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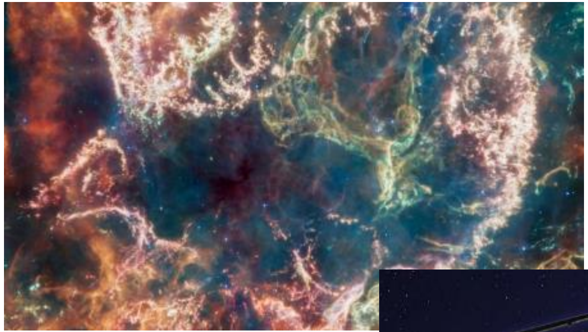
AM of metal mirrors and optical components for space applications

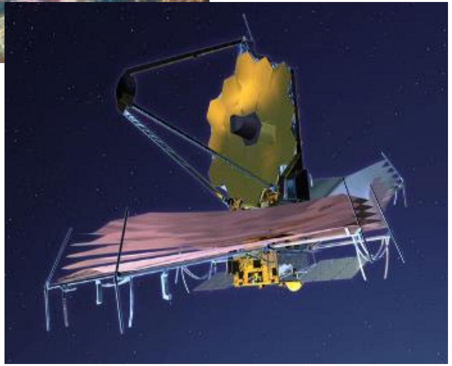
Dr. Nils Heidler

rapid.tech 3D
ADDITIVE MANUFACTURING HUB

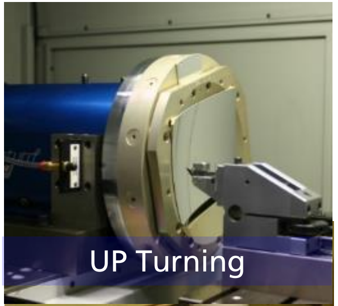
James Webb Space Telescope

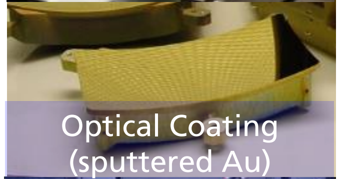


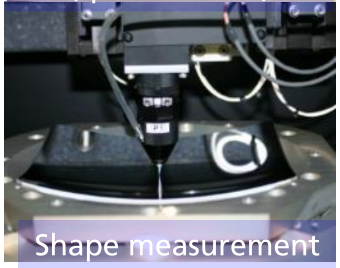
Cassiopeia A ,
a supernova remnant

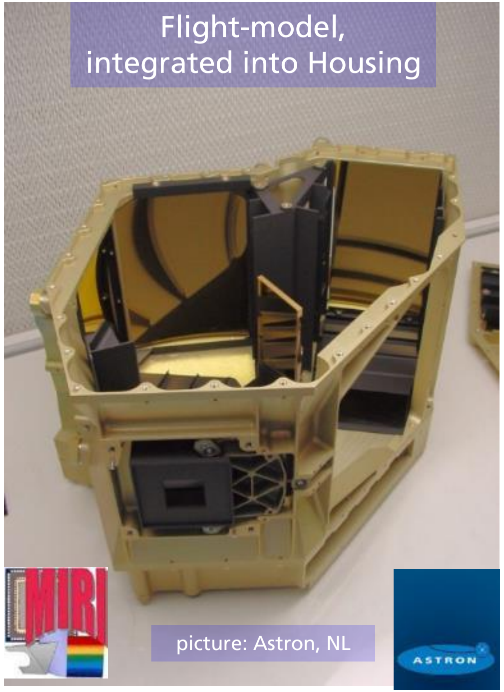


MIRI – Infrared camera and spectrometer
for James Webb Space Telescope (JWST)









pictures: NASA/ ESA / Astron

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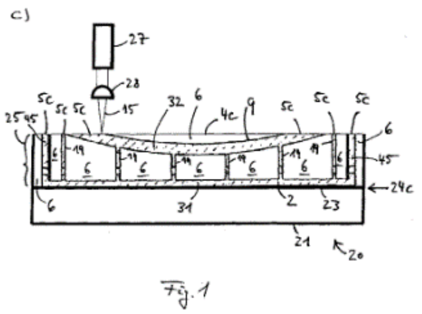
Metal Optics for Space

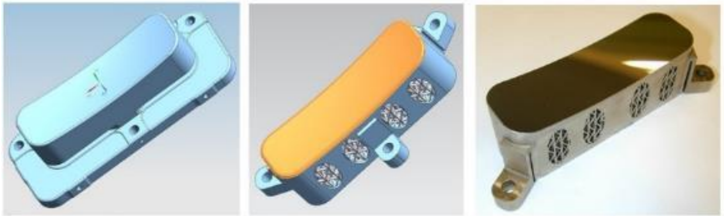
- Optical requirements
  - Surface form deviation
  - Roughness
  - References
- Mechanical requirements
  - Stability
  - Eigenfrequency
- Material
  - Machinable
  - Lightweight
- Process chain compatible

State of the art

- Optical components
  - Ti6Al4V; AlSi10Mg
  - Multiple optical shapes
    - Plane
    - Spherical, aspherical…
  - Light-weight structures
  - Postprocessing tests
    - Thermal treatment
    - Polishing
    - Diamond turning
    - Coating



Schematic sketch of mirror fabrication by AM (IOF Patent, submitted 2011)*



Original design
Mass: 284.6 g
Material: Al 6061
1st eigen freq ~2100 Hz
NiP coating

New design
Mass: 129.7 g

Selective laser melting
Mass: 127.7 g
Material: Ti6Al4V
1st eigen freq ~2100 Hz
NiP coating

Tropomi Mirror demonstrator from ESA Sentinel 5P (2014)**

*EP2739998B1, US 9 599 756 "Method for manufacturing a mirror comprising at least one cavity and optical mirror" (submitted 2011, granted 2017; DE, AT, BE, FR, GB, IT, NL, US, CA)

**https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Mirror_mirror_testing_3D_printing_for_space

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State of the art

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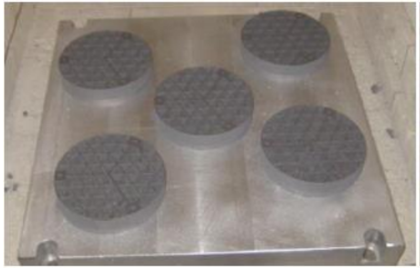
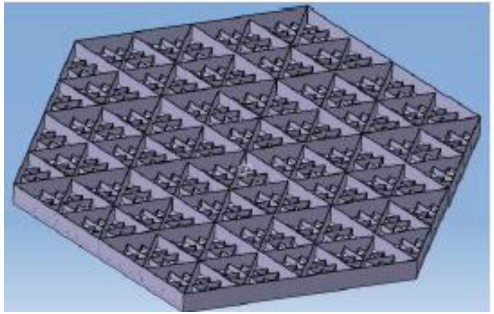
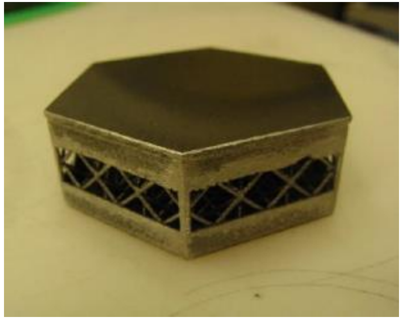


Left: batch light-weighted isogrid test mirror (AlSi10Mg, Ø 75 mm, EOS machine)

Right: conventional Al 6061-T6 (right) and AM (AlSi10Mg) test mirror after diamond turning (2015)*





Lattice light-weighted mirror out of Al and Ti including polishing and coating (2016)**

* Sweeny et al.; SPIE Vol. 9574; 2015

** AM Challenge Workshop; UCL; 2016

State of the art

- Optical components
  - Ti6Al4V; AlSi10Mg
  - Multiple optical shapes
    - Plane
    - Spherical, aspherical…
  - Light-weight structures
  - Postprocessing tests
    - Thermal treatment
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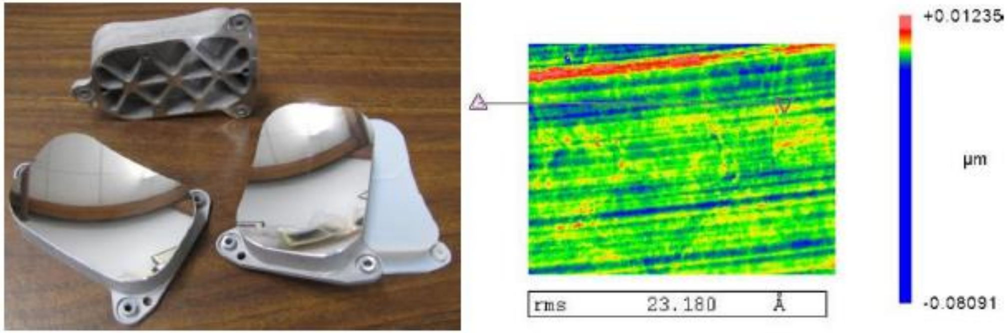
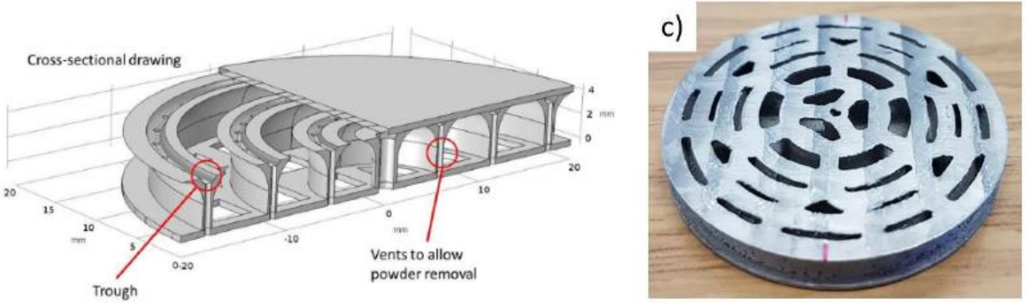


LPBF made mirrors with backside light-weight structure after diamond turning (Aluminium)(2017)*



Optimized light-weighted mirror out of AlSi10Mg (2017)**

*Woodard et al.; SPIE 10181; 2017

** C Atkins et al.; proceedings of: Optics for EUV, X-Ray, and Gamma-Ray Astronomy VIII (2017)

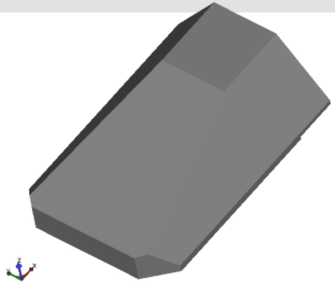
Process Chain

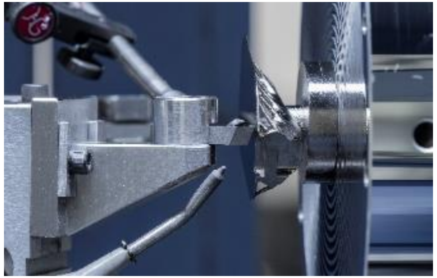
Optical and mechanical Design

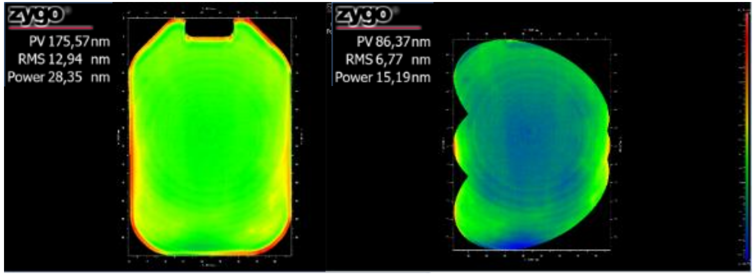
(Additive) Manufacturing of metal mirror base body

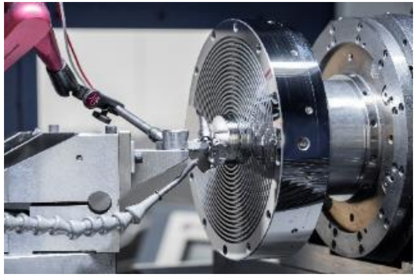
Ultra-precision (UP) diamond turning

Plating (NiP)









Metrology / Characterization

Post-finishing / functional coating

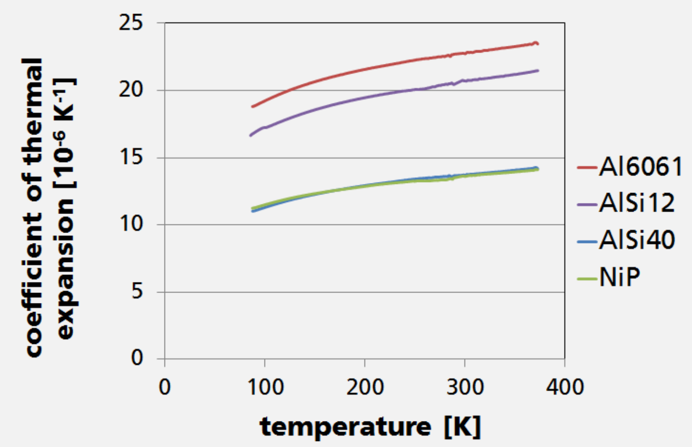
Ultra-precision diamond turning

AM-OPTICS (FKZ02P15B204)
Cooperation with Arges /Novanta

Material

- Metal materials for optics
  - Aluminum, Titanium, Beryllium or their alloys
  - Specific stiffness $\Phi = E/\rho$
  - Young's modulus E
  - Density ρ
- Aluminum with 40 wt% Silicon (AlSi40)
  - CTE matched to electroless nickel plating (NiP)

material	density [g/cm³]	Young's modulus [GPa]	specific stiffness [m²/s²]
TiAl6V4	4.43	114.0	25.7
Al 6061	2.71	69.0	25.5
AlSi12	2.68	75.0	28.0
AlSi40	2.55	107.0	42.0
AlBeMet	2.10	199.0	94.6



Gebhardt, A., Kinast, J., Rohloff, R. R., Seifert, W., Beier, M., Scheiding, S., Peschel, T., "Athermal metal optics made of nickel plated AlSi40," Proc. SPIE 10563, (2014).

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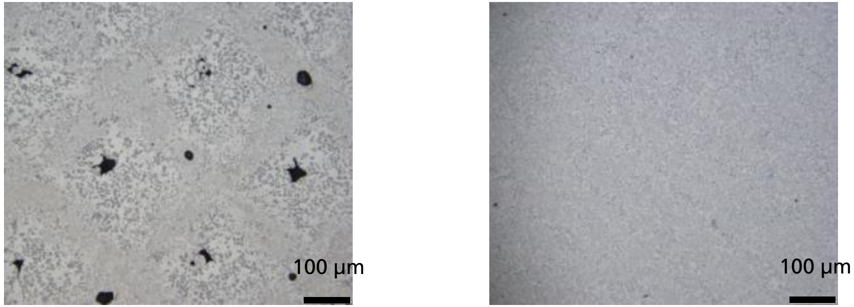
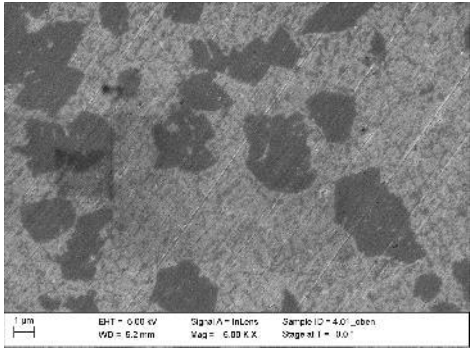
Parameter optimization for AlSi40

- Reduction of porosity by optimizing energy density
- $E_V = \frac{P}{vdh}$ *
  - Energy density E_V / J/mm³
  - Laser power P / W
  - Scanning speed v / mm/s
  - Line hatching d / µm
  - Layer thickness h / µm
- Residual porosity of below. 0,1%
  - $E_V = 50$ J/mm³ **
  - Measurement using 3D-CT and polished samples



Microscopic pictures of polished volume samples
(left: unoptimized parameter set; right: optimized parameter set



SEM picture of volume sample (dark area: primary silicon, gray area: aluminum)

* H. Meier und C. Haberland, “Experimental studies on selective laser melting of metallic parts,” Mater. Sci. Eng. Technol. 39 (2008) 665–670.

** E. Hilpert, J. Hartung, et al., “Design, additive manufacturing, processing, and characterization of metal mirror made of aluminum silicon alloy for space applications,” Opt. Eng. 58(9), 092613 (2019), doi: 10.1117/1.OE.58.9.092613.

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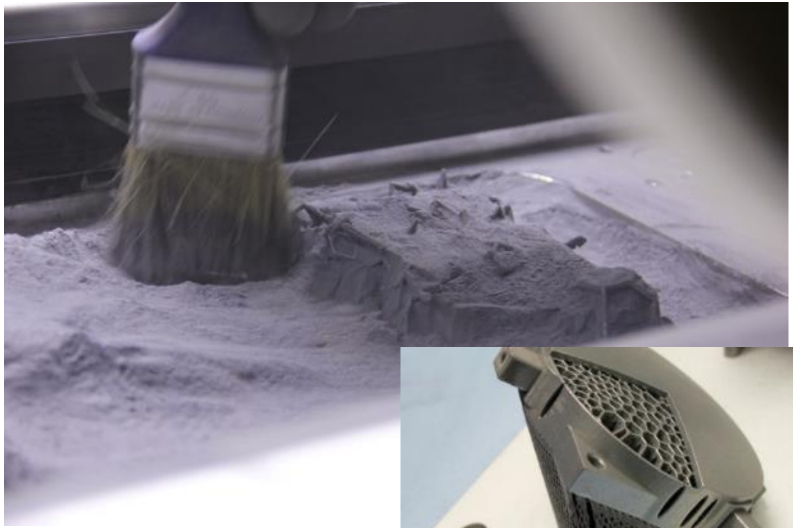
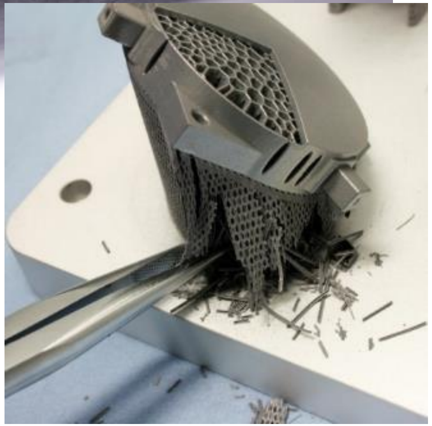
Post-processing

- Processing after AM build process
  - Cleaning
  - Thermal treatment
  - Support removal
  - CNC machining
  - Diamond turning
  - NiP plating
  - Polishing

- Powder removal, cleaning and support removal mainly manual processes



Mechanical removal of powder after AM build process



Mechanical removal of support structure after thermal treatment

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Post-processing

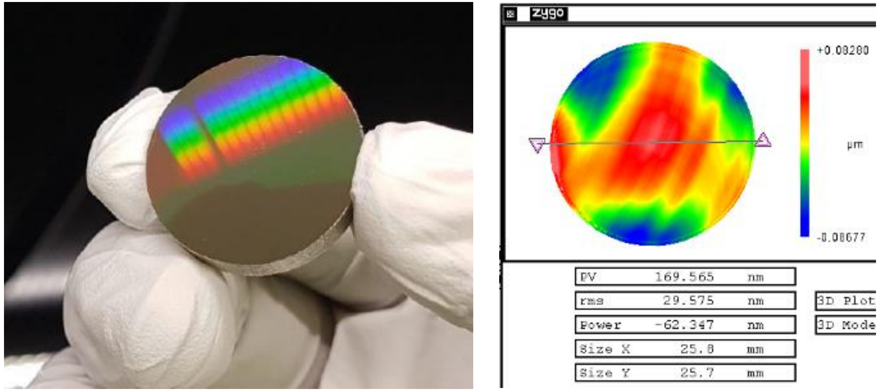
- Processing after AM build process
  - Cleaning
  - Thermal treatment
  - Support removal
  - CNC machining
  - Diamond turning
  - NiP plating
  - Polishing
- NiP plating
  - Necessary as polishing layer
  - Trapping of slightly adhering particles
  - Increasing weight

AM mirror on diamond turning machine

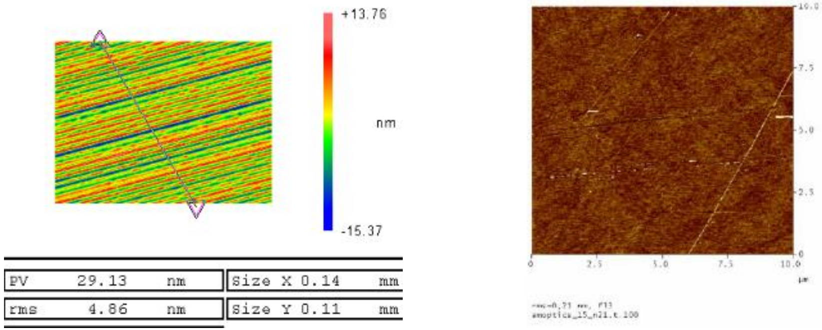
Cross-sectional view of exemplarily part with NiP plating on internal structure

Post-processing

- Processing after AM build process
  - Cleaning
  - Thermal treatment
  - Support removal
  - CNC machining
  - Diamond turning
  - NiP plating
  - Polishing
- Measurement of optical surface
  - Shape deviation < 200 nm PV
  - Surface Roughness < 5 nm RMS (50x WLI)
- Comparable to conventional material



Sample after NiP plating and diamond turning
(left: picture; right: Shape deviation)



Surface roughness after diamond turning (left: 4.9 nm RMS; 50x WLI)
and after final polishing (0.2 nm RMS; AFM)

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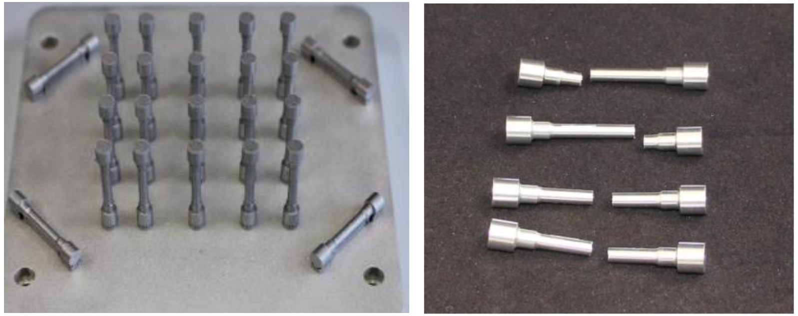
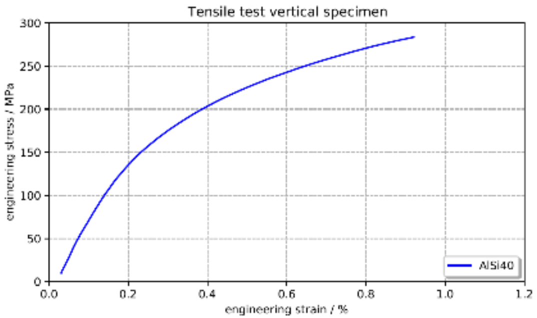
Mechanical parameter

- Tensile testing after thermal treatment
  - Young's modulus: 95 GPa
  - Tensile strength: 270 MPa
  - Yield strength: 185 MPa
  - Elongation: 1 % - 1.5 %
    Brittle behaviour, as expected for AlSi40
- Young's modulus comparable to conventional material
- Tensile and yield strength 20% - 30% higher than conventional material due to fine grained microstructure



Tensile test specimens on AM build plate



Exemplarily stress – strain curve after thermal treatment

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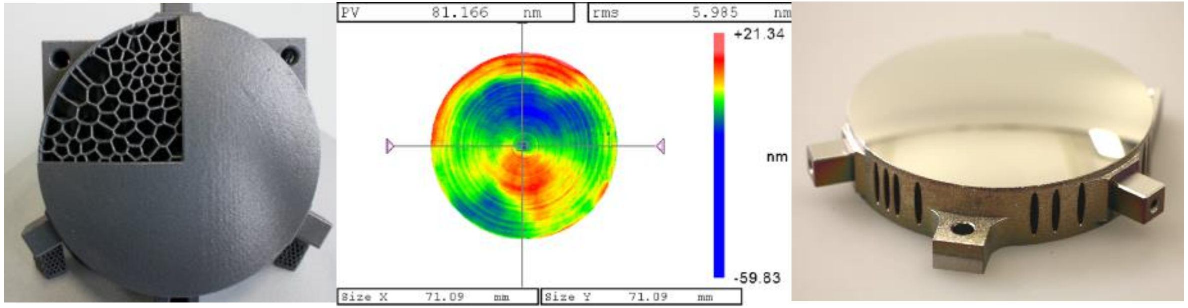
Project Results

- AlSi12 and AlSi40
- Basic design considerations for internal light-weight structure
  - Print through
  - Cleaning access
  - Stiffness
  - Self supporting during AM build process
- Post processing
  - Diamond turning
  - NiP
  - MRF

Drilled holes	Segmented	Triangle segments	Hexagon segments
32 %	65 %	64 %	66 %

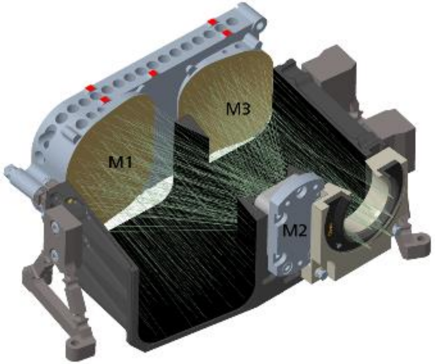
Different light-weight structures for mirror
(degree of weight saving compared to full volume mirror)

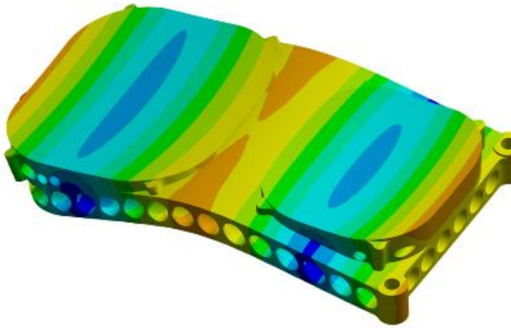


Processing of mirror with irregular internal structure with 60% weight reduction
(left: after AM build process, middle: form deviation after MRF polishing, right: picture after protected Ag coating)

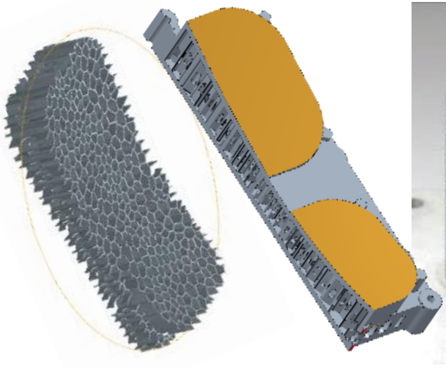
Project Results

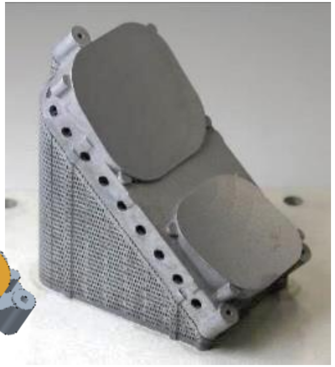
- Three Mirror Anastigmatic (TMA) Telescope
- Mirror modules
  - Two optical surfaces
  - 2D Voronoi cell structure
  - Cell size optimization due to load distribution
  - 64% weight reduction (10% lighter)
  - 3650 Hz first eigenfrequency (10 % higher)

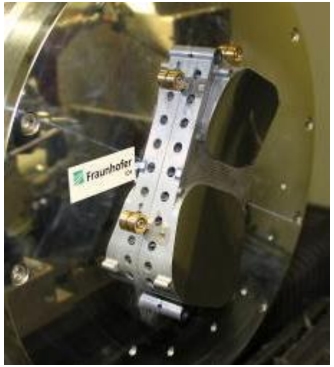




Conventional start design of TMA (left: cut view of CAD System, right: FEM simulation of M1M3 mirror module)







M1M3 Mirror Module (left: internal structure, middle left: CAD cut view, middle right: Module on AM build plate, right: on diamond turning machine)

Heidler et al., “Additive manufacturing of metal mirrors for TMA telescope“, SPIE 10692; (2018)

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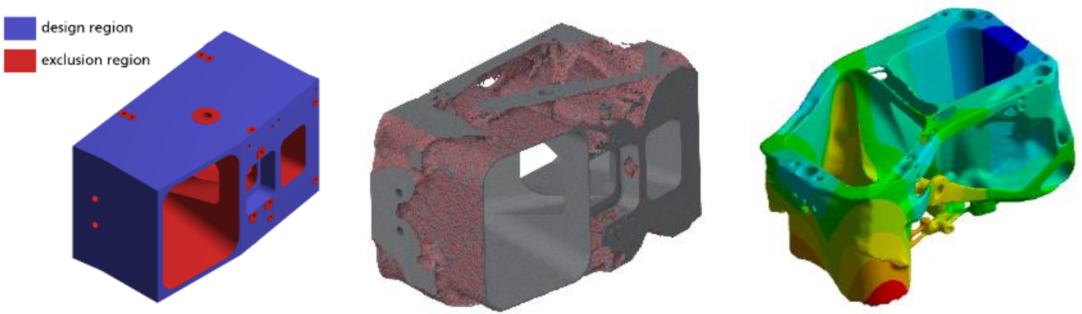
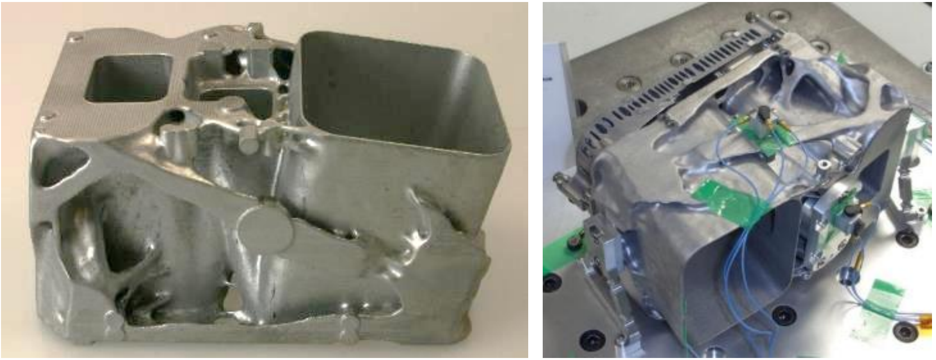
Project Results

- Three Mirror Anastigmatic (TMA) Telescope
- Housing
  - Topology optimized design
    - Light-weight factor
    - Maximum stress
    - Feature size
- Successful vibrational testing
  - First eigenfrequency @1560 Hz
  - Deviation between test & simulation < 8 %



Topology design process for housing (left: design space prior to optimization, middle: model after topology optimization, right: FEM simulation for result validation)



Housing after AM build process (left) and during vibrational testing on system level

v. Lukowicz et al., "Optimization and Additive Manufacturing of a Three-Mirror-Anastigmatic Telescope", ICSO, (2020)

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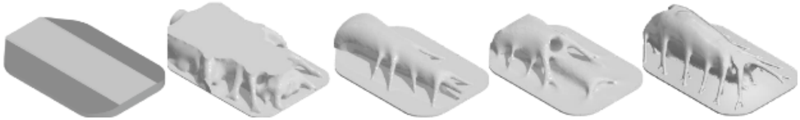
Project Results

- Topology optimized scan mirror
  - Increased torsional stiffness
- UP turning and MRF polishing
  - Complex manufacturing due to mounting on machine
  - Additional mounting structure
  - 86 nm PV form deviation
  - 126 nm PV after mounting adapter removal
  - 2.3 nm RMS roughness (50x WLI)

Typ	SiO2	v01	v02	v03	v04
MOI in kg*m^2	2,7e-6	3,2e-6	1,4e-6	1,6e-6	1,8e-6
Masse In kg	22,5e-3	35,0e-3	23,6e-3	21,1e-3	27,5e-3
Biegefreq. in kHz	0,9	1,9	2,3	3,5	3,5
Torsionsfreq. in kHz	3,1	6,5	6,0	6,7	11,3

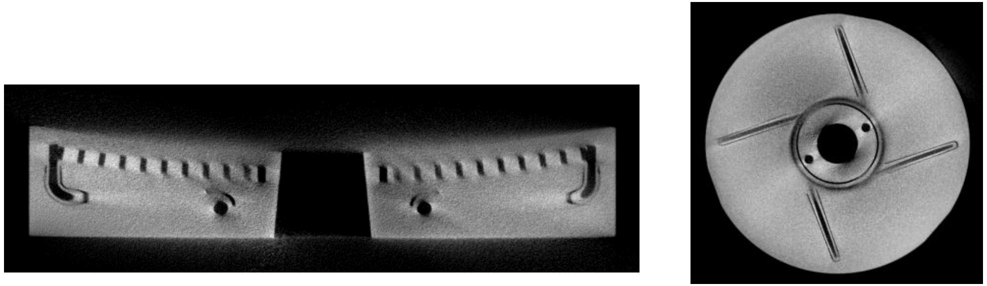


Comparison of different design variants of the scan mirror

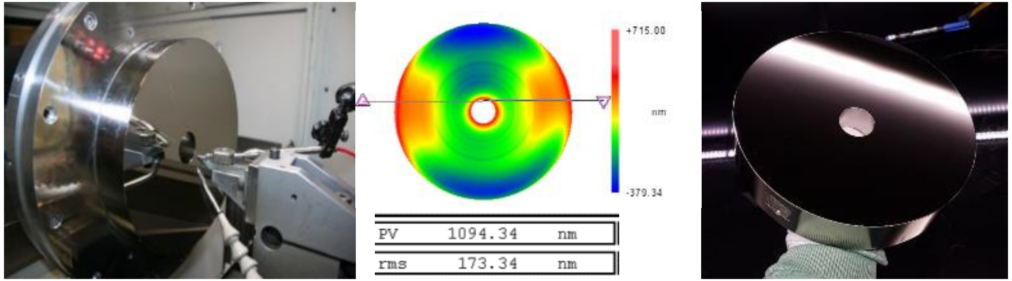
Scan mirror (left: during AM process preparation, middle left: after AM build process, middle right: after final processing incl. diamond turing, NiP plating and polishing, right: final shape deviation after MRF polishing)

Project Results

- EUV collector mirror
  - Internal cooling channels
- AM build job with adapted scanning strategy (chessboard)
- CT scan
  - No detectable voids
  - Powder removal proven
- Process chain incl. EUV polishing
  - 1.1 µm PV form deviation
  - 0.3 nm RMS roughness (AFM 10x10 µm²)
- 67% EUV reflectivity (Bessy II @PTB)



CT Scan of collector mirror after powder removal showing internal cooling structure



Collector mirror (left: on diamond turning machine, middle: shape measurement after MRF polishing, right: after EUV coating)

AM-OPTICS (FKZ02P15B204)
Cooperation with opitX fab GmbH
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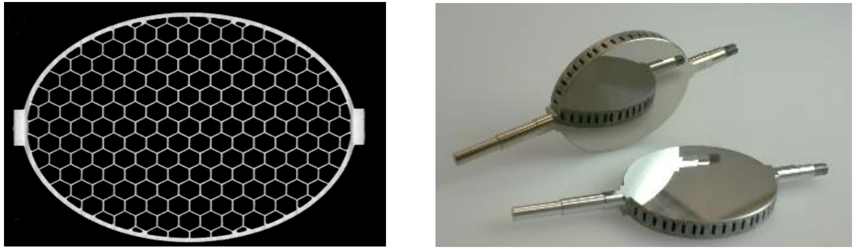
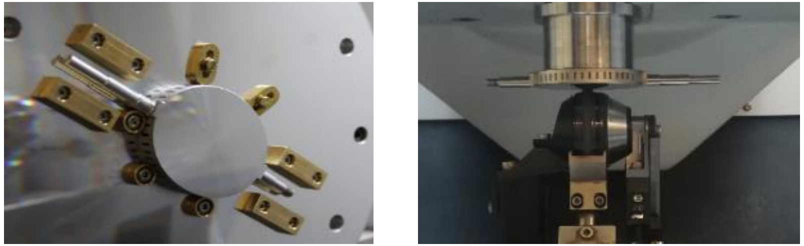
Project Results

- Light-weight mirror for space application
  - Light-weighting vs. stability
- Honeycomb structure (4 mm cell size)
- 50 µm NiP plating
- 23 g w/o NiP, 32 g w/ NiP plating
- Whole process chain incl. MRF polishing
  - 97 nm PV form deviation
  - 1.8 nm RMS roughness (50 x WLI)
- First eigenfrequency > 1.9 kHz



CT scan of internal mirror structure (left) and mirrors after machining (right)

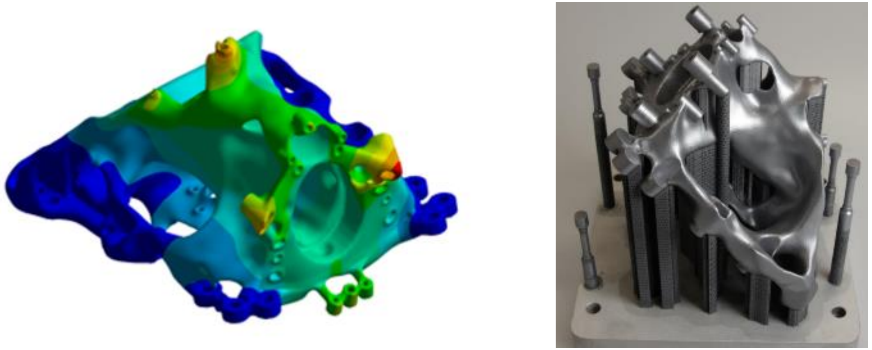


Mirror on UP turning machine (left) and on MRF polishing machine (right)

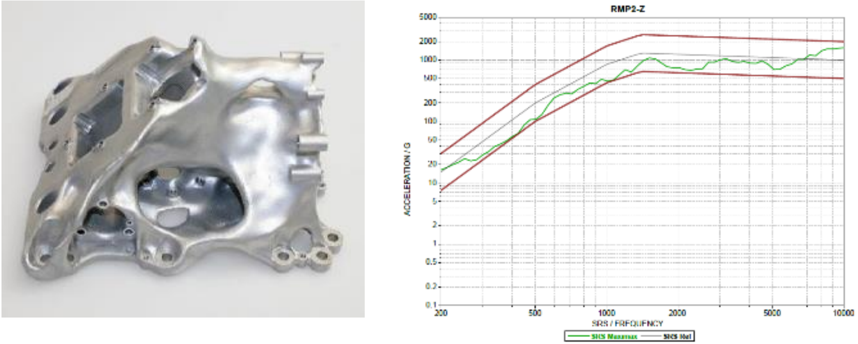
Mirror after gold coating (left) and measured shape deviation (right)

Project Results

- Housing study for laser communication terminal
  - Replacement of AlBeMet
  - Topology optimization with mechanical and thermal requirements
  - Eigenfrequency 2850 Hz
  - High geometrical accuracy (<300 µm deviation)
- 20% weight reduction compared to initial AlBeMet housing
- Successful shock and vibration testing



FEM simulation of topology optimized housing (left) and housing after AM build process (right)



Housing after CNC machining (left) and shock response spectrum of testing (right)

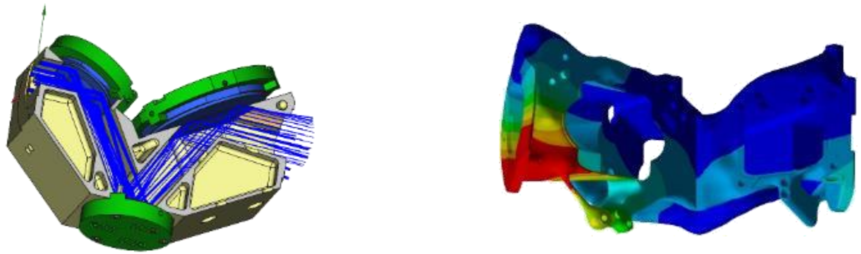
Heidler et al., "Topology optimization and additive manufacturing of an optical housing for space applications" EOS; World of Photonics, München, 2021

TESAT Fraunhofer IOF

Project Results

- Housing for beam expander
- Two designs
- Mass saving of 30 % for foam approach
- Mass saving of 23 % for topology optimized approach
- First eigenfrequency 2130 Hz for topology optimized approach

- Combination of approaches possible



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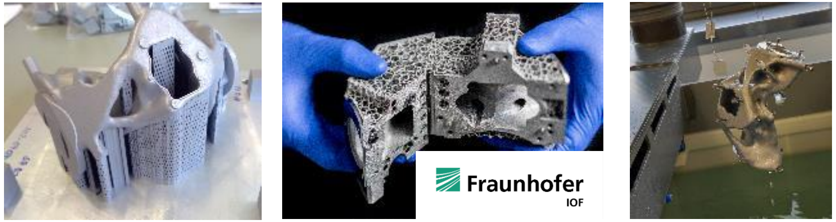
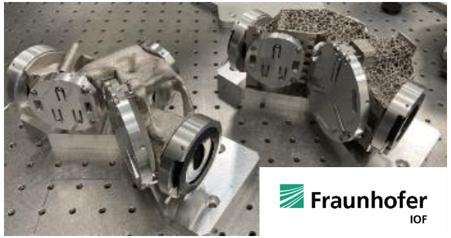


Topology optimized housing after AM build process (left), Foam approach housing (middle), NiP plating (right)



Housings after system integration

Frasch et al., “Optical housing made by Additive Manufacturing” SPIE AT+I, Montréal, 2022
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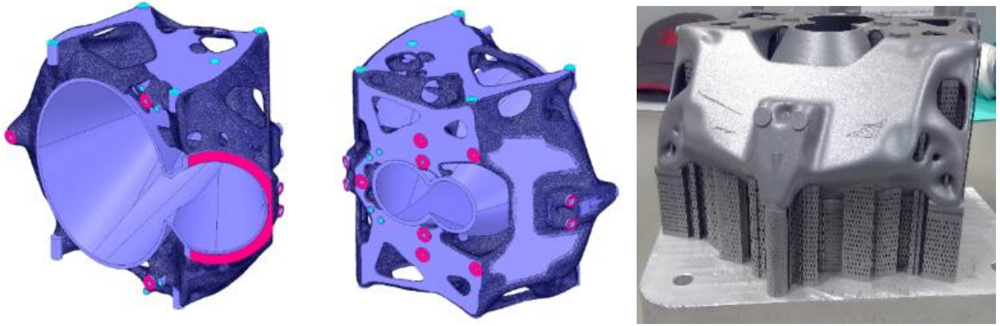
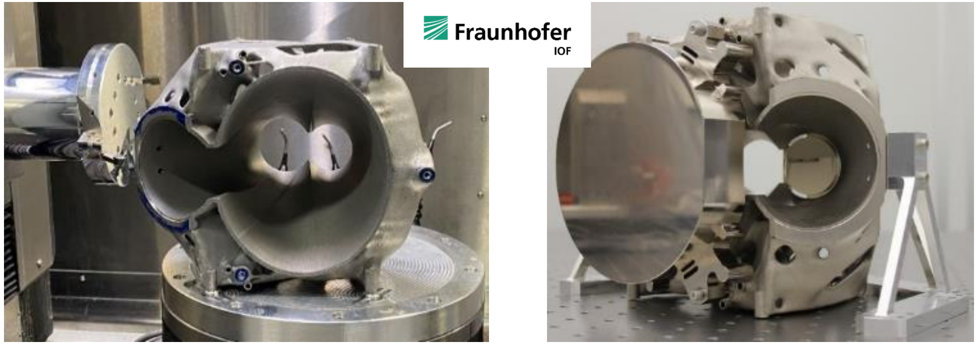
Project Results

- Freeform optical demonstrator system
- Topology optimized housing
  - High design space (230 x 190 x 130 mm³)
  - 10 µm NiP
  - Diamond machining of interfaces
    - 3 µm flatness
    - < 10 arcsec angular misalignment
- Successful system integration
  - Conventional mirror substrates
  - Two freeform optical surfaces



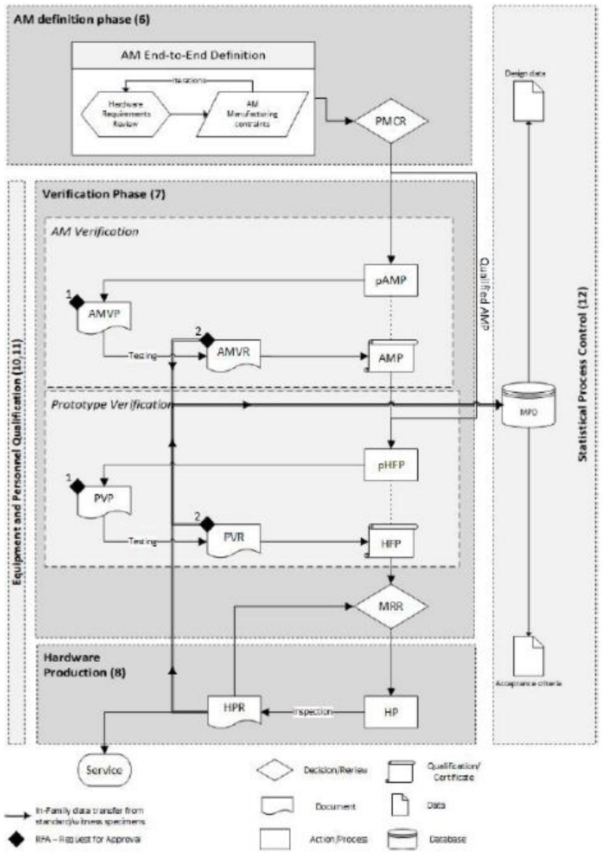
Housing after topology optimization (left, middle) and after AM build process (right)



Housing after topology optimization (left, middle) and after AM build process (right)

AM Qualification

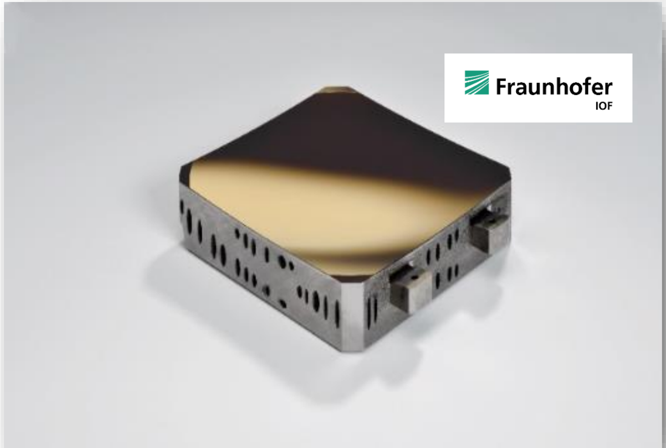
- ESA related projects with qualification according to ECSS-Q-ST-70-80C required
- "Processing and quality assurance requirements for metallic powder bed fusion technologies for space applications"
- First issue released July 2021
- Requirements on process, parts, personnel and equipment

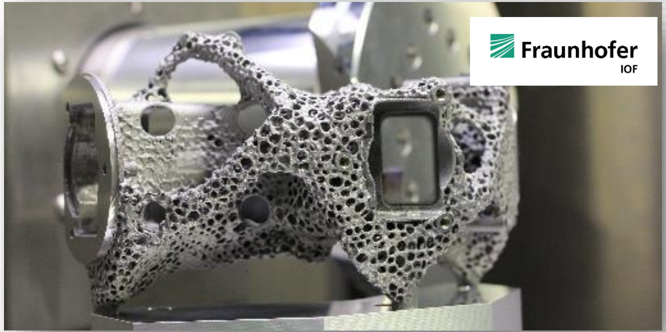


Flow chart showing the steps required to establish a verified metallic Powder Bed Fusion process for space applications

Summary

- Additive manufacturing of metal optical components
  - Mirrors
    - Light-weighting structures for space
    - Internal cooling channels
  - Housings
  - AlSi40, AlSi20 – AlSi50, AlSi12, Al 6061
- Process chain well known and applicability proven
- Optimization on sub aspects (cleaning, data handling, referencing…)
- Qualification of AM process as well as pre- and post-processing ongoing





First flying parts expected soon…

Fraunhofer IOF

Thank You!

14.05.2024 rapid.tech3D, Erfurt

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