Optical fabrication of lightweighted 3D printed mirrors

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ABSTRACT

Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM) 3D printing technologies were utilized to create lightweight, optical grade mirrors out of AlSi10Mg aluminum and Ti6Al4V titanium alloys at the University of Arizona in Tucson. The mirror prototypes were polished to meet the λ/20 RMS and λ/4 P-V surface figure requirements.

The intent of this project was to design topologically optimized mirrors that had a high specific stiffness and low surface displacement. Two models were designed using Altair Inspire software, and the mirrors had to endure the polishing process with the necessary stiffness to eliminate print-through. Mitigating porosity of the 3D printed mirror blanks was a challenge in the face of reconciling new printing technologies with traditional optical polishing methods. The prototypes underwent Hot Isostatic Press (HIP) and heat treatment to improve density, eliminate porosity, and relieve internal stresses.

Metal 3D printing allows for nearly unlimited topological constraints on design and virtually eliminates the need for a machine shop when creating an optical quality mirror. This research can lead to an increase in mirror mounting support complexity in the manufacturing of lightweight mirrors and improve overall process efficiency. The project aspired to have many future applications of lightweighted 3D printed mirrors, such as spaceflight.

This paper covers the design/fab/polish/test of 3D printed mirrors, thermal/structural finite element analysis, and results.

Keywords: additive manufacturing, DMLS, EBM, topological optimization, lightweight, mirror, polish

1. INTRODUCTION

The project aimed to deliver fully functional, 3D printed mirrors to meet the λ/20 RMS and λ/4 P-V surface figure requirements. Models were optimized using Altair Inspire software and preprocessed in SolidWorks and MeshLab, then analyzed with ANSYS. This study project aimed to (1) explore the design space of 3D printed mirrors, and (2) demonstrate the feasibility of polishing 3D printed substrates. The scope of the project included researching the optimal 3D printing processes, optimizing the mirrors for the correct boundary conditions, sending solid models of the chosen designs to 3D printing facilities, polishing the mirrors to refine the reflective surfaces, testing the prototypes, and presenting final designs.

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2. MIRROR DESIGN AND OPTIMIZATION

Funding provided by Lockheed Martin Space Systems Company focused on the optimization, production, analysis, and testing of 3D printed mirror prototypes. The mirror designs were optimized using Altair Hyperworks based on maximum stiffness, lightweighting, and a minimum natural frequency of 250 Hz. Pressure loads, point forces, and gravity were added to the models at specific points across their reflective faces to remove any print-through from the designs [Figure 1(a)]. Print-through occurs when the most rigid portions of a mirror (core grid) are not able to deflect under the polishing pressure, causing that specific portion of the mirror to have material removed quicker than the other sections of the mirror. In turn, this then can cause a cantilever effect between the stiffer ribs at the core of the mirror, resulting in higher material removal at these spots. The finalized designs were able to minimize print-through by adding additional “branches”, which allowed for a more even distribution for material removal during the polishing process.

As shown in Figures 1(b) and 1(c), two different models, top mount and side mount, were optimized in both aluminum and titanium. Designs were optimized taking minimum surface displacement into account. The titanium designs were manufactured by the Keck Lab at the University of Texas in El Paso, on an Arcam A2 EBM machine. The side mounted aluminum design was manufactured by Incodema3D, using an EOS M280 Direct Metal Laser Sintering (DMLS) machine. The team only requested one aluminum model to be donated by Incodema3D.

DMLS and EBM are two metal additive processes that have enabled manufacturing of topologically complex parts, which would be nearly impossible to manufacture via conventional methods.

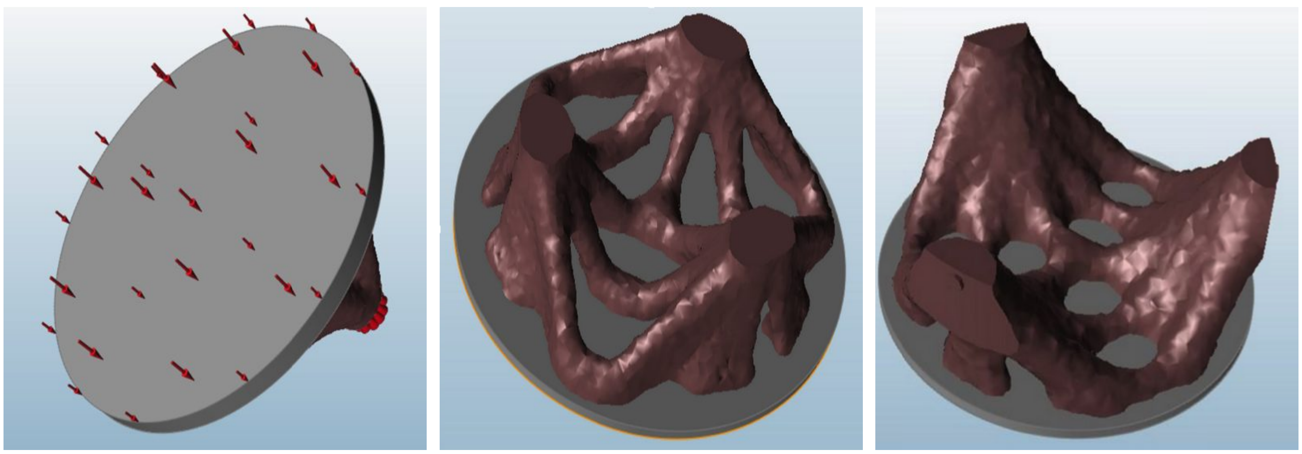

Figure 1. Applied loads and forces (a, left) in Altair Hyperworks to model top mount (b, center) and side mount (c, right)

3. MIRROR PROTOTYPE FABRICATION

The prototype mirrors, made from Titanium (Ti-6Al-4V) and Aluminum (AlSi10Mg), were manufactured by two unique processes. The material properties of the prototype mirrors for finite element analysis are presented in Table 1.

Table 1. Ti6Al4V and AlSi10Mg material properties used for finite element analysis

Material Properties	Ti-6-AL-4-V	Al-Si-10-Mg
Density	4.43 g/cm^3	2.67 g/cm^3
Ultimate Tensile Strength	1020 MPa	320 MPa
Yield Strength	950 MPa	165 MPa
Modulus of Elasticity	120 GPa	70 GPa
Poisson Ratio	0.342	0.33
Coefficient of Thermal Expansion (CTE) at 20°C	8.6 x 10^{-6} /°C	21x10^{-6} /°C

3.1 Steps followed to create the titanium (Ti-6Al-4V) mirrors:

1. Generate STL file from CAD.

2. Used MAGICS by Materialise to setup, orient, and/or add any necessary support structures. In this case, support structures were not needed. The mirrors were printed generating the reflective face as the first layer.

3. Used the ARCAM Build Assembler to convert the oriented file into a readable file for the system.

4. Selected the appropriate processing parameters and conditions which in this case were 50µm layers using powder sized at ~60µm in diameter.

5. Layers of this powder were spread using the machine's raking mechanism.

6. All parts in EBM were fabricated under a high vacuum environment (~10^{-3} torr). A pre-heat step took place after the material was layered, which involves heating the powder to ~50% of the material's melting point (~760°C).

7. A preheating step lightly sintered the powder using the beam at low current (8.8 mA) and high scan speed (14,600 mm/s) to reduce residual stresses and maintain a low thermal gradient during fabrication.

8. Powder was selectively melted according to the geometry of the CAD file using the beam at increased beam power (17mA) and reduced scan speed (500mm/s) to reach the material's melting point.

9. After the first layer was welded, the build platform was lowered (50µm) to allow for a new layer to be raked, with the process repeated until part fabrication was complete.

10. The operator removed the build platform after its temperature was below 100°C (to prevent oxidation of the parts when the machine was opened and exposed to the atmosphere).

11. A powder recovery system was used on the removed platform to blast the lightly sintered powder around the part(s) until the final part(s) were revealed.

12. The sintered powder that was removed from the build platform was re-used for subsequent builds.

13. The parts on the titanium build plate were "popped" off the plate upon cooling due to a thermal expansion difference.

14. Parts were then sent to the University of Arizona student team, which found porosity on the surface and back of the blanks.

15. Titanium parts were sent for the HIP process to BodyCote in Seattle, Washington.

16. Titanium parts were placed into a high pressure/temperature furnace. The furnace was flooded with argon to remove the oxygen. Operational parameters:

a. 1650 +/- 25 Fahrenheit

b. 120 minutes (minimum)

c. 14.75 +/- 0.25 ksi

3.2 Steps followed to create the aluminum (AlSi10Mg) mirror:

1. Generate STL file from CAD.

2. Used MAGICS by Materialise to setup, orient, and/or add any necessary support structures. In this case, support structures were not needed. However, we did need to reorient the side-mount legs to fix on the mirror. This mirror was built with the face as the first layer of the part.

3. Used PSW to convert and orient the STL drawings into a file suitable for the EOS printer.

4. Selected the appropriate processing parameters and conditions. In this case, 30µm layers and powder sized at ~50µm in diameter were used.

5. The aluminum plate was inserted into the EOS machine by the operator and manually leveled using a dial indicator in conjunction with the motors on the machine to move each corner/side of the plate up or down.

6. Powder was tamped down to remove air pockets, ensuring an even spread of powder each layer.

7. Layers of powder were spread using the machine's steel/ceramic wiper blade (right to left).

8. All parts in DMLS were fabricated under a high vacuum environment pre-flooded by argon. A preheat step took place after the aluminum build plate was heated to $80^{o}C$. Once the chamber was below 1000ppm O^2, the machine started.

9. An aluminum powder layer from the powder bed was raised 30µm and swept tightly across onto the plate (an extremely light layer of powder, evenly distributed across the plate).

10. The first layer of metal powder was sintered according to the design from MAGICS/PSW, programmed on the machine. The laser sintered each layer with a laser power of 80W for contour and 370W for bulk, using a scan speed of 1,300mm/s. After each layer, the build plate moved down 30µm, while the powder bed moved up 30µm.

11. Once the build was completed, the operator allowed the machine to cool down while dressing in a hazmat suit for protection from any possible fire or explosion caused by the highly flammable aluminum dust particles.

12. Once the part was cooled, it was placed into the wire EDM, which used electric diodes in the water to cut the part off the plate.

13. The parts were sent to BodyCote for the HIP process.

14. The aluminum parts (AlSi10Mg) were placed into a high pressure/temperature furnace. The furnace was flooded with argon to remove the oxygen. Operational parameters:

a. 950 +/- 25 Fahrenheit

b. 120 minutes (minimum)

c. 14.75 +/- 0.25 ksi

3.3. Post-processing

The HIP process helped to minimize the thermal stresses in the lightweight mirrors, as well as increasing the yield strength and fatigue life. The back-mounted titanium prototype in the second batch had visible porosity on the surface, which was unable to be eliminated in HIP. HIP will only densify the inside of the part, which made it necessary to machine the surface of the mirror.

Although the porosity was gone, the top layer of the prototypes had an extremely rough surface and the aluminum parts had a significant slope over the entire face. In order to reduce the amount of time in the grinding stage, each mirror was resurfaced using a mill, eliminating an estimated 20 hours of effort, as shown in Figure 2.

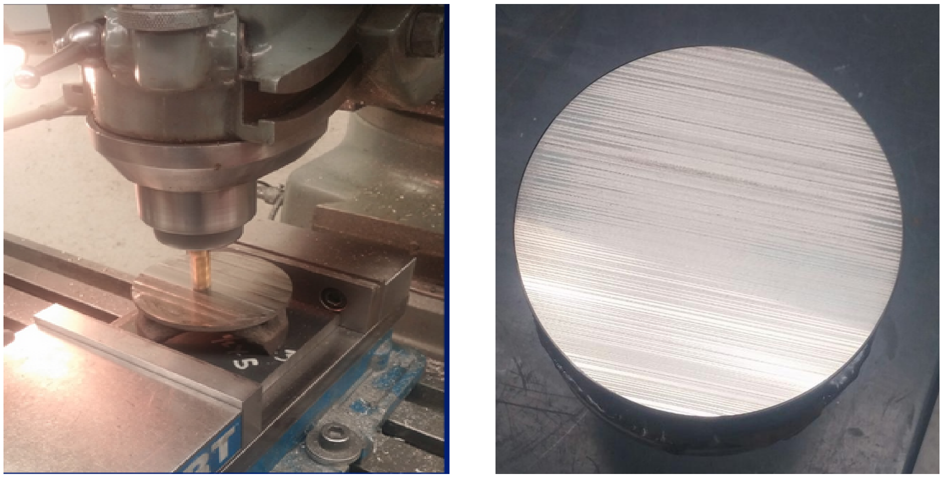

Figure 2: Titanium mirror milled flat to reduce time spent on grinding (a, left), final machined titanium mirror (b, right)

4. INITIAL MIRROR SURFACE

When the substrates were returned from printing and heat treatment, the surfaces were very rough. To get a better idea of what type of surface the team was starting out with, a mechanical profilometer was used to acquire surface measurements every 2mm across the mirror's diameter.

Using SAGUARO [1], an optical data analysis platform developed by Kim et al. at the University of Arizona, the data from the profilometer was combined and the initial surface figure was determined. Figure 3 shows the initial surface measurements of one mirror along with the SAGUARO GUI.

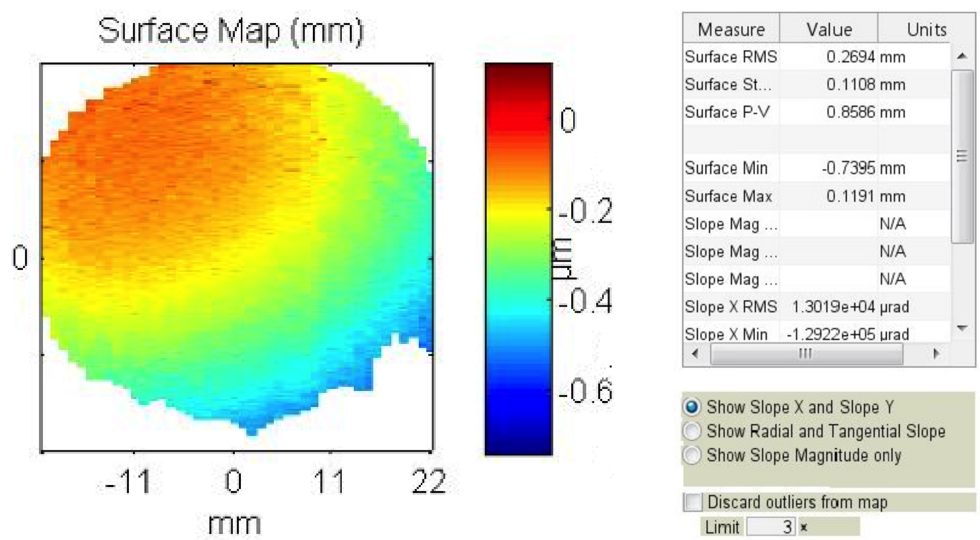

Figure 3. Surface data as seen in SAGUARO GUI [1] (Please, note that only some parts of the mirror were scanned due to metrology hardware limitations.)

The initial P-V of the surface was 858.6µm with an RMS of 269.4µm. However, despite these initially large values, the most important discovery was that there was some off axis power in the mirror surface, as well. Post-processing the data determined a radius of curvature of 9007mm. The initial surface qualities of two mirrors are shown in Figure 4.

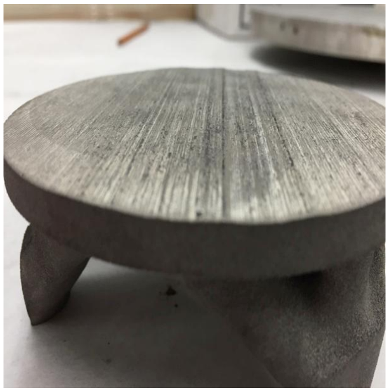
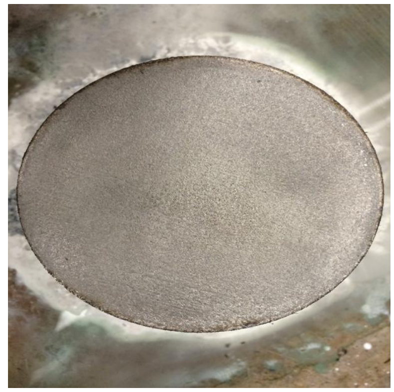

Figure 4. Original DMLS aluminum mirror (a, left), EBM titanium mirror post HIP with visible porosity (b, right)

5. MIRROR GRINDING

After preliminary machining, mirror blanks were subjected to two stages of optical fabrication: grinding and polishing. The grinding stage began by mixing silicon carbide (SiC) grit in water, continually applying the solution to the face of the mirror. The mirror was attached to a spindle that was set to rotate anywhere from 30 to 120 RPM, while a motor arm containing beveled ceramic tiles rotated from 5 to 20 degrees to help grind the material from the flat mirror face, as seen in Figure 5(a). Depending on the stage of the grinding process, different weights were used to apply added pressure to the pitch tool to grind the surface [Figure 5(b)]. Larger weights, up to 14.25 lb., were applied in the beginning for the heavier grind (simultaneously using a 3:1 ratio of water to 80-grit SiC solution), while lighter weights were used for the finer grind (220-grit SiC solution). The device was used to promote an even, random grind so there was as true and level a surface as possible [Figure 6(a)].

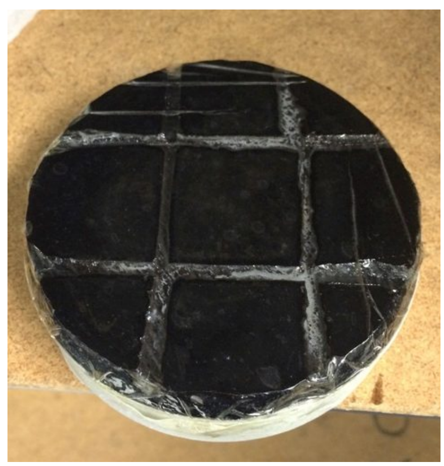

Figure 5. Grinding spindle and SiC grit (a, left), completed pitch grinding tool (b, right),

The ceramic tiles were beveled to 45-degree angles by grinding the edges using the 120-grit SiC-water solution, as seen in Figure 6(b). The 13 ceramic tiles were bonded to the front face of a flat circular piece of steel using cyanoacrylate adhesive (superglue) and was allowed to cool at room temperature overnight [Figure 6(c)]. Similarly, each mirror was bonded to a circular steel fixture using heated pitch and placed into the freezer to adhere properly. After 15 to 20 hours of grinding, the ceramic tiles wore down past the beveled edge and become a scratching hazard to the mirror. A new grinding tool was used every 10 to 12 hours to avoid any possibility of scratching the mirror. The grinding process was continued until the 220-grit solution no longer resulted in a noticeable improvement to the substrate.

Figure 6. Grinding aluminum mirror flat (a, left), beveling ceramic tiles (b, center), completed ceramic grind tool (c, right)

6. MIRROR POLISHING

The polishing process used the same pneumatic device used in the grinding stage, except a diamond compound paste was used in conjunction with various oil-based lubricants. A felt, diamond-embedded pad was adhered to the front face of a steel puck using pitch, and then attached to the top of the mechanical rotating arm. The polishing process began with a 15µm diamond compound and slowly worked down to 0.25µm, as the polishing progressed.

6.1 Titanium Polishing

The titanium mirror used a 30µm diamond-embedded pad and specialized lubricant to polish the surface, as shown in Figure 7(a). The 30µm pad worked extremely well and leveled out many of the peaks in the surface. After nearly 10 hours of polishing, the 30µm pad was replaced by a 12µm diamond compound applied on a felt pad in conjunction with olive oil. The finer diamond paste, along with the olive oil lubricant provided significant progress and results. After 12 hours of polishing, a 3µm compound paste was implemented. Next, the team used a 1µm diamond paste for 12 hours, followed by a 0.5µm paste. No significant progress was made by using the 0.5µm diamond compound, due to time and material restrictions on the project. The best surface finish obtained on the titanium can be seen in Figure 7(b).

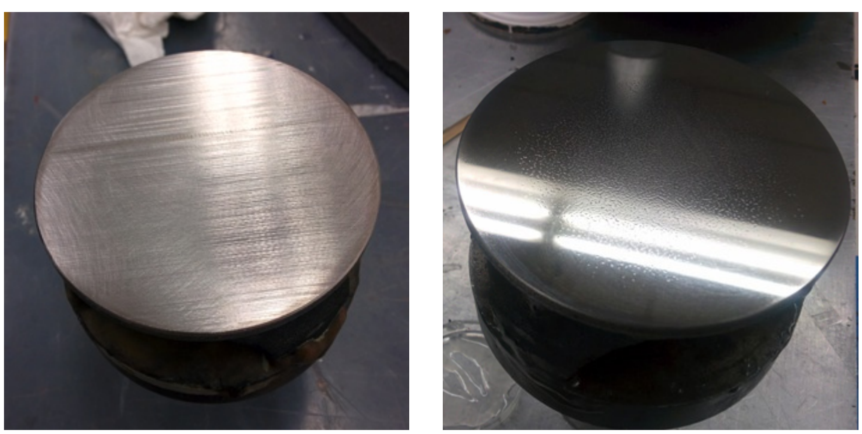

Figure 7. Titanium polishing progression: 30µm diamond embedded pad (a, left), best surface finish (b, right)

6.2 Aluminum Polishing

For the aluminum mirror, the method found to be most effective was using diamond compound on a felt pad with olive oil as lubricant. This method used several step increments starting at 15µm and ending at 0.25µm sizes, as shown by Figure 8(a). This allowed for a gradual increase in quality of the mirror over several sessions of work. Many different water and oil based solutions were tested but all resulted in the aluminum mirror oxidizing. Olive oil is a commonly used lubricant to prevent oxidation of the aluminum as well as lubricating the surface preventing scratches. This tip significantly sped up the polishing process and helped prevent scratches and defects in the mirror.

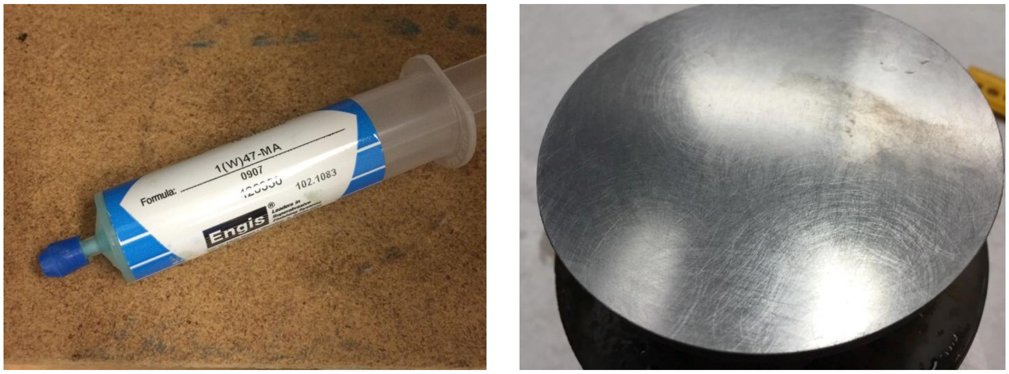

Figure 8. 1µm diamond compound (a, left), scratches from diamond pads significantly affected surface quality (b, right)

Using the aforementioned techniques, optimal micro-roughness was achieved as shown by the polishing progression in Figure 9. Initially, the same types of diamond embedded pads used on the titanium were used to try to polish the aluminum. However, as shown in Figure 8(b), the diamond embedded pads caused scratching in the surface creating much more work for the team. After the diamond pads were deemed to be unfit for the job of polishing the aluminum, the surface was reground using the 220-grit SiC solution and the best procedure was then applied.

Further research into aluminum polishing yielded that India ink [2], made from soot and water, is able to achieve surface micro-roughness values of <8 Å on optical-quality aluminum. In the future, the team will apply the polishing techniques learned from this project, and use India ink to achieve an ultra-fine polish.

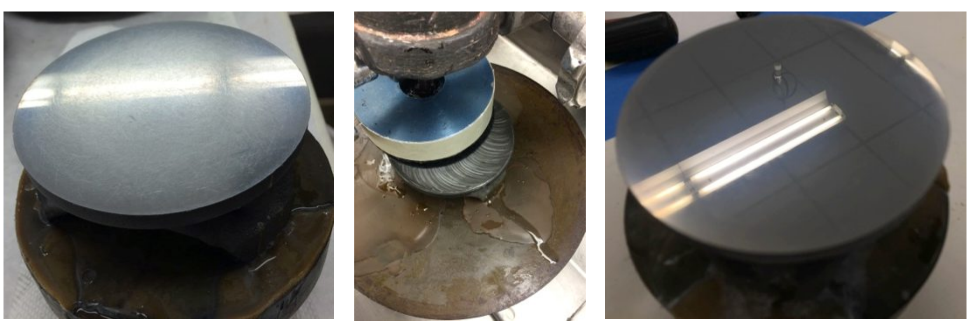

Figure 9. Aluminum polishing progression: 3µm compound (a, left), polishing 0.25 µm (b, center), best finish (c, right)

7. STATIC MIRROR ANALYSIS

Three main components were involved in the analysis of each of the 3D printed mirror designs. The first part consisted of a computer finite element method (FEM) model to assess the structural aspects of the mirror design. Second, physical testing determined the quality of the 3D printing material used in the mirror. Finally, analysis of the optical surface was performed on the polished mirror.

The group used a FEM model to perform static, physical and modal analysis of the mirror designs that had been chosen. The static analysis was completed in SolidWorks, focused on determining the maximum forces required to surpass the material yield strength. Test forces were applied to the mirror substrate to determine when and where the optimized support structure would fail. An additional static analysis consisted of an applied pure shear torque on the mirror substrate edge that simulated an incident that could occur during polishing. The max values obtained from these results can be seen in Table 2. The locations of the stress concentrations and displacements that would lead to failure on the top mounted mirrors are displayed in Figures 10(a) and 10(b).

Table 2. Ti6Al4V top mount and AlSi10Mg side mount static mirror analysis

Mirror Material:	**Ti6Al4V Top Mount**	**AlSi10Mg Side Mount**
Maximum Displacement 250 N Point Forces	2.453 µm	6.684 µm
G's of Shock at 10,050 N Force	550 G's	1024 G's
Max Yield Strength 585 Nm Shear Torque	415 MPa	827 MPa

This static analysis eventually reached the limitations of the SolidWorks' FEM capabilities. Due to the budget constraints and high cost of each printed mirror, no tensile testing was performed to confirm the results obtained from the FEM model. However, physical testing was performed to confirm material properties of each mirror and the polished surface finish.

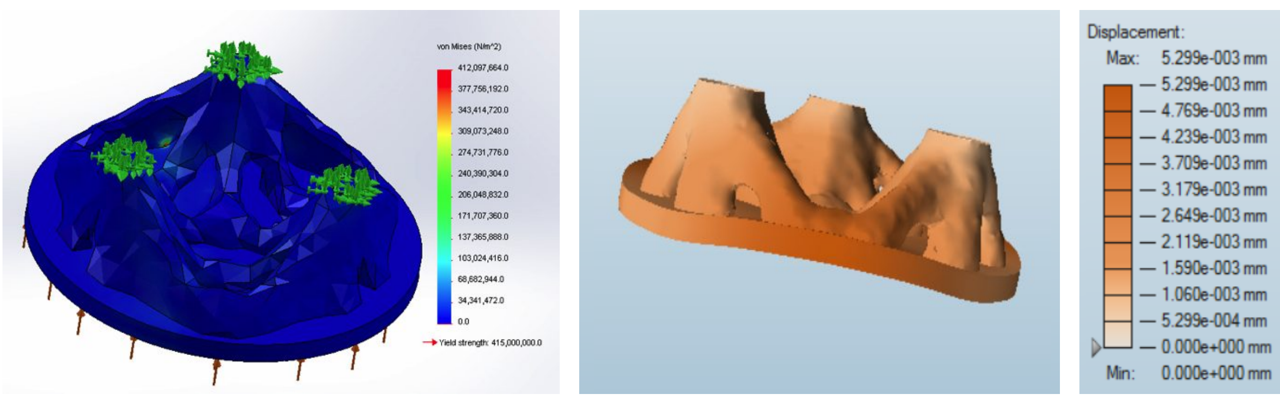

Figure 10. SolidWorks top mount titanium von mises stress analysis (a, left), top mount displacement analysis using 250N radial pressure point forces (b, right)

8. TEST APPARATUS AND FACILITIES

The University of Arizona Optomechanics Lab [Figure 11(a)] and Dr. Kim were extremely supportive in allowing the student team to use their NewView 8000 Series ZYGO interferometer to perform surface testing and analysis, shown in Figure 11(b). The interferometer device uses non-contact optical surface profiling to measure the roughness and topological features at a small cross-section in the mirror. Since the grinding and polishing process was performed to promote randomness throughout the surface, each cross-section was representative of the entire surface.

Figure 11. Optomechanics grinding and polishing lab setup (a, left), ZYGO interferometer used for analysis testing (b, right)

9. PHYSICAL MIRROR ANALYSIS

A physical analysis was used for the remaining 3D printed material and surface finish analysis. As previously stated, one of the major concerns with 3D printing processes is the porosity of the material. Before and after observations were made to see how the HIP process affected the porosity within the prototypes. Overall, the models that received HIP tended to allow for the grinding process to occur much quicker, than without this process.

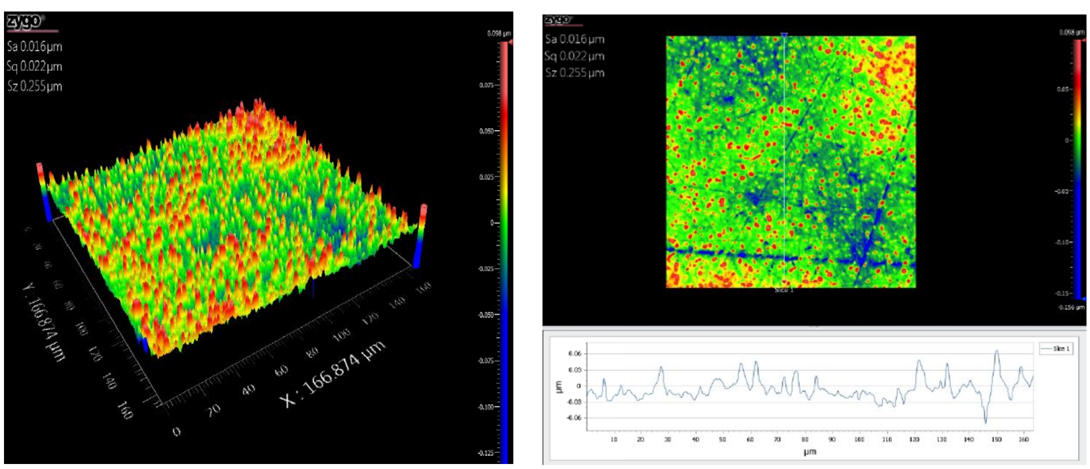

Figure 12. ZYGO interferometer 3D surface view of aluminum mirror (a, left), surface data from aluminum mirror (b, right)

To analyze the surface micro-roughness, the group made use of the University of Arizona Optical Sciences Zygo interferometer. This device was able to measure the optical surface and provide the necessary results, as seen in Figure 12. This device measured the optical surface at a small cross-section of the mirror. The randomness of the grinding and polishing process made it possible to analyze the small cross-section of the mirror surface and provide accurate data for the entire surface.

Overall, the aluminum mirror was found to have a micro-roughness of 22nm. The optimal measurement was 255nm P-V, as shown in Figure 12(a). The best micro-roughness was not quite up to optical quality as the metric used was

10-15Å. However, looking at the surface in Figure 12(b), the surface gave off a good specular reflection, but there was still some halo around the overhead lights, which signifies a drop in the optic's Strehl ratio and overall surface errors.

Comparing the two models, the HIP process was very effective for the aluminum mirror and removed all porosity from the prototype allowing for a fine polish, as displayed in Figure 13(a). However, the HIP process was not as effective on the titanium mirror because there was subsurface porosity in the mirror substrate that was discovered as the polishing process progressed, as seen in Figure 13(b).

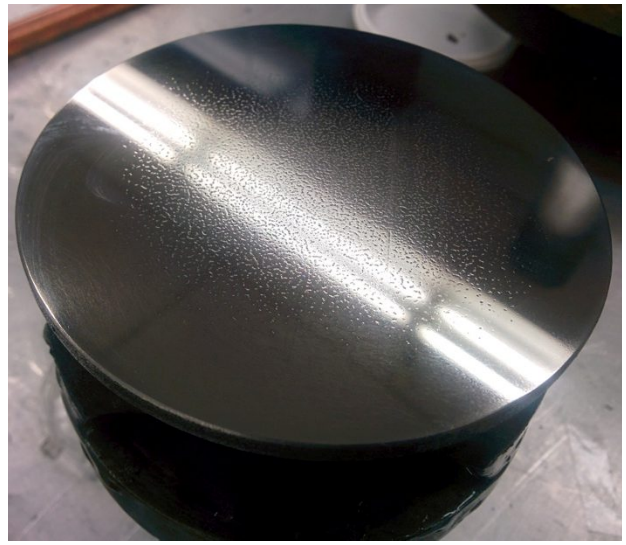

Figure 13. Final aluminum mirror surface finish (a, left), final titanium mirror surface finish (b, right)

10. MODAL AND THERMAL MIRROR ANALYSIS

One of the main test requirements provided by the Lockheed Martin Advanced Technology Center was to measure the modal and thermal properties of each prototype. Since this project was created with intentions of applications in space, it was extremely important that the mirrors survive the vibrations and extreme changes in temperature within a launch vehicle. The goal was to first apply FEA to each mirror at room temperature using ANSYS, and later analyze the prototype under the conditions in space. To begin, FEM analysis was under the assumption that the mirror was an isotropic material, which was later found to be highly anisotropic. This in itself was an important discovery.

The main priority for the team was to polish each model to its best possible RMS value and then analyze the model using the FEA analysis. Unfortunately, there was insufficient time and the model could not be imported into ANSYS. The difficulty in importing the models into ANSYS and SolidWorks was caused by the way the STL files were created for Altair Inspire optimized models. The sheer number of faces on a single model was a major hurdle because programs can only handle a limited number of faces. MeshLab, as seen in Figure 14, was able to reduce the number of faces by nearly 40,000. However, attempting to reduce these face numbers caused errors in the surfaces that could not be fixed automatically by the programs and thus the model would not import into ANSYS. Although the analysis could not be performed in ANSYS it was still noted how critical it was to determine how the mirror reacts to different modal and thermal effects in room temperature to make definite conclusions.

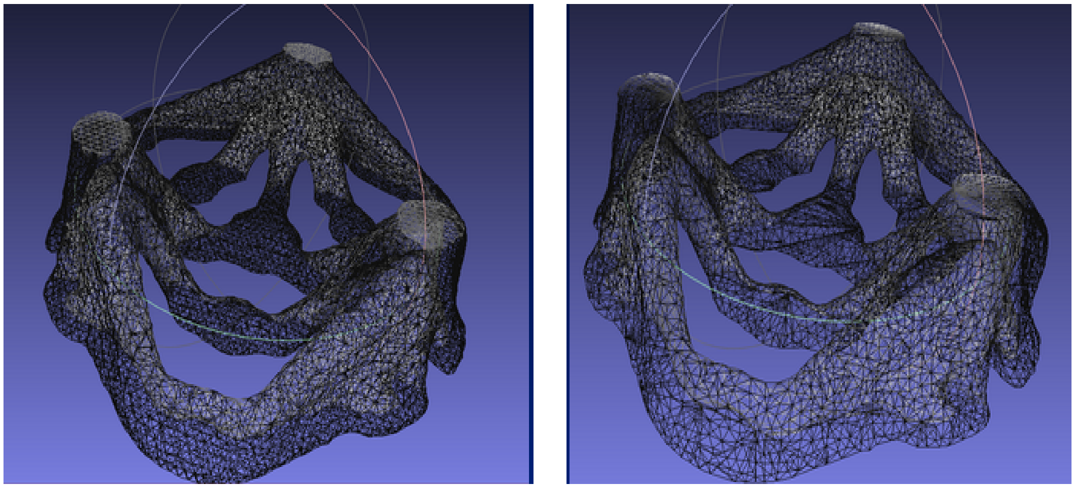

Figure 14. MeshLab faces reduction: 59,300 faces (a, left), MeshLab 20,000 faces (b, right)

11. SUMMARY

This paper provides each step our team of University of Arizona students (seen in Figure 15) followed to design, optimize, manufacture, analyze, grind, polish, and test aluminum and titanium 3D printed mirrors. Detailed descriptions involving all of the processes performed were provided throughout this manuscript.

While the value of 3D printing mirrors is clear, the implementation and technology supporting it is not quite to the stage where a team can concretely say that it can be done better than traditional methods. Machine parameters must be fine-tuned to minimize porosity when printing optical blanks. An additional strategy to mitigate porosity is to coat the optical surface with another metal (i.e. aluminum or nickel). The aluminum mirror did not have the obvious faults of porosity and the team was able to achieve a best micro roughness of 22nm RMS. With enough time and materials, the team is confident that an aluminum mirror can be polished to a quality desired by Lockheed Martin. The repeatability of 3D printing processes will need to improve to allow for better polishing results and make use of 3D printing for optics more mainstream and economical.

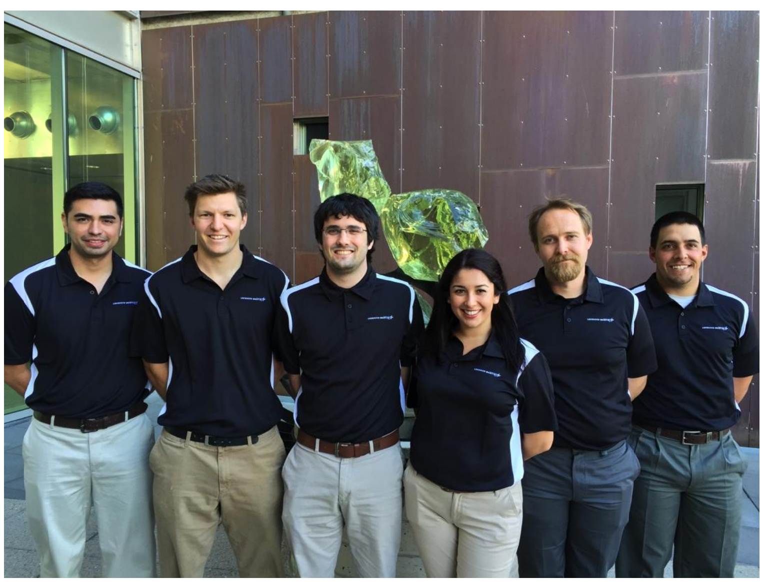

Figure 15. University of Arizona team, left to right: R. Bates, H. Herzog, J. Segal, A. De La Torre, J. Smith, and J. Calis

APPENDIX I: ALSI10MG EOS M280 MACHINE PARAMETERS

Powder CofC: see attachment "AlSi10Mg_powder_cert"

Powder supplier: see attachment "AlSi10Mg_powder_cert"

Powder D10, D50, D90: see attachment "AlSi10Mg_powder_cert"

Number of times the powder was recycled: three times

Percentage fresh and recycled powder in the mix (if applicable): 100% recycled powder

Built file/ program#: machine model and s/n: EOS M280 and 1243

Layer thickness: 30µm

Type of laser: class 1

Laser OEM: iPG Photonics

Laser power (contour and bulk): contour = 80W; bulk = 370W

Laser fiber diameter: 100-500 µm

Laser wavelength: 1060-1110 nm

Scanning speed: 1300mm/sec

Laser scanning pattern: X and rotated

Scan spacing: 0.020mm

Percentage overlaps (between adjacent laser scan tracks): 0.02mm

Hatch distance: 7.00mm

Controlled atmosphere: argon

Stops during build: none

Filter changes during build: none

APPENDIX II: ALSI10MG MATERIAL DATA SHEET

Alloy Name: AlSi10Mg

Description: gas atom, AlSi10Mg powder, 20-63 μm rev01

Table 3. Incodema3D AlSi10Mg material test data sheet

Chemical Analysis (Wt%)				Size Analysis		
Specific Range			Actual	Actual Range		
Element	**Min.**	**Max**		**Size**	**Unit**	**%**
Al		Balance	Balance	63	μm	0.5
Cu		0.05	0.0001	Test = Sieve		
Fe		0.25	0.174			
Mg	0.25	0.45	0.321			
Mn		0.1	0.003			
N		0.2	0.002			
Ni		0.05	0.004			
Pb		0.02	<0.001			
O		0.2	0.084			
Si	9.00	11	9.692			
Sn		0.02	<0.001			
Ti		0.15	0.009			
Zn		0.1	0.002			
Others Ind		0.05	<0.05			
Others All		0.05	<0.05			

ACKNOWLEDGMENTS

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