MULTI-FUN

ENABLING MULTI-FUNCTIONAL PERFORMANCE THROUGH MULTI-MATERIAL ADDITIVE MANUFACTURING

# Investigations into the robustness of additively manufactured, embedded electrical conductors


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https://www.mamc2022.org/

www.multi-fun.eu


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# Outline

- ❑ Motivation & Challenge
- ❑ What has happened so far …. short reminder to
  - Deposition of conductive & insulating layers
  - Functional integration into light metals by WAAM
- ❑ Robustness during manufacturing
- ❑ Robustness during mechanical testing
- ❑ Conclusions & Outlook
- ❑ Acknowledgments



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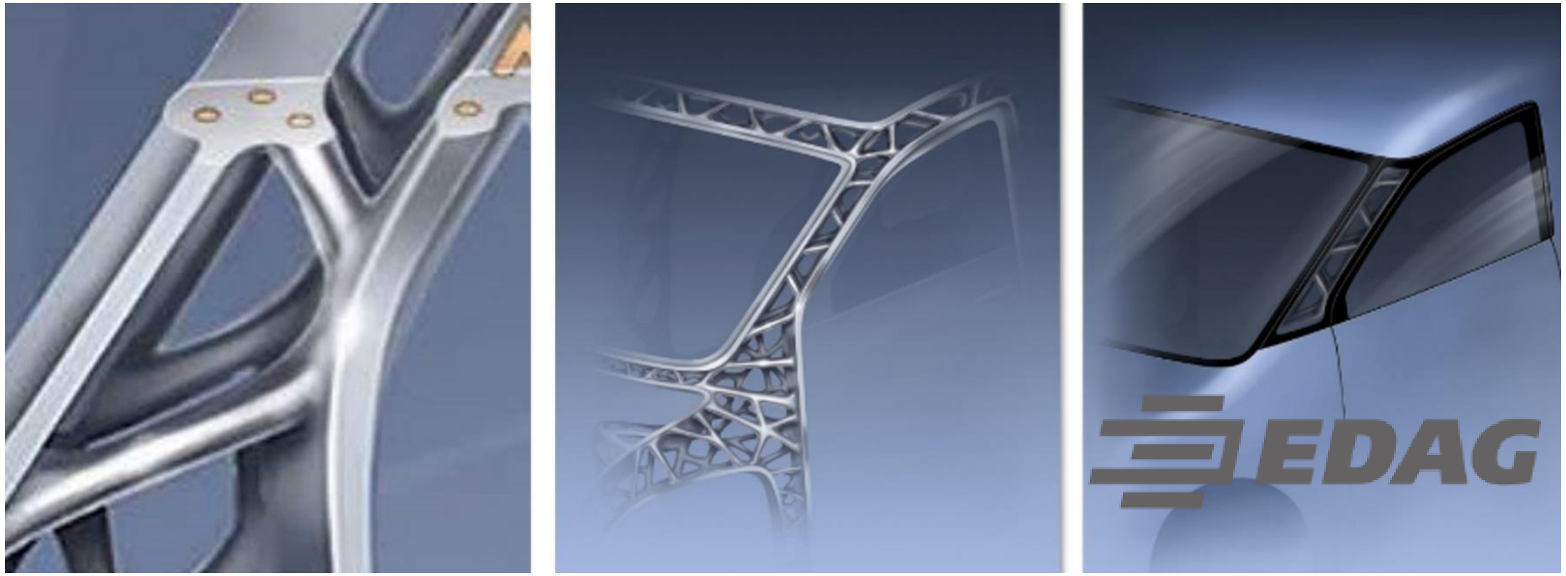
# Motivation for investigation about the integration of electrical conductors into light metal components

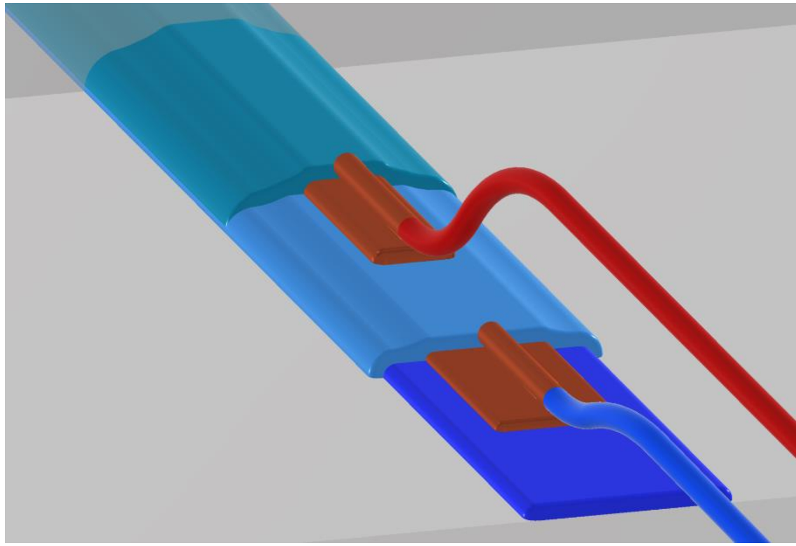
- Enabling new designs
- Exploiting novel DED technologies
- Demonstrating multi-material manufacturing opportunities

Example: MULTI-FUN Demonstrator, designed by EDAG:
**“See-through A-pillar”**



# Main challenges of integrating metal conductors into metal components by DED

- Introducing insulator materials separating metal conductors from structural metal
- Focussing on DED technologies for automated 3D manufacturability
- Connecting integrated copper tracks with other cabling
- **Robust processing**
- **Automation of all processes**



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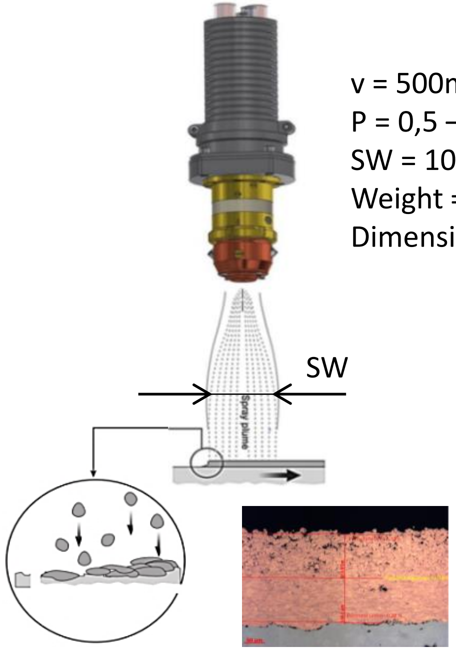
# Layer deposition by INOCON's InoCoat technology ("APPD")

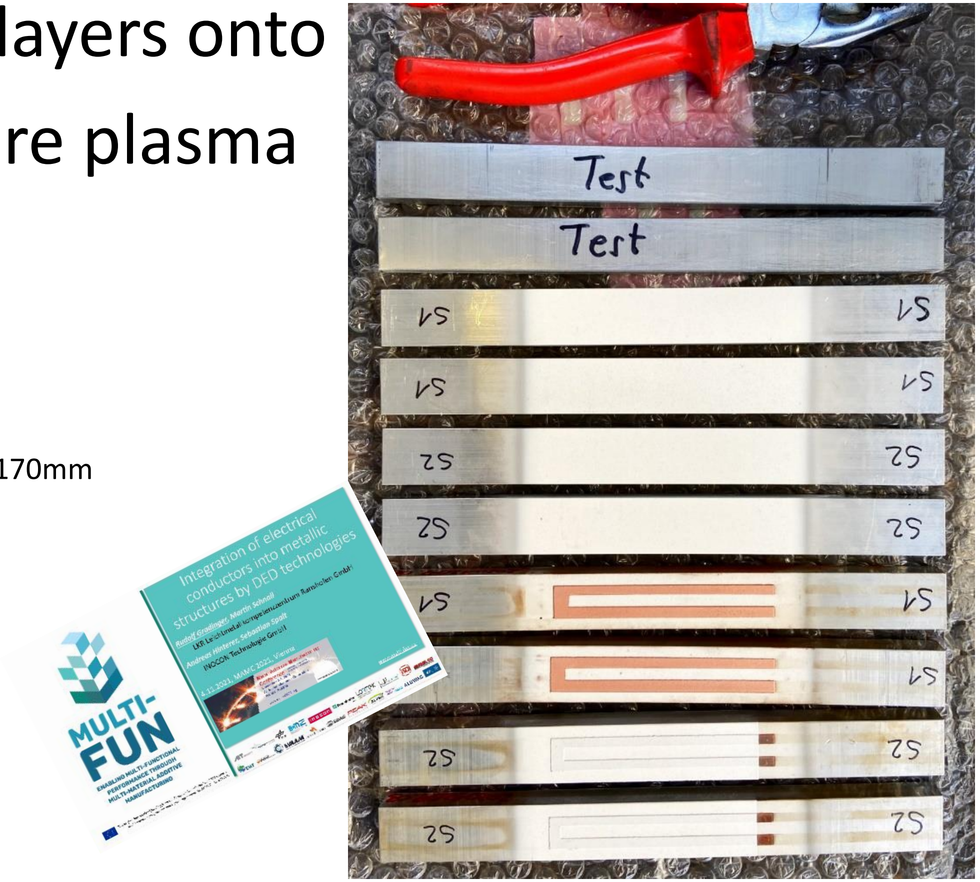
Deposition of electrical insulation & conductive layers onto metal parts by APPD (APPD=atmospheric pressure plasma deposition)


INOCON




v = 500mm/s
P = 0,5 – 17kW
SW = 10 – 80mm
Weight = 1,7kg
Dimension: 70x70x170mm

Source: Heimann, Plasma spray coating (2008)





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# Embedding the conductor/insulator stack by WAAM


**Next step: _____**

**Aluminium layers by WAAM**

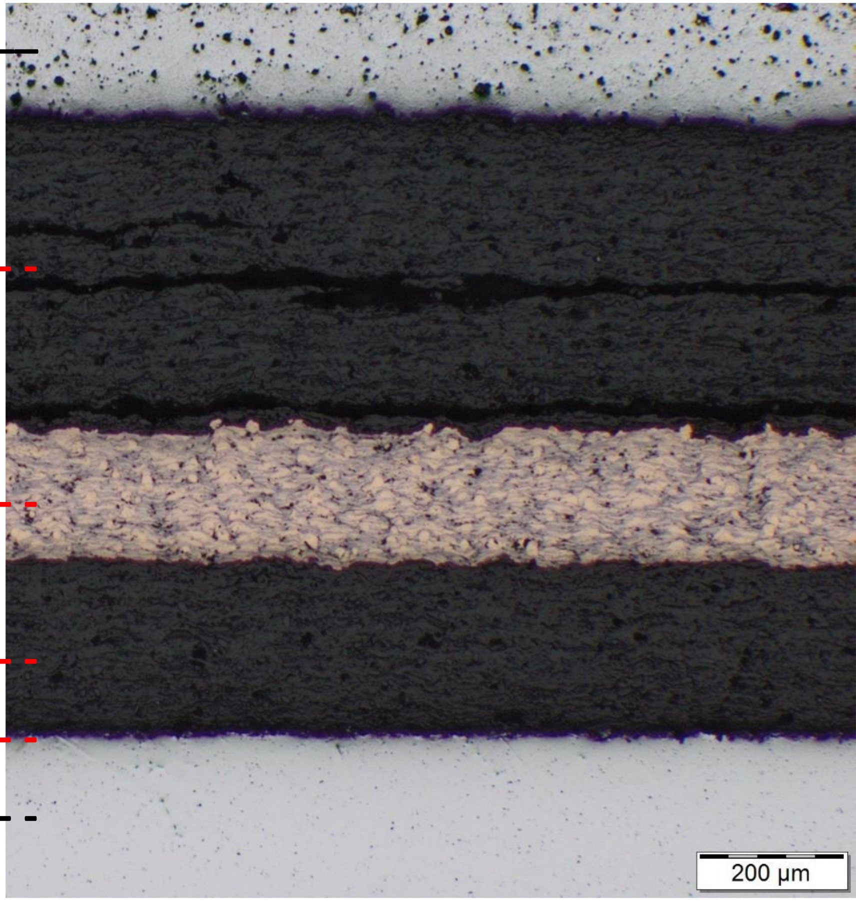
$Al_2O_3$ insulation layers

Cu electr. conductive layers

Al2O3 insulation layers

**Surface treatment**

Aluminium substrate



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# Embedding the conductor/insulator stack by WAAM (2)


**Next step:** ______

**Aluminium layers by WAAM**

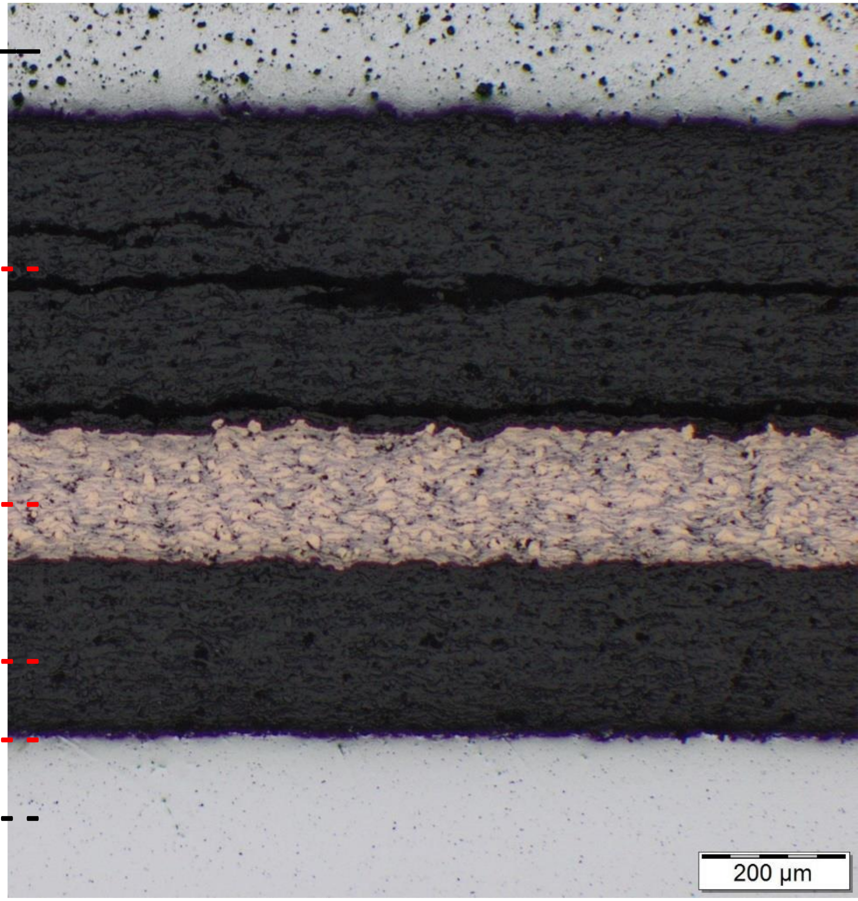
$Al_2O_3$ insulation layers - - -

Cu electr. conductive layers - - -

Al2O3 insulation layers - - -

**Surface treatment** - - -

Aluminium substrate - - -



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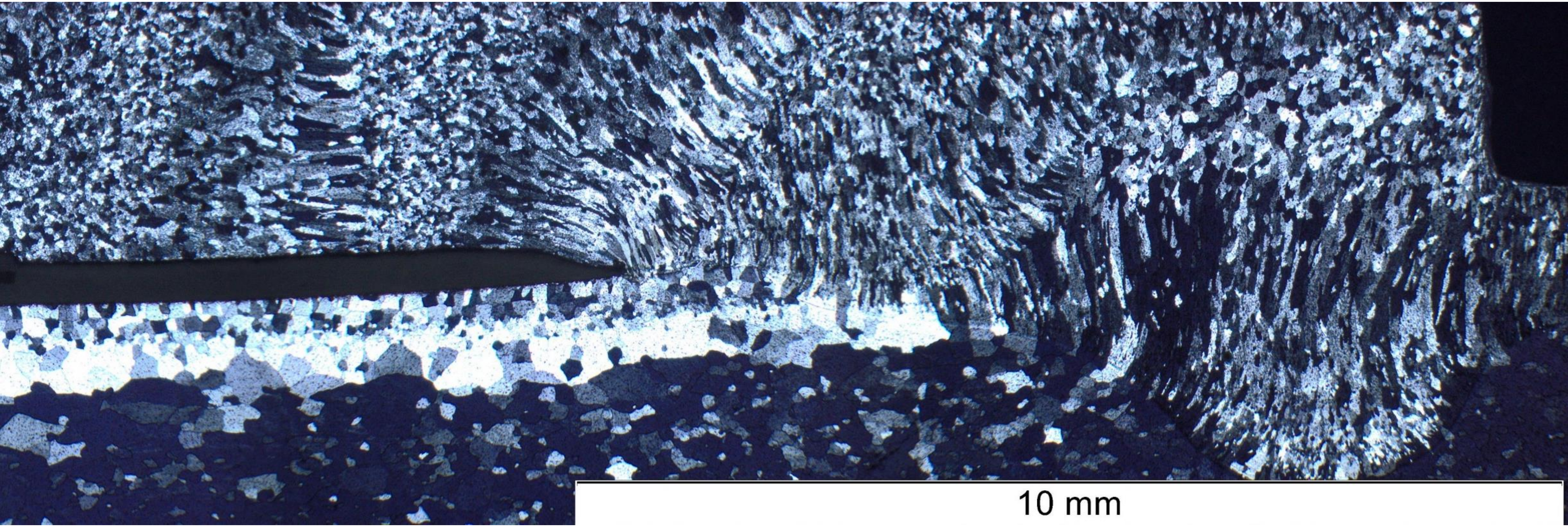
# Embedding the conductor/insulator stack by WAAM (3)





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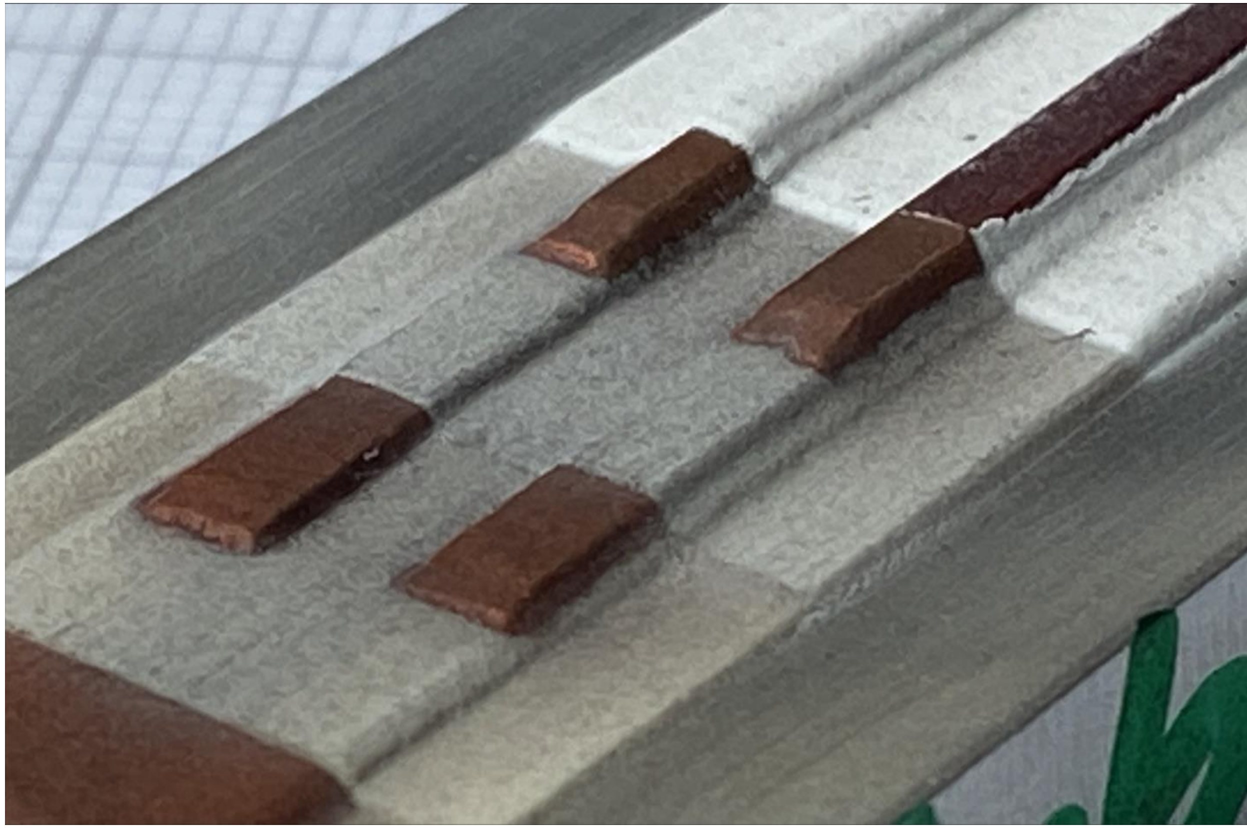
# Robustness during manufacturing

- Proper surface treatment of the metal substrate before applying APPD
- Following general thermal spraying process recommendations, esp. no sharp edges & corners of both the surfaces as well as the layer stack
- Apply proper masking to avoid unfavourable effects caused by overspray



▲ *5 insulated conductive layers*

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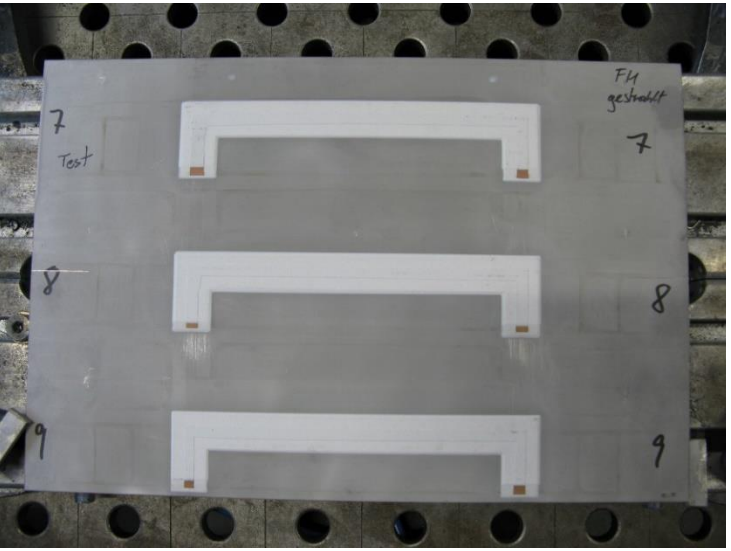
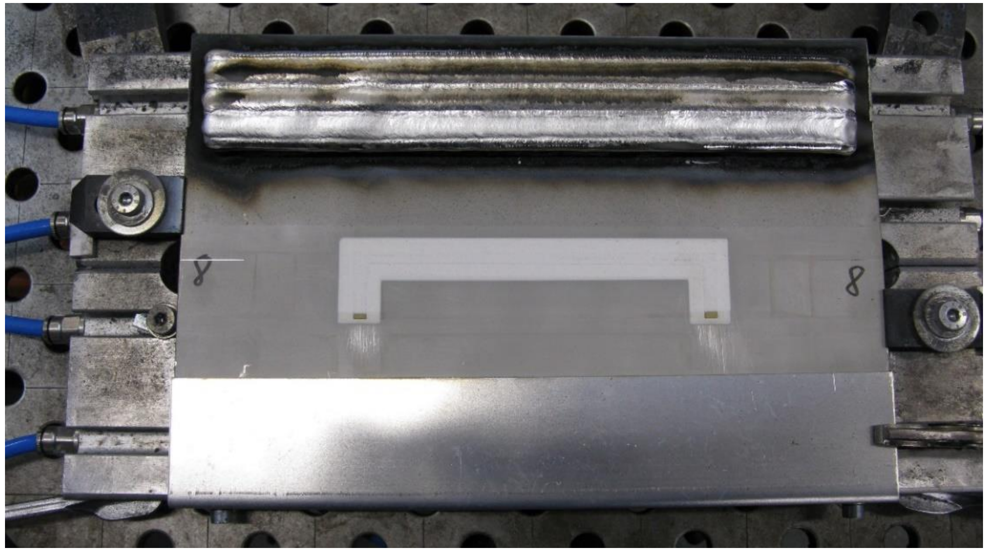
# Robustness during manufacturing (2)

- Adapt the WAAM strategy for non-conductive substrate when applying transferred arc
- Avoid high distortion of the substrate during WAAM (otherwise the layered stack will debond or break)





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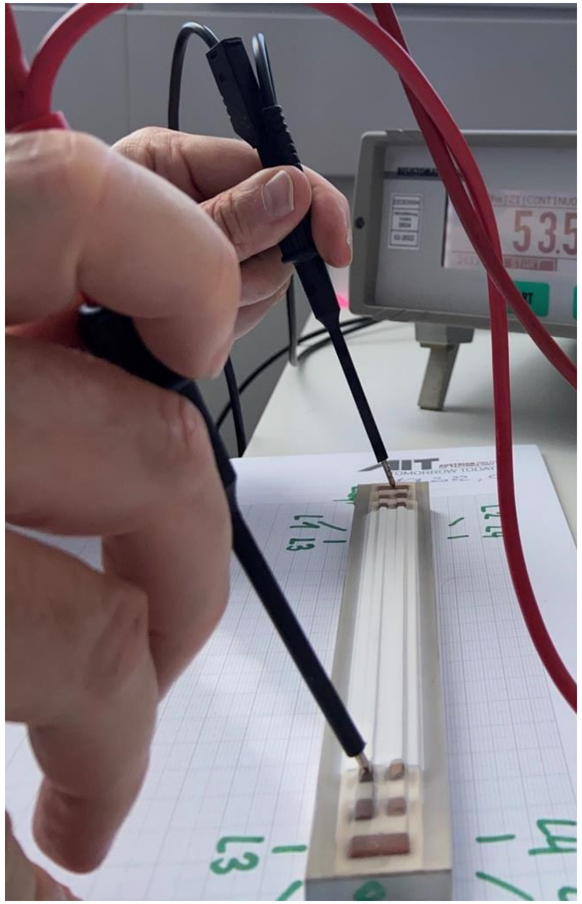
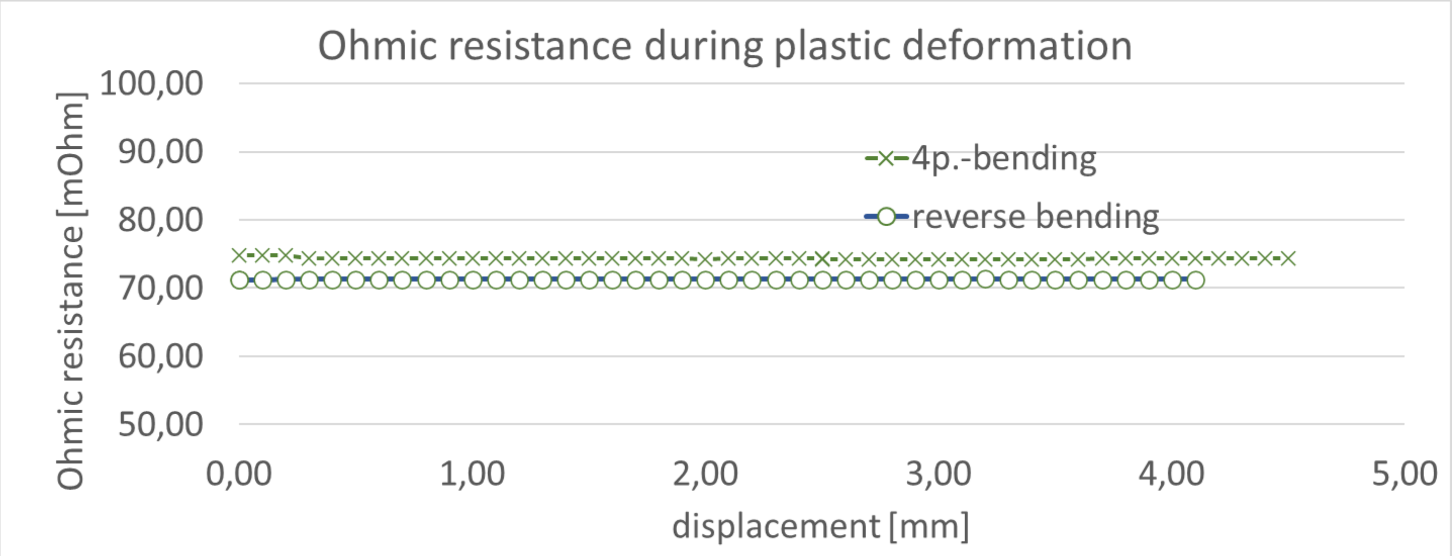
# Robustness during manufacturing (3)

- No influence of the WAAM process to the electrical resistance of the Copper stack (resulting values scatter lower than the scatter from manual measurements)
- No influence of the WAAM process to the insulation properties of the ceramic stacks (unless no breakage occurs at the end of the stacks)
- Debonding of stacks does not lead immediately to loss of conductivity
- Weld fume does not harm the values of manual electr. testing



# Robustness during mechanical testing
# 4-point-bending


- Samples designed with the stacks positioned in the neutral zone (appro. in the middle to the sample's height)
- Measuring the samples during bending as well as reverse bending (straitening) showing small effects during both procedures running in the plastic regime





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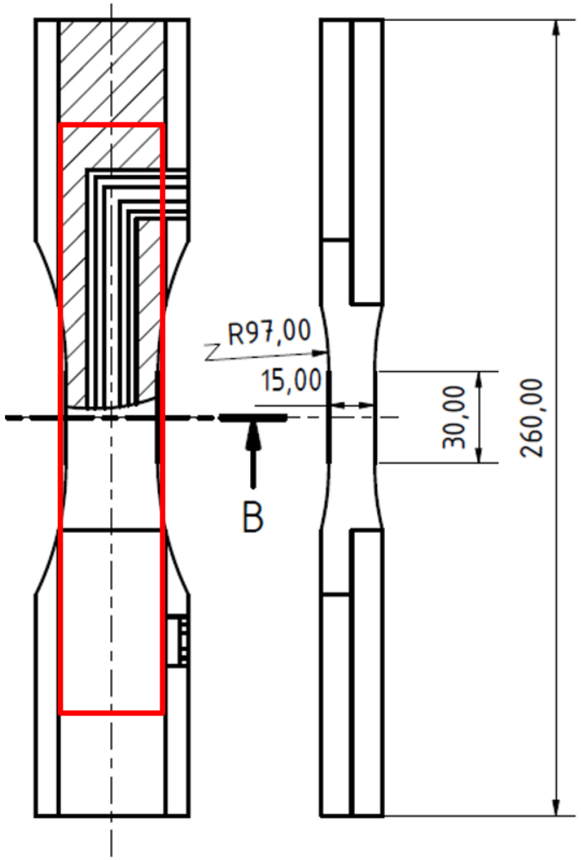
# Robustness during mechanical testing
# Fatigue testing

- Fatigue test regime: oscillating tensile load with varying max. load values
- 10 Mio. cycles in 25h duration
- Fatigue test samples subsequently used for static tensile testing





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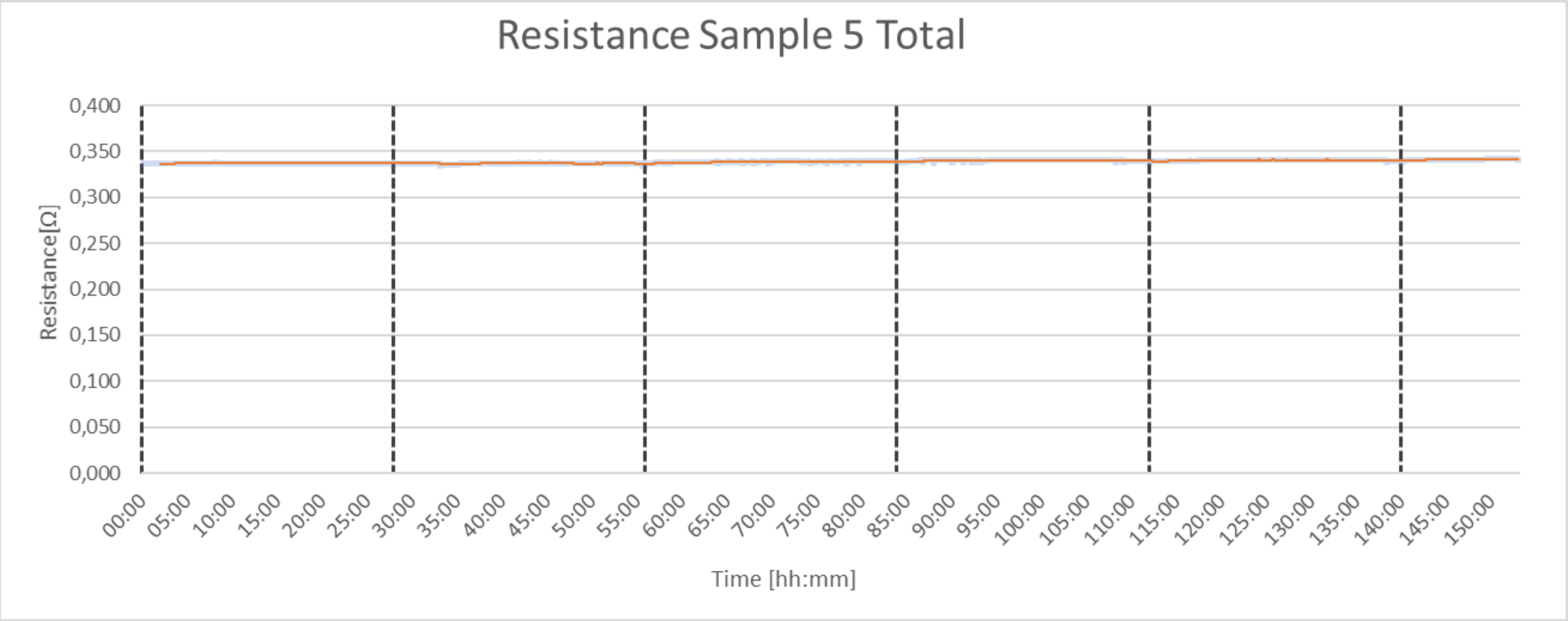
# Robustness during mechanical testing
# Fatigue testing (1)

- Test regime: oscillating tensile load with increasing max. values (up to 50% of YS)
- 10 Mio. cycles in 25h duration ► *total values (Ohm) showing nearly no fatigue*





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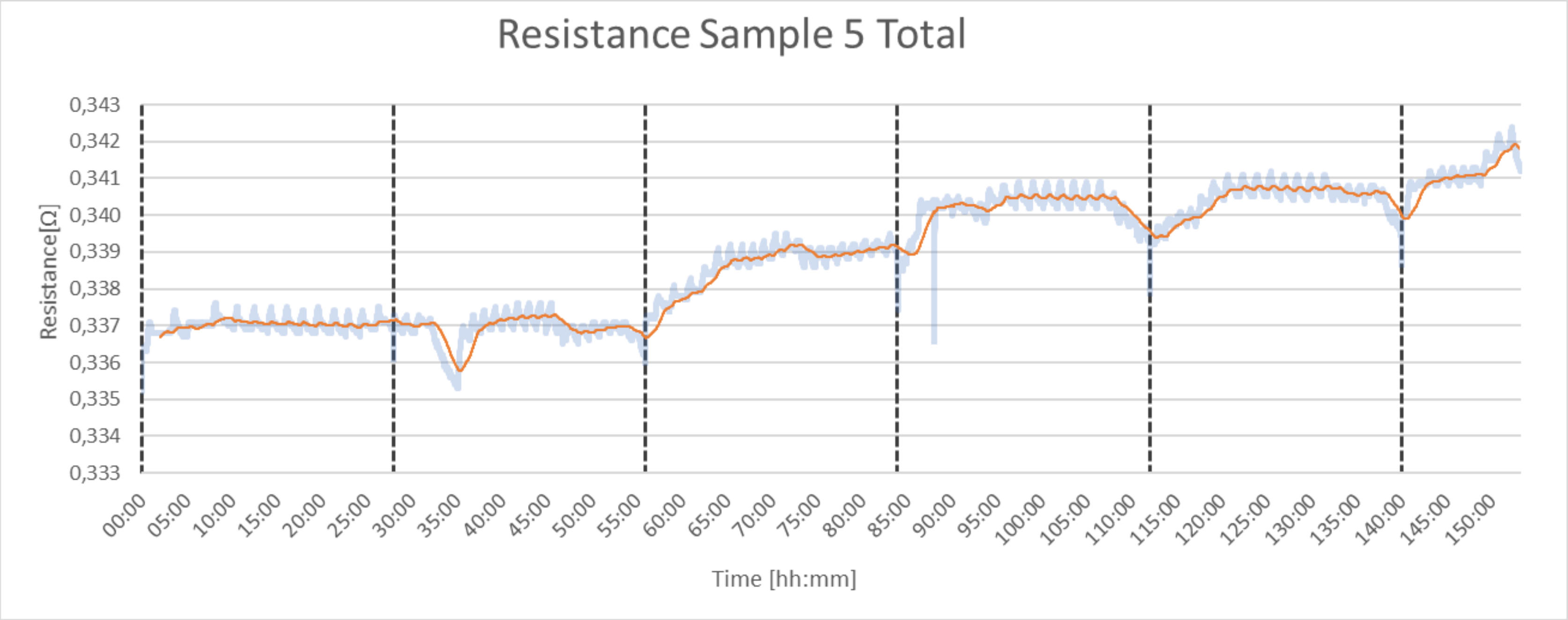
# Robustness during mechanical testing
# Fatigue testing (2)

- Test regime: oscillating tensile load with increasing max. values (up to 50% of YS)
- after >55 x $10^6$ cycles ▼ *effects from temperature changes & increased loads <2%*





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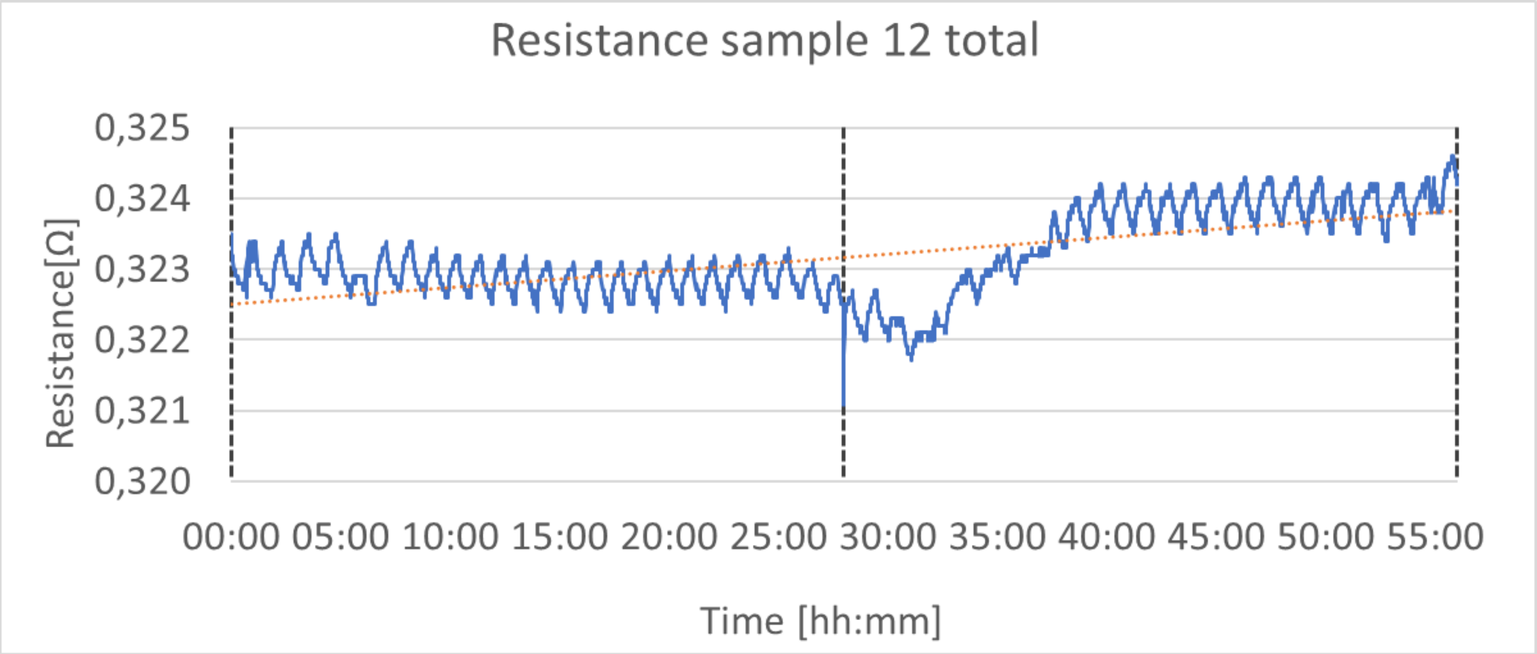
# Robustness during mechanical testing
# Fatigue testing (3)

- Test regime: oscillating tensile load with increasing max. values
- 20 Mio. cycles in ~55h duration ▼ *effects from temperature changes (Nov. 2021)*





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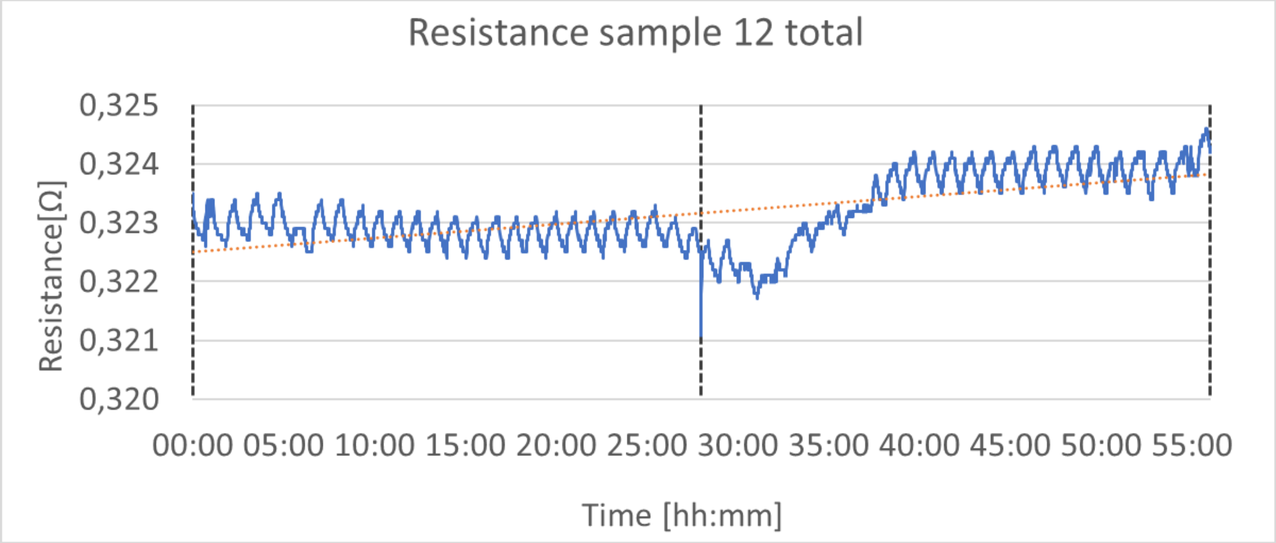
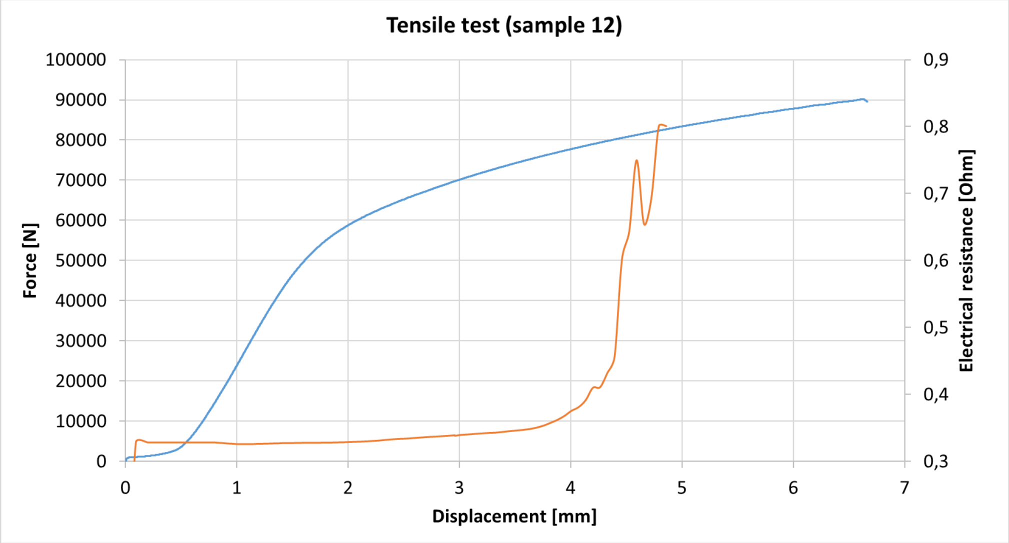
# Robustness during mechanical testing
# Tensile testing after fatigue testing

- Static tensile testing after 20 Mio. cycles fatigue testing





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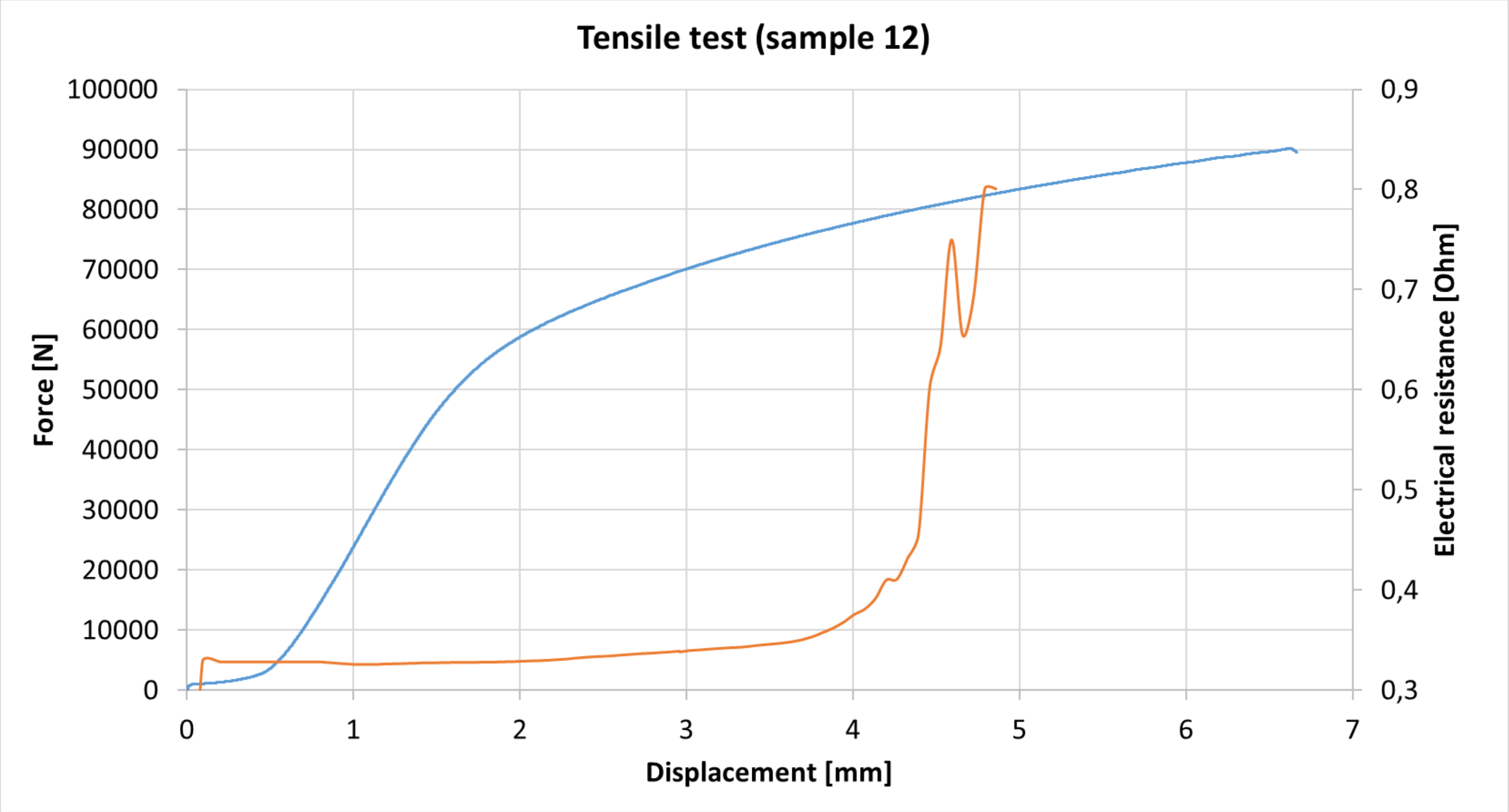
# Robustness during mechanical testing
# Tensile testing after fatigue testing (2)

Tensile testing showing only small effect of plastic deformation (up to 2mm displacement) on the electrical resistance, obviously showing a deteriorated conductor layer stack beyond 3mm total displacement





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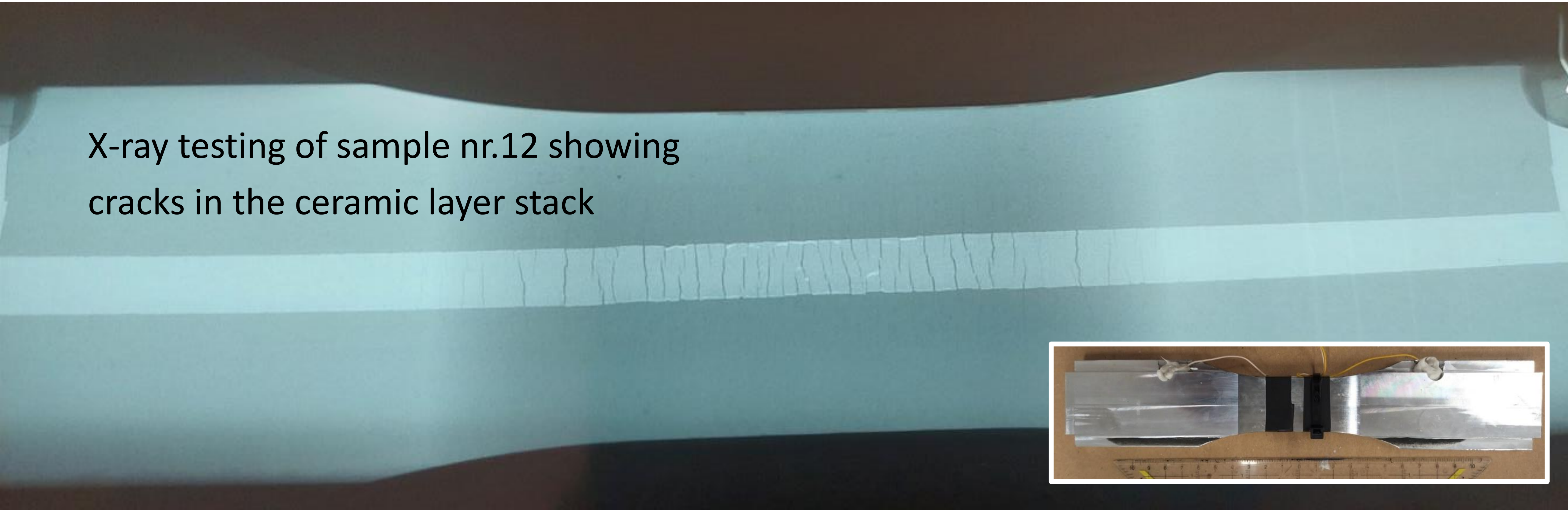
# Robustness during mechanical testing
# Tensile testing after fatigue testing (3)



X-ray testing of sample nr.12 showing cracks in the ceramic layer stack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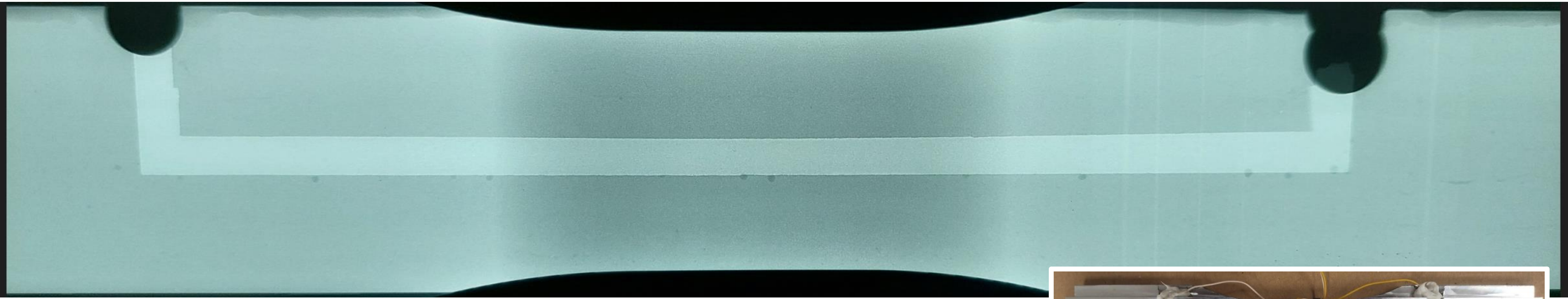
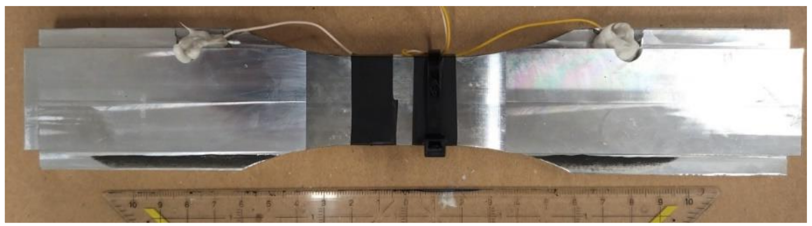
# Robustness during mechanical testing
# Tensile testing after fatigue testing (4)

COMPARISON:

X-ray testing of another sample in as built condition







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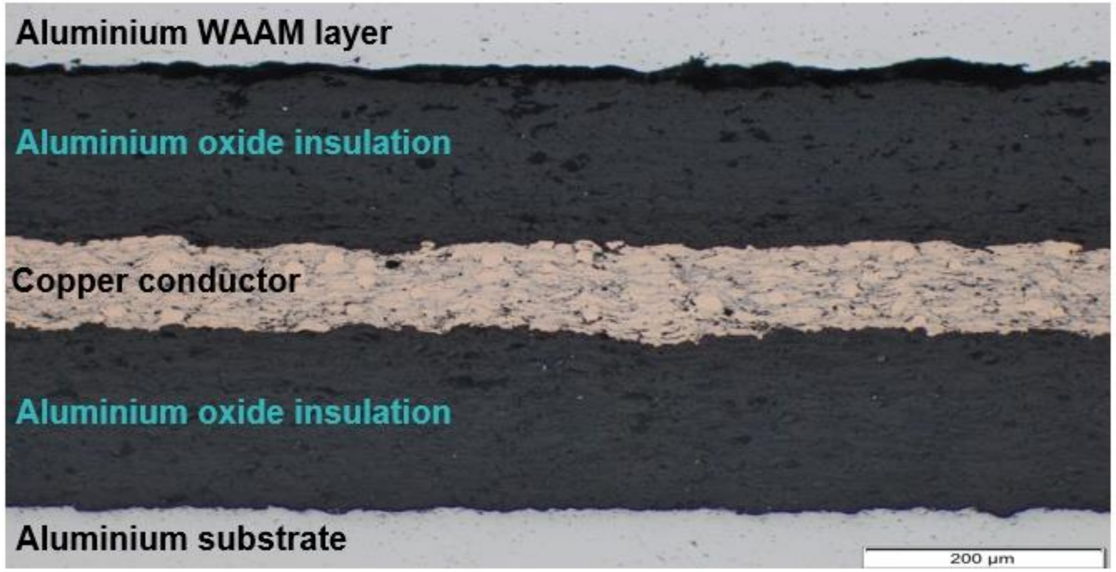
# Conclusions & Outlook

- Embedding of insulators & conductors into aluminium substrate by APPD & WAAM successfully shown on 2D specimen level
- Simple specimen design showing good robustness during manufacturing & testing
- ➢ Upscaling to larger sizes and 3D geometries ongoing but still challenging
- ➢ Postprocessing investigations for increased electrical conductivity ongoing

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# Next opportunities to meet MULTI-FUN team members

- Wednesday, 09:00, MAMC 2022, **Andreas Klug & Stefan Karanovic (AVL)** giving their plenary talk about "Additive Manufacturing for Advanced Automotive Measurement Systems - Opportunities & Challenges"
- MULTI-FUN Speed Tech Forum (Oct 5th 2022, Salzburg) with contributions from **EWF, WAAM3D, RHP, Inphotech, INOCON, DLR, MIGAL & LKR** → see www.MULTI-FUN.eu & register for free: https://www.eventbrite.co.uk/e/multi-fun-speed-tech-forum-tickets-385582576867


- **Stewart Williams (Cranfield University)** giving the keynote lecture "The Contribution of Wire-based Directed Energy Deposition Additive Manufacture to Light Weight Structures and Sustainability" at LKR's 12. RANSHOFENER LEICHTMETALLTAGE 2022 conference in Salzburg on Oct. 7th 2022 , see https://www.lmt.ait.ac.at/


- **Stewart Williams (WAAM3D) & Eurico Assunção (EWF)** contributing to the Panel "The Future of Standardisation" October 20th 2022 during "I AM" (International Additive Manufacturing) Conference https://event.asme.org/IAM/Program/Standardization-Panel

I-AM 2022


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# Thank You!

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