Mechanical properties and hydrogen tolerance of particle-reinforced CCA produced by additive manufacturing (MarioCCArt)

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IWT Leibniz-Institut für Werkstofforientierte Technologien

MAX-PLANCK-INSTITUT FÜR EISENFORSCHUNG GmbH

First SPP phase: Project PaCCman

Title: Particle-strengthened Compositionally Complex Alloys – Interlinking powder synthesis, additive manufacturing, microstructure evolution and deformation mechanisms (PaCCman)

V. Uhlenwinkel
(3 yrs funding)

IWT
Stiftung Institut für Werkstofftechnik
Bremen

E. A. Jägle (1.5 yrs funding)

Max-Planck-Institut
für Eisenforschung GmbH

G. Dehm (1.5 yrs funding)

Alloy casting
⇩
Powder atomization
⇩ / ⇙
L-PBF | Powder optimization
⇩
Heat treatment
⇩
HR analysis (APT, TEM)

Approach for the first project phase

Alloy design approach:

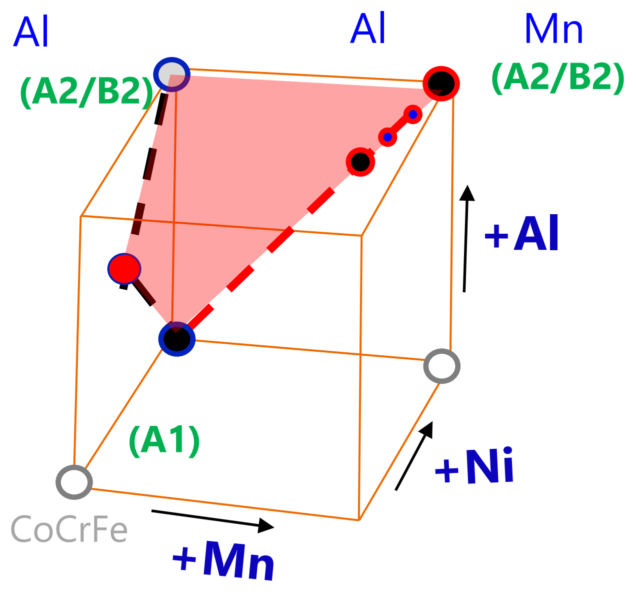
- Design space: CoCrFe +Ni +Mn +Al +N
- Thermocalc simulations

Synthesis approach:

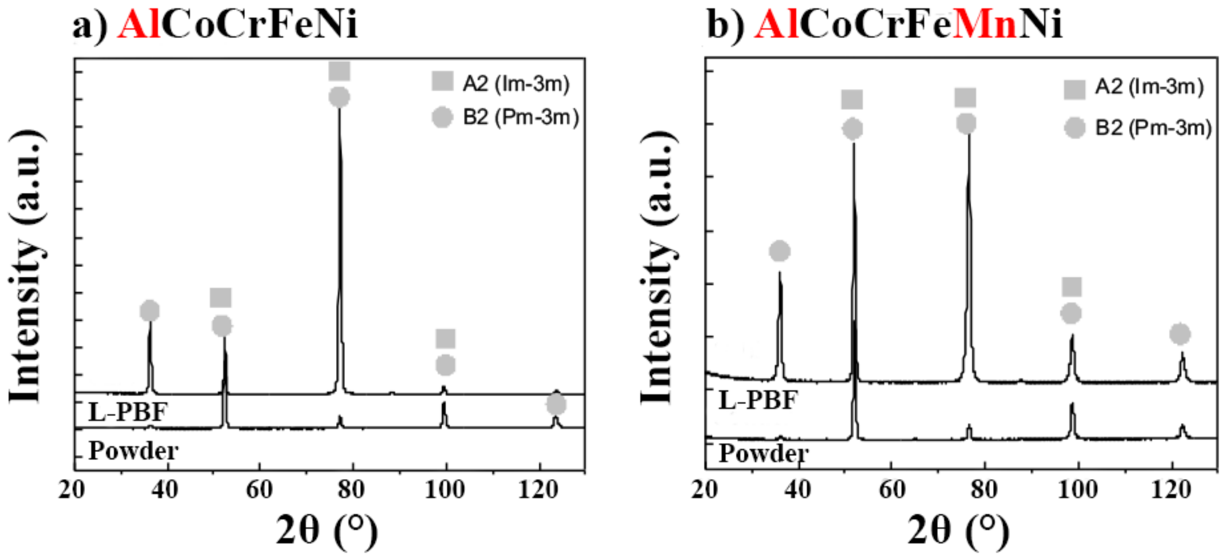
- Casting (MPIE) and atomization (IWT) of master alloys (CoCrFe, CoCrFeNi, CoCrFeNiAl, $CoCrFeNi_{0,5}Al_{0,5}$, CoCrFeNiAlMn)
- Atomization under Ar- and N_2-atmosphere
- Powder blending -> L-PBF processing
- Heat treatments

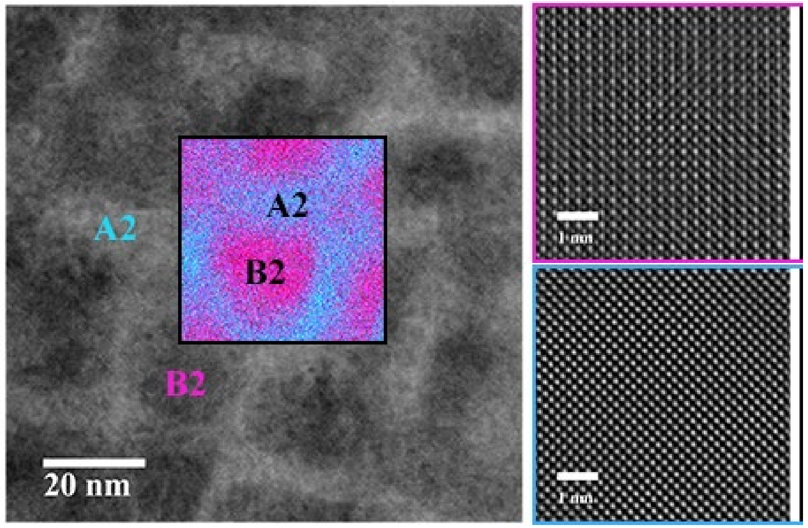
Analysis approach:

- XRD, SEM +EDS, +EBSD for homogeneity and phase analysis
- HR-analysis by TEM and APT
- Mechanical properties: HV, macroscopic tensile tests, micropillar compression



Results first project phase: Microstructure

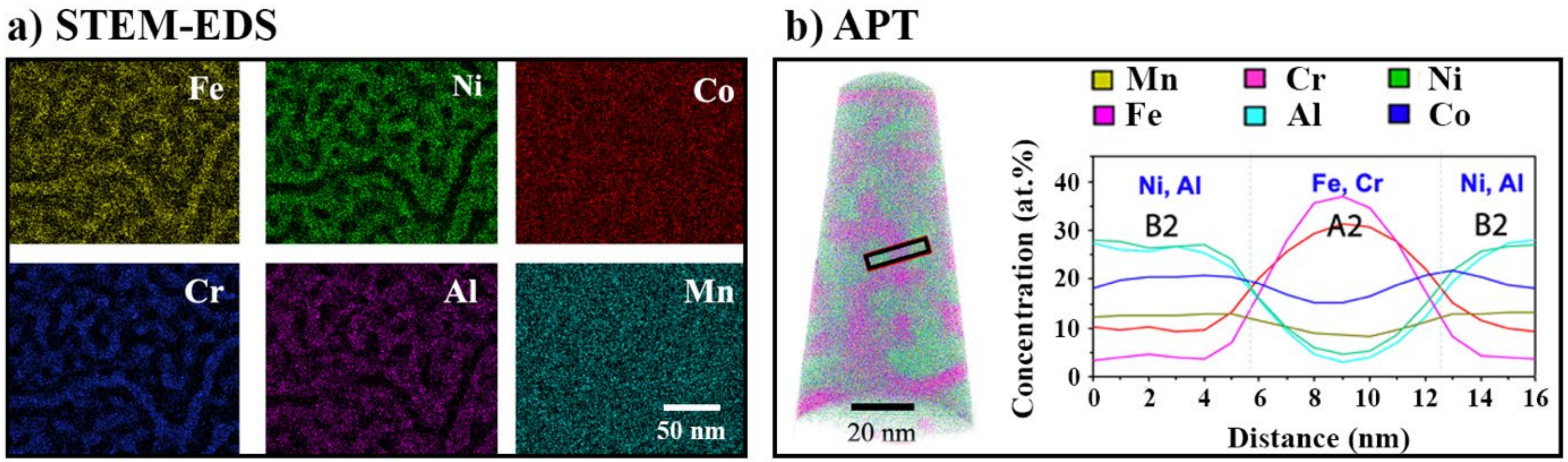




AlCoCrFeMnNi:

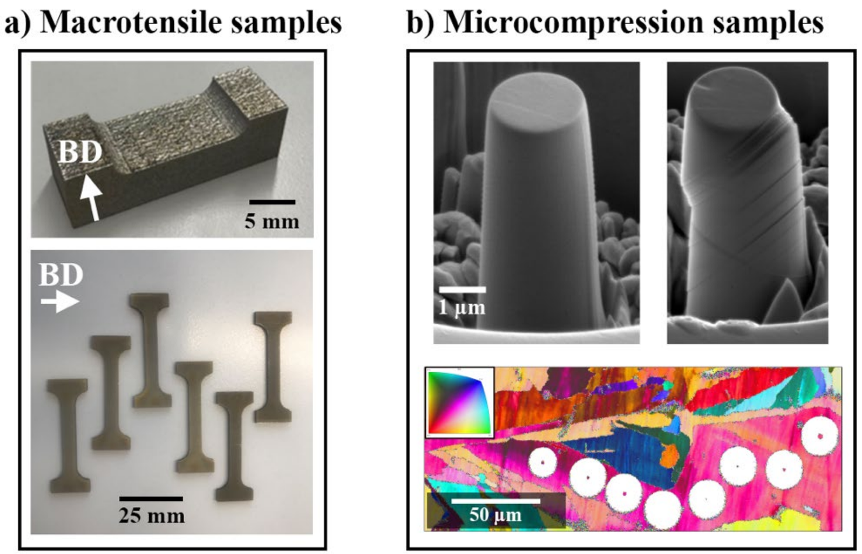
A2/B2 phase separation via spinodal decomposition

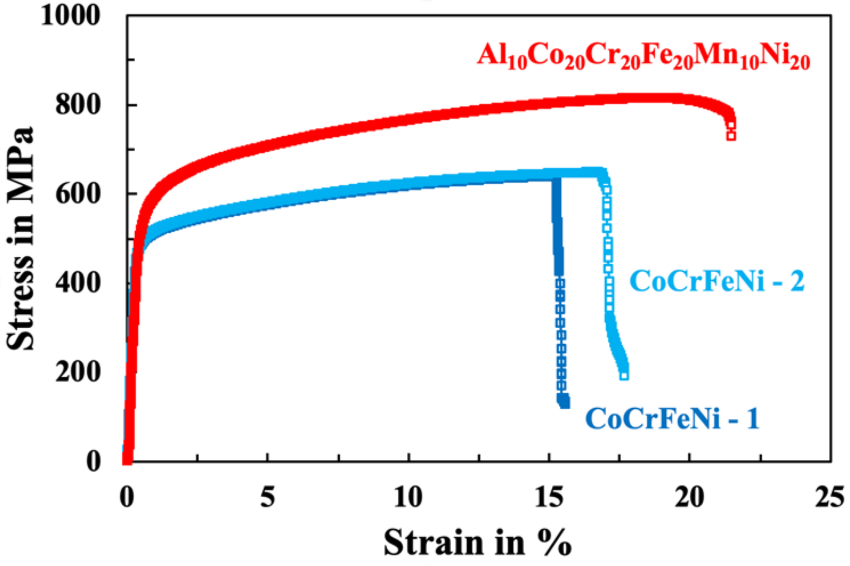
Cannot be completely suppressed by high cooling rates in L-PBF



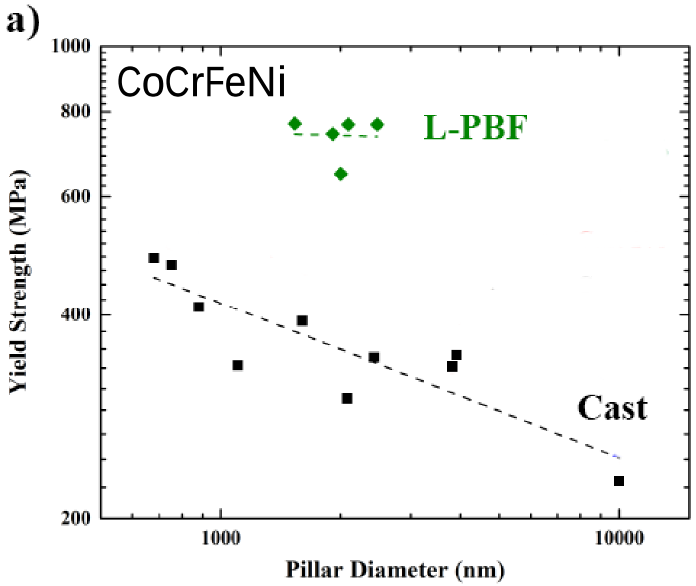
Jung, Peter, Gärtner, Dehm, Uhlenwinkel, Jägle. *Additive Manufacturing* **35**, 101337 (2020).

Results first project phase: Mechanical properties

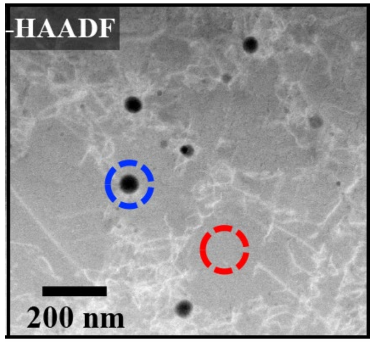




Al-, Mn-addition improves strength (both A1 structure)



L-PBF:
no size effect due to oxides (<100nm)



Cast:
smaller-is-stronger

Second SPP phase: Project MarioCCArt

Title: Mechanical properties and hydrogen tolerance of particle-reinforced CCA produced by additive manufacturing (MarioCCArt)

Strategy: use established process routes to investigate p-CCA as material for the hydrogen economy

V. Uhlenwinkel
(2 yrs funding)

IWT
Leibniz-Institut für Werkstofforientierte Technologien

E. A. Jägle
(2 yrs funding)

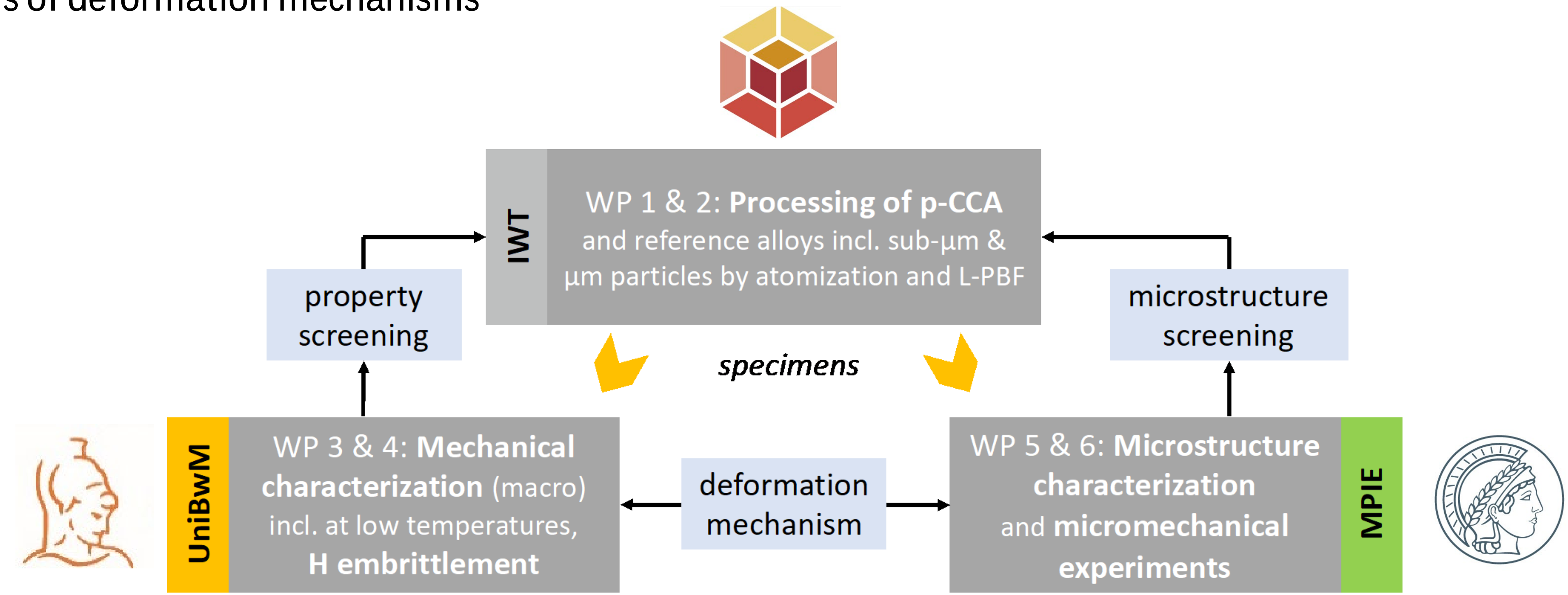
der Bundeswehr Universität München

G. Dehm
(2 yrs funding)

MAX-PLANCK-INSTITUT FÜR EISENFORSCHUNG GmbH

MarioCCArt approach

- Keep focus on particle-reinforced CCA. Goal: high strength at RT, high ductility at low T
- No variation of base alloys: only $Co_{25}Cr_{25}Fe_{25}Ni_{25}$ (A1, med. entropy) and $Al_{10}Co_{20}Cr_{20}Fe_{20}Mn_{10}Ni_{20}$ (A1, high entropy)
- Instead, add particles *ex-situ* by nano- and micro-particle addition before L-PBF and *in-situ* by reaction during L-PBF
- Focus on promising mechanical properties of p-CCA: low-temperature strength & ductility and H-tolerance
- Determination of mechanical properties beyond simple tensile tests (fracture and fatigue) and high-resolution analysis of deformation mechanisms



MarioCCArt hypotheses

Focus topics:

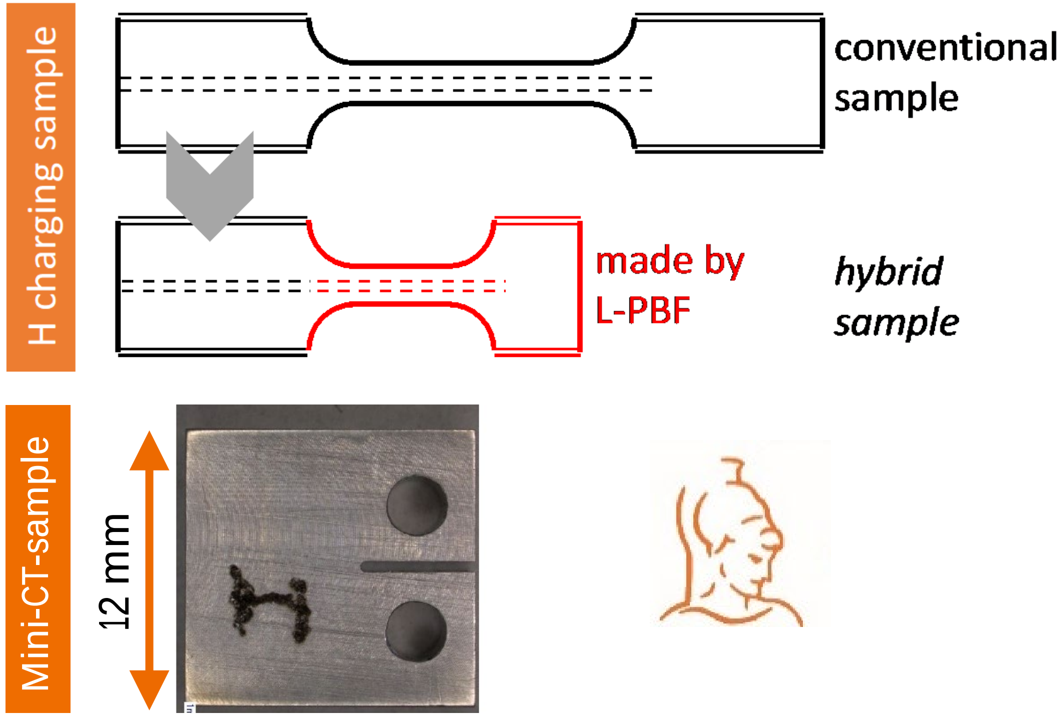
1. p-CCA synthesis	-> see next presentation
2. Mechanical properties	• Nano-particles increase strength at RT and low T, do not deteriorate fracture toughness and fatigue resistance • Mico-particles have a negative effect on fracture and fatigue
3. Hydrogen tolerance	• Stability of the matrix towards TRIP deformation determines H-embrittlement resistance • Particles do not negatively impact H tolerance
4. Deformation mechanisms	• At low T, deformation mechanism changes from DL-based deformation to twinning

Mechanical testing

Macroscopic:

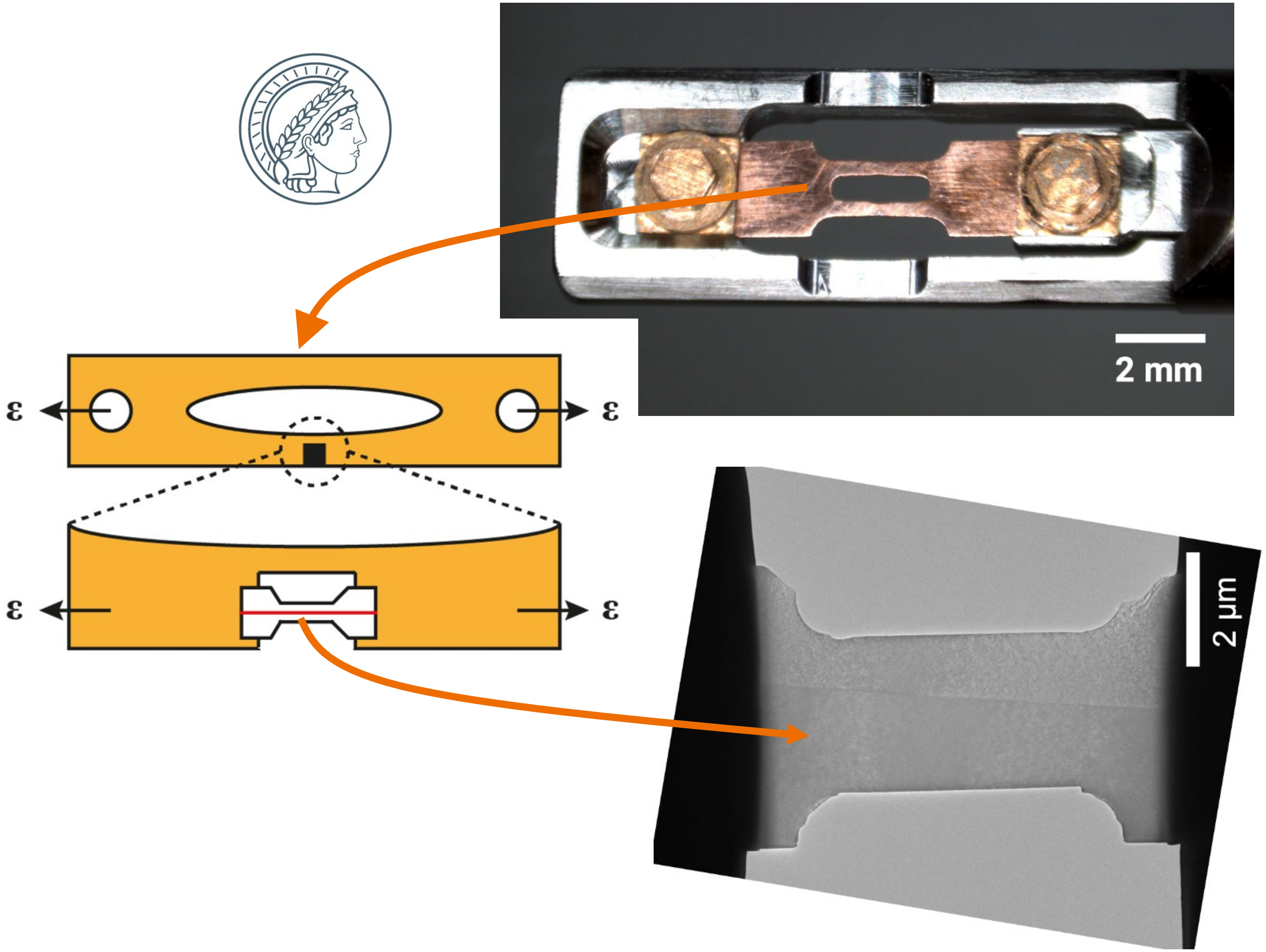
The limited available powder quantities require

- scaled-down specimens
- hybrid conventional/L-PBF specimens



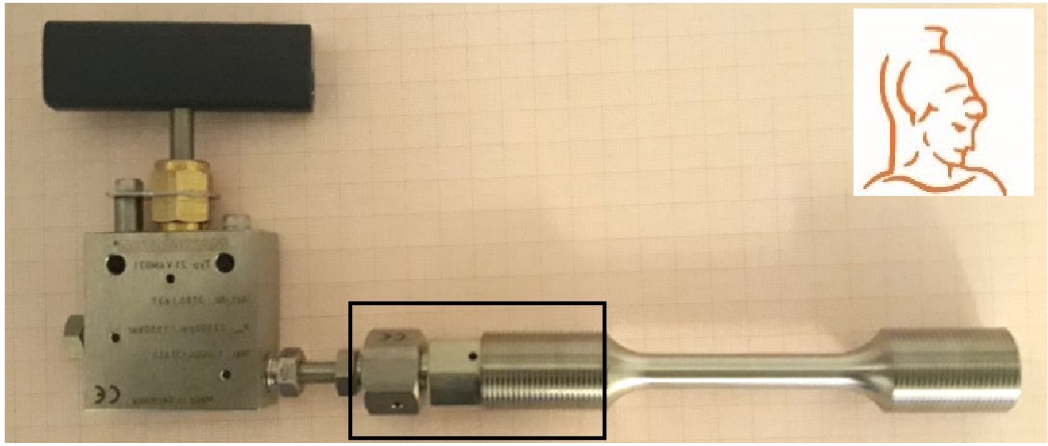
Microscopic:

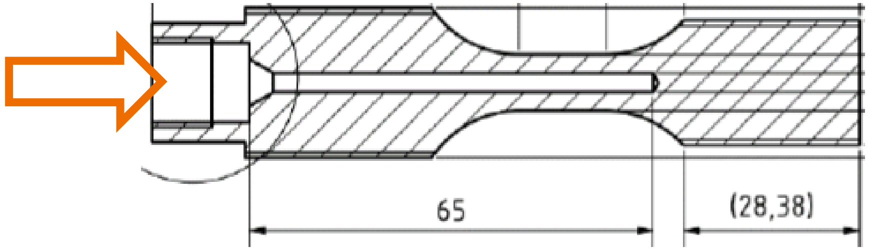
In-situ tension in the TEM



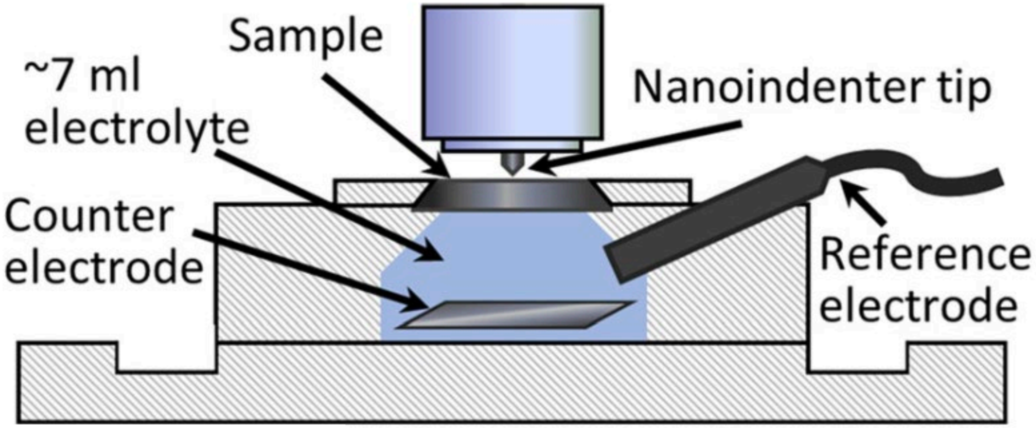
Hydrogen embrittlement studies

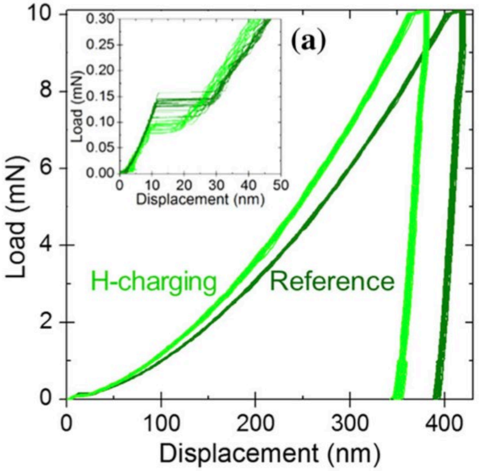
Macroscopic:
gaseous charging of hollow specimens





Microscopic:
electrochemical charging of thin specimens





Duarte, Dehm et al.:
J Mater Sci (2021) **56,** 8732

Conclusions

- **Synthesis of particle-reinforced CCA**
  by process route powder atomization –> powder formulation –> additive manufacturing
- **Mechanical characterization of p-CCA at RT and low temperatures**:
  macroscopic (hybrid & scaled-down) and microscopic (TEM in situ tension) specimens
- **Hydrogen tolerance of p-CCA**
  macroscopic testing (gaseous charging, tension and fatigue)
  and microscopic testing (electrochemical charging, nanoindentation)

Thank you for your attention!

Questions?

Contact: Dr. Elena Bernardo Quejido, elena.bernardo@unibw.de

Approach second phase SPP

Focus topics:

1. p-CCA synthesis	-> see next presentation
2. Mechanical properties	• tensile tests, fracture toughness, fatigue resistance • requires scaled-down specimens • RT and down to LH_2-temperatures
3. Hydrogen tolerance	• Macroscopic: Hollow (TT, fatigue) specimens @UniBwM • Microscopic: electrochemical (backside) charging in-situ in nanoindenter @MPIE
4. Deformation mechanisms	• HR chemical analysis by STEM/TEM and APT • In-situ straining in TEM (in-situ cooled)