2015 SPIE Mirror Technology Days
Application and Testing of Additive Manufacturing for Mirrors and Precision Structures
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GENERAL DYNAMICS
Mission Systems

Overview

Additive Manufacturing (aka AM, and 3-D printing) offers profound advantages in lead-time, consumption of expensive raw materials, while enabling new and innovative design forms.

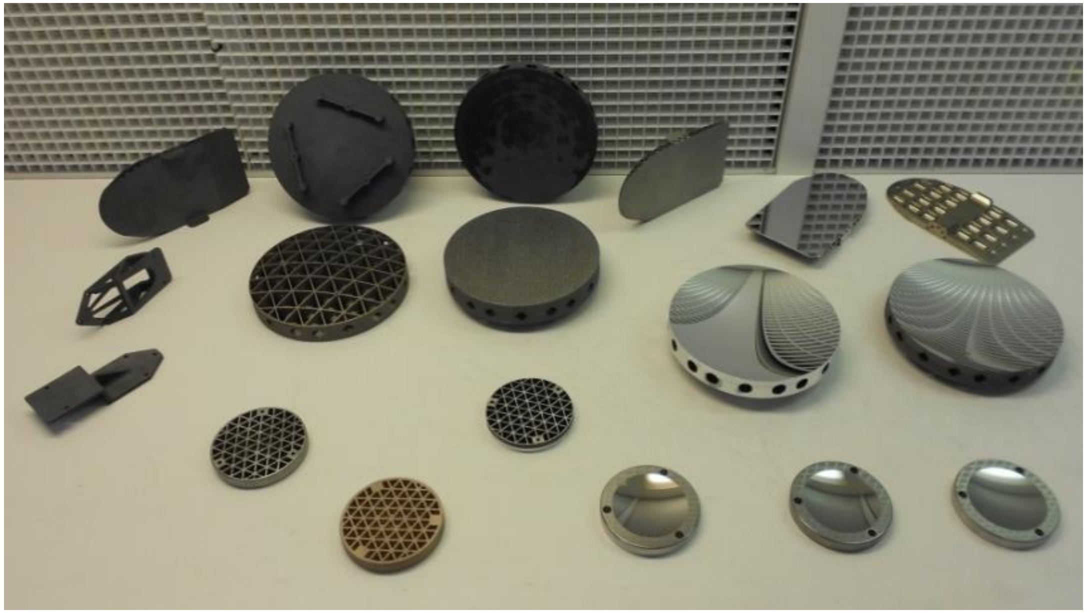
General Dynamics and industry partners have begun to apply this technology for mirrors and precision structures used in the aerospace, defense, and precision optical instrumentation industries.

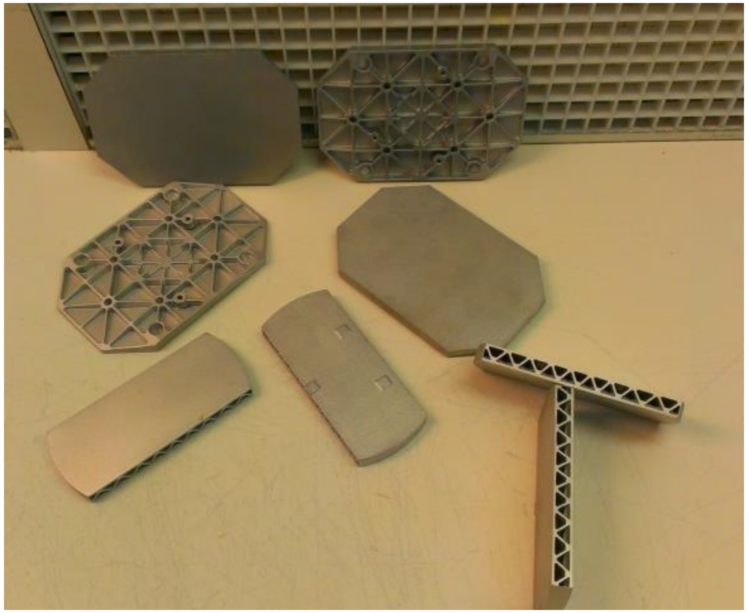
Aggressively light-weighted, open and closed back test mirror designs, 25-150 mm in size, were designed and produced by AM from multiple materials.

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.

Introduction





Assorted test mirrors designed, 3D printed and optically processed by General Dynamics to assess the application of additive manufacturing for a wide variety of aerospace and commercial applications for mirrors and ultra-precision structures.

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 can approach mechanical properties observed in bar and plate materials.

In most cases, strength is not a driving criterion for mirrors and precision structures, but dimensional stability and isotropic CTE are critical.

Discussion: AM process Pros/Cons

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.

Discussion: 75 mm test mirrors

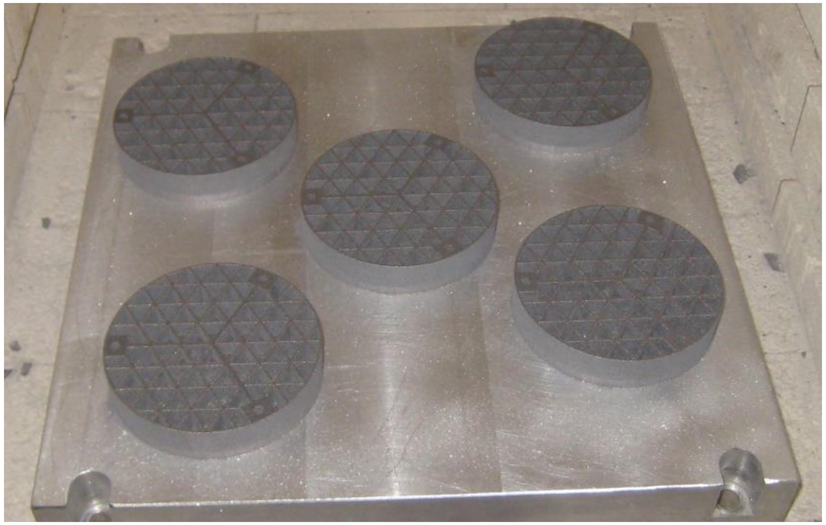
In order to evaluate dominant AM technologies applied to various materials, we defined a universal 75 mm test mirror design with aggressive, open back, isogrid triangular light-weighting.

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.

A summary of the materials and processes evaluated in the form of 75 mm test mirrors are shown in the table II as follows:

Discussion: 75 mm test mirrors



At left five 3-D printed AlSi10Mg aluminum test mirrors on the build plate after de-powdering operations

At right diamond point turned solid Aluminum 6061-T6 verses similarly processed AlSi10Mg.

Discussion: 75 mm test mirrors

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

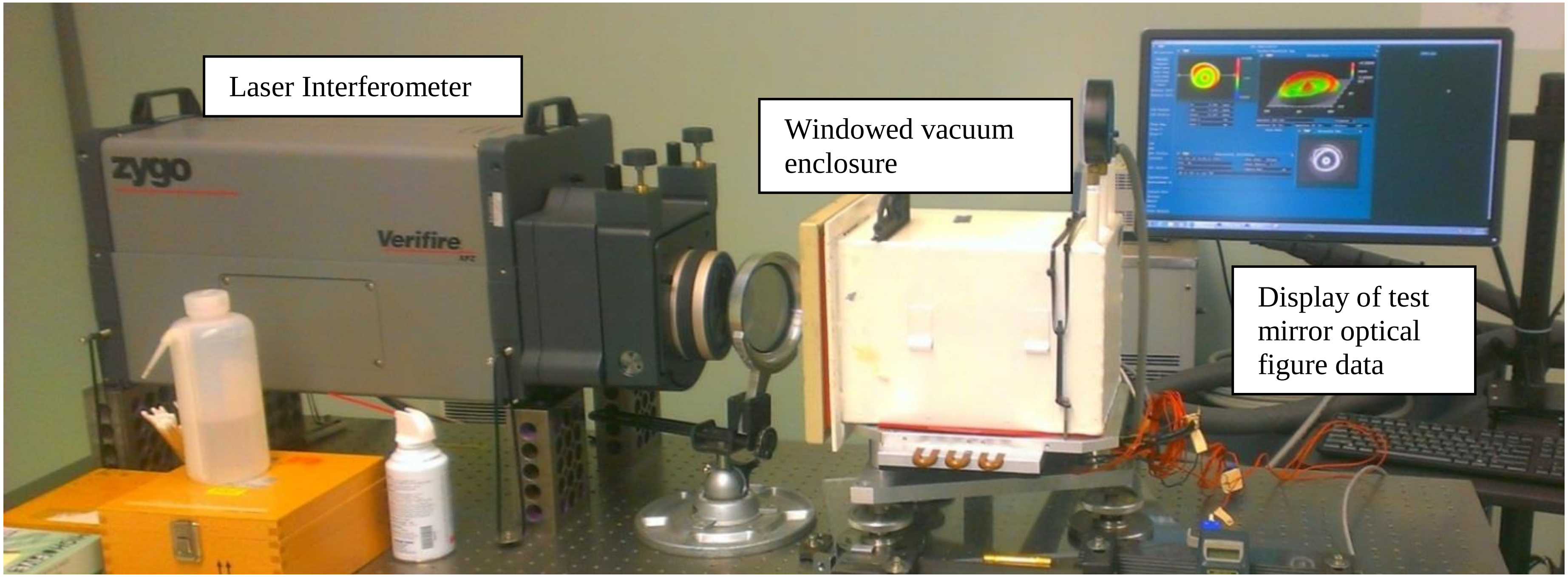
Table II: AM powder materials and comparison bar materials down-selected by General Dynamics as part of this investigation.

Discussion: 75 and 150 mm test mirrors

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.

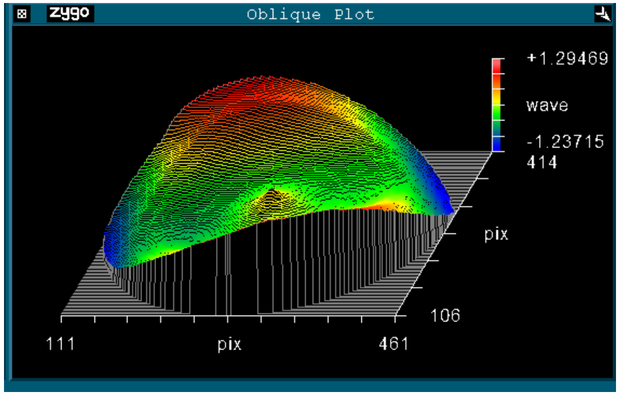
Then each test mirror was mounted to a heat exchanger within a windowed vacuum enclosure for measurement of the optical figure over a range of temperatures

Discussion: 75 and 150 mm test mirrors

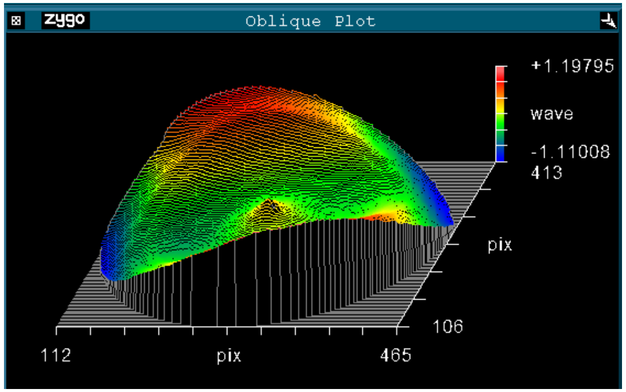


Interferometric thermal vacuum test apparatus used to measure plano and concave spherical test mirrors produced by additive manufacturing ranging in size from 75-150 mm in aperture.

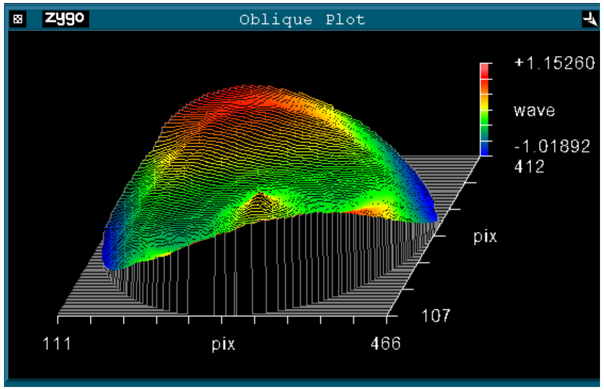
Discussion: Interferometric Results 75 mm



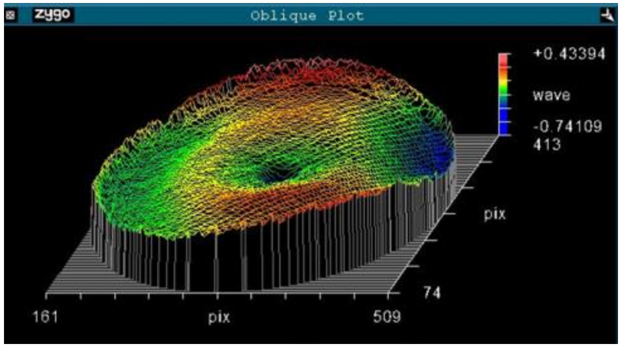
3” DMLS AlSi10Mg cc sphere at 0°F



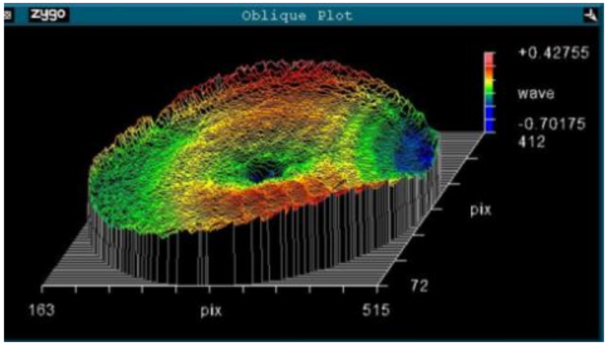
3” DMLS AlSi10Mg cc sphere at 70°F



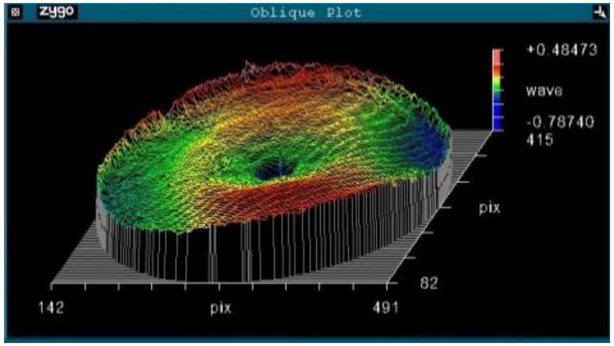
3” DMLS AlSi10Mg cc sphere at 140°F



3” EBM Ti6Al4V cc sphere at 0°F

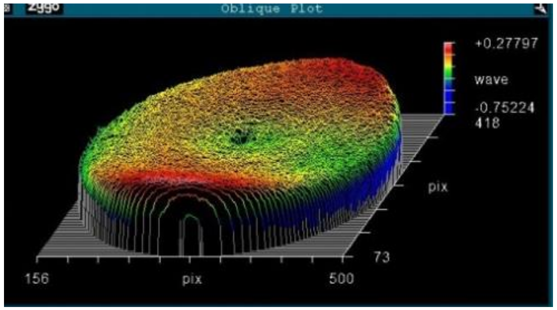


3” EBM Ti6Al4V cc sphere at 70°F

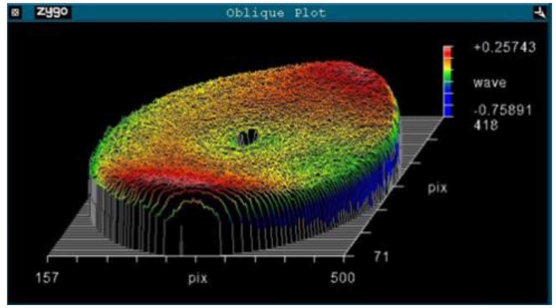


3” Ti6Al4V cc sphere at 140°F

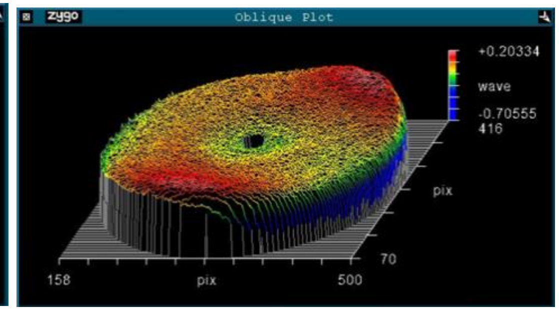
Discussion: Interferometric Results 75 mm



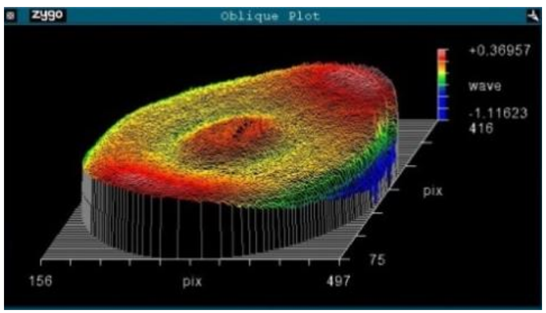
3” BJ 420SS/Brz cc sphere at 0°F



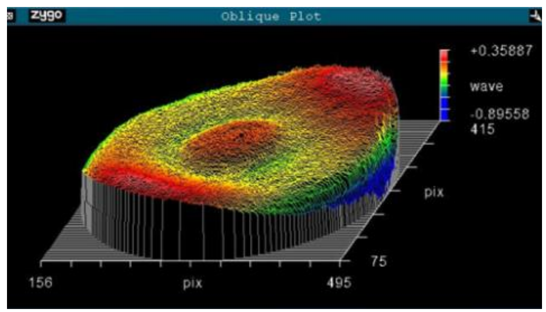
3” BJ 420SS/Brz cc sphere at 70°F



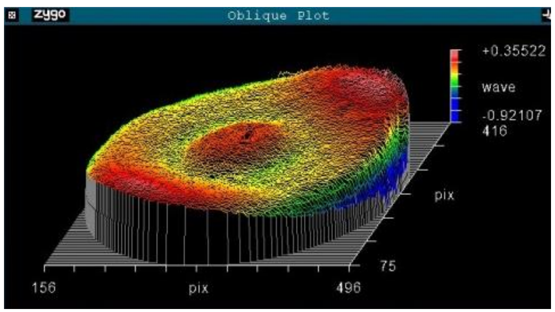
3” BJ 420SS/Brz cc sphere at 140°F



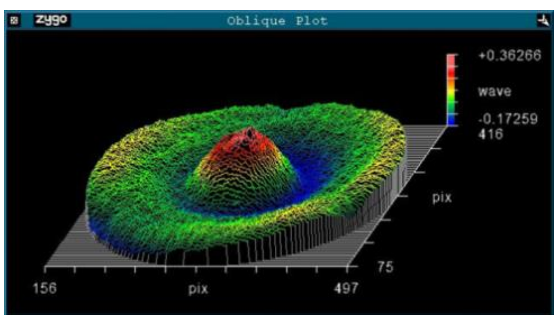
3” BJ/HIP Inconel cc sphere @0°F



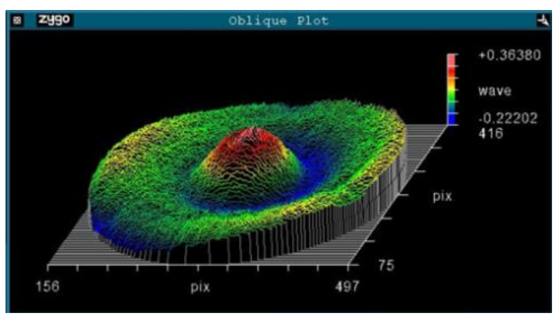
3” BJ/HIP Inconel cc sphere @ 70°F 3”



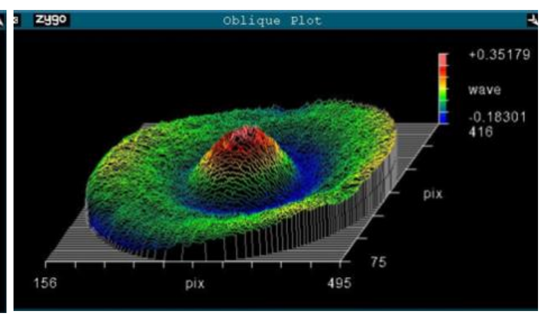
3” BJ/HIP Inconel cc sphere @ 140°F



3” BJ/no-HIP Inconel cc sphere at 0°F

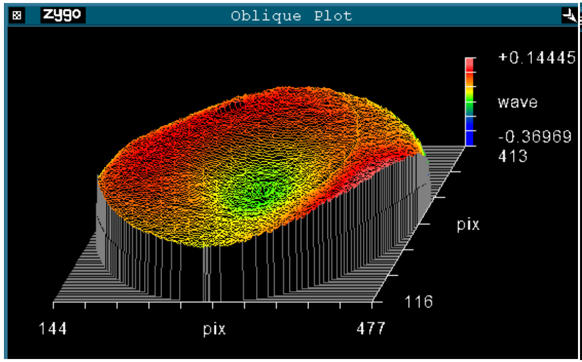


3” BJ/no-HIP Inconel cc sphere at 70°F

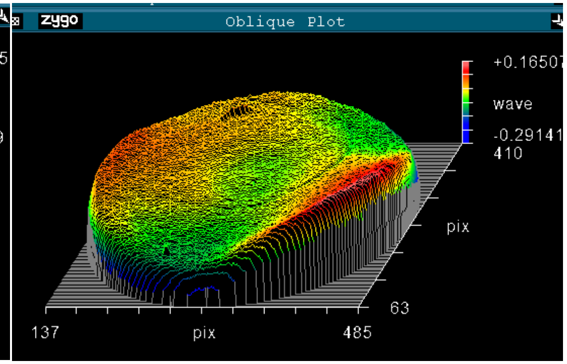


3”BJ no-HIP Inconel cc sphere at 140°F

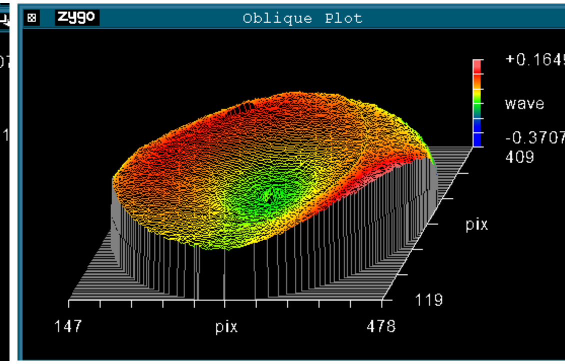
Discussion: Interferometric Results 75 mm



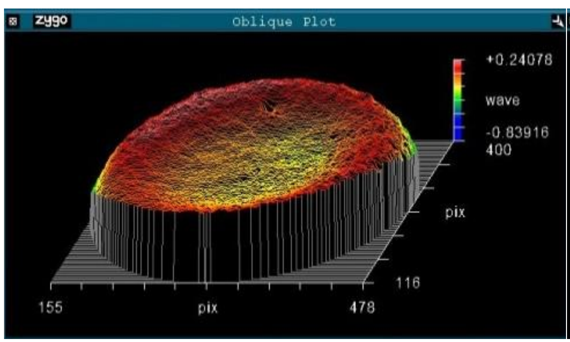
3” AlBeMet162 cc sphere @0°F



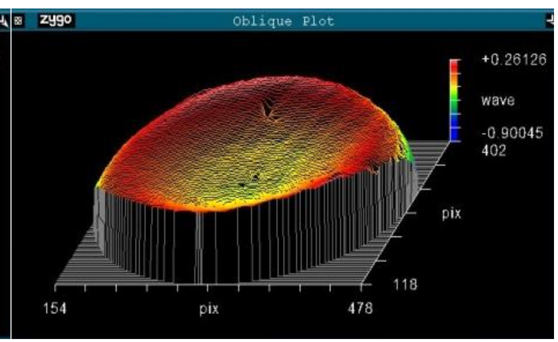
3” AlBeMet162 cc sphere @ 70°F 3”



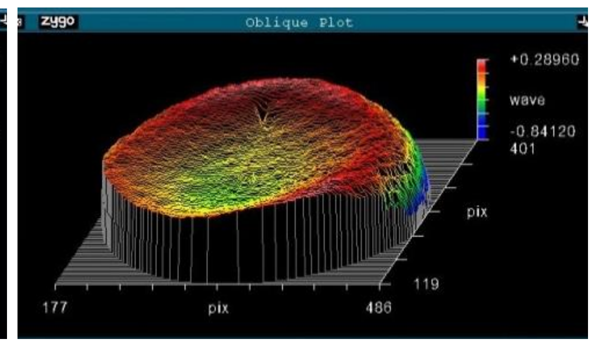
3” AlBeMet162 cc sphere @ 140°F



3” AlBeCast-950 cc sphere @0°F

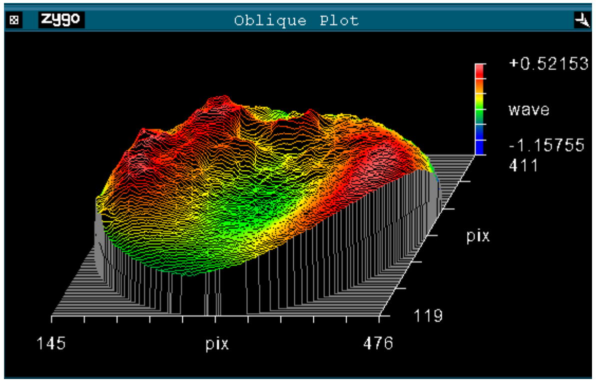


3” AlBeCast-950 cc sphere @ 70°F 3”

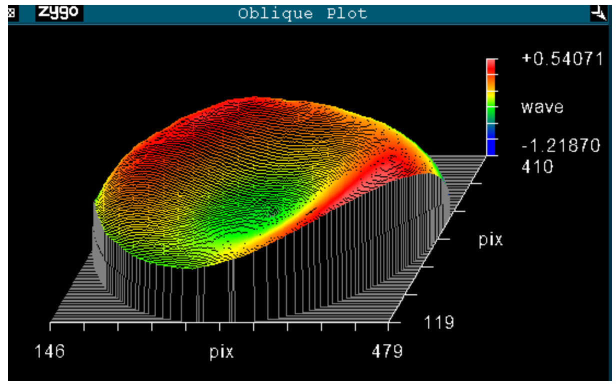


3” AlBeCast-950 cc sphere @ 140°F

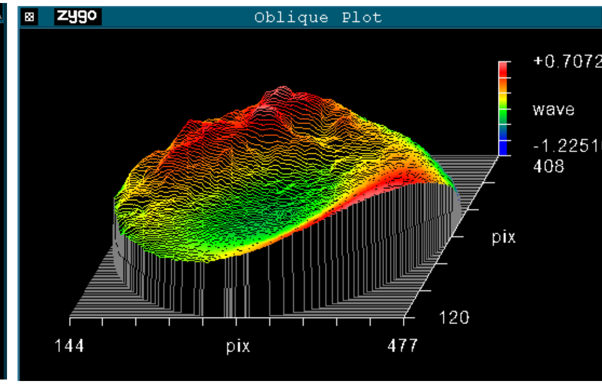
Discussion: Interferometric Results 75 mm



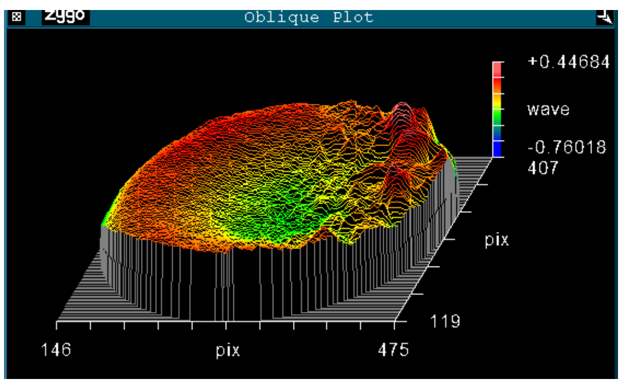
3” AlBeCast-910 cc sphere @0°F



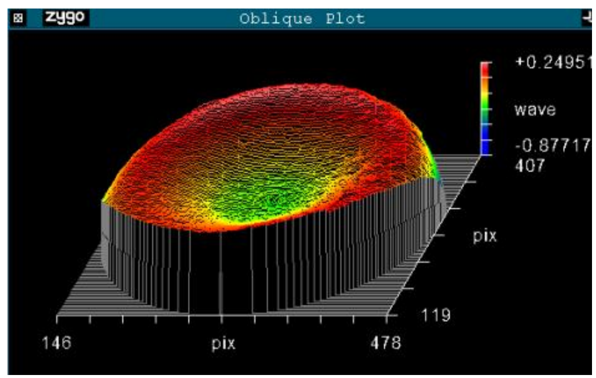
3” AlBeCast-910 cc sphere @ 70°F 3”



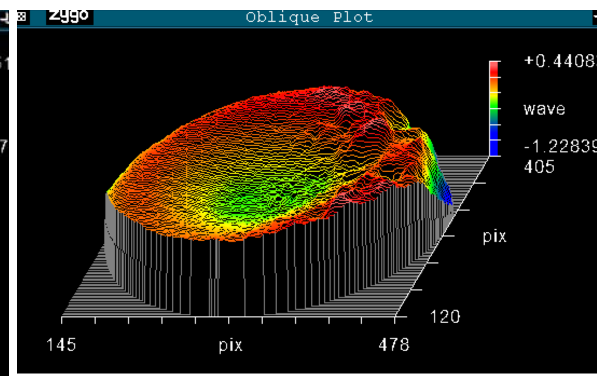
3” AlBeCast-910 cc sphere @ 140°F



3” AlBeCast-920 cc sphere @0°F



3” AlBeCast-920 cc sphere @ 70°F 3”



3” AlBeCast-920 cc sphere @ 140°F

General Preliminary Findings

Interferometric results for light-weighted AM specimen compared well to solid control pieces made from bar stock. In the future we will need tighter figure and other improvements to see a difference.

Ti6Al4V, 420SS/bronze, and Inconel 625 were highly stable, isotropic in CTE, and did not exhibit stress release effects during optical finishing.

AlSi10Mg was highly dense and optically processed well but variations in stress release effects were seen when machining work was applied. Otherwise good stability and isotropic CTE were seen after thermal cycling. Post heat treating after AM is seen as necessary to release stress and control tempering.

Bare polished aluminum beryllium specimen all were subject to stress release effects but stabilized after thermal cycling. AlBeCast specimen showed anisotropic CTE effects while AlBeMet162 did not.

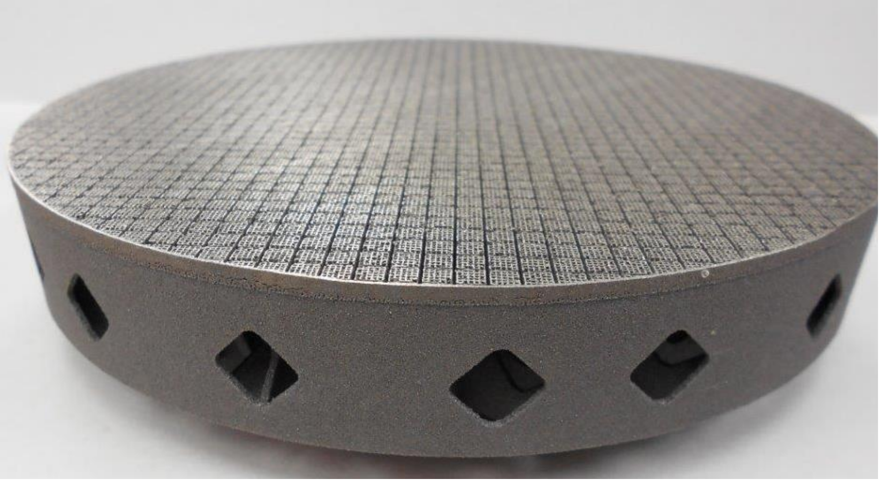
Atomized spherical powder with limited re-melting during sintering is seen as pivotal to achieving refined and randomized metallic grain structure required for optimal finishing and dimensional performance on the optical measurement scale.

Larger and more complex AM Design Forms

After achieving promising results on smaller specimen, General Dynamics designed and manufactured several larger flat and spherical test mirror designs in the 150 mm aperture range made from aluminum AlSi10Mg.

We have also branched into producing complex prototype precision optical structures such as for gimbals.

150 mm AM open back spherical mirror

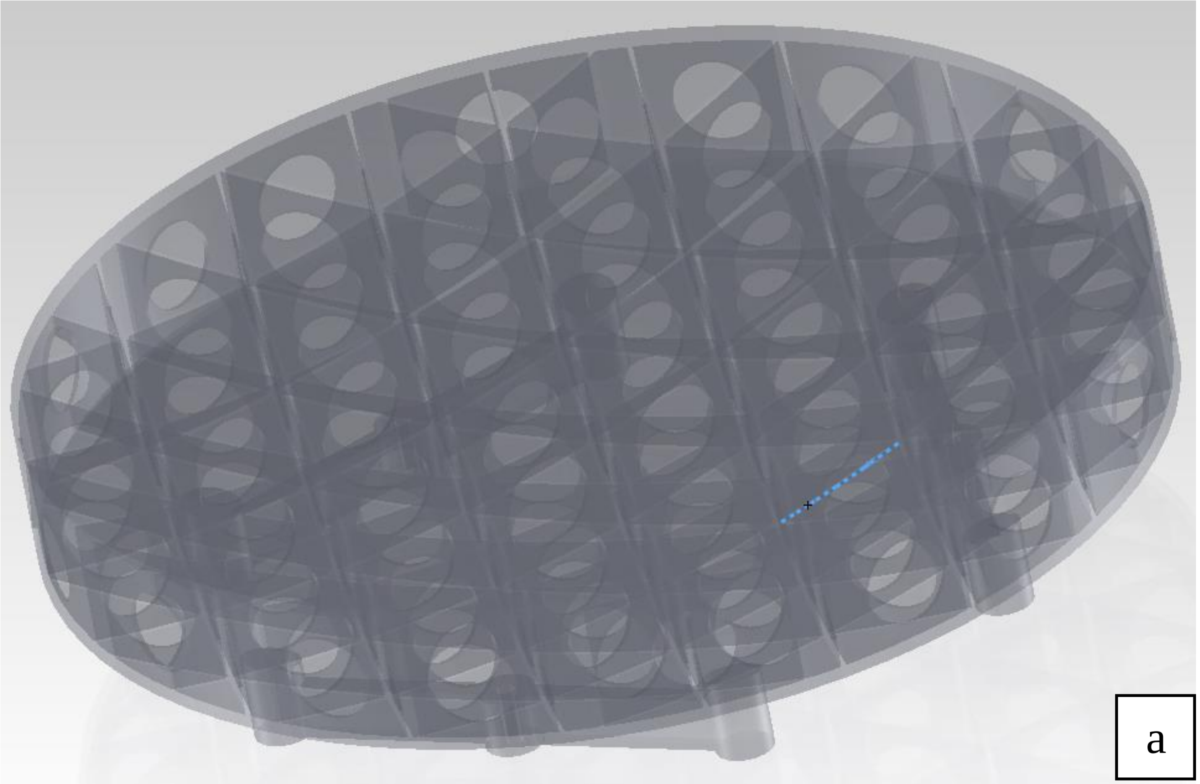


Shown prior to machining off the support structure from the dome of the optical surface

Features:

- Open back, isogrid design, 1.25 mm walls, small corner radii,
- mounting bosses projecting from 50% mirror thickness
- Centered diamond shaped holes in center of each rib
- Optically processed to demonstrate stability and temperature performance

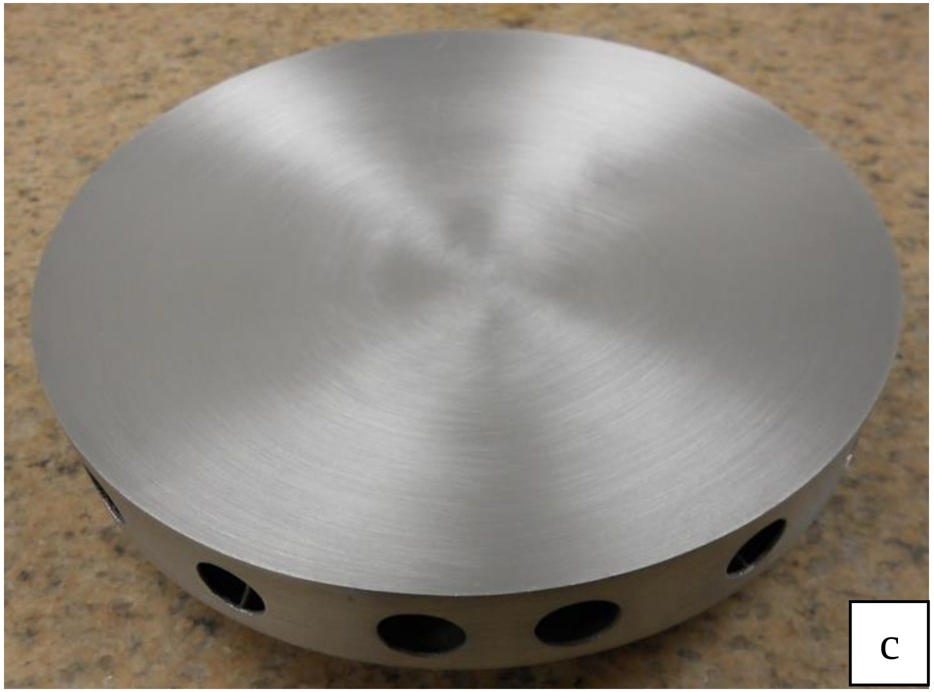
AM 150 mm closed back spherical mirror



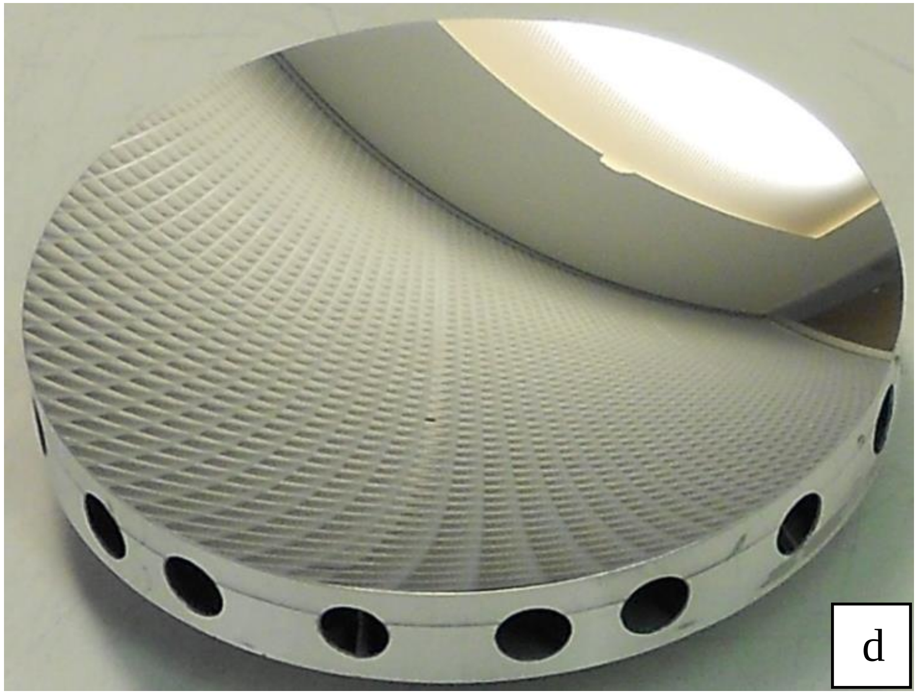
Features:

- closed back, isogrid design, 0.75 mm walls, small corner radii,
- Integrally printed tangent bar mounting flexures
- Centered circular holes in the center of each rib
- Optically processed to demonstrate stability and temperature performance

AM 150 mm closed back spherical mirror

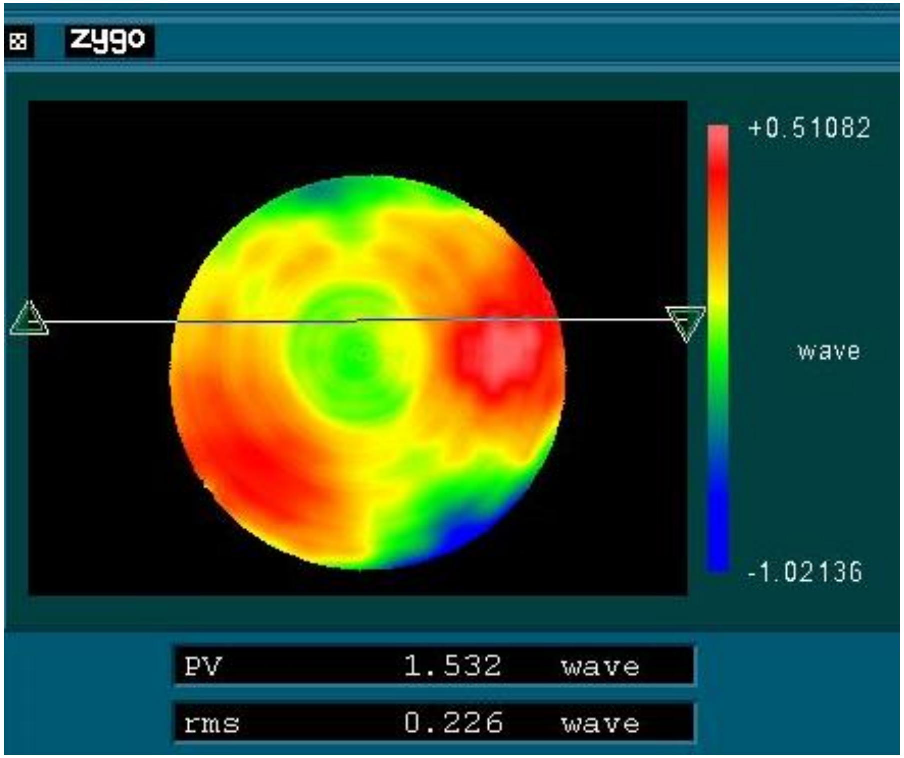


After machining off scaffolding

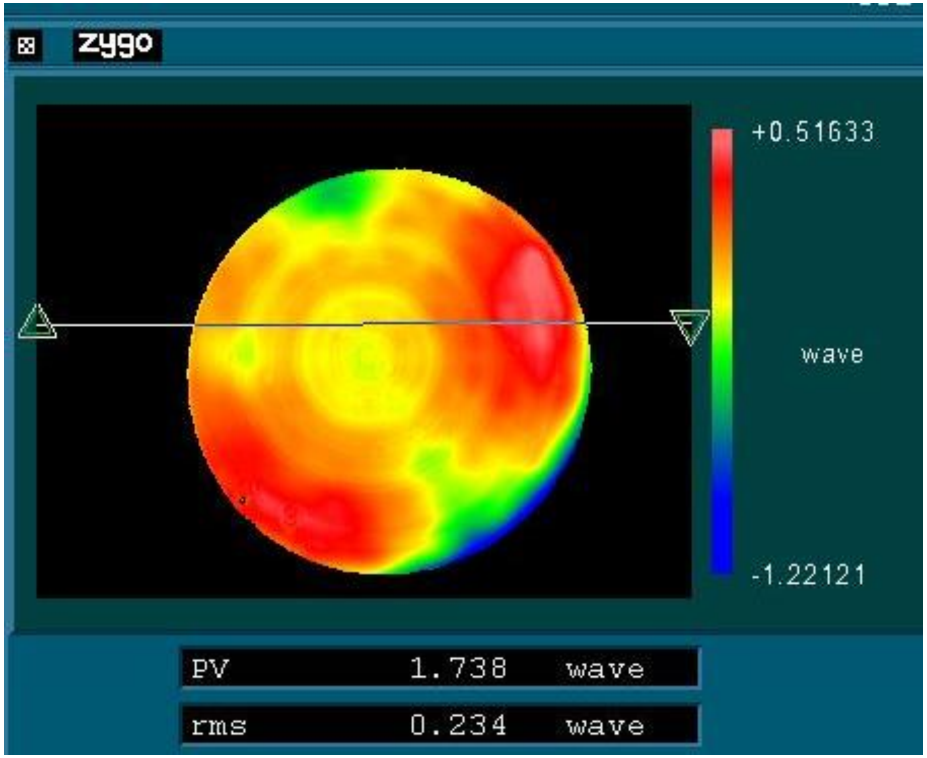


After diamond point machining to achieve about 1.50 wave P-V optical figure and 60 Angstroms RMS Finish

AM 150 mm closed back spherical mirror

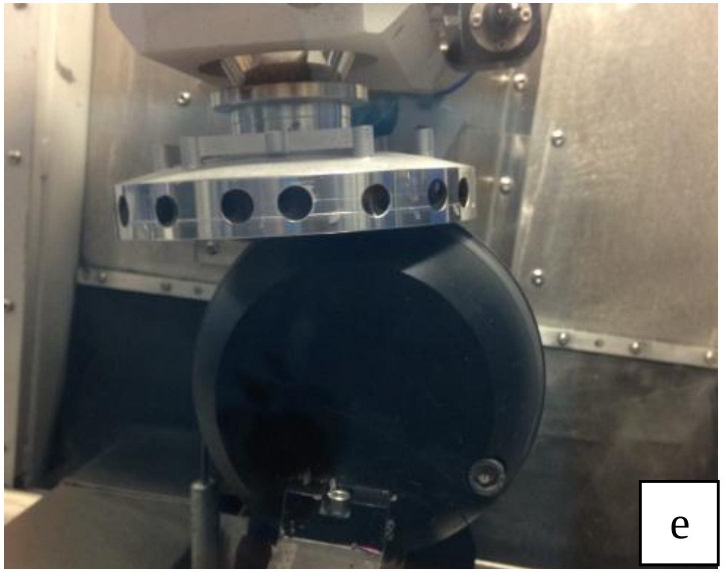


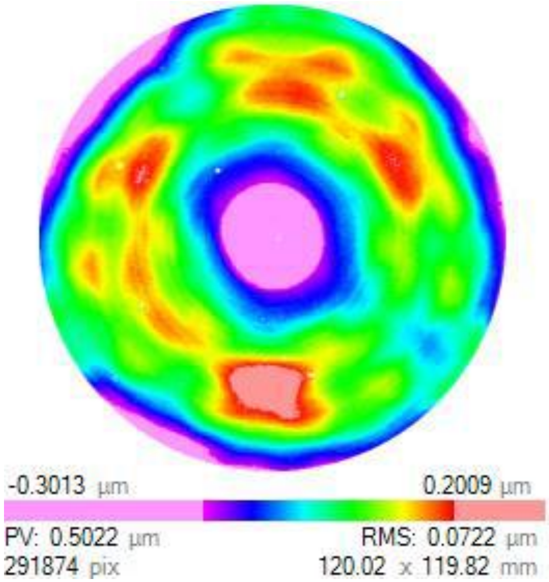
Surface figure at 70°F

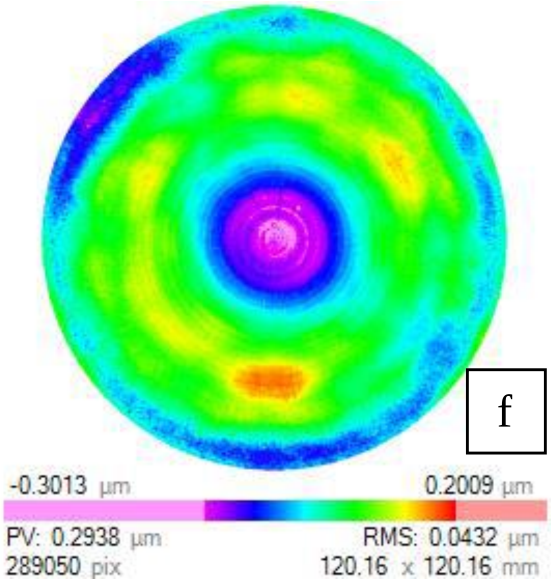


Surface figure at 150°F

AM 150 mm closed back spherical mirror



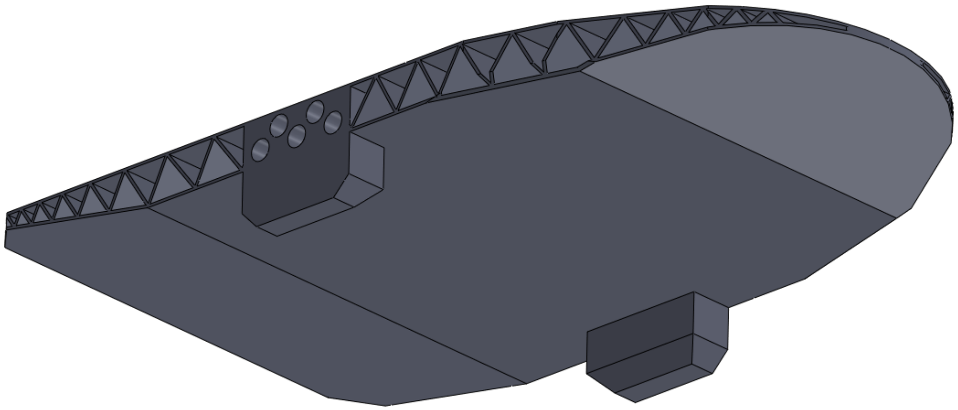


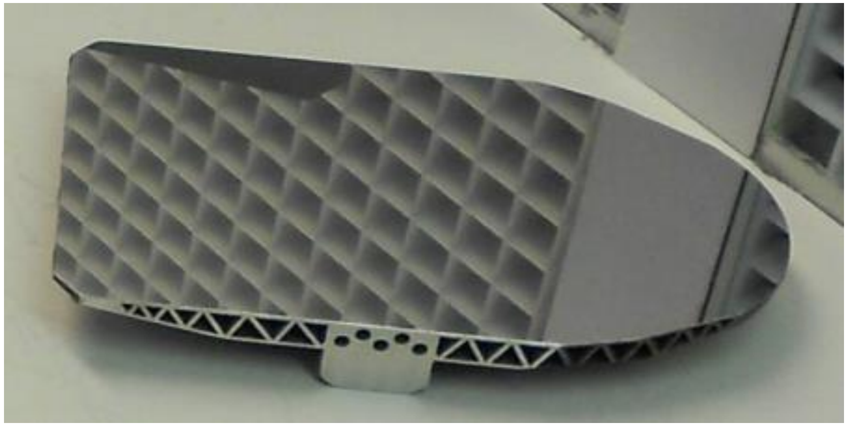


Trial experiment with MRF computer polishing at QED Technologies on bare aluminum 3-D printed optical surface.

Removal function was predictable: 50% hit was programmed, 40% achieved, on only one run.

150 mm AM closed back flat mirror

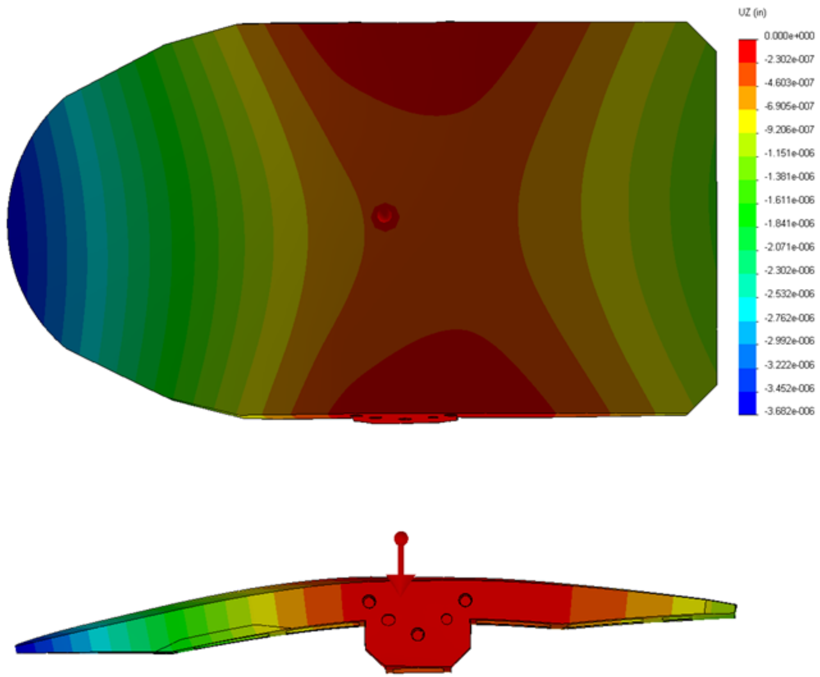


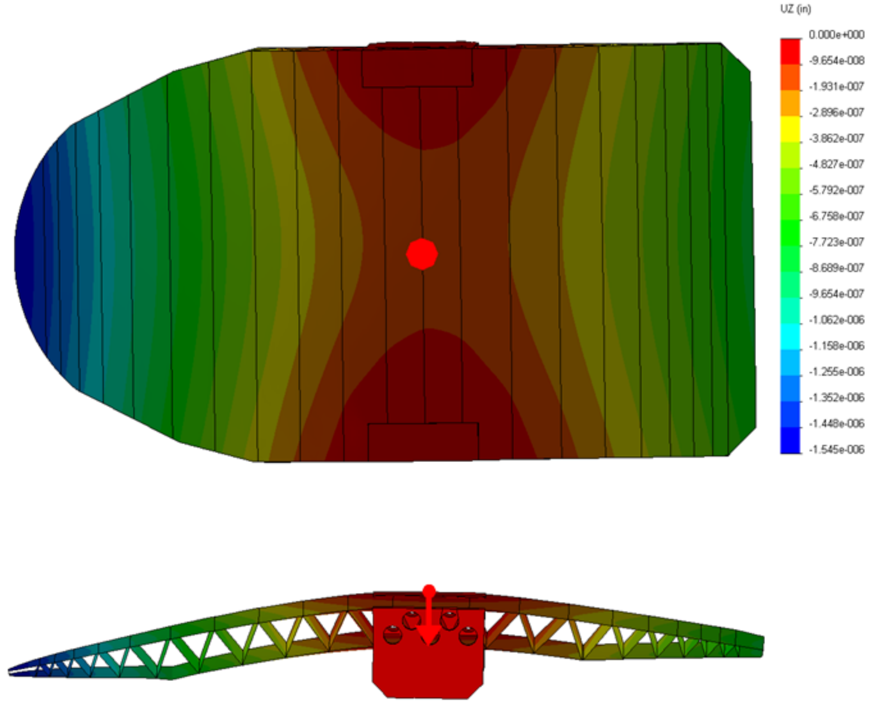


Features:

- Identical outside dimensions and mounting interface to an open back machined beryllium mirror made in production.
- Interior extruded bridgework is nearly impossible to machine but easily achieved by AM aluminum at both 0.50 mm and 1.25 mm thicknesses.
- 40 Angstroms RMS surface finish after diamond point flycutting attests to the achievable density and homogeneity of sintered atomized aluminum powder
- Structural efficiency and mass reduction dramatically improved from open back mirror when modeled in beryllium.

150 mm AM closed back flat mirror





Self weight deflection of current Be mirror = 2.5 µin

Self weight deflection of notional Be AM mirror = 1.0 µin

150 mm AM closed back flat mirror

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

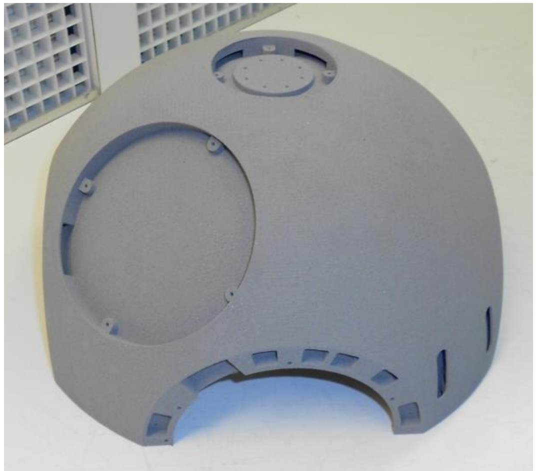
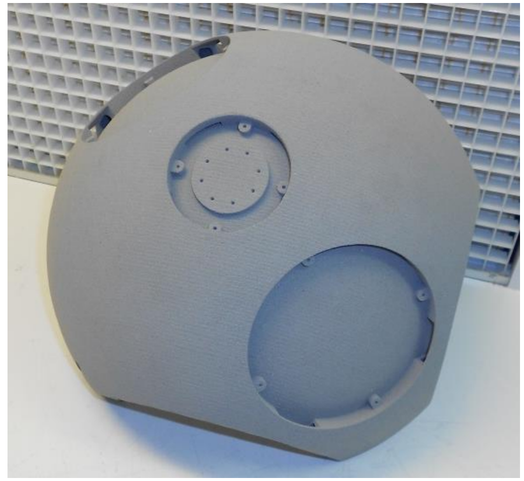
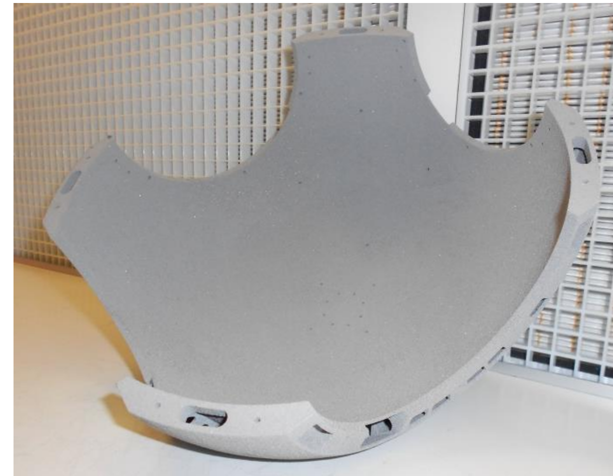
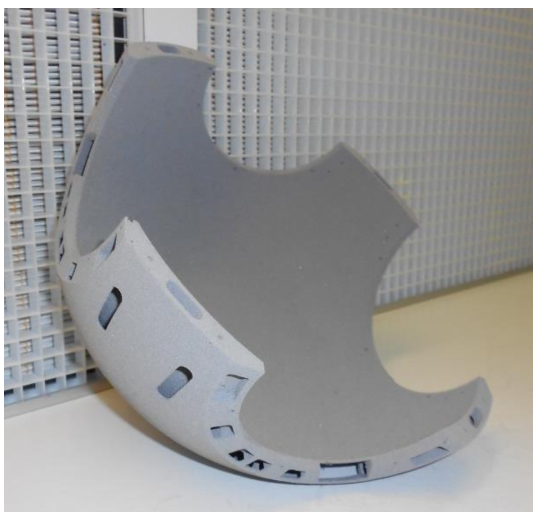
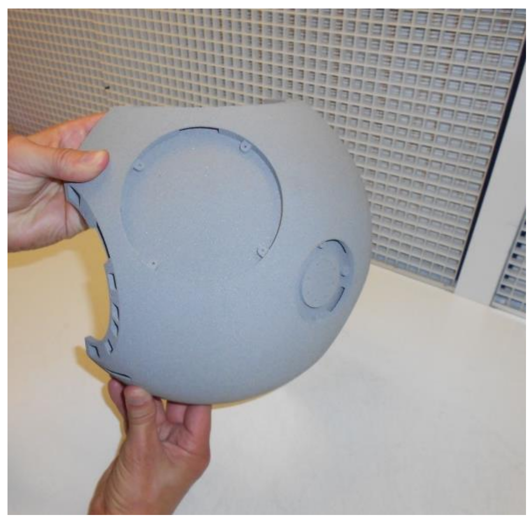
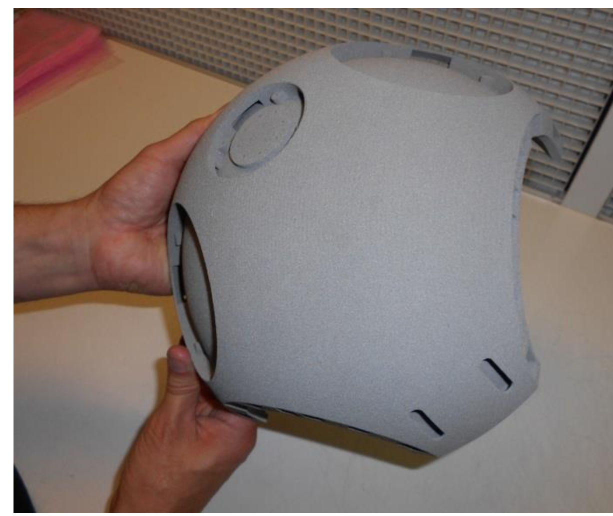
Table III: Above is a summary of the cost, schedule, and performance advantages realized by a notional AM generated beryllium or aluminum beryllium mirror over a current production beryllium mirror that is machined from solid block material.

AM of Optical Structures :

Precision structures that relate optical components and systems similarly benefit from the potential of additive manufacturing to reduce cost, reduce lead-time, improve structural efficiency, combine multiple parts, etc. These structures also require exceptional dimensional stability.

1. Telescope metering structures
2. Gimbal structures
3. Lens barrels
4. Optical benches
5. Navigational platforms

Hollow Core Structures: Direct 3DP Sintered stainless steel

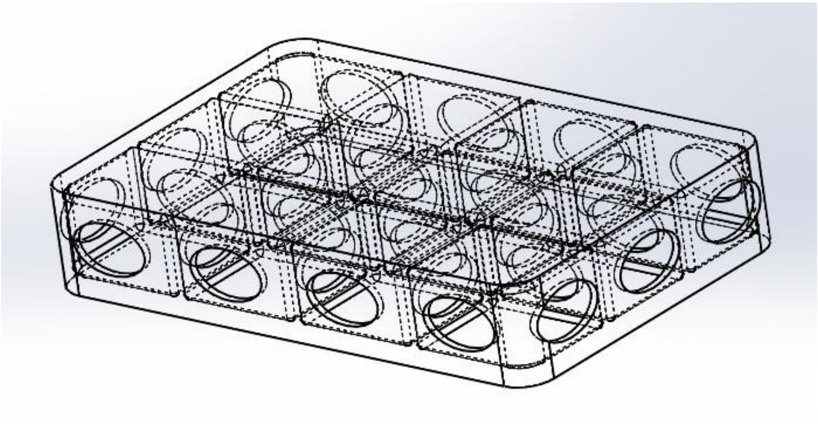
Present: 3.4 lbs of SS powder   Future: 0.80 lbs Be powder

AM at General Dynamics: Cullman, AL

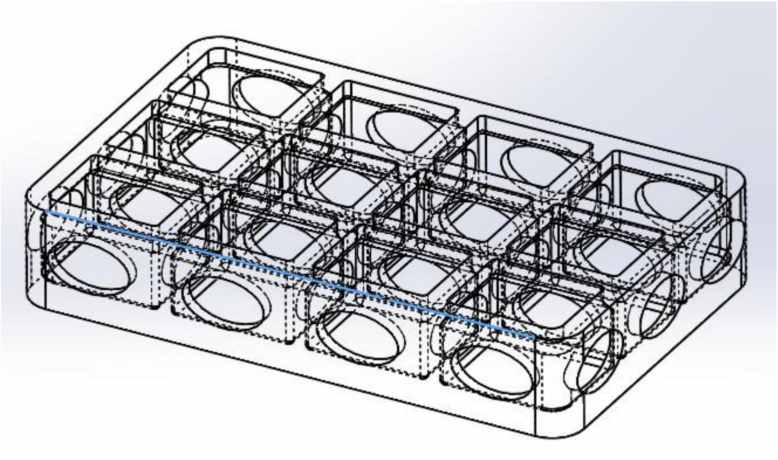
After completing our survey of various AM technologies, materials and outside manufacturers, we have now begun to experiment with these technologies in house at our Cullman, AL facility.

We began with stainless steel and have begun to produce small test components made from beryllium including plano test mirrors, spherical test mirrors, x,y,z tensile bars, etc.

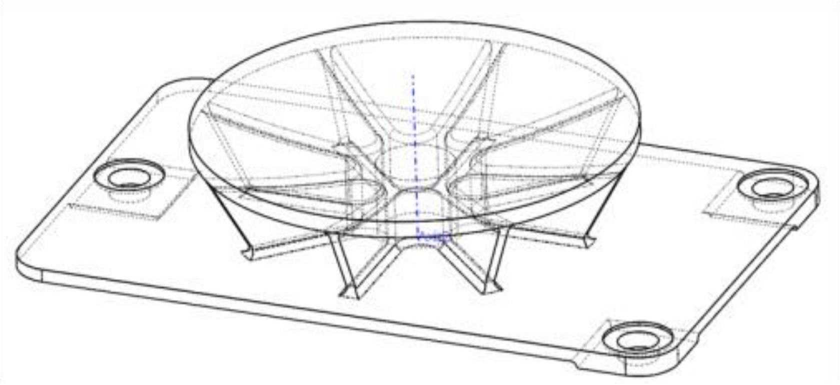
Discussion: Alternative Design Forms



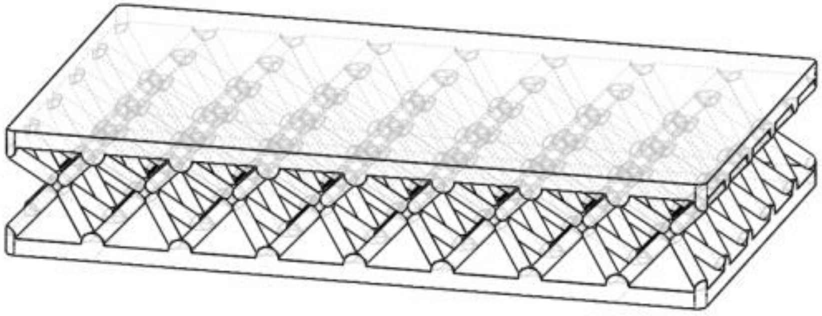
Fully closed back, vented pockets



Semi-closed “T” back, vented pockets

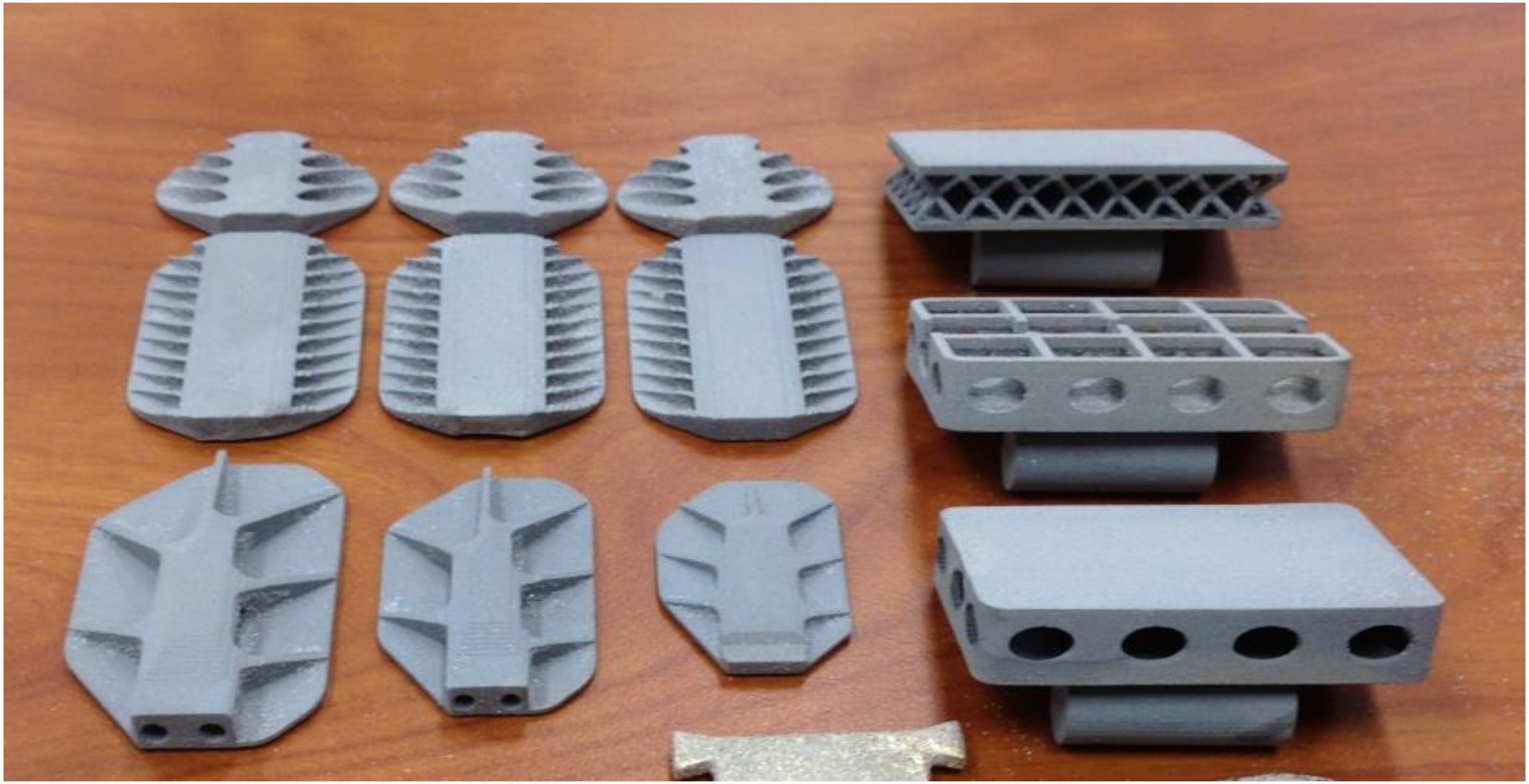


Aggressive light weight powered mirror



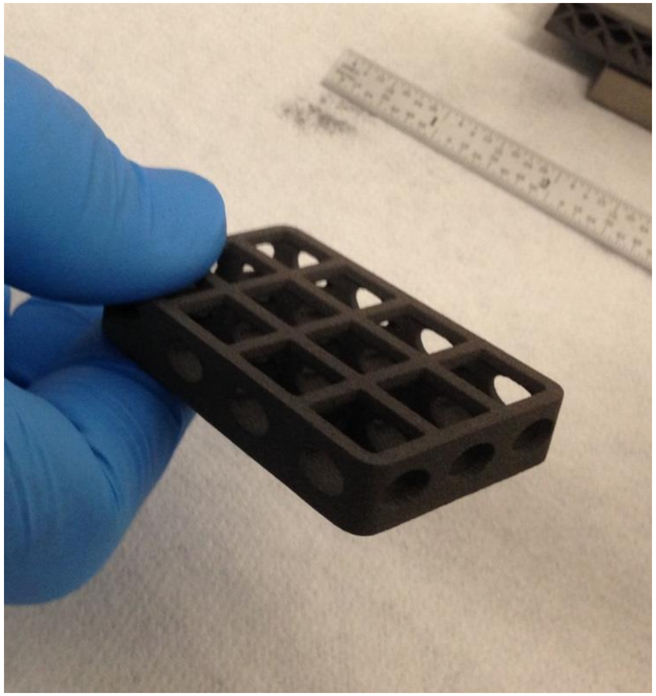
Fully closed back, lattice structure

Outcome of Stainless Steel Sintering

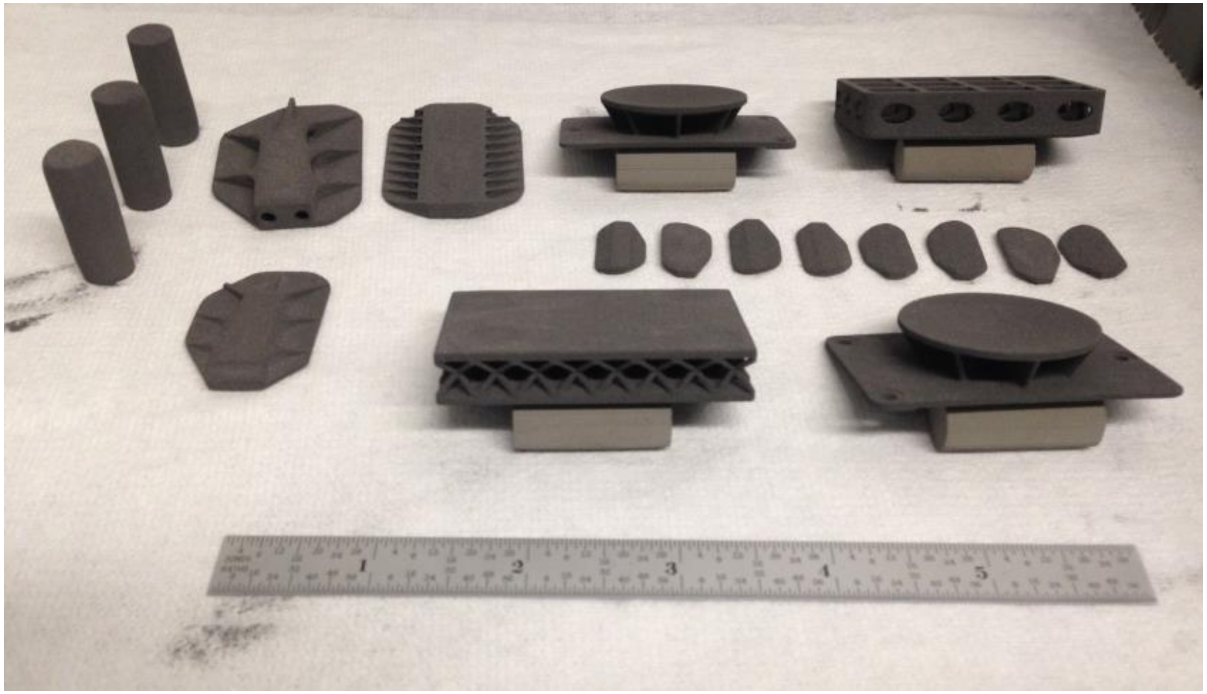


Batch of 3-D printed sintered stainless steel test mirrors.

Beryllium Parts Successfully 3-D Printed



3-D printed beryllium flat test mirror designed with T-rib section and elliptical cross holes.



Assorted 3-D printed beryllium parts. These include flat and spherical test mirrors, galvo mirror prototypes, and cylindrical bars for machining and tensile test experiments

Summary:

All of the AM mirror specimen optically processed and tested so far as part of this project exhibited good to excellent density, homogeneity, dimensional stability, and isotropy of thermal expansion over temperature on the optical scale of measurement.

Relative stress release, achievable surface roughness, density, homogeneity, and CTE isotropy among tested materials and applied processes, is readily seen after optical finishing and interferometric testing over temperature.

Conclusions

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.

Similarly, AM processing of ceramic powders such as SiC, Zerodur, fused silica, etc seems feasible.

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 will also continue to further differentiate this exciting technology from traditional methods.

Moving Ahead in 2016 and beyond:

We are expanding our capabilities to 3D print, heat treat, and qualify much larger and more refined beryllium test specimen and products.

We are developing a supply chain of outside suppliers for materials such as aluminum that we can bring in house for critical heat treatment and precision manufacturing operations.

We welcome collaboration with the optics and precision instrument community as we continue to explore the limits of additive manufacturing technologies for mirrors and related precision structures made from high performance materials.

Thank you for your attention and this opportunity to present on our continuing progress in this exciting emerging technology area.