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Printed Athermal Mirror (PAM) based on AlSi40 and NiP coating for space application

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Most optical instruments for space applications in the areas of earth observation, science and optical communication require high performance optical mirrors. Driving requirements are typically low Surface Form Error (SFE), high structural stiffness over a wide temperature range, a low micro roughness and low mass.

A promising material combination for optical mirrors is the usage of the aluminium alloy AlSi40 as mirror substrate and electroless Nickel phosphorous (NiP) as coating for the optical surface. The main advantage of this combination is the CTE compatibility of AlSi40 and NiP over a large temperature range. In addition, NiP coated surfaces can be easily diamond turned and polished. This material combination thus enables relatively fast production cycles even for a mirror surface roughness in the few-nm range.

Within the ESA GSTP SME4ALM program, the feasibility to produce optical mirrors from AlSi40 by additive manufacturing (AM) was demonstrated. Main objectives were the determination of AlSi40 AM parameters and material properties as well as the demonstration of advantages of AM (e.g. topology optimization, monolithic design, lattice structures). By consequent improvement of the Laser Powder Bed Fusion (LPBF) manufacturing process, similar material properties to bulk AlSi40 were obtained. Up to 40% improvement were achieved for relevant material properties such as stiffness and SFE.

Based on the good results of the first project, a follow up program was launched by ESA (also in the context of ESA-GSTP) with the objective to design and print an optical mirror with TRL ≥ 5.

This paper will summarize the development program and results of the follow-up project, in particular:

- Design and testing of lattice structures
- Definition of a cleaning process
- Transfer of AlSi40 processing strategies to industrial-scale machines
- Design and testing of a mirror demonstrator, which is representative for space applications

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).

Among the variety of materials used for mirrors in space-optical instruments, one of the most common materials is Aluminium due to its availability, thermal conductivity, price and ease of manufacturing. Downsides of Aluminium, however, are its high CTE of ~24 µm/K and its limited Young´s modulus of ~70 GPa. As optical instruments in general require a very stable form, position and orientation of the individual mirrors with respect to each other and other parts of the instrument on the level of a few micrometer and arc seconds, special care has to be taken in their mechanical design.

For space-optical instruments, in particular, the harsh environmental conditions during launch and in orbit even increase the demand for a stable structure and an insensitive material and thermo-mechanical design. Therefore, in high-performance applications, where thermal and mechanical loads cannot be shielded or reduced to a level that would allow the use of Aluminium, ceramic and glass-ceramic materials such as Zerodur and SiC or other metals as Beryllium are employed. Especially where the application demands large mirrors, i.e. above ~100 mm in aperture, Aluminium typically is discarded as a material. In addition, the surface roughness that can be achieved via diamond turning and polishing of Aluminium-6061 is "only" on the order of 10nm. Such surface roughness may significantly decrease the straylight performance of an optical instrument. For Zerodur and SiC (with dedicated surface layers), values on the order of ~1nm and below are state-of-the art and enable a low scattering behaviour and thus high straylight performance. Although these materials enable a low surface roughness, a zero-CTE approach in case of Zerodur and a low CTE and high thermal conductivity approach for SiC, however, they are more expensive and more difficult to manufacture, leading to longer lead times and higher costs.

The AlSi40 material bridges the gap between these two worlds of low-cost but less performant Aluminium and high performant but expensive ceramics and glass-ceramics (or even toxic materials in case of Beryllium). The CTE is reduced to about half with respect to pure Aluminium. Moreover, the mixture of Al and Si can be steered in such a way that its CTE can be matched to the one of a NiP coating, thus avoiding any bi-metallic bending effects between substrate and coating (which would be present in the case of Aluminium). The great benefit of the NiP coating is that it can be diamond turned and polished down to ~1nm surface roughness, allowing a high performance with respect to straylight reduction.

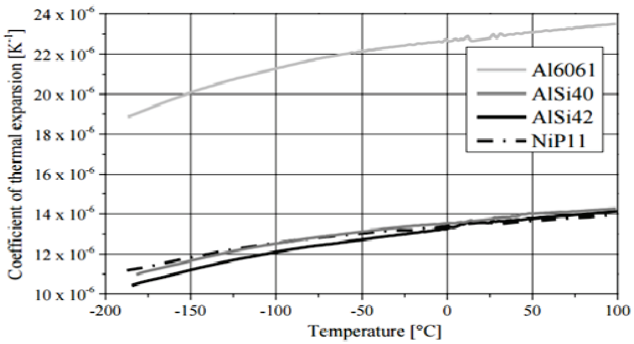


Figure 1 CTE for different aluminium alloys and NiP11 [1]

Overall, the material combination of AlSi40 for mirror body and structure and NiP coating on the optical surface allows an a-thermal design, i.e. a design that isotropically expands or shrinks with changing temperature but does not deviate in the optical surface form from a scaling effect in the radius of curvature. AlSi40 can thus be seen as a cost-efficient material for small and medium-sized mirrors that offers a good performance.

Additive Manufacturing (AM) offers a variety of technical features to improve the design of a structural component. It offers a high degree of design freedom which enable the manufacturing of topologically stress optimized structures, which could not be manufactured with conventional technologies, e.g. lattice structures as monolithic structures. Furthermore AM-methodologies enable the realization of complex structures from materials which usually are hard to achieve caused by the limited processability by conventional manufacturing methods (e.g. milling, forming). Utilizing Laser Powder Bed Fusion (LPBF) can be used for the manufacturing of complex structures composited from hollow spaces and thin structures [2].

Objective of the PAM (Printed Athermal Mirror) project is to explore the advantages of AlSi40 / NiP in combination with AM to realize high performance optical mirrors for a wide range of applications. To reach this, different expertise have been joined in the team:

1. Kampf Optic Telescope (KTO): Opto-mechanical design of optical mirrors
2. Fraunhofer Institute for Material and Beam Technology (IWS): Design and development of additive manufacturing
3. Airbus Space & Defence: Large system integrator for optical instruments

2. ENGINEERING APPROACH

The PAM engineering approach was based on the results achieved in the predecessor project "ESA GSTP SME4ALM". Main achievements were:

- Reliable printing of AlSi40 with LPBF: AlSi40 is difficult to print. In a stepwise approach with several iterations and repetitions proper LPBF process parameters could be determined to achieve a homogeneous material setup, with high density and w/o cracks
- AM material characterisation: Material properties of printed bulk AlSi40 were assessed for different AM configurations (vertical or horizontal print direction)
- AM adapted mirror design: A stepwise approach was applied for the design and analysis of an 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.

A first mirror was built based on a combination of bulk and lattice structures, refer to next figure.

Figure 2 AM mirror demonstrator developed and manufactured within previous ESA GSTP.

The realized mirror demonstrator has a reduced mass of ~40% and reduced WFE of 20% in comparison to the design baseline. The achieved technology readiness level of the printed mirror is rated as TRL 4. Justification for TRL 4:

- Feasibility of additively manufacturing an AlSi40 mirror with NiP coating was demonstrated on sample and component level, supporting the proof-of-concept.
- Preliminary functional performance requirements were established for an IR-application of the printed mirror.
- Performance and survival of the printed mirror at a typical space environment was verified by finite element analysis.
- A breadboard was manufactured and its performance was verified in a laboratory environment.

The PAM optical mirror, which shall be developed and manufactured in the framework of this project shall have TRL5 at the end of the activity. Justification of TRL5:

- The PAM optical mirror shall be a space application.
- Preliminary performance requirements shall be clearly defined for the space application.
- Optical, mechanical, thermal and thermo-elastic performance of the PAM optical mirror shall be verified by tests at space representative loads.

The following main verification tasks have been derived to achieve TRL5

- Characterisation of lattice structures: design and manufacturing of different lattice structure concepts and characterisation with mechanical tests
- Demonstration of a high-performance optical surface: Surface Form Error (SFE) < 10 nm rms, surface roughness < 1 nm Ra
- Demonstration of optical stability of a printed AlSi40 during thermal cycling with a representative mirror shape
- Demonstration of a representative optical mirror under representative space conditions

3. PAM MIRROR REQUIREMENTS

For a mirror, the benefit of additive manufacturing is seen mainly in a reduction of mass and an increase of the stiffness-to-mass ratio beyond the means of traditional light-weighting. For a scan mirror, the moment of inertia could be reduced or the stiffness-to-moment of inertia ratio increased.

The benefit of fast prototyping for a mirror unfortunately is reduced to the manufacturing of the mirror structure since the manufacturing of the optical surface, i.e. the diamond turning and polishing of the optical surface, has to be performed in a traditional way after the additive manufacturing of the mirror structure. Here, a comparison of the time required for additive manufacturing should be compared to the time required for diamond turning and optical polishing.

Two main technical aspects should be considered for the choice of an application of the PAM mirror: The optical and mechanical complexity of the mirror design and the environmental loads the mirror has to withstand.

In order to evaluate the applications, the following criteria have been set by the study team:

1. Technical readiness of state-of-the art of AM and post processing of optical surface(s) and mechanical interfaces
2. Improvement of stiffness/mass ratio or “improved light-weighting”
3. Simplification of MAIT: Integral mirror & interface or several mirrors on one substrate
4. Envelope: Limited printing volume of ALM machine “Renishaw AM250/400” used in this study
5. Reduce technical risks by simple and unambiguous verification in scope of PAM project
6. Business opportunity: Reduction of costs and lead time, possible serial production of mirrors

The criteria have been applied to several past and existing optical instruments (laser communication, earth observation). Two suitable applications have been identified for PAM:

1. Scan- or pointing mirrors due to high stiffness to moment-to-inertia ratio (refer to chapter 5)
2. M1-M3 part of a TMA telescope for a compact hyperspectral application due to simplification of integration and alignment and due to the improvement of its stiffness-to-mass ratio (refer to chapter 8

The small dimensions of the scanning mirror (elliptical shape with 113 x 80 mm) enables a representative verification under thermal-vacuum cycling using a small TV chamber. Therefore, the scanning mirror shall be used as a subcomponent model for verification of

- Feasibility of high performance optical surfaces
- Thermal stability of PAM over thermal-vacuum cycling

Verification of the PAM requirements on system level shall be performed with combined M1-M3 mirror assembly (application “2”).

4. LATTICE STRUCTURES

Lattice structures (internal microstructures, see Figure 3) are one of the key enablers for AM mirrors to achieve a very low aerial density. Only AM technologies can manufacture the unique geometries of lattice structures, which combine high stiffness and low mass.

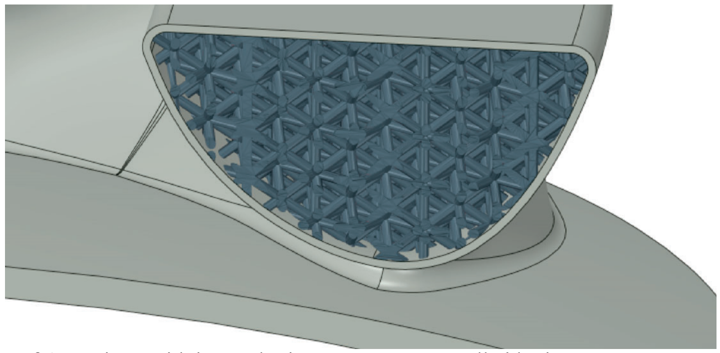


Figure 3 Cut view of AM mirror with internal microstructure, a so-called lattice structure

Based on a literature review, a set of different lattice structure geometries were evaluated by analysis to determine optimal lattice parameters in terms of specific stiffness (apparent elastic modulus vs. apparent density). Most “optimal” in this context means stiff, light and of sufficient buckling strength.

The main lattice parameters of were:

- Lattice pattern (see Figure 2 for potential lattice patterns, many others are possible)
- Size of single strut (min. size is determined by manufacturability by AM)
- Volume fraction (how much volume of a unit cell is occupied by printed material)

Next figure illustrates some examples for lattice structures.

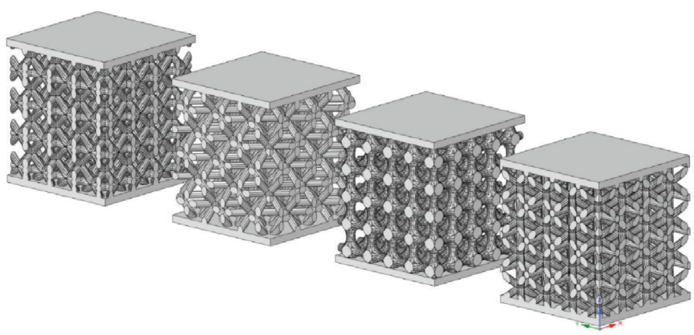


Figure 4 Examples for potential geometries of lattice structures. Test samples have a size of 20x20x20mm³.

A set of generic lattice structure geometries was evaluated by linear elastic finite element analysis to determine optimal lattice parameters for optical mirrors. The main lattice parameters of this study were:

- Total size of samples was 3x3 unit cells with a unit cell size of 20x20x20mm³
- Volume fractions between 10% and 70% were assessed
- The lattice design had to be open cell, to allow powder removal after AM

Based on the study of lattice parameters and a parametric model of a generic optical mirrors, the following requirements were derived for lattice structures:

- The volume fraction of the lattice structures for the PAM mirror shall be between 20% to 40%, to avoid excessive form errors of the optical surface.
- The surface area of the lattice structure per volume of the unit cell coated with 50µm of NiP shall not change the mass of the unit cell by more than 5 %.
- The elastic modulus of an internal lattice structure should be as high as possible to reduce the WFE of a generic optical mirror for space applications, particularly with respect to the diamond turning load case.
- The shear modulus should be low compared to the elastic modulus, which means that the Poisson ratio should be high.

For the lattice characterization by mechanical test, two lattice designs were selected that have a high tensile/compression modulus and a relatively low shear modulus. The lattice designs shall be evaluated at a volume fraction of 20%.

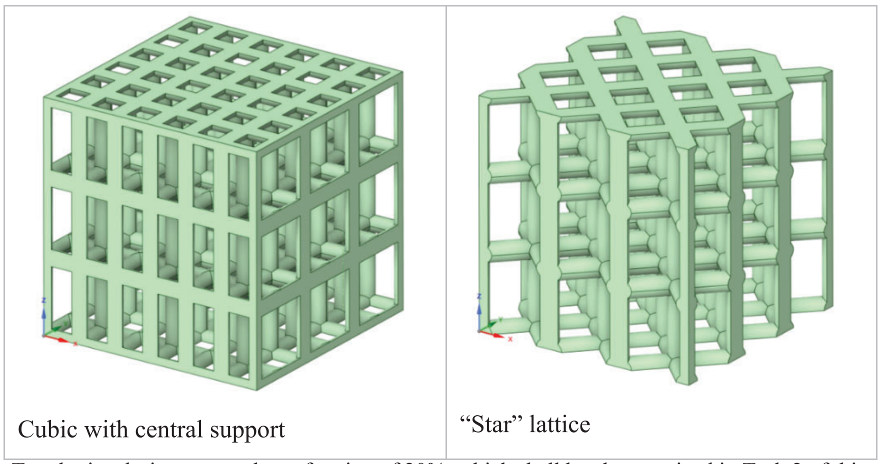


Figure 5 Two lattice designs at a volume fraction of 20%, which shall be characterized in Task 2 of this study

For manufacturing of both lattice designs the parts were rotated around 45° around the x and y axis to achieve an inclination angle of around 45° at almost every strut. For supporting cone supporting structures were applied. The part orientation on the substrate plate is illustrated in Figure 6.

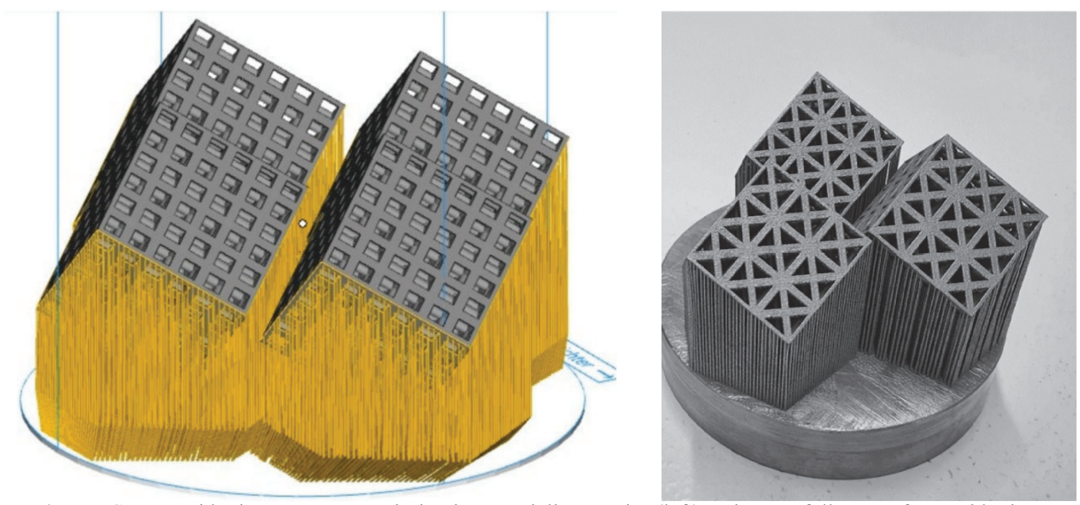


Figure 6 Supported lattice structures as design in Materialise Magics (left) and sucessfully manufactured lattice structures (right)

The optical mirror is based on the application of NiP (Nickel Phosphorus). The chemical nickel layer is deposited in an electroless chemical process. In order to characterize the impact of the NiP coating on the mechanical characteristics of the lattice structure, NiP was applied to half of the lattice sample.

Compression testing of the lattice cubes was carried out on a MTS 810 compression testing machine (model number 510.30, see Figure 7). To ensure that the specimens are centred during the process, steel dies with a special pocket are used, into which the cube specimens can be inserted with a perfect fit. The upper press plunger is mounted on a ball joint to assure homogeneous force application over the entire contact area of the lattice cube.

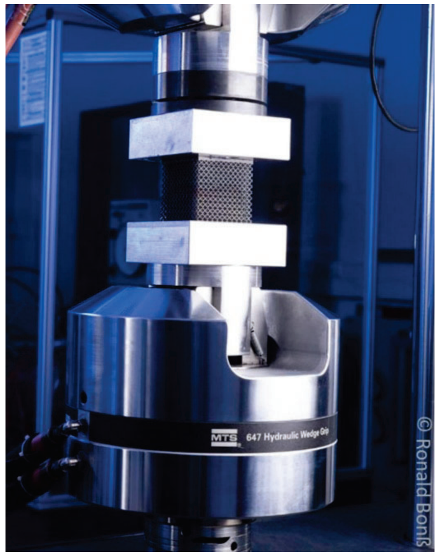


Figure 7 Setup for lattice structure compression testing

The graphical representation in Figure 8 shows a significant improvement of the respective compression strengths of each lattice type by almost 200 % after NiP coating. Apparently, the NiP coating dramatically enhanced the stiffness of the lattice structures. Moreover, the coating might have covered some of the surface irregularities (roughness, attached particles, …) which otherwise might have acted as crack-initiating defects (see Table 1).

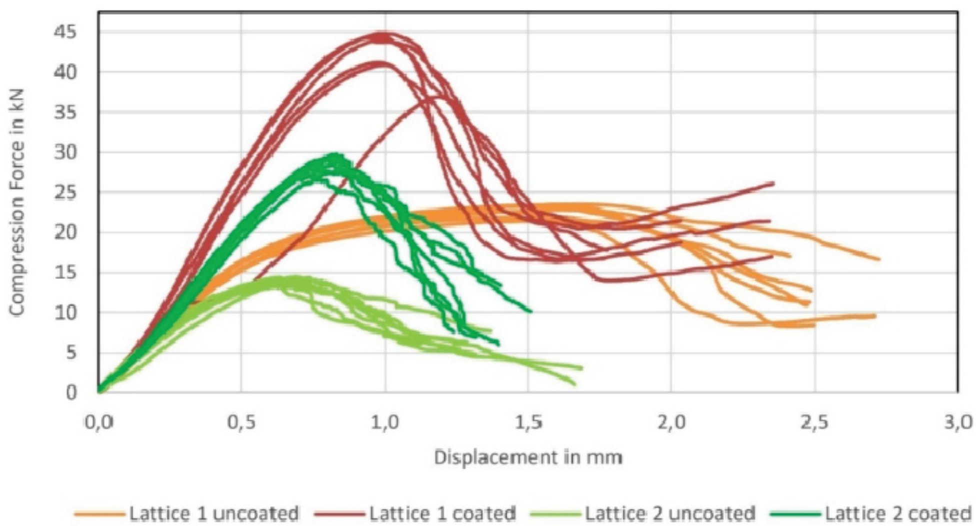


Figure 8 Compression force - displacement curves for tested lattice samples

Table 1 Results of the compression testing

	ΔL at $F_{Comp.max}$ in mm	Global Elongation at $F_{Comp.max}$ in %	Strength in N/mm^2	Elastic Stiffness[1] in kN/mm
Lattice 1 – uncoated	1.52	5.08	126.31	36.16
Lattice 1 – coated	1.01	3.35	235.38	57.23
Lattice 2 – uncoated	0.65	2.17	77.50	29.50
Lattice 2 – coated	0.80	2.67	158.37	44.12

The reasons for the increase of stiffness after coating is not yet well understood, further investigations are necessary.

5. SUBCOMPONENT DESIGN

The PAM subcomponent design is based on a scanning mirror for laser communication. The elliptical mirror with the dimension of 113 mm (long axis) and 80 mm (short axis) has to be compliant to:

- Operational temperature range: -30° - +80°C
- Mass: < 200 g
- First natural Eigenfrequency: > 800 Hz
- Surface Form Error: < 12 nm rms
- Surface roughness: < 1 nm Ra

In addition to high vibration and shock loads, a pressure load of 7.5 kN for Diamond Turning (DT) was considered in the design. The mirror envelope and some parameter variations of it were assessed to understand the driving design parameters and the potential for AM specific design.

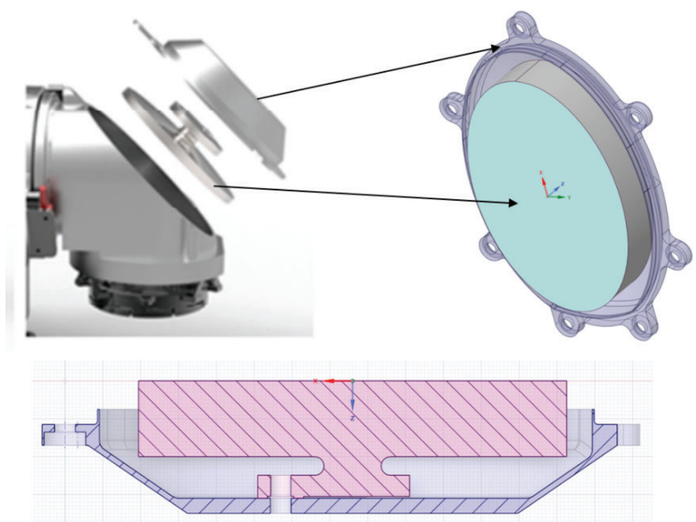


Figure 9 (top left) Explosion view of laser scan mirror in laser scan communication terminal. (top right) Envelope of mirror with cap. (bottom) Cut view of mirror envelope and cap

The mass requirement can only be reached by light weighting design. In order to compare the AM topology optimized design, a sandwich structure design was used for comparison. Main goal for the topology optimization was selected for maximum strength to increase the mirror performance wrt SFE.

[1] The stiffnesses are to be considered as approximations.

The two developed designs were verified for the same load cases as the baseline design to determine mass, first eigenfrequency and the WFE at ambient temperature and at operational conditions. A NiP coating of 50µm was assumed on the optical surface. Next table summarizes the results of the "conventional" sandwich and the AM optimized topology design.

Table 2 Results of assessment of two mirror designs

Internal design	Requirement	Honeycomb	Mixed topology (Lattice 20%)
Mirror mass, g	<200	163	200
1. Eigenfrequency, Hz	>800	1232	1300
WFE at ambient, nm	<10.7	5,9	2,8
WFE at operation, nm	<14	8,8	6,1

Although the mirror with traditional light-weighting is lighter, the AM specific design achieves a higher eigenfrequency and lower WFE at ambient and at operation. Next figure illustrates the mixed topology design.

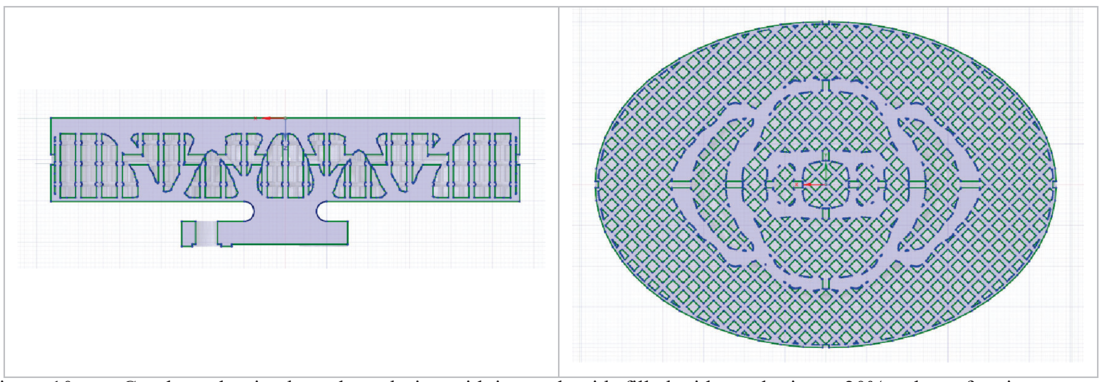


Figure 10 Cut through mixed topology design with internal voids filled with star lattice at 20% volume fraction.

6. SUBCOMPONENT MANUFACTURING

The subcomponent manufacturing encompass the following manufacturing steps:

1. Printing in 45° angle with (optical surface upside)
2. Post-machining of mechanical interface and mirror backside
3. First DT of optical surface
4. Application of NiP coating ~75 µm
5. Second DT of optical surface
6. Polishing

The lattice structure as well as other test samples which have been manufactured in the context of the AlSi40 parameter development were performed at a lab scaled Aconity Mini machine at the IWS. However, the dimensions of this machine is not sufficient to print the later demonstrator. Therefore, a machine had to be found, which fulfils the following criteria:

- Suitable substrate heating of > 400°C
- Similar optical configuration (laser, spot size)
- Availability
- Build volume compliant to the dimensions of the demonstrator

Before printing of the subcomponent, the feasibility to transfer the process parameter from one AM machine to another had to be verified. Therefore, a suitable machine had been chosen and the existing parameter set had to be validated via microstructural investigations and characterization of the mechanical properties.

The Centre for Product and Process Development (ZPP) at ZHAW School of Engineering in Winterthur (Switzerland) was selected as external partner for the processing of the material on their AM400HT in an industrial environment. The same AlSi40 powder feedstock material that had been used at Fraunhofer IWS was delivered to their institution and the previously developed parameters were validated.

The compression samples manufactured at the industrial machine exhibit a slightly lower compression strength compared to the previous tested samples, while the elastic stiffness is only slightly reduced. Especially the target lattice structure shows very similar stiffness values (see Figure 11).

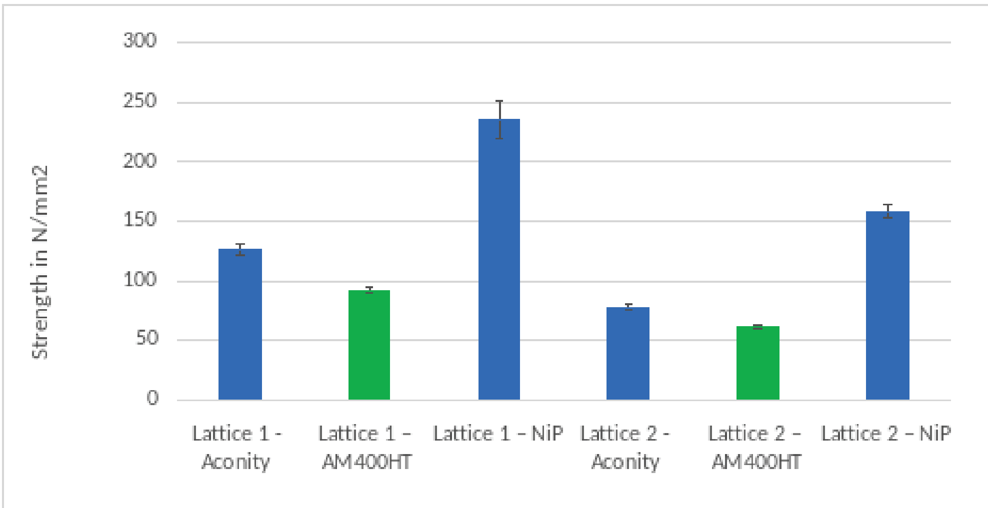


Figure 11 Comparison of the strength of the measured lattice cubes

The transfer of the developed process chain to an industrial machine with regards to material properties was evaluated as successful. Minor setbacks regarding mechanical performance, which might be caused by microstructure, geometrical differences and surface morphology/ roughness offer potential for future adjustments of the process.

In summary of the transfer to an industrial machine can be considered successful and suitable for further processing of AlSi40 for the mirror application. Even though some valuable learnings can be derived from the transfer. Even a one-to-one transfer of a parameter set developed on one machine to a non-identical machine with similar configuration (technological, optical, process control) is not possible without changes in some parameters. As shown a minor increase in scan speed was needed to get dense material similar to the developed parameter set on the lab machine. So minor differences can lead to a limited reproducibility on another machine. The effect on reproducibility is even bigger when the configurations changes more drastically, like different laser systems or spot-sizes. Therefore, it is advised to always validate existing parameter sets when transferring them between machines.

Next images illustrate the printing process of the subcomponent.

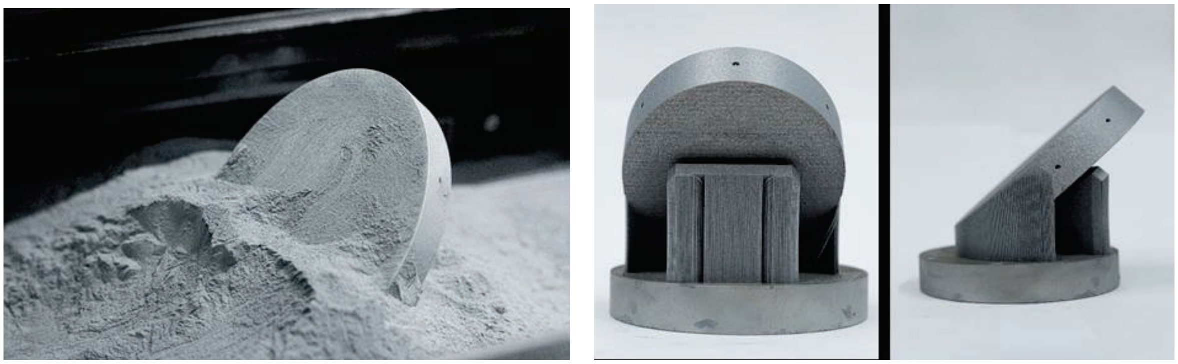


Figure 12 Printed subcomponent in the powder bed, subcomponent with support structures

After printing, the interfaces, reference surfaces and the mirror surface have been milled, refer to next figure.

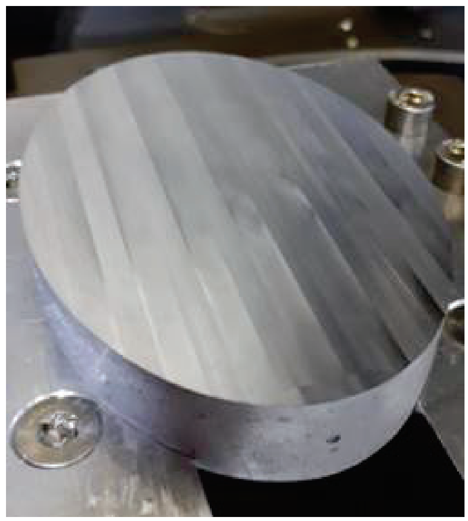


Figure 13 Subcomponent after mechanical manufacturing

After manufacturing the subcomponent has been processed by Diamond Turning (DT). DT of aluminium and other mirror materials is a standard process of ultra-precision manufacturing. After first DT of the mirror surface, a layer of ~75 µm of NiP coating was applied to the mirror. Unfortunately, the lattice structure inside subcomponent could not be coated with NiP. The holes around the mirror edge are too small to allow the coating fluids to flush inside the lattice structure. After "NiPing" the subcomponent was diamond turned for a second time.

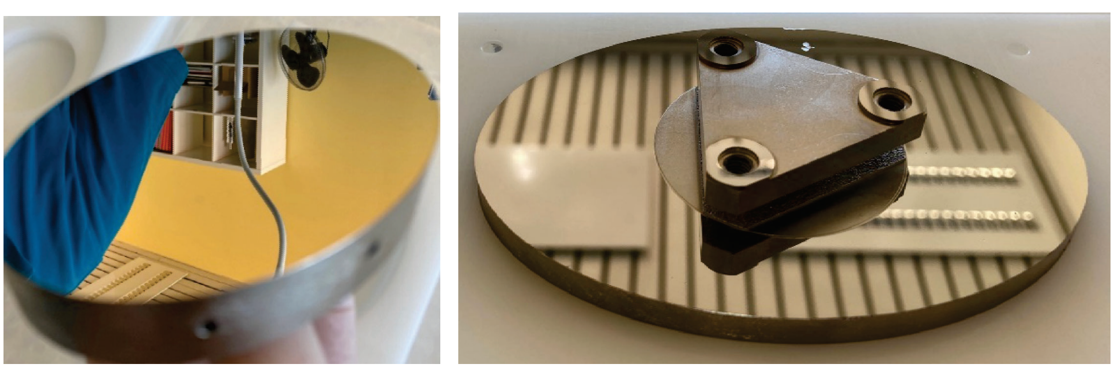


Figure 14 Mirror after diamond turning

In order to reach the specifications, the subcomponent was also polished by the Technische Hochschule Deggendorf. By application of a stepwise approach using classical polishing and Magneto Rheological Finishing (MRF). Next table illustrates the Surface Form Error after MRF.

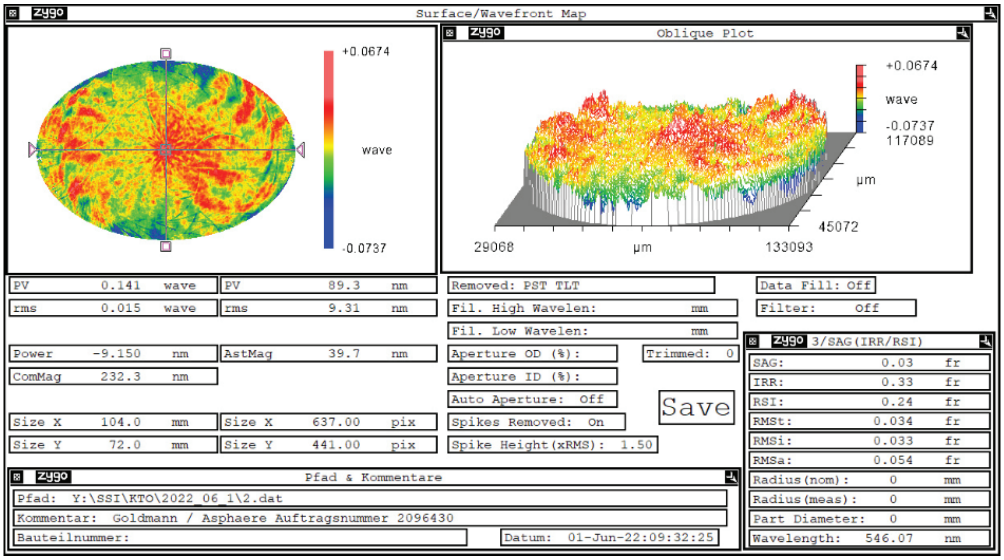


Figure 15 Surface Form Error of the subcomponent after MRF polishing

Next table summarizes the mirror properties after DT and polishing.

Table 3 Properties of optical surfaces after diamond turning and polishing

Requirements	Diamond Turning	Polishing
WFE rms < 12 nm	n/a	9,3
WFE PV < 97 nm	272	89,3
Roughness < 1 nm Ra	2,64	1,5

The requirement of surface roughness is slightly not compliant. It turned out that the used polishing technologies enabled either full compliance of SFE or surface roughness. The delta from 1,5 nm Ra to the required 1.0 nm Ra is considered negligible.

7. SUBCOMPONENT TESTING

The objective of the thermal vacuum tests was to verify the compliance of the PAM subcomponent mirror with the specified environmental loads in terms of structural integrity and optical performance. The thermal environment specified for the subcomponent encompasses the following temperature ranges:

- Operating temperature range from -30°C to +80°C
- Non-operational temperature range from -30°C to +105°C

The subcomponent was mounted on a cooling/heating plate inside a thermal vacuum chamber (TVC). The temperature levels were applied by cooling or heating an interface plate, to which the subcomponent was mounted on. To measure the wavefront error (WFE) of the optical surface of the subcomponent, an optical set-up was placed outside the TVC. The measurements were performed in double-path configuration through an optical window in the TVC.

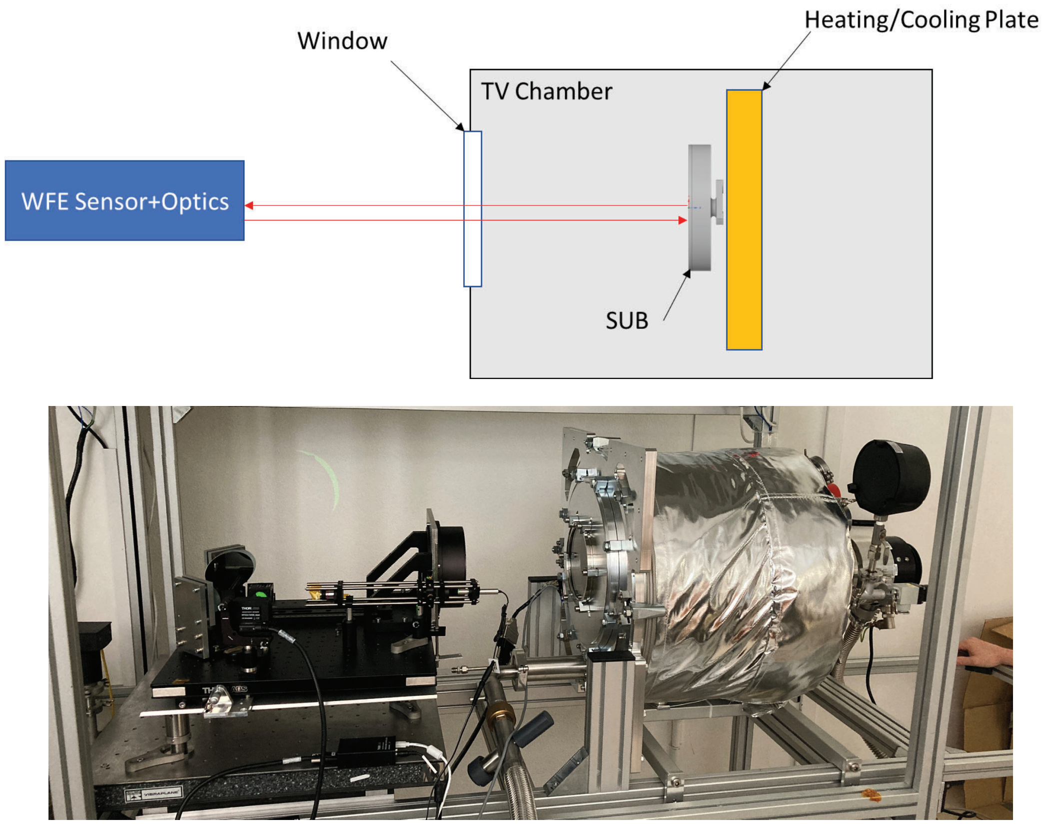


Figure 16 Test setup of PAM thermal vacuum tests

Thermo-couples were glued to the subcomponent and the cooling/heating plate to control temperatures during the test. Twelve thermal cycles (see figure below) were performed to verify the change in optical performance of the subcomponent due to potential changes in the material. Each test cycle went through the operational and non-operational temperature range.

The soak temperature levels were considered reached, when the average temperature of the mirror (measured by thermo-couples) was within ±1.0K of the goal temperature and the temporal gradient of this average temperature was below 2K/min. Soak time was 1h per temperature level.

The first test cycle was performed at temporal gradients <=10K/h. For the following test cycles, the temperature change between temperature levels was within ±1K/min measured at the mirror.

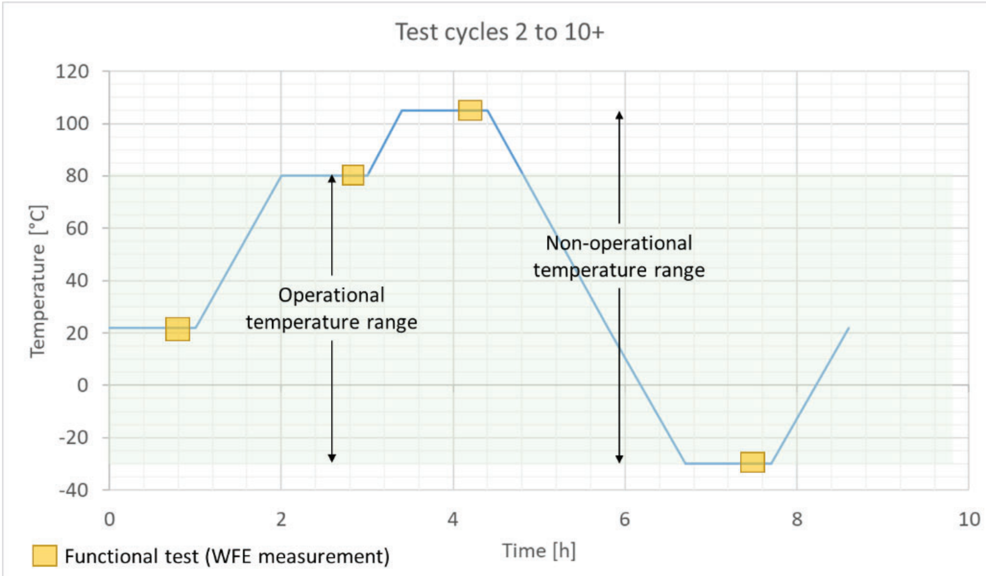


Figure 17 Thermal cycling

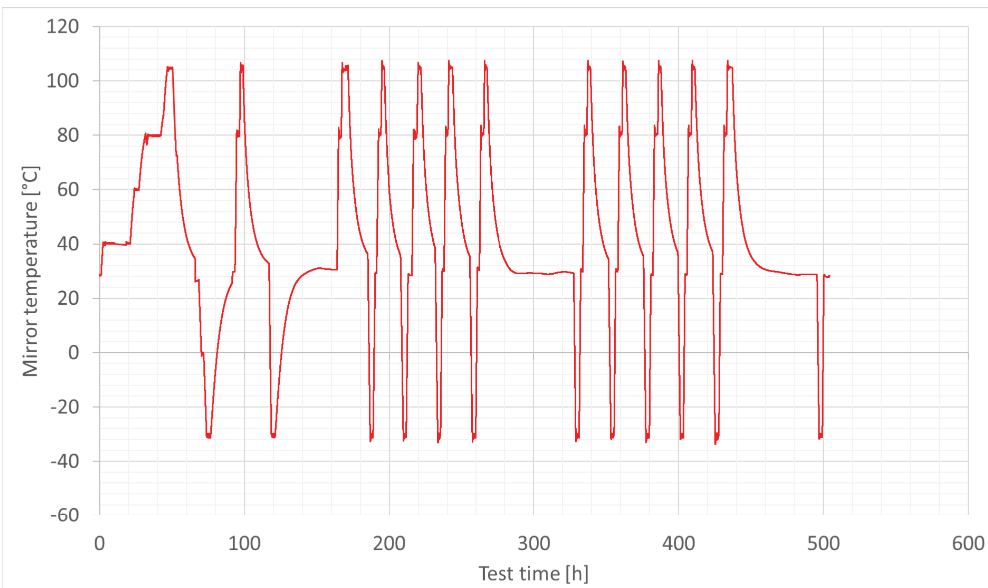


Figure 18 Temperature at subcomponent during twelve cycles of thermal vacuum testing.

The thermal cycling has been performed till the beginning of August 2022. Evaluation of the optical performance at each soak temperature level is ongoing.

8. PAM DEMONSTRATOR

The mirror concepts trade-off by Airbus resulted in a specification for the PAM application design based on a M1-M3 integral mirror of the a-focal FORUM telescope (see figure below).

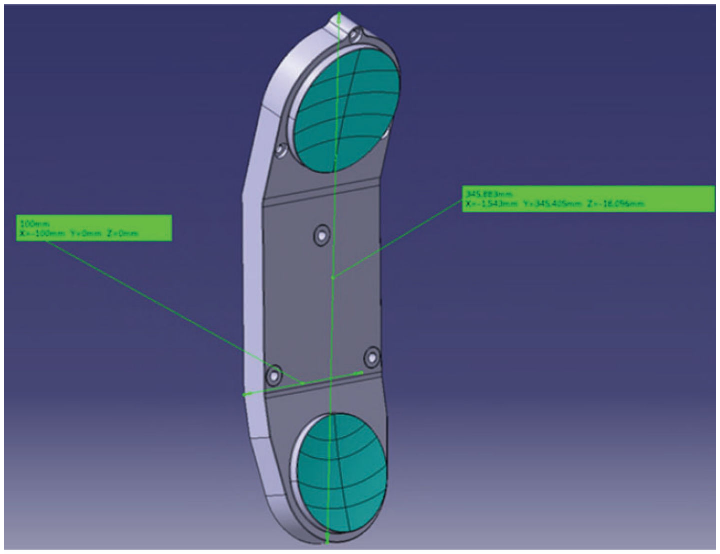
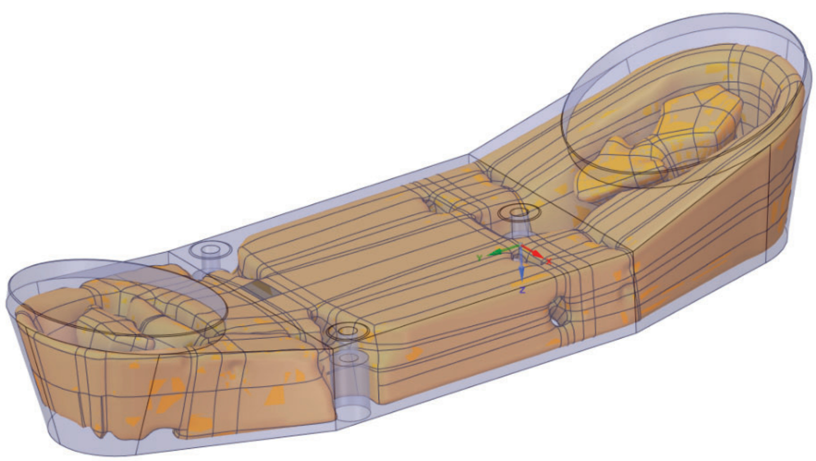


Figure 19 Design envelope of M1-M3 mirror of FORUM FSI telescope [AD2].

Based on the specification, the M1-M3 mirror design was adapted for additive manufacturing with AM specific design methods developed within the PAM project. The design was iterated with IWS to improve manufacturability. A mixed topology optimization approach was applied to reach optimal mass distribution and stiffness inside the mirror with an average density of 38% for the design load cases.

Regions identified by the topology optimization for lattice material (orange-coloured volumes in Figure 20) were filled with a lattice structure with cubic side diagonal supports at 20% volume fraction. The developed design was verified for the same load cases as for a conventional design to determine mass, first Eigenfrequency and the WFE.



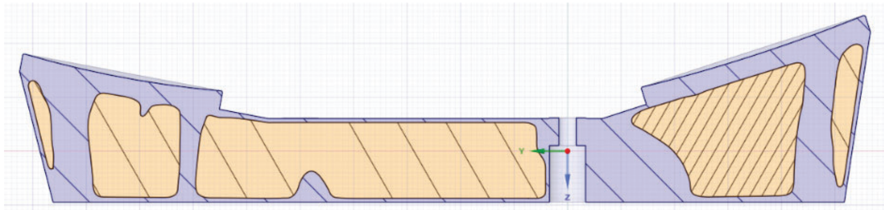


Figure 20 Sectional view of M1_M3 mirror design adapted to manufacturing constraints with mixed internal structure made of bulk material and lattice structures (represented by orange volumes)

The adaption of the CDR design to further manufacturing constraints resulted in a decrease in optical performance, but also a decrease in mass. However, the optical performance is still far below the requirements.

Table 4 Comparison of conventional and closed structure design to topology optimized design presented at CDR.

Name	Units	Requirement	Conventional	Topology optimized
1st eigenfrequency	Hz	>480	797	1171
M1 WFE RMS	nm	<40	16,6	14,1
M1 WFE PV	nm	<320	58,5	67,3
M3 WFE RMS	nm	<40	13,1	13,6
M3 WFE PV	nm	<320	73,0	109,2
Mass	N	<1,583	1,515	1,250

Conclusions for PAM CDR design:

- AM specific design achieved much lower mirror WFE than conventional and closed structure design → large margin for telescope WFE.
- Relative stiffness between mirrors is higher than for conventional design.
- Eigenfrequency is higher for equal mass

9. SUMMARY

The main objective of the study is to increase the TRL of printed optical mirrors with AlSi40 to >= 5. Main tasks were the design and characterisation of lattice structures, the transfer of the AM process for AlSi40 to an industrial machine and the verification of the performance of Printed Athermal Mirrors (PAM). In a stepwise approach with several iterations and repetitions proper LPBF process parameters could be determined. Material properties were assessed for different lattice structures, with and without NiP coating. NiP coating increases considerably the stiffness of lattice structures, although the reasons for this are not well understood.

A stepwise approach was also applied for the design and analysis of a subcomponent and demonstrator mirror, in particular for the implementation of topology optimization. Several design iterations have been performed to improve the design stepwise. The current solutions for subcomponent and demonstrator have either a higher stiffness, improved WFE or reduced mass in comparison to the conventional design baseline. Thermal stability has been tested in a thermal vacuum tests with representative temperatures (ops, non-ops) and thermal cycles. Results will be available in September 2022. The demonstrator will be built in August 2022, final machined and tested till the end of 2022.

10. ACKNOWLEDGEMENT

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