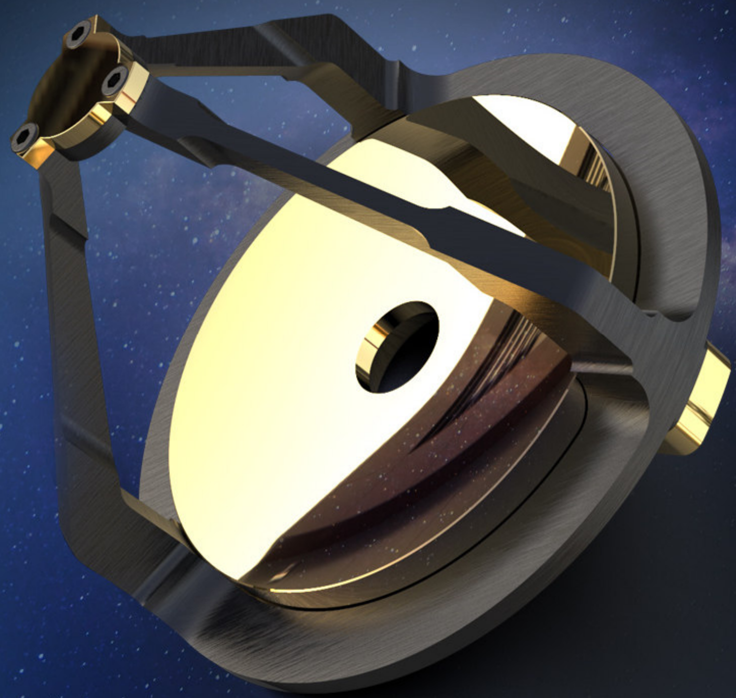
Herstellung von Ultrapräzisionskomponenten mittels Diamantzerspanung – an der Grenze des physikalisch Machbaren



Dr. Olaf Dambon, son-x GmbH

17. Tagung "Feinwerktechnische Konstruktion"
26. & 27. September 2024, Dresden

- Shop floor space of 700 m²
  - Incl. 200 m² highly temperature-controlled
- Office Space of 400 m²

son x
ultrasonic precision

Company Profile

- son-x GmbH founded in 2011 as a spin-off from Fraunhofer
- Based in Aachen, Germany
- Focus on ultra precision manufacturing
  - Ultrasonic Tooling Systems (UTS)
  - Ultra Precision Machining
- Optical component manufacutring:
  - Mirrors
  - Mould inserts
  - Plastic lenses
  - Infrared Lenses

Research Location Aachen

↘ **RWTH Aachen University**

↘ 45,000 students

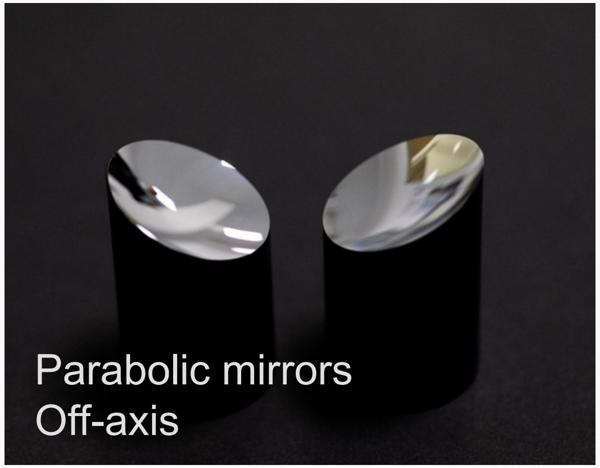
↘ **FH Aachen – University of Applied Sciences**

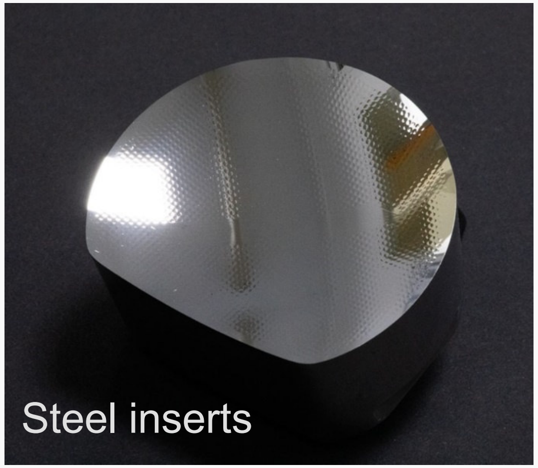
↘ 15,000 students

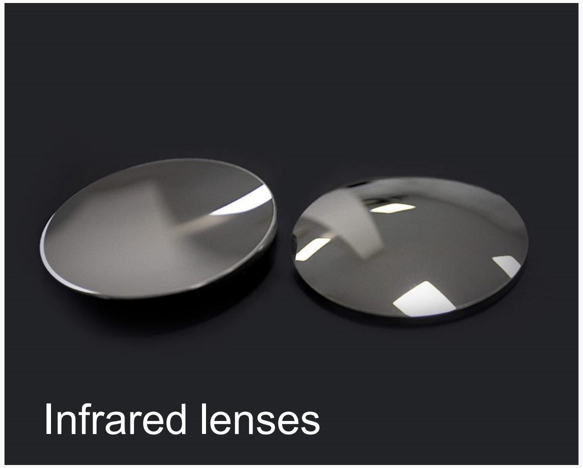
↘ **Fraunhofer Institute for Production Technology IPT**

↘ more than 500 employees

Overview of Ultra Precision Components

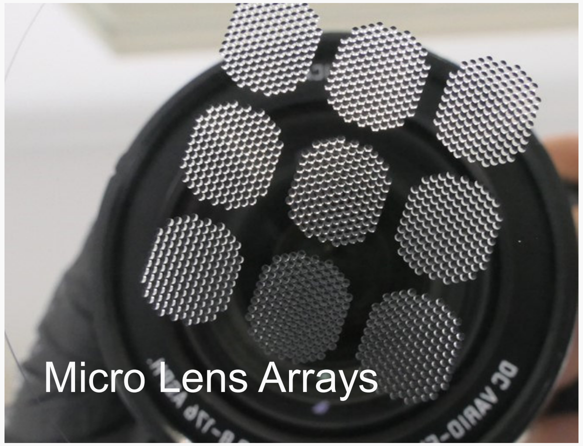

Parabolic mirrors
Off-axis


Steel inserts


Infrared lenses


Space Optics


Steel inserts


Micro Lens Arrays

Outline

- Introduction ✓
- Ultra Precision Diamond Turning
  - Process Characteristics
  - A Brief Historical Overview
- Process Variation – Ultrasonic Assisted Diamond Machining
  - Fundamentals
  - Application Examples
- Ultraprecision Diamond Turning of Aluminum Mirrors
- Summary

Ultraprecision Manufacturing

– Key technology for the high-efficient metal mirror fabrication –

Raw material and pre-machined workpiece

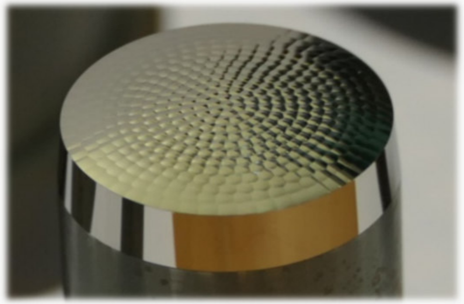
Roughness: 1 µm
Form accuracy: 10 µm

Value per piece
10 $ - 100 $

Ultraprecision manufacturing ("Diamond Turning")

Value increase of 10x - 100x

Finished part



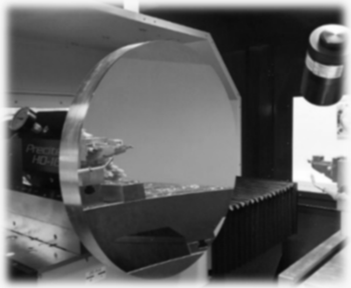
Roughness: 0.001 µm
Form accuracy: 0.1 µm

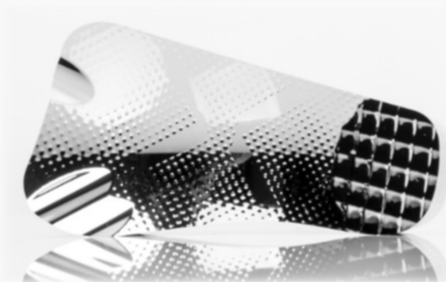
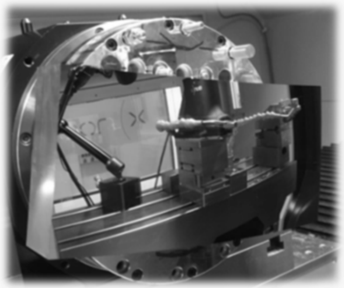
Value per piece
1,000 $ - 10,000 $

Machining with Monocrystalline Diamonds

son ⟩⟨ ultrasonic precision

- Very high geometrical freedom
  - Spheres, Aspheres, Structures (diffractive, fresnel)
  - non rotational symmetric geometries
- Surface roughness (Ra << 5 nm)
- Form accuracy (P-V << 250 nm)
- Different transmissive and reflective materials can be manufactured



Advances in Ultra Precision Machining

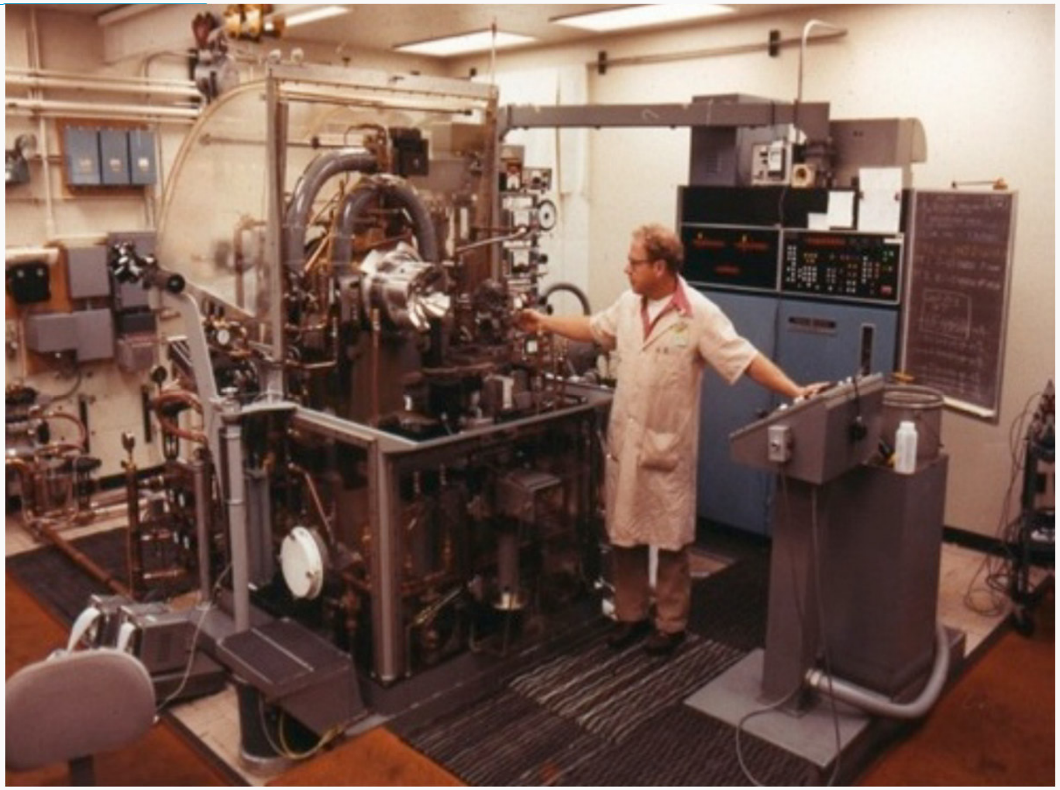
– Early modern day developments –

- During World War II **Polaroid** built their first diamond turning machine to produce 100 mm, highly aspheric Schmidt Plate Correctors – spindle error motion was reportedly 0.25 microns
- In the 1950s **Taylor & Hobson** developed "aspheric generating equipment" for high quality camera lenses using diamond tools to crush glass surfaces
- In the late 1950s, efforts at the **USAF Materials Laboratory** developed an X-Y generator for aerial reconnaissance optics using Moore #3 platforms
- **Philips** undertook work on early diamond turning lathes at about the same time to produce the optics required for electronic microscopes, parabolic reflectors & Schmidt Plates

Source: Lawrence Livermore National Laboratory

Advances in Ultra Precision Machining

– 1968: First Diamond Turning Machine (DTM1) at Lawrence Livermore –

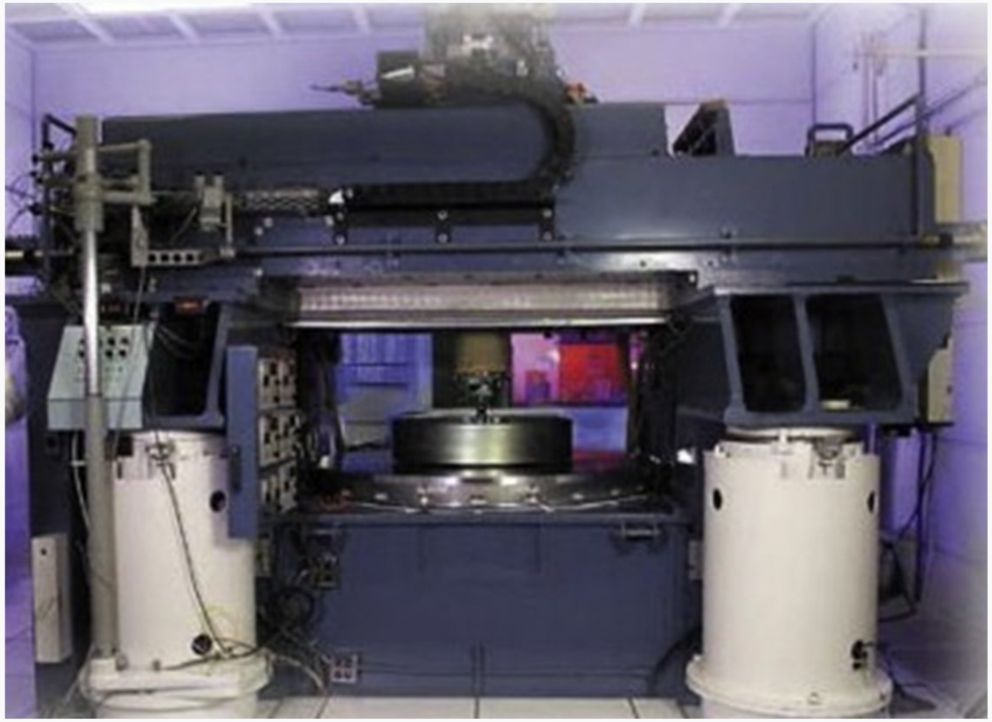


- Moore #3 plain way X-Y base, capable of 25 nm repeatability
- Initially stepper motor drives later converted to an NC system
- Featured isolation system & 150 liters per minute oil shower system

Source: Lawrence Livermore National Laboratory

Advances in Ultra Precision Machining

- DTM-3 at Lawrence Livermore National Laboratory
  - 1.5m capacity
  - operational early 80s
- Realizable Performance:
  - Form Deviation PV: 0.1-0.2 µm
  - Surface Roughness Rms: 20-25 nm



Source: Lawrence Livermore National Laboratory

Advances in Ultra Precision Machining

- Pneumo MSG-325
  - 300mm capacity
  - operational mid-late 80s
- Realisable Performance:
  - Form Deviation: 1-2 µm
  - Surface Roughness Rms: 10 nm

Source: Pneumo Precision

Advances in Ultra Precision Machining

- Moore Nanotech 250UPL
  - 300mm capacity
  - operational today
- Realisable Performance:
  - Form Deviation: 0.1 µm
  - Surface Roughness Rms: < 1 nm

Diamond Turning Lathe Nanotech 250UPL

Source: Moore Nanotechnology

Improvements in Metal Mirror Performance

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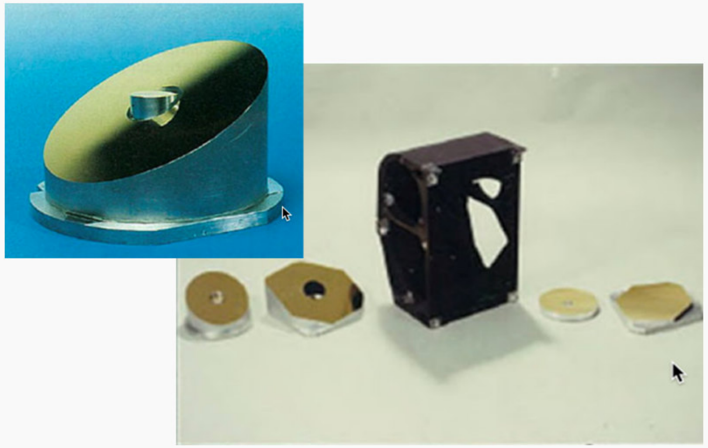
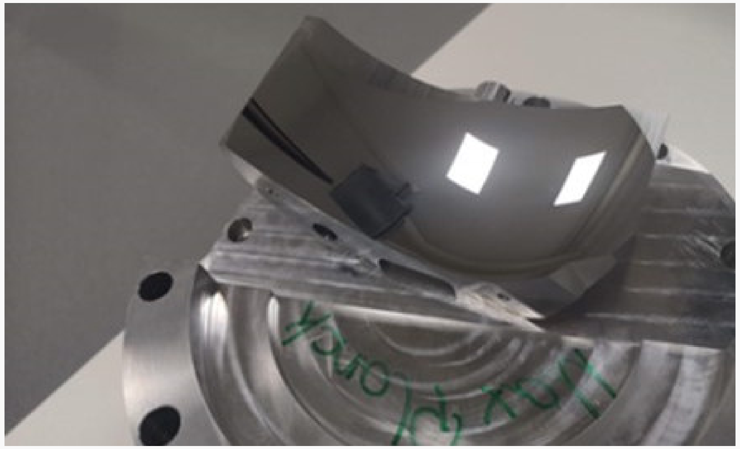


Source: Royal Observatory, Edinburgh

Optics produced for an Astronomical Spectroscopy Instrument – machined on a MSG325 (late 80s)

- Flats, Spheres, Aspheres; 200mm aperture
- 6061 Aluminium
- Form PV 1-2 µm, Roughness Rms 10 nm



Source: son-x

Optics produced for Scientific Analysis (Wendelstein 7-X Stellarator) – machined on a Precitech UPM1000 (2019)

- Off-Axis Asphere, D = 300 mm
- Aluminium RSA905
- Form PV < 150 nm, Roughness Rq < 3 nm

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Machining with Monocrystalline Diamonds

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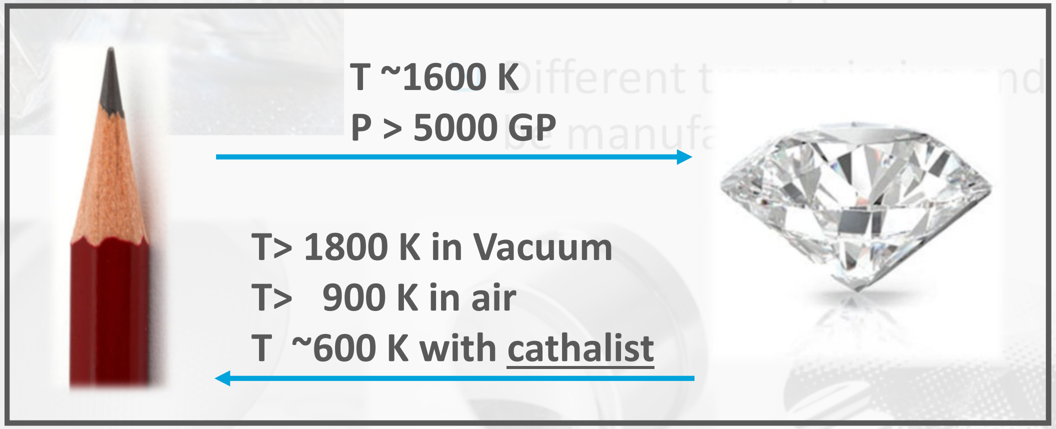
Machining of ferrous metals not possible!

Why?

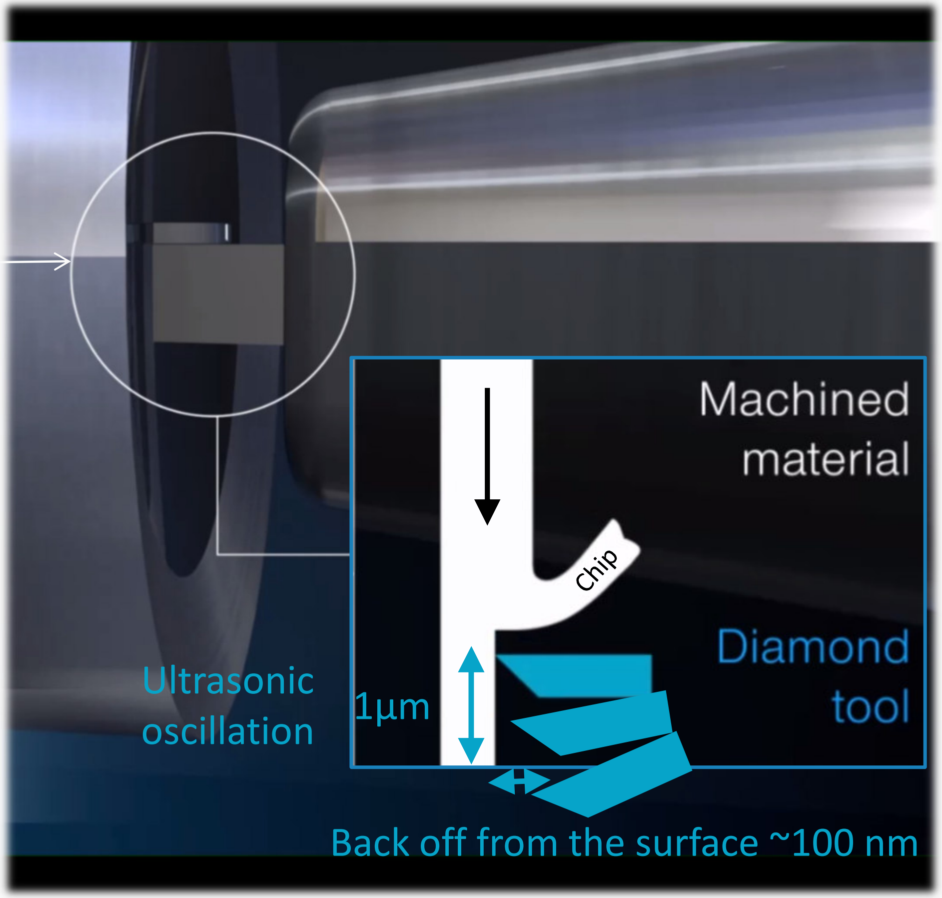
- Iron and carbon have a high chemical affinity.
- Diamond is transformed into graphite by this reaction, iron is a catalyst.



- Pressure + heat + contact time + catalytic effect

Schematic of Ultrasonic Assisted Turning

- Cooling
- Intermitting chemical interactions
- Less friction and forces
- **Reduced tool wear!**



Principal Setup of Ultrasonic Hardware

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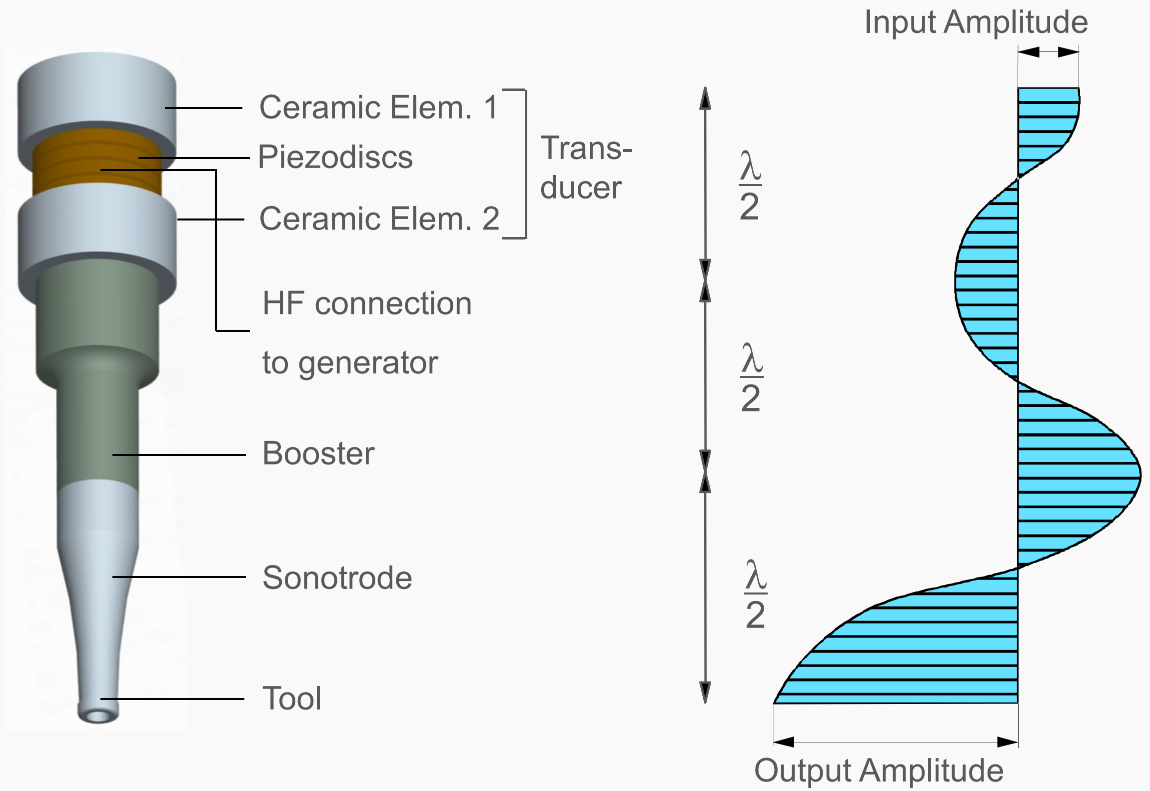
- ↘ HF generator sends high-frequency electrical signals
- ↘ Piezoelectric element transforms electrical energy into mechanical vibration
- ↘ Booster and sonotrode amplify the amplitude and transfer it to the tool



The Ultrasonic Tooling System UTS2

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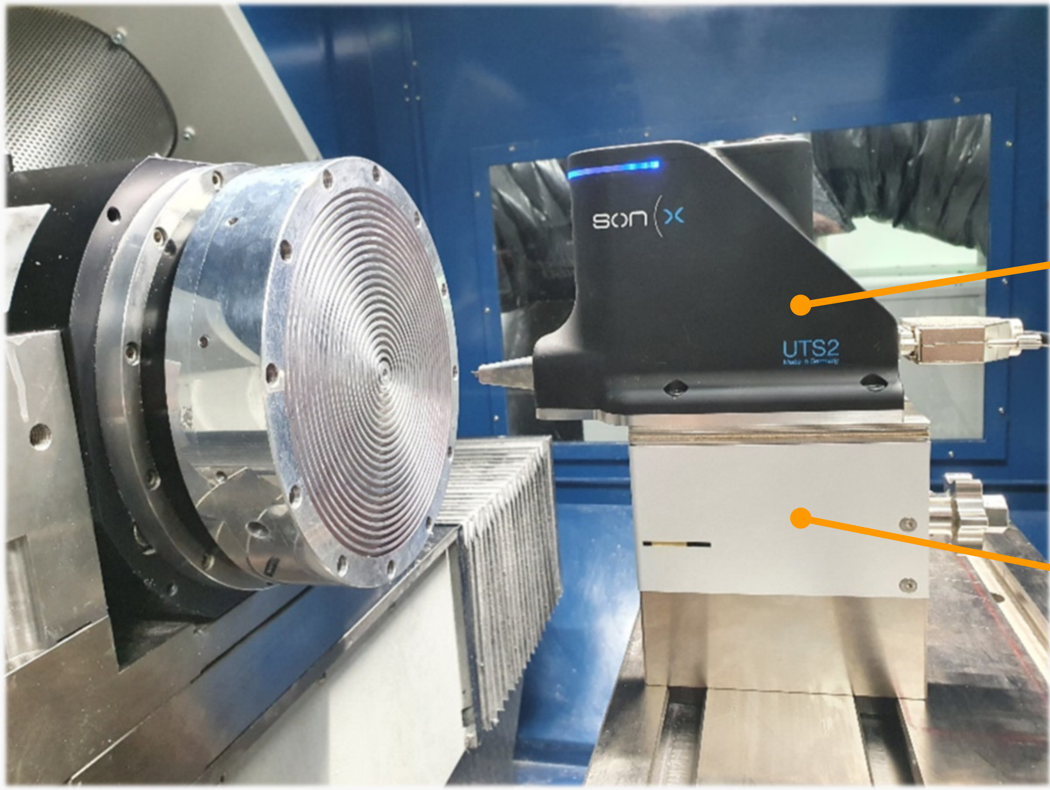
- Enables direct machining of:
  steel, Invar, Inconel, glass.
- Working frequency 100 kHz.
- Can be integrated into all standard, commercial UP-machines.
- Optional micro height adjustment.
- Easy to use and integrate

Designed, manufactured & assembled in Germany

UTS2 Integration into UP-Machines

– Easy mounting – similar to conventional tool holders –

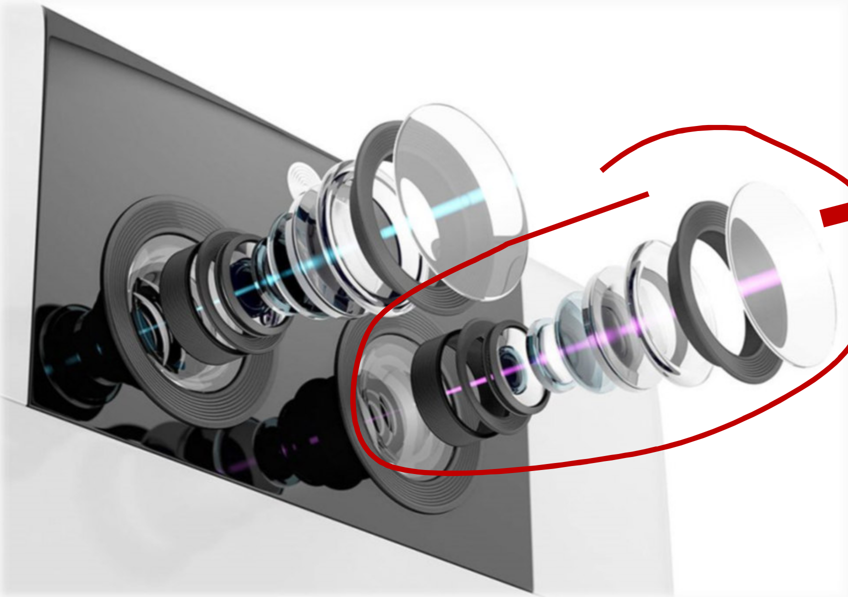


Tool Holder (UTS2)

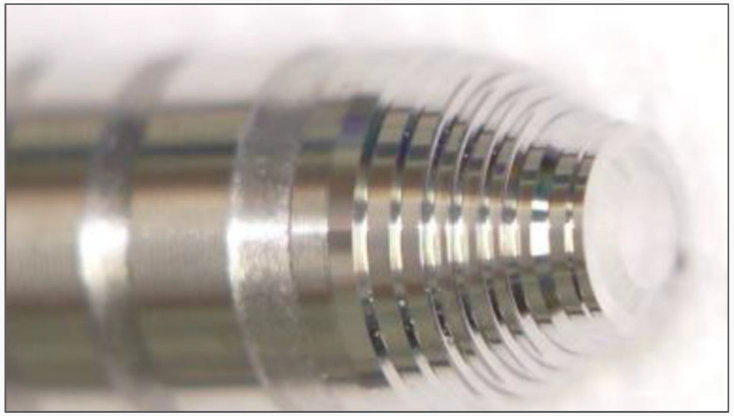
Height Adjustment Unit

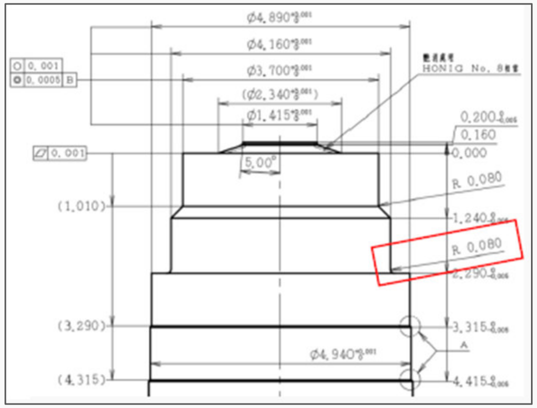
Application Example

– Barrel pin core –



Source: www.dxomark.com





Tolerances

- +/- 0.25 µm

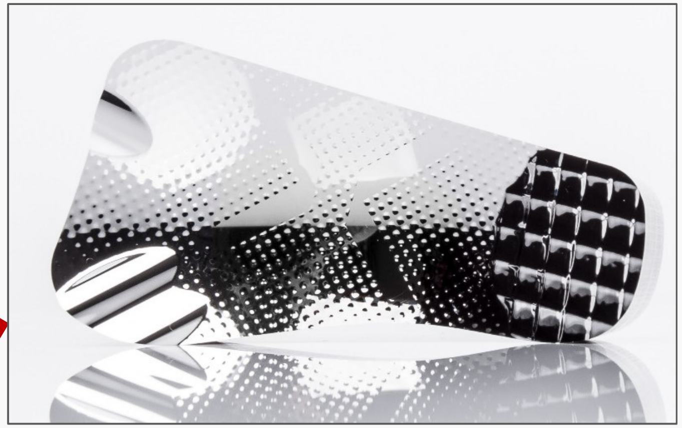
Highest accuracy on:

- Diameter < 0.500 µm
- Centricity < 0.200 µm
- Roundness < 0.100 µm

Application Example

– Mold inserts for automotive lighting –

Source: www.micksgarage.com



- Material: Hardened Steel (> 50 HRC)
- Diameter ~70 mm
- Basic shape: freeform
- Different elements on surface (>> 100 lenslets)
  - Microstructure
  - Waves
  - Lens Array

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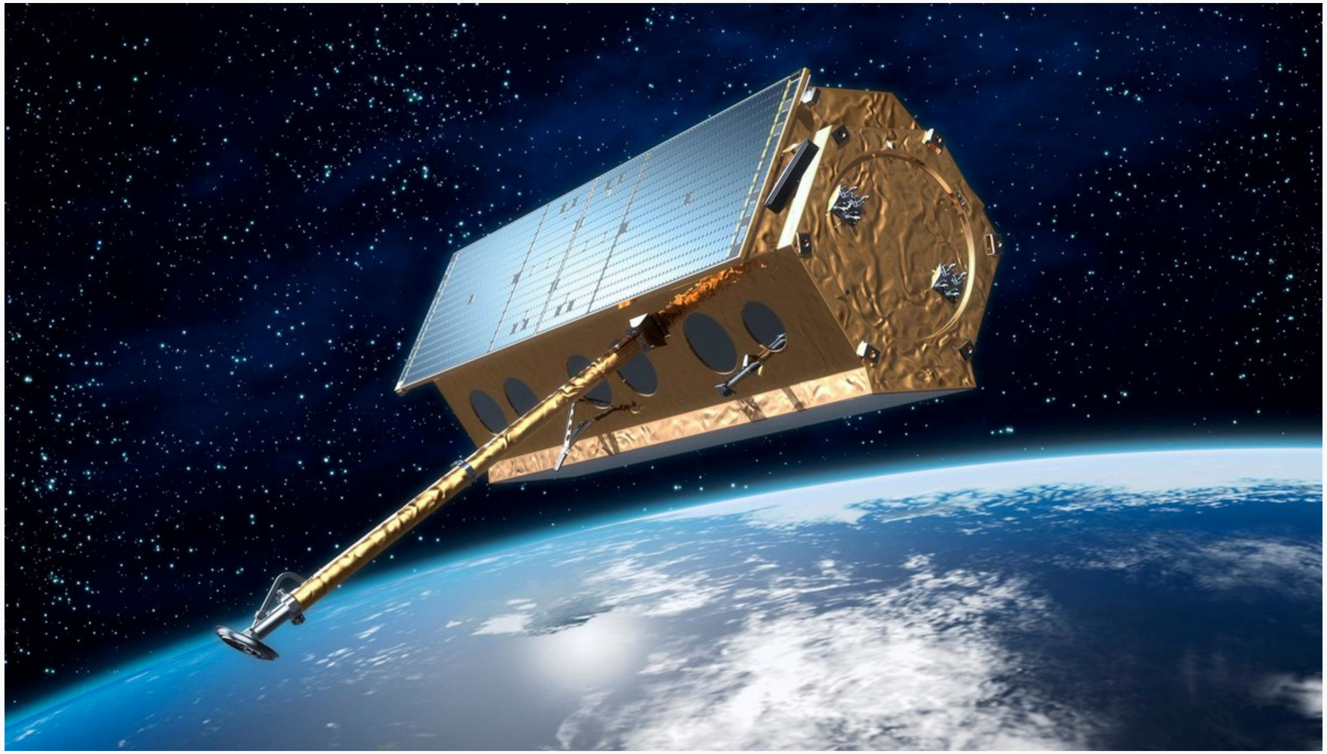
Satellites Communicate via Laser

– Bandwidth multiplication by using laser beams instead of radio signals –


Satellite TerraSAR-X

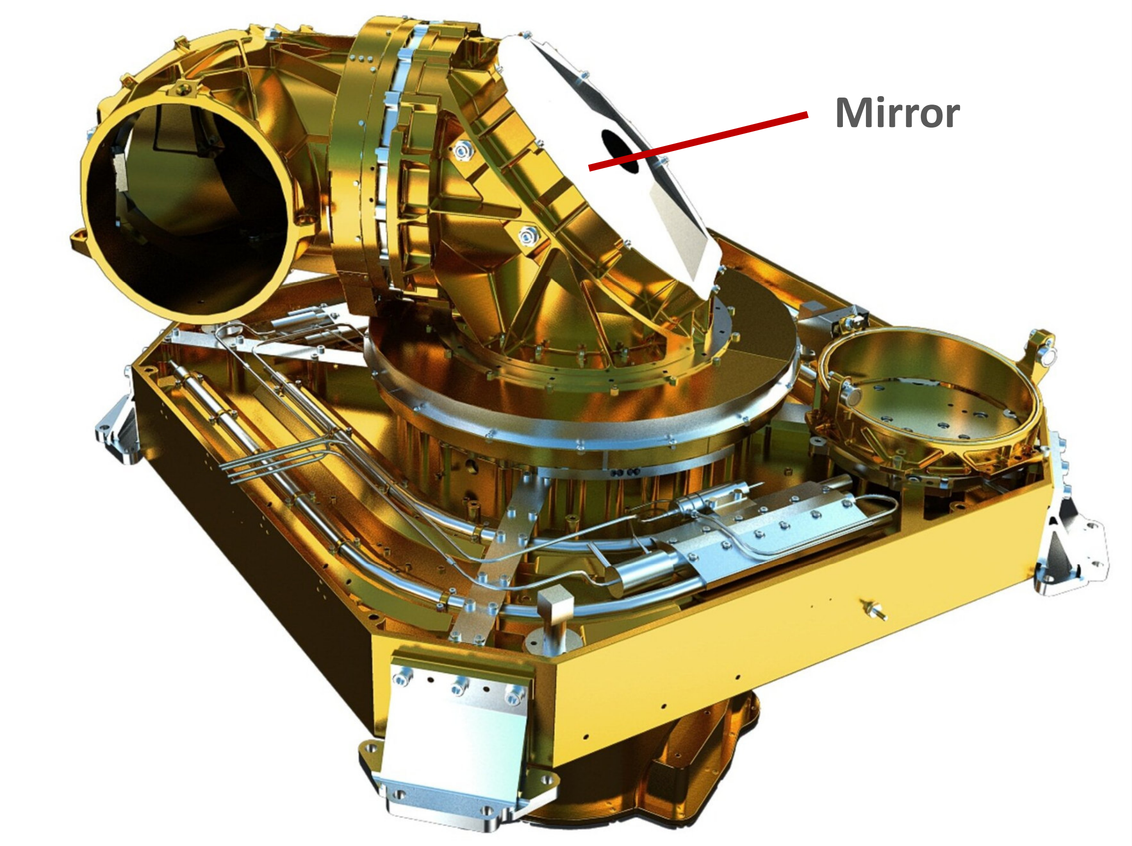
Enabling communication by means of laser light

- 2008 – first communication between two satellites using laser light (*TerraSAR-X* and *NFIRE* satellites)
- Laser light activated by pump modules integrated in Laser Communication Terminals (LCT)
- bandwidth achieved is a hundred times greater than with conventional radio wave transmission (5.5 GBit/s)

Source: DLR, Wikipedia, www.scinexx.de

Laser Communication Terminal (LCT)

– Device for transmitting signals over long distances using light –



Source: Tesat Spacecom GmbH

Satellite Communication for "Big Data"

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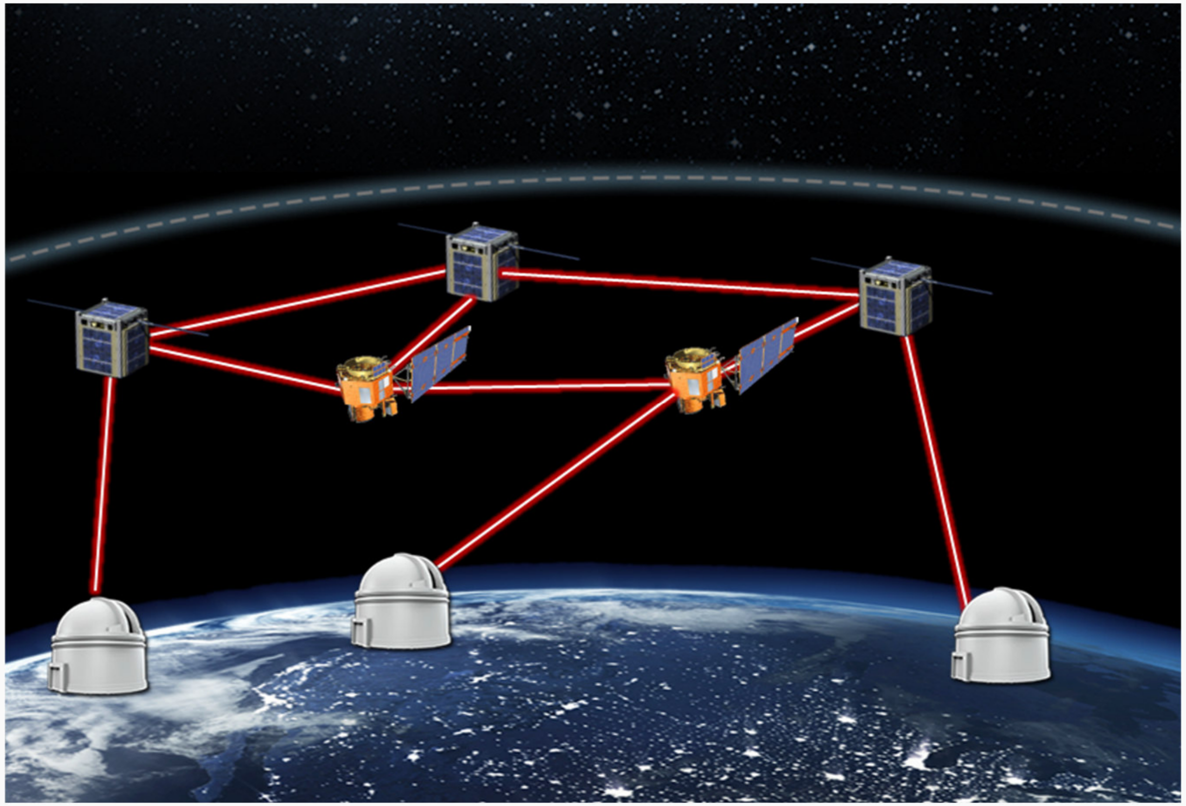
Enabling Human Megatrends

- Smart cities
- Autonomous cars
- High speed internet everywhere
- Artificial Intelligence

➔ **Required amount of satellites: 2,000 - 4,000 p.a.**



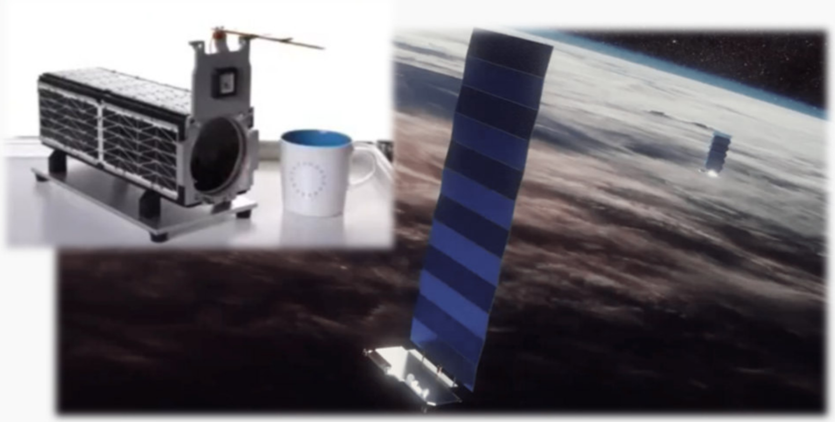
Motivation – Key Market "New Space"

– Paradigm shift - from complex individual production to series production –

Today – Scientific

- Approximately 3,000 satellites (in 2018)
- Main applications: earth observation (climate, traffic, military,…)
- Mass >> 1,000 kg
- Costs >> 100,000,000 USD (!)

Future - Industrialized



Source: Starlink

- In 2030 >> 10,000 (!) satellites (only Starlink claims 30,000 up to 2027)
- Main application: data communication
- Mass << 1,000 kg
- Costs << 1,000,000 USD (!)

Questions & Approach

Questions

- ↘ How do future mirror designs look like and how can they be standardized?
- ↘ Which material can be used to meet the technological requirements?
- ↘ Which technology is capable to generate these highly demanding ultraprecision qualities?
- ↘ Which technology is capable to fabricate large volumes?
- ↘ How do future production lines look like?

Approach

➔ **Fabricating aluminum mirrors by diamond turning**

Metal Mirrors – Properties and Advantages

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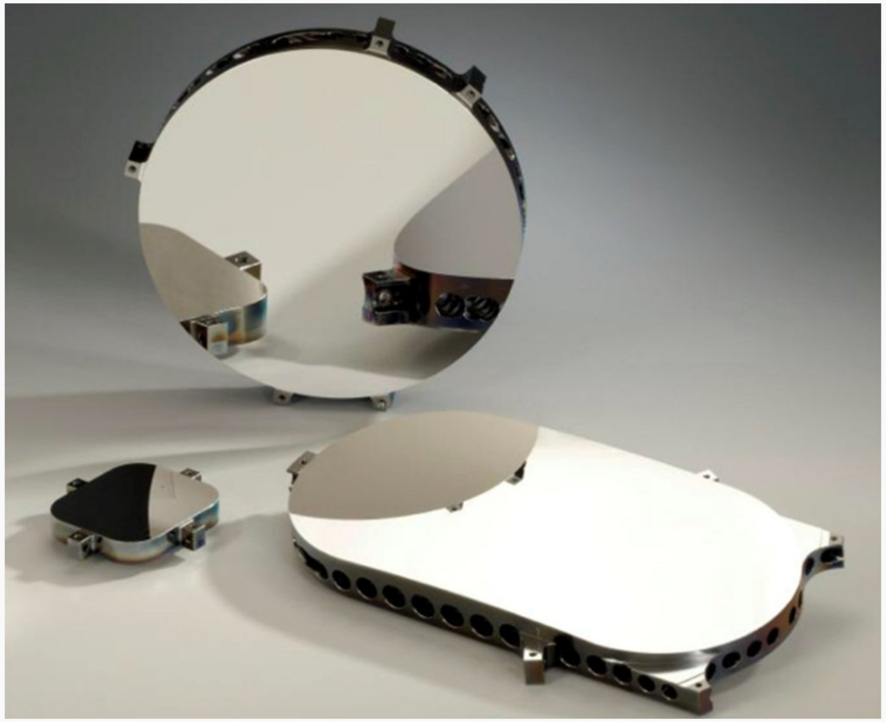
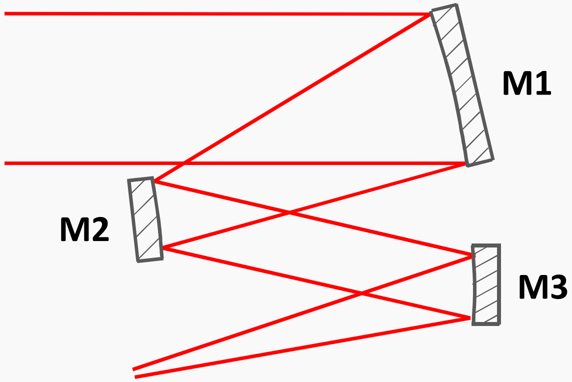
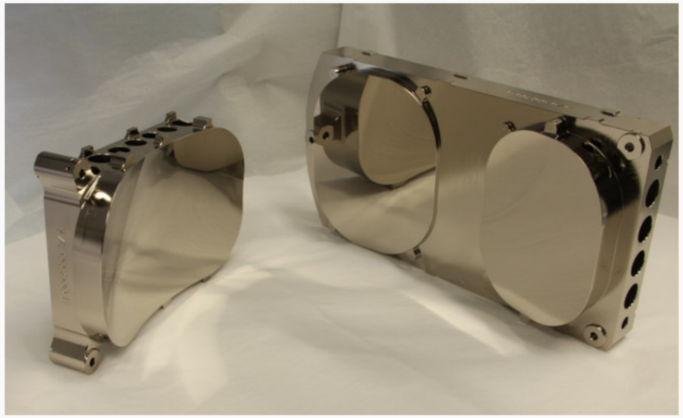


Source: Fraunhofer IOF

- Relatively inexpensive materials and ease of blank manufacture
- Direct integration of mounting and reference features
- Ability to add heating/cooling channels and relatively high thermal conductivity
- High percentage of light weighting possible
- Material matching between mirror and mounting structure

Telescope Designs – TMA*



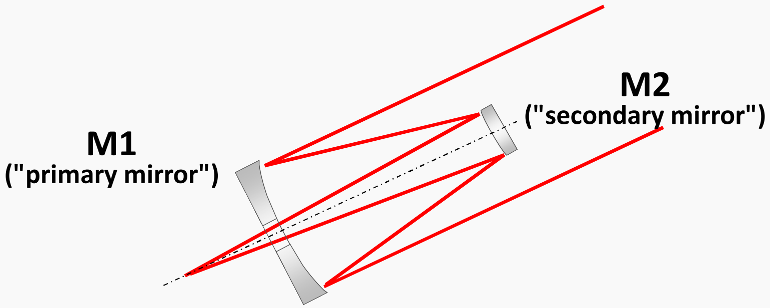


Source: Fraunhofer IOF

- Using 3 curved mirrors enabling to minimize all three main optical aberrations – spherical aberration, coma, and astigmatism
- Enables both a wide field of view and relatively small geometrical dimensions of the telescope
- Individual mirror geometries off-axis (freeform)

*TMA = Three Mirror Anastigmat

Telescope Designs – Cassegrain



Source: son-x

- Incoming light captured by a concave parabolic main mirror ("primary mirror")
- Reflected light captured by a convex hyperbolic "secondary mirror"
- Allows compact designs
- Individual mirror rotational symmetric

Metal Mirror Production Process Chain

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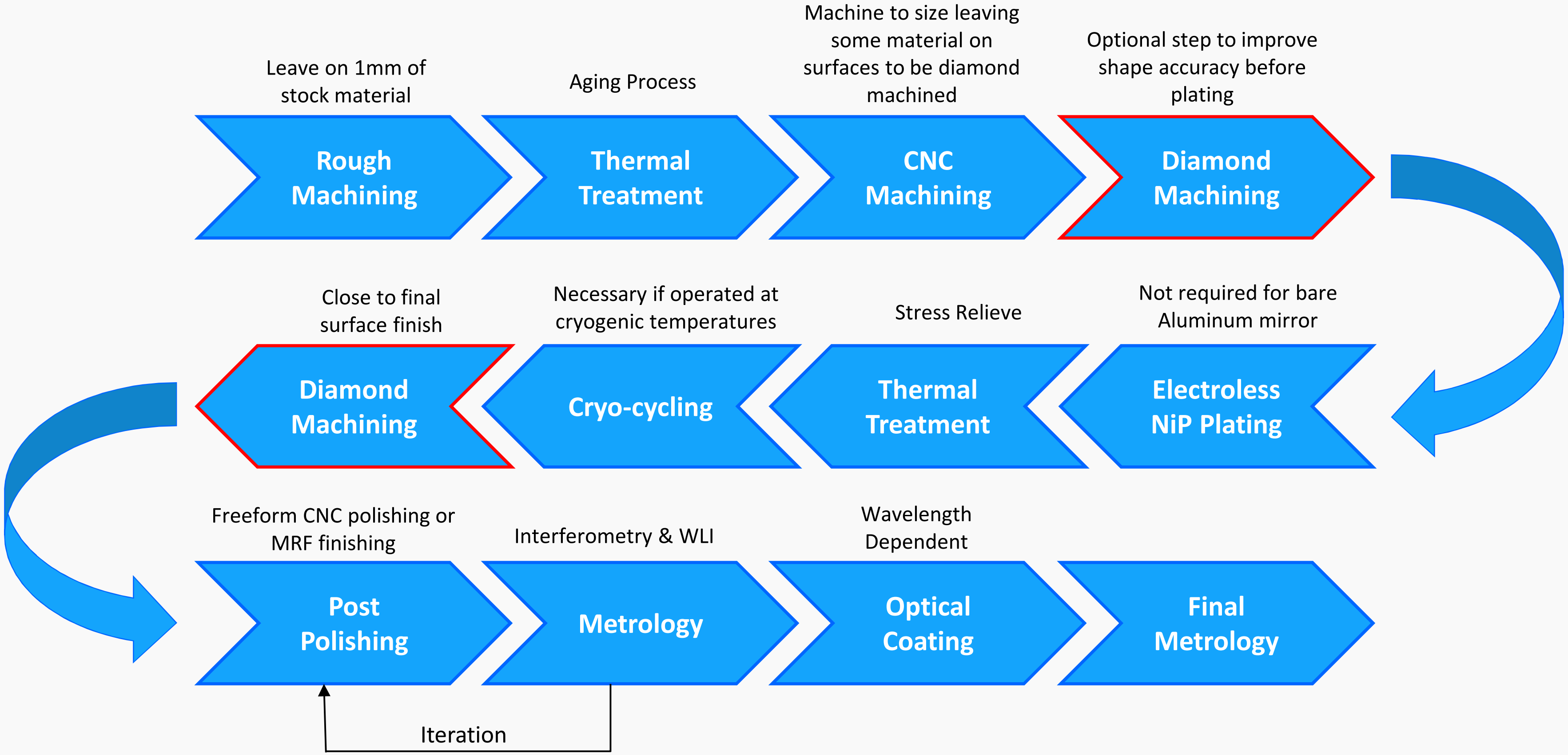

Machine Systems for Metal Mirror Manuf.

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Blank Fabrication

5-Axis CNC Machining >1000mm capacity

Diamond Machining

Diamond Turning Machine 1000mm Capacity

Post Polishing

MRF Post Polishing 1200mm Capacity

CNC Freeform Post Polishing 1200mm Capacity

Source: DMG, Precitech, QED Technologies, Zeeko

Metrology Systems for Metal Mirror Manuf.

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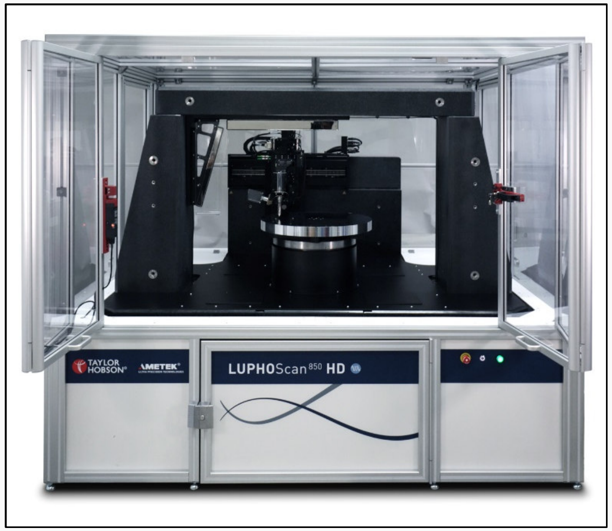
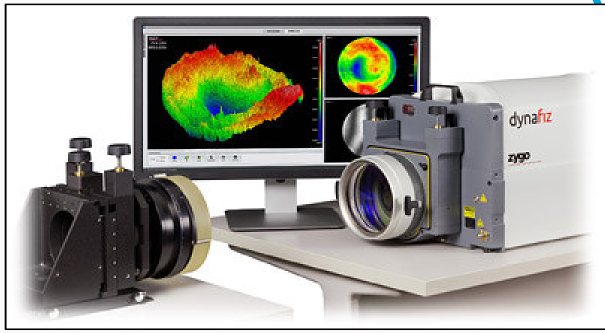
Blank Fabrication → **Diamond Machining** **&** **Post Polishing**

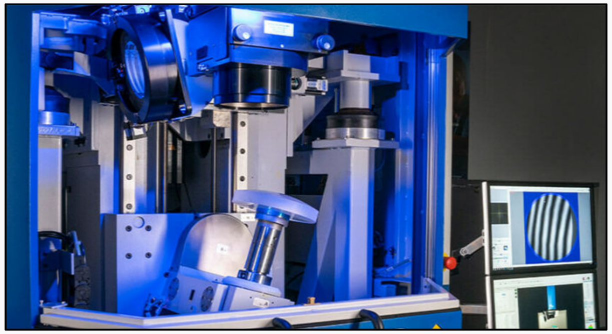
Multi Axis Coordinate Measurement Machine

Multi Wavelength Interferometer



Laser Interferometer + Holograms





Stitching Interferometer

Source: Zeiss, Tylor Hobson, Zygo, QED Technologies

Example – Off-axis TMA Metal Mirror

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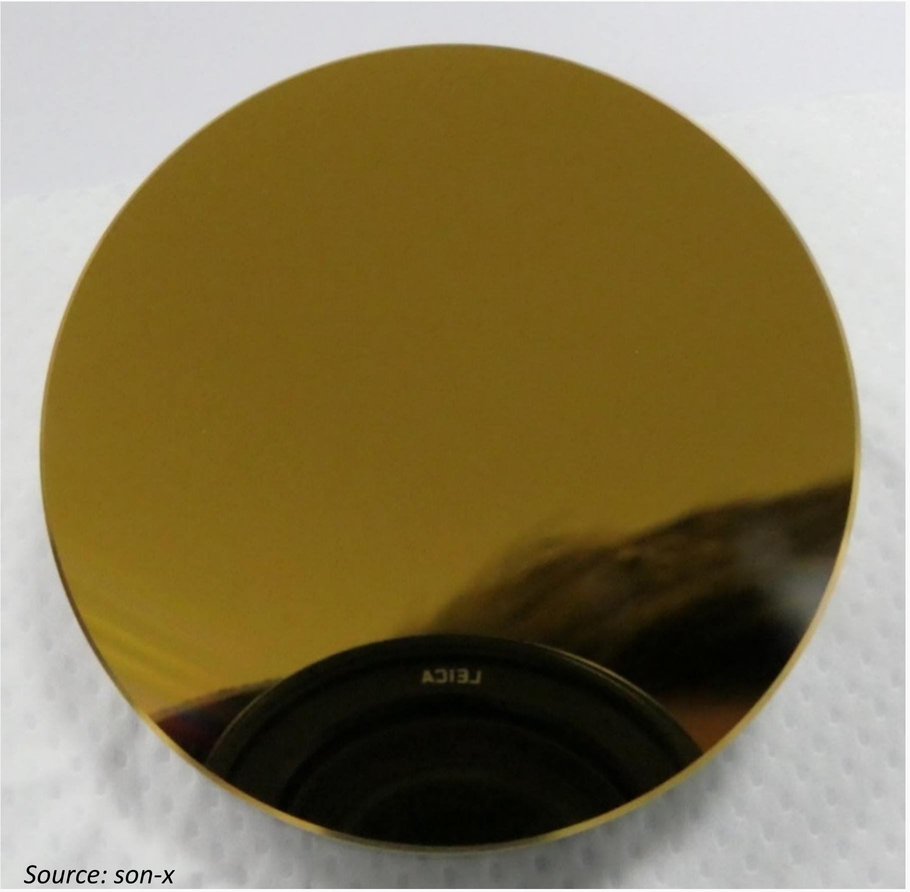
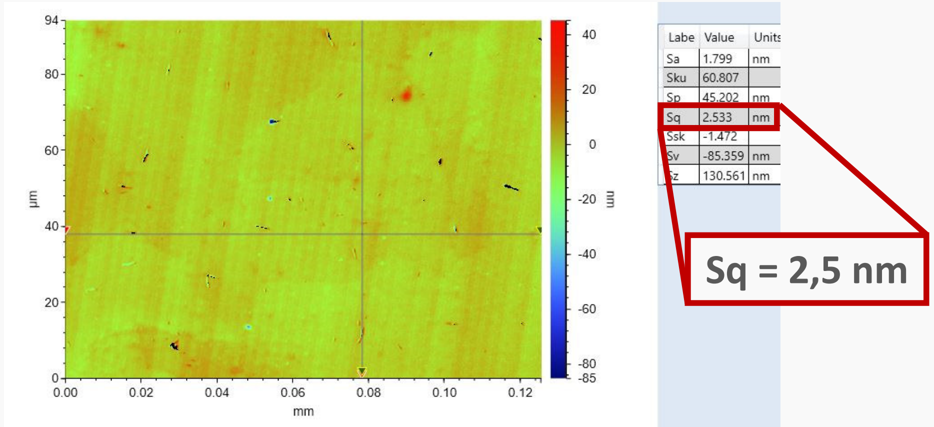


Source: son-x

- Off-axis aspheric mirrors with protected gold coating
- Clear optical aperture = 115 mm
- Surface roughness Rq < 5 nm
- Wavefront error WFE < 30 nm RMS



Example – Off-axis TMA Metal Mirror

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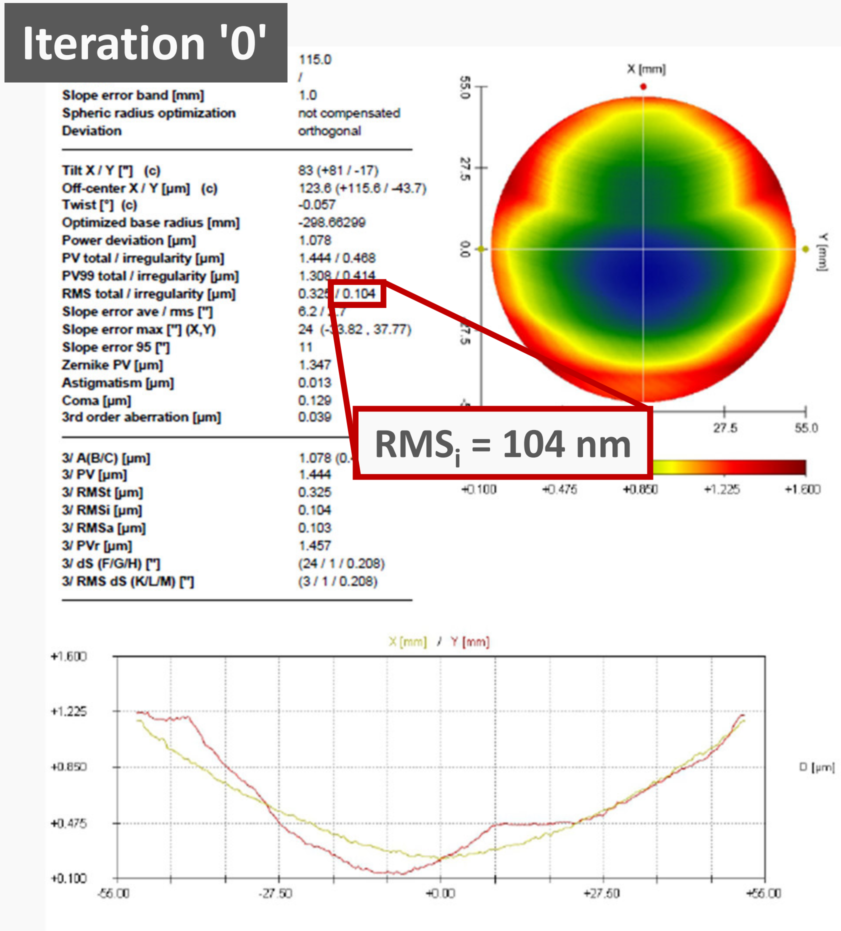

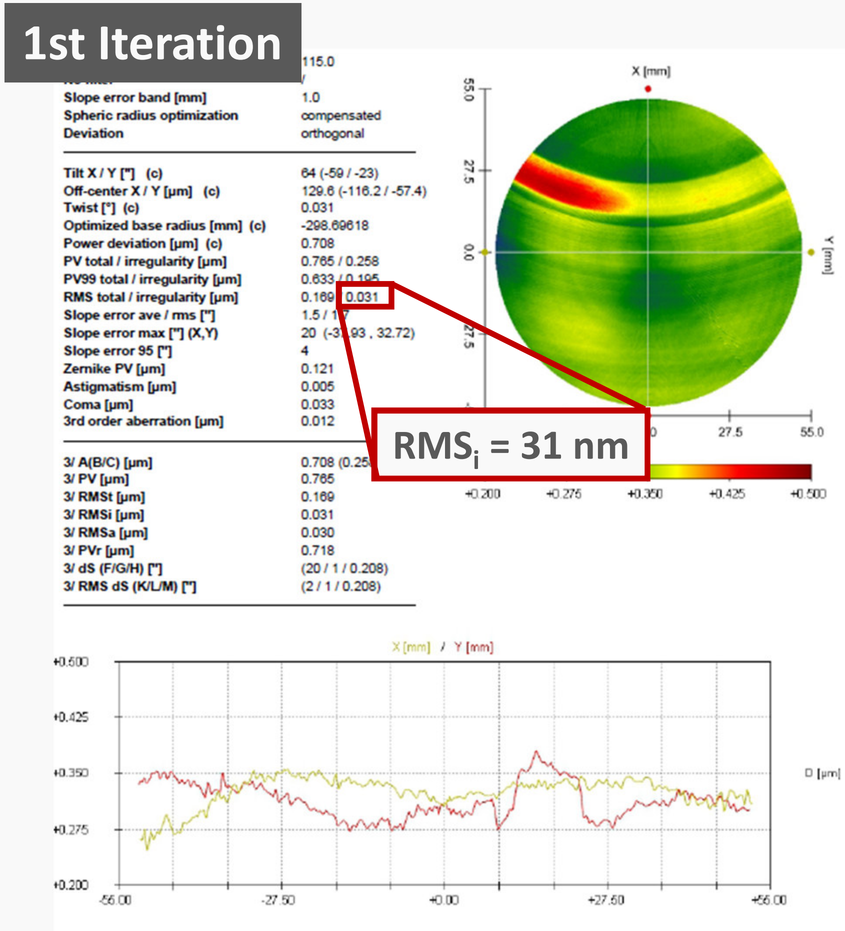

Outlook – Additive Manuf. of Mirror Blanks

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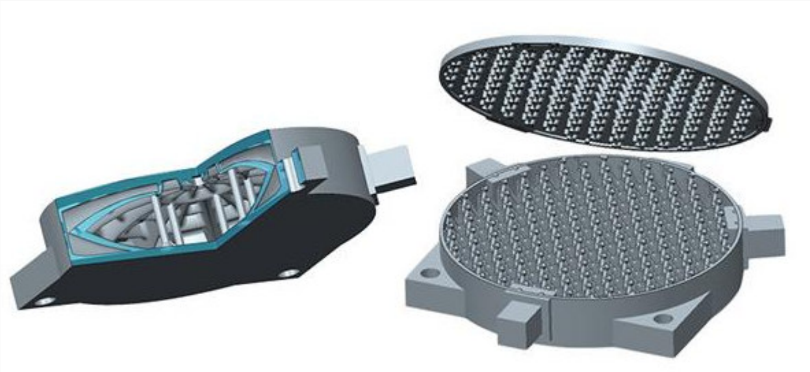

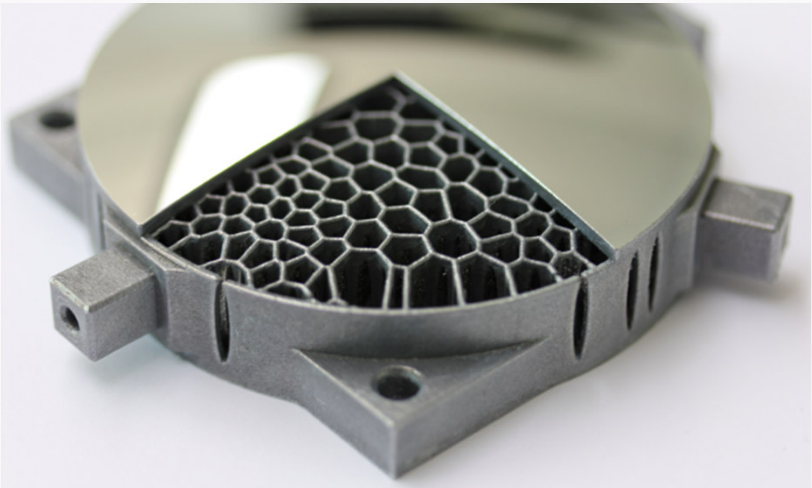

Source: Fraunhofer IOF

- Significant potential for customized mirror designs
- Improved weight relieving – up to 85% vs 60-65% for conventional CNC machining
- Possibility for complex mounting structures that cannot be conventionally machined
- Huge savings on material wastage – ref. weight relieving
- Improved delivery times and reduced overall cost of mirror substrates

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Summary

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- Ultraprecision Diamond Turning (Machining) is a well established technology in optics manufacturing
- Ultrasonic assistance can expand the machining performance and makes it applicable for new applications.
- Metal Mirrors have Tremendous Potential – for Small and Large Apertures as well as for Small and Large Volumes
- Further developments in both the technology and its applications request the close cooperation between industry and academia.

Source: Fraunhofer IOF

Thank You.

son-x GmbH

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