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Additive manufacturing of metal optic systems for space applications

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Abstract

Additive manufacturing (AM) methods enable the production of components with a high freedom of design. This benefit is especially important for the high demands of space applications, where structural stability and mass savings of optical components are as important as the optical function.
The present investigations focus on the description of a process chain for the manufacturing of metal mirrors and metal housings for optical systems as telescopes or spectrometers for space applications. The applied powder bed fusion process directly melts Aluminum - Silicon metal powder with 40 wt% Silicon (AlSi40). Post processing steps are necessary to clean the internal volume and finalize the functional surfaces. Therefore, diamond turning and milling machines are used. An electro-less nickel polishing layer allows different polishing processes to reduce the roughness of the optical surface.

Keywords: optics; selective laser melting; metal mirror; optical housing; space application; mass reduction; AlSi40;

1. Introduction

Opto-mechanical systems for space applications require complex optical elements such as aspherical or freeform surfaces in order to meet the increasing requirements of optical designs. The mechanical realization of these surfaces can be achieved with metal optics, which offer an athermal and lightweight design, cost-efficient manufacturing and high-quality optical surfaces. Telescopes for space applications are based on precise, mass-reduced and stable assemblies of multiple mirrors to image the incoming beam with low aberrations onto a light sensing element [Vukobratovich et al. 2011]. State of the art light weighted

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metal optics are realized by removing material from the interior by conventional machining in means of drilling or milling [Beier et al. 2016]. Using AM techniques, the freedom of design increases considerably and complex internal lightweight structures can be realized [Hilpert et al. 2019; Scheiding et al. 2013]. Additionally, topology optimization can be used to improve the mechanical properties of mass-reduced optical housings.

Considering additive manufacturing as the prefabrication step for the mirrors, the whole process chain is still valid, but has to be adapted on certain points. During the CAD design phase, a material offset is added to all functional surfaces of the optical element to ensure enough material volume for the subsequent cutting processes.

The focus of this paper is on the description of the process chain for the design and manufacturing of optical elements and on the realization by AM using an aluminum material with 40 wt% Silicon (AlSi40). This material offers good mechanical properties, is simple to process and it is adapted to match the coefficient of thermal expansion to a necessary polishing layer for high performance optics. It offers a higher specific stiffness compared to other aluminum alloys. Beryllium and its alloys offer an even higher specific stiffness, but they are hazardous and thus the processing is complex and expensive.

2. Additive Manufacturing

The initial design for the AM process has to be generated by a CAD software since the direct buildup of the material is done by layer wise melting of the metal powder. The AM-related data processing includes the orientation of the CAD model within the building volume, the addition of supporting structure, and finally the slicing of the complete model into thin layers. Transferring the sliced data onto the SLM machine (Concept Laser M2 Cusing), the physical buildup of the part is accomplished. Figure 1 shows the schematic setup of the machine, the detailed process is decribed in [Hilpert et al. 2019].

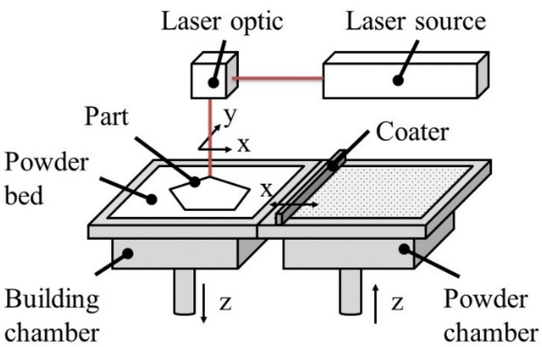

Fig. 1. Schematic setup of selective laser melting machine [Hilpert et al. 2019]

By using optimized process parameters (scanning speed, laser power) for the melting of the AlSi40 powder material, solid mirror base bodies with a very low porosity of below 0.05% are produced. An exemplarily metal mirror after the manufacturing process is shown in Figure 2.

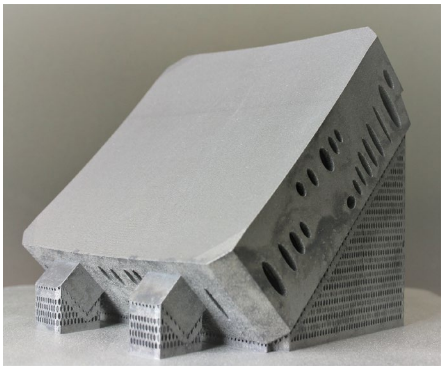

Fig. 2. Metal mirror attached to the base plate by support structure after additive manufacturing process

3. Process Chain

The process chain for the conventional manufacturing of metal mirrors is well established and depends on the intended spectral range of the application, which influences the requirements for the surface roughness and the surface shape deviation [Steinkopf et al. 2008, Beier et al. 2015, Hartung et al. 2018]; see Figure 3. Ultra precise (UP) single point diamond turning is a well suited process for the machining of non-ferrous metals and enables optical surfaces for long wavelength applications (IR, NIR). For shorter wavelengths, the scattering losses on those surfaces due to the periodic structure of the UP turning process requires additional polishing layers. The surface roughness of the optical mirrors for the IR and NIR range with approx. 10 nm RMS (root mean square) can be improved by using polishing layers to 1 nm RMS and below for the VIS and UV spectral range.

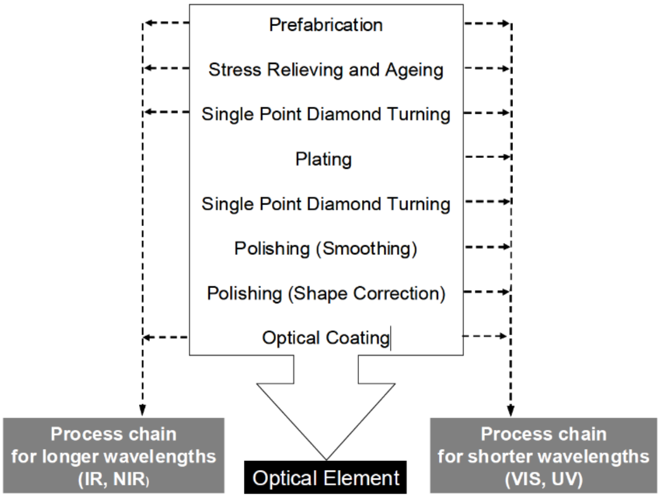

Fig. 3. Process chain for the fabrication of metal mirrors [Steinkopf et al. 2008]

After the additive prefabrication of the metal mirror base body, a stress relieving heat treatment is applied to minimize internal stress from the production step and from the mechanical machining. Internal stress could otherwise lead to deformation of the mirror throughout the following manufacturing steps and hence to a degradation of the shape of the optical surface.

The cleaning procedure of AM parts is of great importance, since loose powder material has to be removed from the complex internal volumes [Heidler et al. 2017]. All internal volumes have to be opened to the external surrounding to realize the powder removal. In addition, partly adhering particles occur on all surfaces and have to be removed, too. This is accomplished by the combination of mechanical and chemical cleaning processes. Conventional cleaning processes like shot blasting are not possible since not all internal surfaces can be reached.

The UP turning process can be applied to the AM metal optics. The surface form deviation and the roughness after machining the AM made AlSi40 optics are comparable to optics made of conventional AlSi40 base material.

The plating material for VIS and UV applications is often an X-ray amorphous electroless nickel phosphorus (NiP)-polishing layer [Gebhardt et al. 2017]. The CTE of this polishing layer matches very well to the CTE of AlSi40, reducing the bimetallic bending effect. The process of plating NiP on the AM made metal optics have to be adapted to ensure a uniform and completely closed layer on the rough internal surfaces. This is important to avoid electrochemical corrosion between the AlSi40 base material and the NiP layer.

After the plating step, a second single point diamond turning is used to realize the intended high form accuracy of the optical element. Subsequent polishing techniques further improve the form and the roughness of the optical surface. In Figure 4, the optical parameters of a metal mirror made by additive manufacturing are shown.

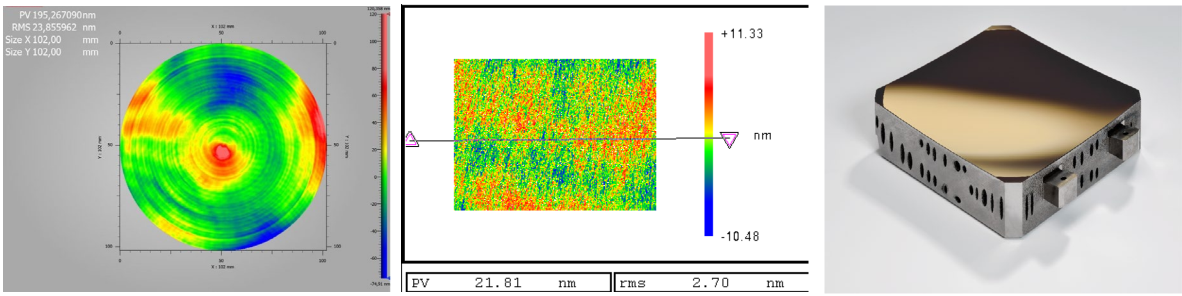

Fig. 4. Final form deviation of 195 nm peak-to-valley (left) and white light interferometry surface roughness of 2.7 nm RMS (middle) of an AM metal mirror (right) with a clear aperture of approx. 100 mm for VIS applications after polishing

4. Conclusion and Outlook

The shown process chain is applicable to realize high quality metal optics and can be further adapted to realize the housing structures for telescopes or spectrometers for space applications. Figure 5 shows the topology-optimized housing of a three-mirror anastigmatic telescope (TMA) with three optical mirrors. Two of these optical mirrors are based on one substrate. All mirrors are made by additive manufacturing out of AlSi40. Ongoing qualification processes shall demonstrate the feasibility of the presented technology for future space missions.

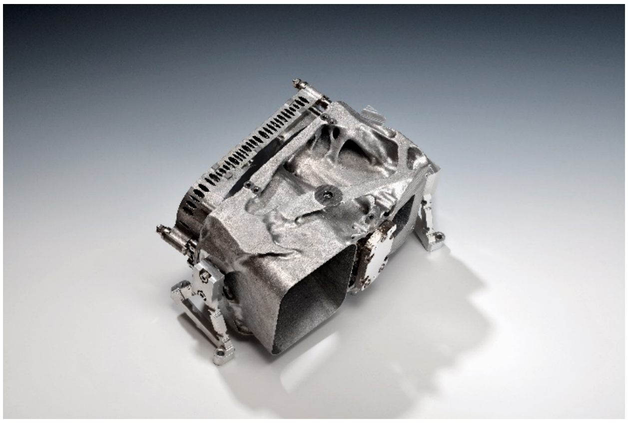

Fig. 5. TMA Telescope and mirrors made by additive manufacturing out of AlSi40

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