International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

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International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik,
Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 1118015 · © 2018 ESA
and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2535960

Additive Manufacturing of an AlSi40 mirror coated with electroless Nickel for cryogenic space applications

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ABSTRACT

Advanced Manufacturing (AM) has the potential to improve existing technologies and applications in terms of performance, light-weighting and costs. In the context of the SME4ALM initiative, launched by DLR and ESA, the company Kampf Telescope Optics GmbH (KTO) in cooperation with the Fraunhofer Institute for Material and Beam Technology (IWS) have assessed the feasibility of AM to build a high-performance optical mirror for space applications.

For the assessment of the AM potentials, a mirror design concept for cryogenic instruments for observations in the IR and NIR range was baselined. In a second step, Nickel-Phosphorus (NiP) was selected as optical coating. The combination of coating and mirror material is a primary design driver for optical performance. Both materials must have a very similar CTE as well as be compliant to modern optical manufacturing (diamond turning, polishing). As a promising candidate for NiP coating the AlSi40 was selected for the mirror structure.

The potential advantages of AM for optical mirrors in terms of mechanical performance, cost, and manufacturing time were exploited. The achievement of those objectives was / will be demonstrated by:

1. verifying AM material properties and manufacturability of AM mirrors by material sample tests and subcomponent tests
2. designing AM mirror demonstrator by structural, thermal, and optical performance analysis
3. applying and elaborating AM specific design methods (topology optimization, sandwich structures with internal microstructures, monolithic design, etc.)
4. manufacturing, assembling, and testing AM mirror demonstrator to verify manufacturability and optical performance
5. comparing optical and mechanical performance of the AM mirror demonstrator to a conventional mirror by numerical analysis to exploit potential advantages of AM

Keywords: Additive Manufacturing, AlSi40, optical mirror, cryogenic application, AM specific design

1. INTRODUCTION

High performance optical mirrors are key components of scientific instruments in astronomy and space applications, in particular for cryogenic instruments in IR and NIR. The selection of the combination coating / mirror base material represents a primary design driver for a mirror system. Different thermal expansions will decrease the optical performance of the mirror at cryogenic temperatures. Both coating and base material must be compliant to modern high precision manufacturing (e.g. diamond turning) as well as modern polishing technologies (chemical, mechanical, ion beam). A well-suited combination of coating and base materials is Nickel-Phosphorus (NiP) and the Aluminium alloy AlSi42. Effects due to thermal expansion are negligible due to a very similar CTE. A further advantage of AlSi42 in comparison to the standard space Aluminium Al6061 is the higher Young's-modulus and the lower density, which gives the designer more flexibility for light-weighting.

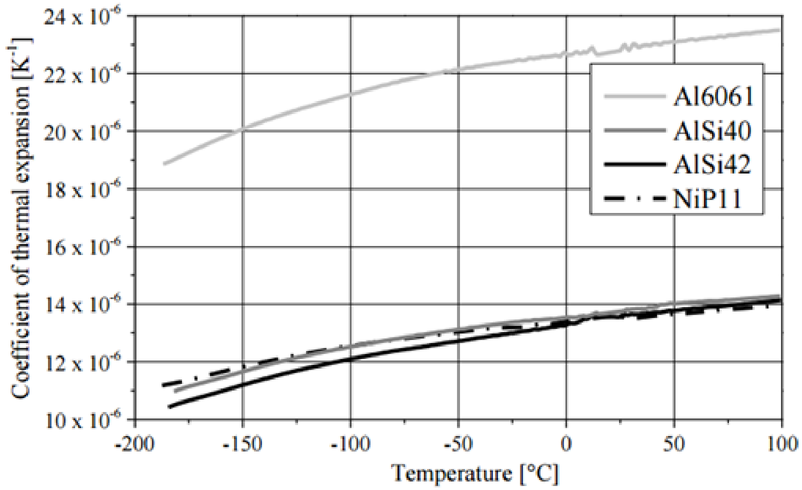


Figure 1 **CTE for different aluminium alloys and NiP11 [1]**

AM offers a variety of technical features to improve the design of a structural component:

- topologically optimized structures, which could not be manufactured with conventional technologies, e.g. cavity, undercut, etc.
- multi material build-ups
- stress optimized structures
- monolithic structures

KTO is specialized in the design of optical systems, with a core competence in optical and opto-mechanical design while the IWS are experts for material and beam technology. The objective of this technology development activity is to combine both competences in order to:

1. Assess the feasibility of Advanced Manufacturing (AM) to build high performance optical mirrors for space applications.
2. Exploit the potential advantages of AM for optical mirrors for space applications in terms of optical and mechanical performance, light weighting, cost, and manufacturing time.

2. ENGINEERING APPROACH

In order to assess the potentials of an AM optical mirror, a conventional mirror design was elaborated for comparison. Based on comparable ESA missions (TIRI, EUCLID), the following performance requirements were specified for a mirror for a typical space application.

Optical requirements

- radius of curvature: R~380mm
- clear Aperture: CA~200 mm
- diameter of mirror: D~210mm
- wave front error: WFE < $\lambda/2$ in visible range (~628nm) = ~300nm pV
- Final surface roughness: ~74nm RMS after coating

Mechanical requirements

- 1st Eigenfrequency of hard mounted mirror: f > 2000 Hz
- 1st Eigenfrequency of hard mounted mirror assembly: f > 500 Hz

Physical requirements

- The mirror shall have a diameter of 210 mm.
- The mirror shall be mounted on an athermal interface structure to an optical bench made of Aluminium with three I/F points.

Although AlSi40 and similar Aluminium-Silicon alloys have already been investigated for AM applications (Silicon content ranging from 18% to 60%) [2, 3], the handling of this material in an AM processes cannot be considered as a standard process. In a literature research the following conclusions were derived:

- AlSi40 can be processed by Selective Laser Melting (SLM)
- Dense samples with no cracks or pores larger than 24,5 µm were manufactured
- Distribution of Si particles can be influenced by heat treatment
- Homogeneous distribution can be achieved by a heat treatment at 360 °C for 6 hours
- Tensile strength “as-built” exceeds the bulk materials tensile strength
- As-built SLM specimens are less ductile than bulk material specimens
- Heat treatment can be used to initiate grain growth and therefore decrease tensile strength but increase ductility

Based on the preparatory work the main activities were divided into

- **AM process development**: Determination of the AM parameter set to get AlSi40 with the proper density and material characteristics
- **AM adapted mirror design**: Development of an optical mirror which encompass the AM benefits as well as the properties of AM AlSi40 (being good or bad)

3. AM PROCESS DEVELOPMENT

The processing of AlSi40 by means of SLM is at a very early stage of development. Only little knowledge about material-specific manufacturing constraints was gathered so far. An AM process has manifold degrees of freedom and all related parameters have to be fine-tuned in the course of the process development. The major steps can be divided into

- powder procurement and characterization: Particle size and particle size distribution, flowability
- SLM parameters such as laser power, scanning speed, energy density and preheating
- component setup such as orientation of the component to the laser (vertical or horizontal manufacturing), usage and design of support structures
- post processing (heat treatment, Hot Isostatic Pressing (HIP))
- material characterization (NDI, tensile tests

The AlSi40 powder was procured from the company Nanoval (custom built) and was characterized for relevant powder parameters such as particle size, flowability and chemical composition. The tests showed that the powder is comparable to commercially available SLM powder material.

The manufacturing of dense AlSi40 specimens is dependent on the SLM parameters (e.g. laser power, layer thickness, and exposure time) and the component setup during manufacturing (preheating, pattern rotation and support structure.

For each SLM parameter study 15x cuboid specimens (10 x 10 x 15 mm³) were manufactured using a 200 W (Nd:YAG-Laser, λ=1064 nm) AM250 from Renishaw. After each SLM parameter study the component setup during manufacturing was varied as well as indicated in the following table.

Table 1 Variation of component setup

Parameter study	Preheating [°C]	Pattern rotation [°]	Support Structure
1	170°	0°	No
2	170°	67°	No
3	24°	67°	Yes
4	170°	67°	Yes

With a total of 4 parameter studies and each time 15 parameter sets a total of 60 (4 x 15) cuboids were manufactured and characterized to determine the optimized SLM parameter set and component setup. Next figure illustrates the deviating results of the cuboid specimens.

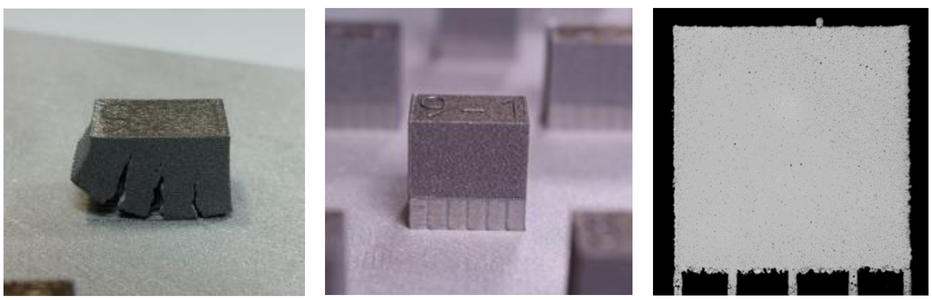


**Figure 2 Left: Parameter study 1, parameter set 9;
middle: Parameter study 4, parameter set 9;
right: metallographic investigations of 4/9**

Metallographic investigations of the cuboids manufactured using the optimized set of parameters show that the formation of cracks as well as the density of finely dispersed evaporation pores were reduced. With CT measurements a relative density of 99.72 % could be determined.

The post processing after AM (heat treatment, HIP) has an important impact on micro structure, relative density, Young's modulus, tensile strength, CTE, and surface roughness. Therefore, different sample configurations were tested:

- AB: as built, no post treatment
- HT: heat treated, T = 400 °C, t = 6h
- HIP: HIPed, T = 400 °C, t = 2h, p = 1950 bar Ar
- HT + HIP: heat treated, T = 400 °C, t = 6h + HIPed, T = 400 °C, t = 2h, p = 1950 bar@Ar

During manufacturing, post-processing and testing the brittle material properties lead to failure of several samples which required the change of SLM process parameters as well as sample design for mitigation.

Notch effect during tensile tests

Within the built process 1 and 2 (= manufacturing cycle, 4 in total) tensile test samples were built in vertical direction. The sample design was compliant to D-IN 50125, a standard for testing of metallic parts.

However, due to notch effects all tested samples (5 samples) broke within the thread during tensile tests (refer to figure 2, left side). Hence, the nominal sample diameter was reduced to 3 mm. By using this modified shape (Type B) all remaining samples were tested successfully.

Figure 3 **Change of sample design required due to notch effect (left: old design, right: modified shape Type B), built process 1 and 2**

Sample breakage due to residual stresses

100 % of the horizontal samples manufactured in build process 1 and 2 broke during the removal from the substrate. It was assumed, that the temperature and CTE difference between the melted material and the substrate (built plate in the SLM machine) create residual stresses which results in cracks. By introducing a pin-support structure the residual stresses could be reduced and 40 samples be built and removed from the substrate without breakage (built process 3). However, only 7 out of 40 samples did not show any cracks during visual inspection. These 7 samples were post processed according to the modified sample geometry (refer to figure 3, right) and tested successfully.

Support Structure Desing **As built specimen**

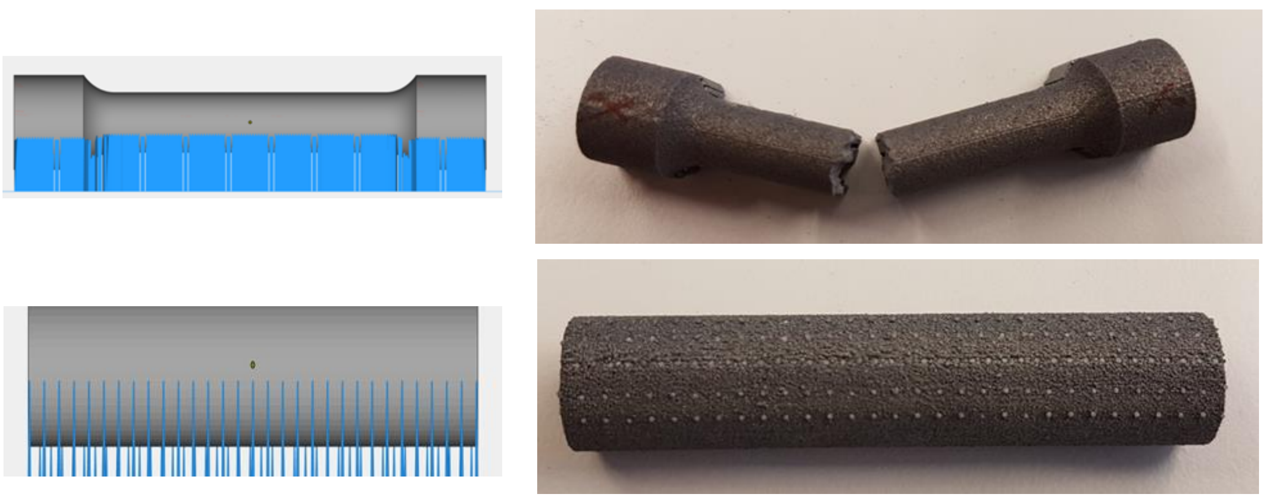


Figure 4 **Change of support structure design for built process 3 due to failure of horizontally built tensile test samples (built process 3)**

Reduction of crack formation

Further improvements of the AM process were investigated to reduce the high waste (82%) observed in built process 3. On one side, the scan vector length was reduced from 15 mm to 4 mm (refer to (1) in next figure). On the other side, the cylindrical shape used within build process 3 was replaced with a near net shape geometry (refer to (2) in next figure. Both mitigations were combined with the pin support structure used in build job 3. In both cases the waste could be reduced to 0%. All samples of built process 4 were tested in as-built configuration (no heat treatment and no HIP).

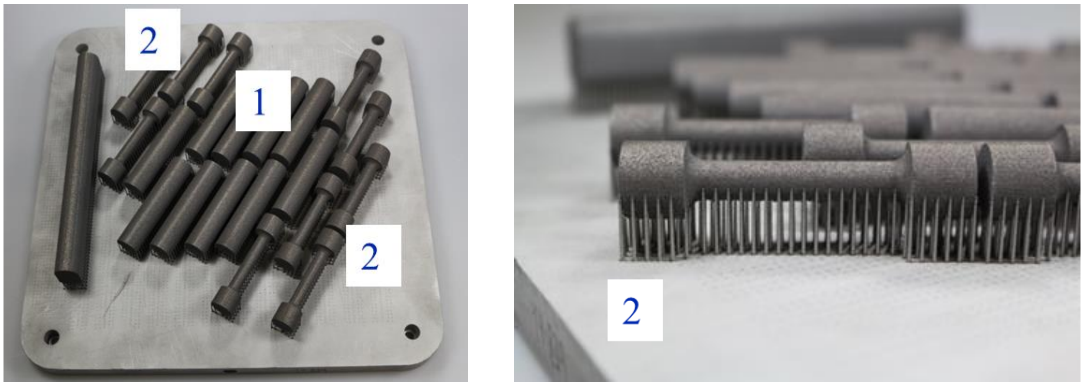


Figure 5 **Change of sample design and SLM parameter for built process 4**
Left: overview of manufactured samples for built process 4 and normal shape with reduced scan vector (1); right: near net shape with pin support structure (2)

In the next table, the results of the material characterization are summarized. The post processing heat and HIP reduces the strength of the material (built process 1, 2, 3) in comparison to as-built (built process 4) but increases considerable the ductility of the material (and thus reducing the brittleness of the material). Moreover, the heat treatment might be highly beneficial for decreasing distortion during the upcoming demonstrator manufacturing.

Table 2 **Strength Material data**

Material properties	**Bulk material**	**HT, HIP vertical**	**HT, HIP horizontal [MPa]**	**As Built horizontal, near net shape [MPa]**	**As Built horizontal, shortened scan vector [MPa]**
Built process	n/a	1 + 2	3	4	4
Ultimate Tensile Strength	225 MPa	287 ± 10 MPa	272 ± 47 MPa	372 ± 23 MPa	371 ± 20 MPa
Yield Strength	155 MPa	178 ± 16 MPa	182 ± 22 MPa	313 ± 20 MPa	319 ± 13 MPa
Elongation	TBD	1.1 ± 0.1 %	1.1 ± 0.3 %	0.6 ± 0.3 %	0.5 ± 0.2 %

Table 3 **Other material data**

Material Property	**AM AlSi40**
Relative Density (CT. dvoxel =6 µm, HT+HIP)	99.70 %
CTE (HT+HIP, vertical)	13.3*10-6/K @ 20 °C
Ra (mean surface roughness of IWS surface roughness sample, regardless of orientation)	22.6 µm
Rz (mean surface roughness of IWS surface roughness sample regardless of orientation)	160.3 µm

All in all, additively manufactured AlSi40 shows a brittle behaviour comparable to the bulk material, which has an elongation at rupture of 1.0-1.5%. Thus, special rules have to be applied for the design with AM AlSi40. Reduced to its most simple form, brittleness introduces two new aspects into the structural design problem:

1. The need for highly refined stress analysis methods.
2. The need to treat material strength in a statistical manner.

This is mainly due to the strong dependence of the fracture toughness of brittle materials on surface flaws (refer to Rz in Table 3). However, the surface roughness of AM specific designs cannot be improved in some cases (cavities, undercuts, etc.). Thus, more general design rules have to be derived from the performed material test campaign. A reasonable approach is therefore to use a minimum strength (mean - 3 standard deviations) and apply a FOSY of 1.25 and a FOSU of 2.0 (safety factors for metallic parts for verification by analysis only) and use the lower of the two stress limits.

Table 4 Derivation of design limit stress for AM AlSi40

Strength (Build-plate 2, HT+HIP, vertical)	**Mean**	**1σ**	**Mean-3σ**	**FOSY**	**Design Limit Stress**
	[MPa]	**[MPa]**	**[MPa]**	**FOSU**	**[MPa]**
Yield Strength	178,0	16,2	129,3	1,25	**103,4**
Ultimate Tensile Strength	287,0	10,6	255,3	2,0	127,6

4. AM ADAPTED MIRROR DESIGN

For comparison of the benefits, the AM optical mirror shall be compared with a conventional baseline design. A conventional baseline design was derived from an existing mirror assembly designed by KTO for a different application of comparable loads and requirements (Figure 3). The mirror is made of Al6061-T6 and the Bipods are made of Ti6Al4V. The optical surface was achieved by diamond turning. Only mirror diameter, height, and the type of optical surface (spherical instead of aspherical off-axis) were adjusted for the baseline design.

Figure 6 Conventional mirror design:

One of the main advantages of AM is the direct implementation of topology optimization. Topology optimization is a technique whereby a structure is optimized by distributing material freely in a given design domain. This technique is limited for conventional manufacturing (drilling, milling, turning) but its full potential can be exploited for AM.
Topology optimization requires a mathematical formulation, consisting of constraints and an objective function which is to be minimized or maximized. Conventional structural topology optimization uses a “minimum compliance” formulation, which seeks to maximize the structure’s stiffness for a given mass.
The minimum compliance formulation results in structures that resist mechanical loading well, but do not necessarily produce good optical performance. Ideally, optimization of an optical mirror should directly minimize the wavefront

error. However, a mathematical formulation that expresses this exactly may not result in good numerical behaviour. If possible, other factors such as dynamic behaviour and structural integrity should be considered in the formulation as well.

Two approaches to optimization were considered:

1. The topology optimization module of the finite-element software ANSYS was used to evaluate potential formulations in order to test whether commercial software is suitable for optimizing optical mirrors
2. Additionally, KTO developed a custom tool for topology optimization (TopOpt), which provides greater freedom in formulating optimization objectives

Figure 7 displays the 4-step development approach for the AM mirror.

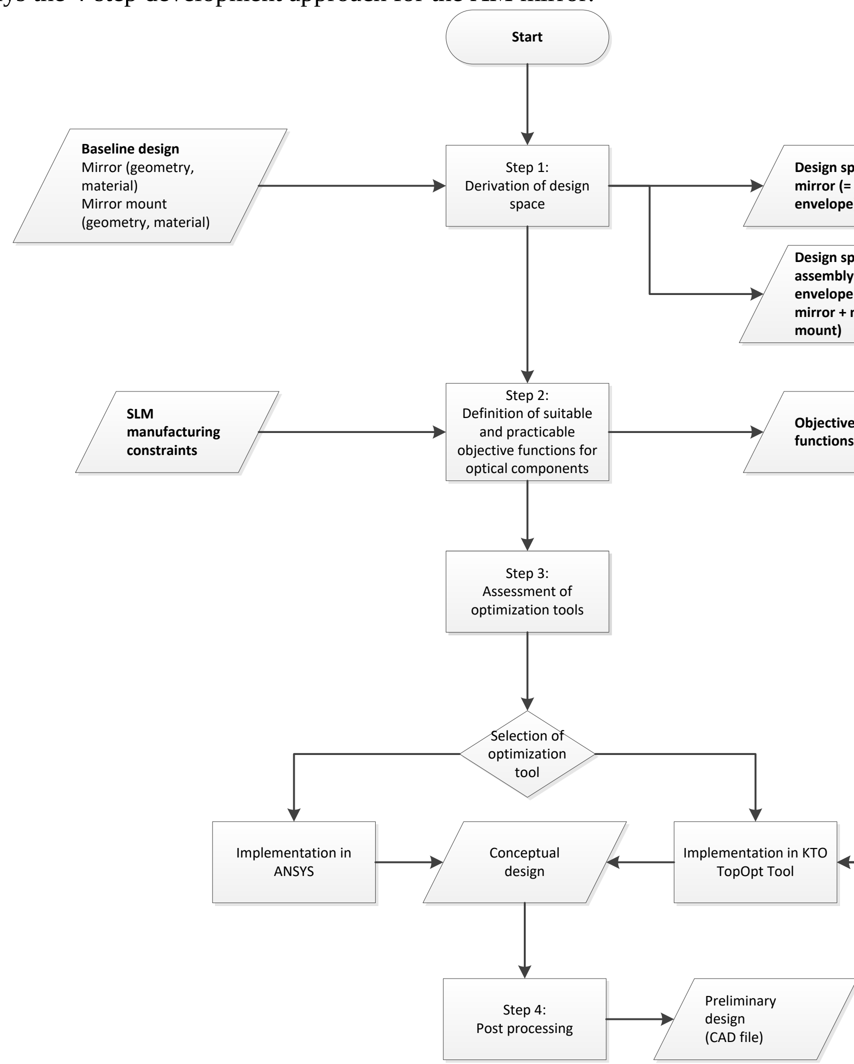


Figure 7 Development approach for design of AM mirror demonstrator.

In step 1) the optimization design space is defined based on the geometry of the baseline mirror (mirror and mirror mount). Optimization objectives specific to optical mirror applications were derived in step 2 in consideration of environmental loads and performance requirements, e.g.

- Minimum global compliance
- Minimum RMS surface deviation
- Minimum surface compliance

Using these inputs, two optimization approaches were tested concurrently to evaluate the feasibility of the derived objectives and the capabilities of existing commercial software and custom software (step 3).

Finally, manufacturable designs were constructed based on the output of the optimization process (step 4).
Several design loops were performed with the described development approach and the design concept was improved stepwise. While the initial ANSYS-optimized design has good theoretical performance, a mirror in this form is most likely impractical to manufacture, even with AM. As Figure 8 shows, the structure is stiffened by the development of a sandwich structure that forms a large cavity in the middle of the design domain. Building this geometry with SLM would require the use of support structures filling a large portion of the interior volume. Removal of supports from this region would be very difficult, if not impossible.
Optimization of a monolithic mirror assembly proved to be infeasible. This approach requires a formulation that attempts to satisfy two contradictory goals simultaneously, and does not result in designs with good performance. Additionally, the brittleness of AlSi40 makes it unsuitable for a rigid-body joint; therefore a second material is necessary for the isostatic mirror mounts (bipods in Figure 8, made out of Titanium).

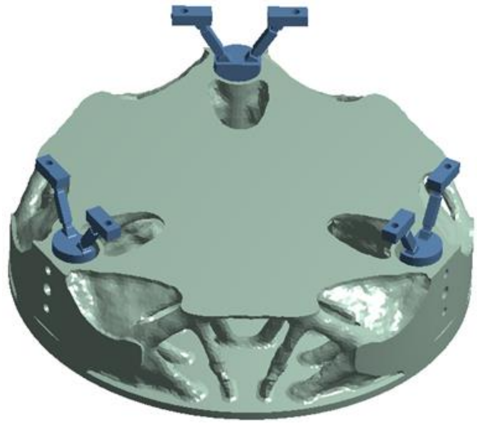


Figure 8 **Mirror design iteration #5 (ANSYS), including Bipods**

Designs optimized to use internal lattices would likely need no support structures to build the reinforcement on the mirror's backside, since the lattice structure supports material built above it. Designs can be optimized to exclusively use lattice material in the design domain, which is subsequently closed with a skin of solid material, or can be optimized using a multi-material model that mixes lattice and solid material freely. Two designs were produced based on these concepts (Figure 9).

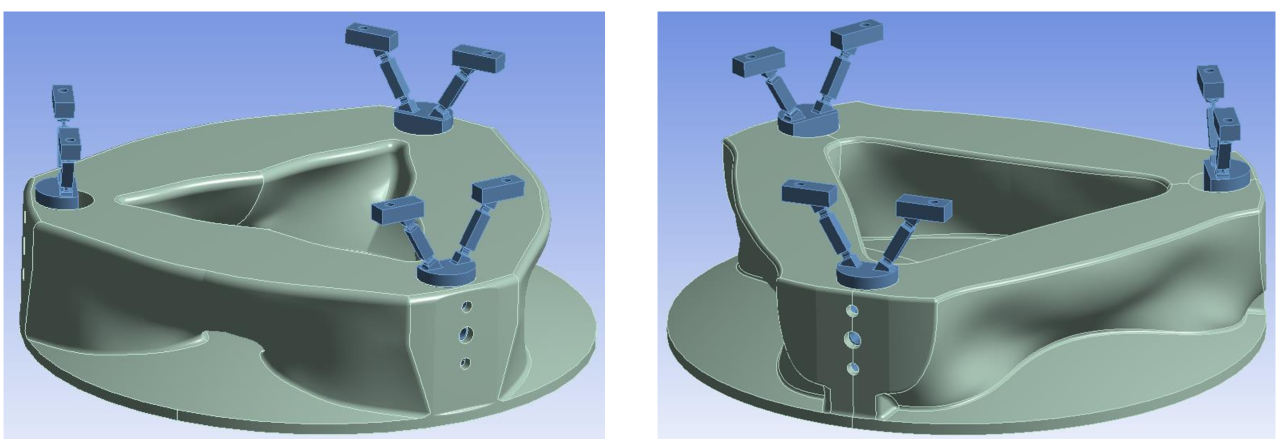


Figure 9 **Mirror design iteration #6 (TopOpt) and #7 (TopOpt), including Bipods**

The optical performance of each not only meets the requirement, but is an improvement over the baseline design. The optimized mirrors exhibit a mass reduction of 30-40% (refer to Table 5)

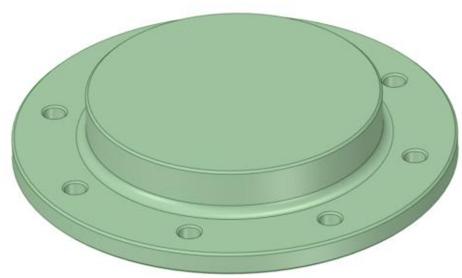
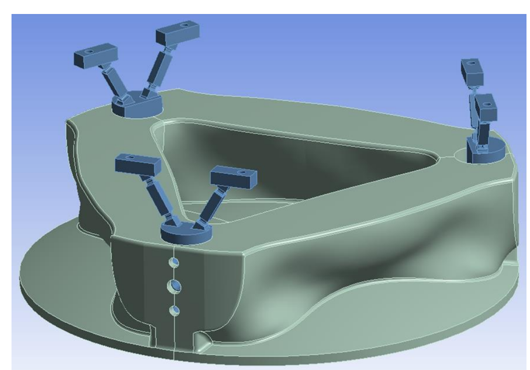
Table 5 **Comparison of three optimized mirrors to the baseline design.**

Metric	Units	Baseline	Iteration #5 (ANSYS)		Iteration #6 (TopOpt)		Iteration #7 (TopOpt)	
			Solid		*Lattice*		*Mixed Solid+Lattice*	
Mass	g	2328	1604	-31%	1431	-39%	1579	-32%
1. Eigenfrequency	Hz	510	535	+5%	569	+12%	548	+7%
RMS WFE (axial)	nm	48,7	18,2	-63%	20,6	-58%	18,3	-62%
RMS WFE (lateral)	nm	51,3	58,0	+13%	41,6	-19%	40,5	-21%
Manufacturability		excellent	good (TBC)		good (TBC)		good (TBC)	

5. NEXT ACTIVITIES

The development study shall be finished till November 2018. Currently preparation of AM is ongoing of a subcomponent NiP coating and a mirror demonstrator. Next table illustrate the design and purpose of the test articles.

Table 6 **Overview of test activities**

Name	Purpose	Design
Subcomponent for NiP coating	• Determine as-built surface roughness of optical surface • NiP on AM AlSi40 • Optical verification	
AM Demonstrator (without coating)	• Verify feasibility of building complex structure with large dimensions. • Verify effect of thermal post-treatment on mirror with large dimensions. • Verify feasibility of mechanical post-processing of large mirror. • Verify surface roughness of as-built optical surface of large mirror. • Verify optical surface distortion of as-built mirror (effect of large dimensions)	

6. SUMMARY

The objective of the study was to assess the potentials of AM for advanced optical mirror design with AlSi40. Main tasks were the development of an AM process for AlSi40, inclusive material characterization, and the development of an AM adapted mirror design. In a stepwise approach with several iterations and repetitions proper SLM process parameters could be determined. Material properties were assessed for different AM configurations (vertical or horizontal print

direction) and it can be concluded, that the material properties of bulk AM are consolidated with a high level of confidence.
A stepwise approach was also applied for the design and analysis of the AM optical mirror, in particular for the implementation of topology optimization. Due to limitations of commercially available SW tools, a custom tool was developed to optimize for mirror specific requirements. Several design iterations have been performed to improve the design stepwise. The current solution has a reduced mass of 30% and reduced WFE of 20% in comparison to the design baseline. The AM demonstrator will be built in October 2018

7. ACKNOWLEDGEMENT

This project was funded in the scope of the ESA GSTP program "Assessing the Use of Advanced Manufacturing to Improve and Expand Space Hardware Capabilities" in cooperation with the Fraunhofer Institute for Material and Beam Technology (IWS) in Dresden.

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