for supporting structures and drive motors. Beryllium is a particularly good fit for these applications because it is both very light and very stiff giving rise to a specific stiffness that is about 6.3X greater than most common structural metals such as aluminum, titanium, steel, and magnesium. Silicon Carbide mirrors can approach the specific stiffness of beryllium (up to about 5.5X over aluminum) but are heavier, more difficult to process, and much more fragile.

CMM Optic routinely designs and/or manufactures beryllium mirrors for optical scanners and LOS stabilization. For basis of comparison, we have contrasted the cost and performance of a conventionally machined (subtractive manufactured) production mirror with open back light weighting pockets used on a production Airborne EO/IR LOS stabilization system to a notional mirror design optimized for manufacture by the AM technology. By using AM, the back of the mirror can be closed and the walls can be made much thinner. The notional mirror, shown in figure 8, has identical outer dimensions and mounting interface features to the design of the production mirror. The notional design requires much less input material, is presumably much lower cost, much shorter lead-time and also improves the structural efficiency for resisting deflections due to acceleration loads. Resultant mass and inertia reduction could also result in reduced cost and mass for motors and supporting structures that comprise the system around the operation of the mirror. CMM Optic also successfully produced and optically finished an aluminum AlSi10Mg version of the notional design form to demonstrate the feasibility and promise of AM technologies for this important application. The AlSi10Mg substrate was proven to be 100% dense and readily sustained optical tolerances for surface figure and surface finish after diamond point machining.

Table III below compares relative performance, cost, and delivery schedule for the notional AM generated beryllium, aluminum beryllium metal matrix composite (MMC), LOS stabilization scan mirror compared to the current production design. An inventory of powder that can be made into any size of shape by AM technologies virtually eliminates a lead-time disadvantage that is commonly experienced in the procurement of custom sized blocks of beryllium for conventional machining operations. It can also be seen that lower cost and lower performing aluminum beryllium MMC AlBeMet162 can compete with beryllium performance due to design advantages. AlBeMet162 also has a better match to the CTE of a thin applied layer of electroless nickel plating that is routinely applied to mirrors of this nature to enable refined optical requirements after polishing.

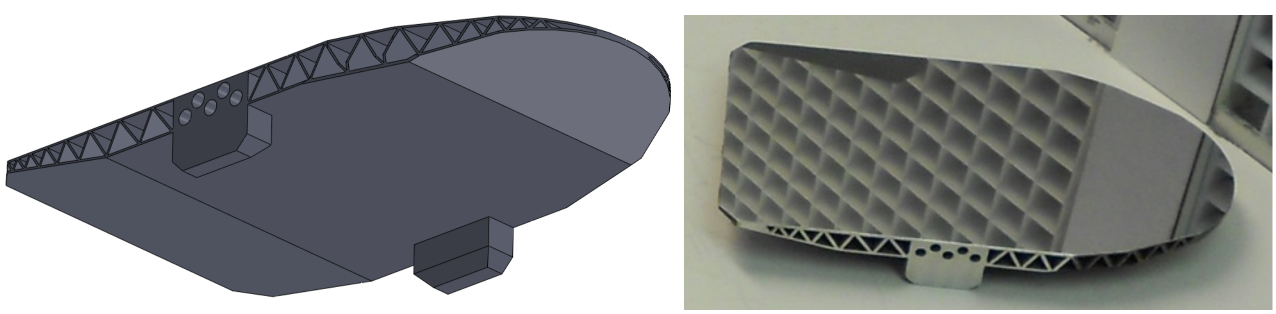

Figure 8: CMM Optic produces a beryllium mirror for a production airborne EO/IR system that is machined from a solid block of beryllium material with an open cell pocket structure. At left is a notional beryllium mirror with identical overall dimensions and interface mounting that is redesigned for AM technologies by closing the back side, thinning all of the wall sections and employing a high efficiency extruded bridgework structure that cannot be produced by conventional manufacturing methods. At right the notional mirror was prototyped and optically finished out of aluminum alloy AlSi10Mg by the DMLS AM process. The resulting surface finish was less than 50 Angstroms RMS after diamond point flycutting operations.

Criteria	Current Design	Alternate Design #1	Alternate Design #2	Remarks
Blank material	Beryllium	Beryllium	AlBeMet162	AlBe alloy is lower cost. CTE match of nickel plate is better
Blank shape	rectangular	None (powder)	None (powder)	Machined blanks nested and EDM wire cut two at a time
Blank Mass	454 grams solid	44 grams powder	56 grams powder	AM yields 10X mat'l mass savings
Blank Cost (Be)	$1500	<<$1500	<<$1500	Could be <$200 for AM
Blank lead time	8 weeks	0 weeks	0 weeks	AM powder reserves can be inventoried
Final Mass	115.4	40 grams	52 grams	74% scrap during machining Negligible scrap by AM
Self weight deflection	2.5 micro inch	1.0 micro inch	1.5 micro inch	Supported at drive shafts, smaller = better
First Modal Frequency	4654 Hertz	5054 Hertz	4127 Hertz	Free of constraint
Rotational Inertia	140,232 g*mm^2	51,000 g*mm^2	75,000 g*mm^2	Defines motor size, gimbal mass smaller = better
Mirror fab at GD-GIT	8 weeks	2 weeks	2 weeks	Excluding optical processing

Table III: Above is a summary of the cost, schedule, and performance advantages realized by a notional AM generated beryllium or aluminum beryllium mirror over a current production beryllium mirror that is machined from solid block material.

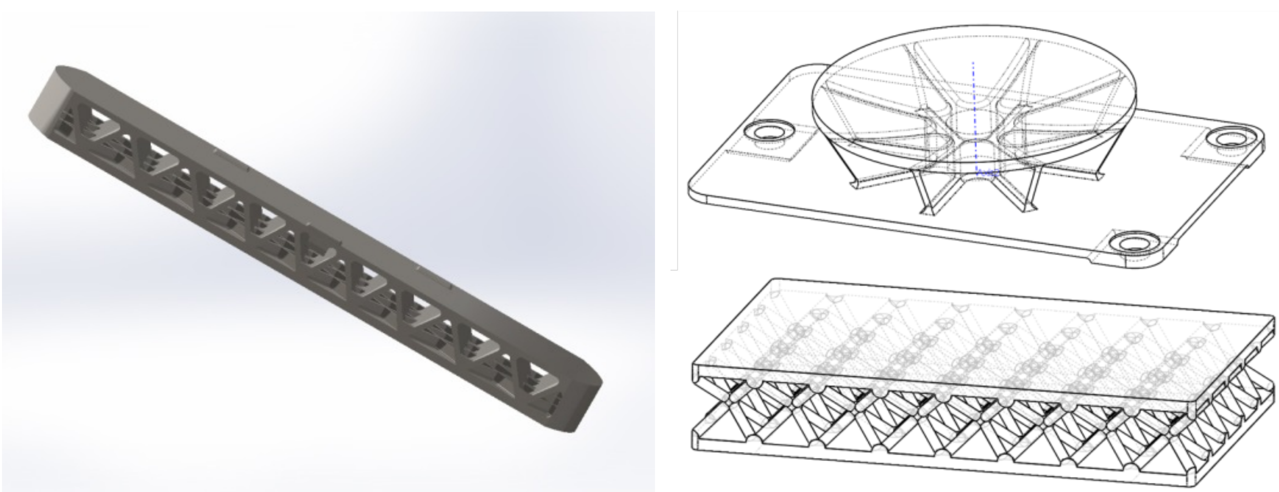

Figure 9: At left is a 75 X 150 mm light-weighted mirror design for a commercial LIDAR system that has been printed in both 100% density AlSi10Mg by DMLS and 60% density 420SS by binder jetting. AM technologies readily enable porous construction of mirror substrates followed by electroless nickel plating for refined optical finishing. Besides the extruded bridging, the mirror back sheet is reinforced by an isogrid of short interior wall. At the upper right is a design concept for future off-axis aspheric mirrors. At the lower right is a test mirror concept that will explore the relative manufacturing and optical performance merits of a free form lattice type light-weighting structure. All of these design forms are difficult or impossible to manufacture by conventional methods.

2.5 AM Case Study #5: Other AM design forms that are being developed by CMM Optic

DMLS and EBM can directly generate very thin walls of fully dense and tempered metal but are limited by both overhang criteria and build speed. By comparison, binder jetting can very quickly produce green forms that must be further processed by curing, sintering, and heat treating. The binder jetted green forms are fragile thus requiring greater wall thickness than required for DMLS and EBM, but binder jetting can solidify powder when using underlying powder as support. This is a significant advantage over DMLS and EBM. DMLS and EBM can produce components that are essentially as pure the powder that is used. Components produced by binder jetting will have a small percentage of evenly distributed binder related carbon artifacts that are not fully burned out during sintering processes.

Figure 9 above illustrates several parts that have been printed, or will soon be printed, to further examine the relative cost and performance relationships among DMLS, EBM and binder jetting AM technologies. AM also enables the creation of fine porous structures from metals and ceramics that can be over-plated with other materials such as electroless nickel plating and/or infiltrated to 100% density. Topographical optimizations can result in free-form lattice type structures that can appear otherworldly in comparison to conventional designs.

3.0 SUMMARY:

All of the AM mirror specimen tested as part of this project exhibited excellent density, homogeneity, dimensional stability, and isotropy of thermal expansion over temperature on the optical scale of measurement and compared well with bulk materials in these regards. The DMLS process for aluminum alloy AlSi10Mg showed variations in residual stress release that can be corrected by application of appropriate heat treating operations. Two batches of highly stressed parts were traced to the use of insufficient laser power at one of our suppliers. AM AlSi10Mg diamond point machined surprisingly well, approaching that possible with 6061-T6. An MRF computer polishing experiment at QED Technologies on a bare AM aluminum mirror resulted in predictable figure convergence, removal of diamond turning artifacts, and reduced surface roughness, but at the expense of a gray and hazy surface that could be attributable to low temper caused from previous heat treating experiments. Titanium 6Al4V, 420 stainless/bronze, and Inconel 625 test mirrors made by EBM and binder jetting showed very little indication of stress release during optical finishing operations.

Aluminum beryllium test mirrors of the same design were manufactured by Materion as investment castings made from polymer patterns using the AM methodology of stereo lithography apparatus (SLA). AlBeCast-910, -920 both showed good global dimensional stability but some indications of localized anisotropy of CTE over temperature. AlBeCast-950 appeared to perform nearly as well as AlBeMet162 block material that is produced by sinter/HIP of gas atomized MMC aluminum/beryllium spherical powder. All of the AlBeCast test mirrors had evidence of fine porosity but this did not prevent grinding and polishing of smooth optical surfaces that could be tested at visible wavelengths. Investment casting of aluminum beryllium products, spurred by AM rapid prototyping methods, is growing in industry-wide acceptance. Direct additive manufacturing of beryllium containing materials is expected to eventually arise as a complimentary technology to investment casting in the optical instrumentation and precision engineering markets.

Advanced, high strength, low CTE, low mass polymers such as PEKK will likewise become more available for opto-mechanical applications when applying AM. Our investigations have shown that very intricate and ultra-light PEKK parts can be fashioned by AM for potential aluminum replacement at much lower cost than DMLS of AlSi10Mg. Both fiber-filled and unfilled PEKK test parts have been evaluated. Fiber filled components are stronger but we saw significant warping issues that may be attributable to preferential alignment of fibers to the direction of the wiper system used to level the powder as each layer is built up. Unfilled specimen did not experience warping issues. Attempts were made to process unfilled PEKK test mirrors to optical tolerances, but the material was found to be too low in reflectance for optical measurement without applying an optical coating. Low reflectance is a positive attribute for structures such as lens barrels to minimize propagation of stray light in an optical system.

AM of gas atomized spherical metal powder appears to inherently result in highly randomized and homogenous metallic grain structure. Near net shaping processes, such as investment casting, require complete melting and re-solidification of metal resulting in variable grain growth and separation of elements in the melt due to directional flow patterns and differential cooling dynamics. AM processes such as DMLS, and EBM melt the metal but on a highly localized basis. Binder jetting relies on sintering and HIP and thus similarly limits the degree of re-melting of the randomized spherical powder. Relative stress release, density, homogeneity, and CTE isotropy among tested materials and applied processes, is readily seen after optical finishing and interferometric testing over temperature.

Small scale gas atomization also enables creation of customized boutique spherical powder batches of highly pure and homogenous materials for consolidation by AM with little material waste. New aluminum powders can be developed to enhance optical finishing operations such as diamond point machining, optical polishing, strength, and other design and manufacturing properties that are of interest. A foray to both diamond point machine and computer polish AlSi10Mg mirrors using MRF at QED Technologies yielded promising initial results. Other gas atomized aluminum alloys, processed by similar AM methods, are likely to produce further advances.

Continuous improvements in AM technologies and metal powder atomization will inevitably improve the quality, cost, and material choices available for making mirrors and precision structures. Also AM processes are highly scalable so processes and test results that are promising for small parts should apply almost as well on much larger parts.

Topologically optimized designs that can be created by AM will revolutionize many product types. Bio-inspired topological optimizations that can exploit emerging AM technologies able to change the density and material type in a continuous manner as a part is built can further differentiate this exciting technology from traditional methods.

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1. Materion Corporation, Elmore, OH (contributed AlBeCast 3” test mirror substrates)
2. University of Louisville (contributed EBM generated Titanium 6Al4V 3” test mirror substrates)
3. Stratasys Direct (contributed DMLS generated AlSi10Mg 3” test mirror substrates)
4. ExOne Corporation (contributed 420/bronze and Inconel 3” test mirror substrates)
5. Oxford Performance Materials (contributed 3” and 6” test mirror substrates)
6. 411 Engineering (contributed design and FEA support)
7. QED Technologies, Rochester, NY (contributed MRF polishing run on AM generated bare aluminum mirror)

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