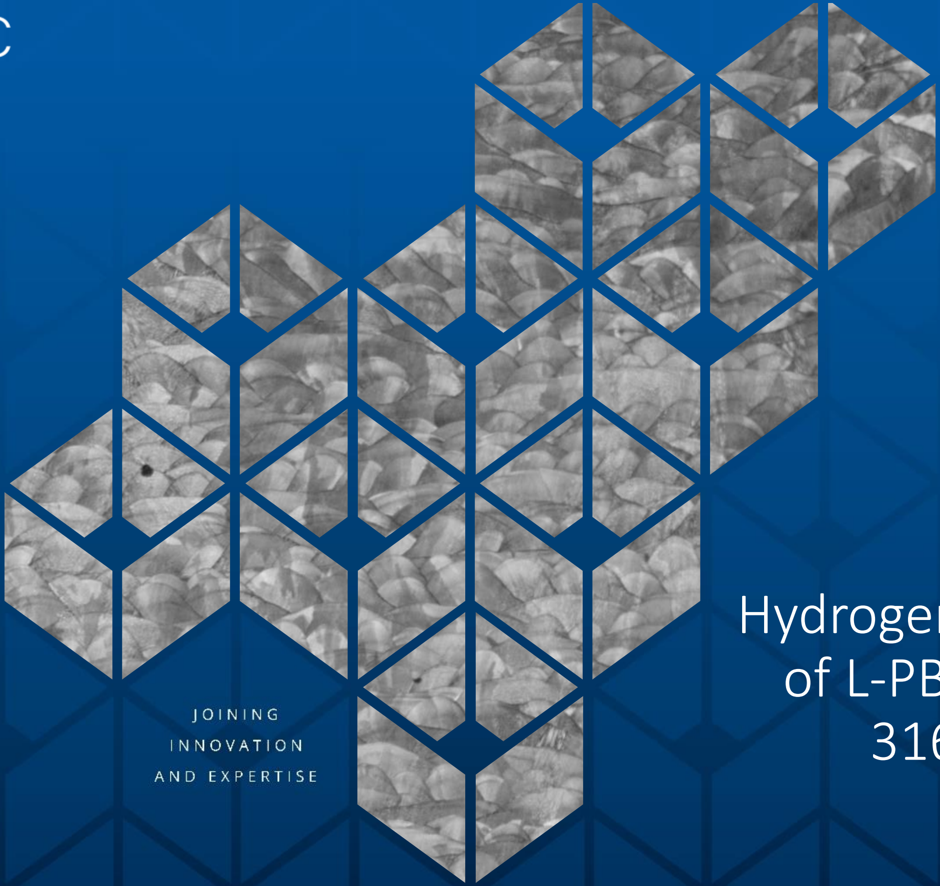


JOINING
INNOVATION
AND EXPERTISE

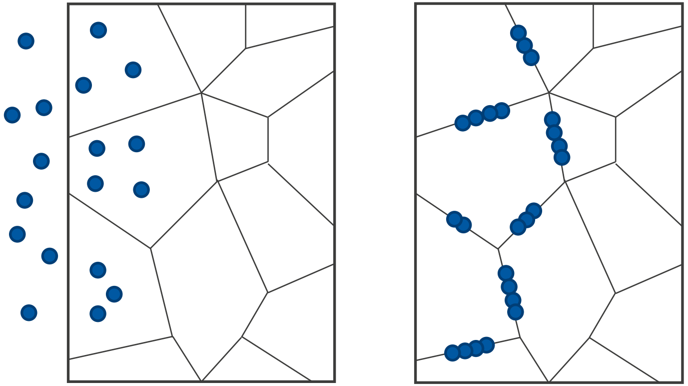
Hydrogen embrittlement of L-PBF manufactured 316L stainless steel

Yixiang Jin
Prof. Pedro Rivera
Dr Briony Holmes

Hydrogen Embrittlement

Liquid hydrogen storage tank
By Tom Fawls, CC BY-SA 3.0 via Wikimedia Commons
https://commons.wikimedia.org/wiki/File:Liquid_hydrogen_storage_tank_at_Launch_Pad_39B.jpg

Hydrogen Induced Cracking
© CEphoto, Uwe Aranas
https://commons.wikimedia.org/wiki/File:Steel-with-Hydrogen-Induced-Cracks-01.jpg

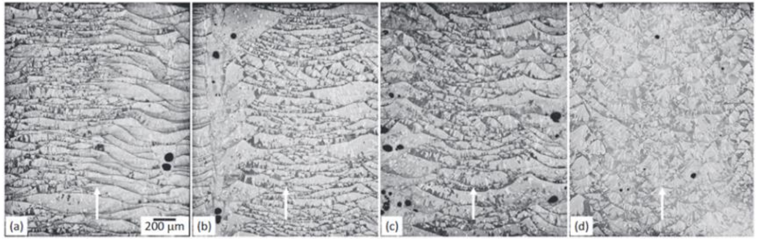


Hydrogen Interaction with metals

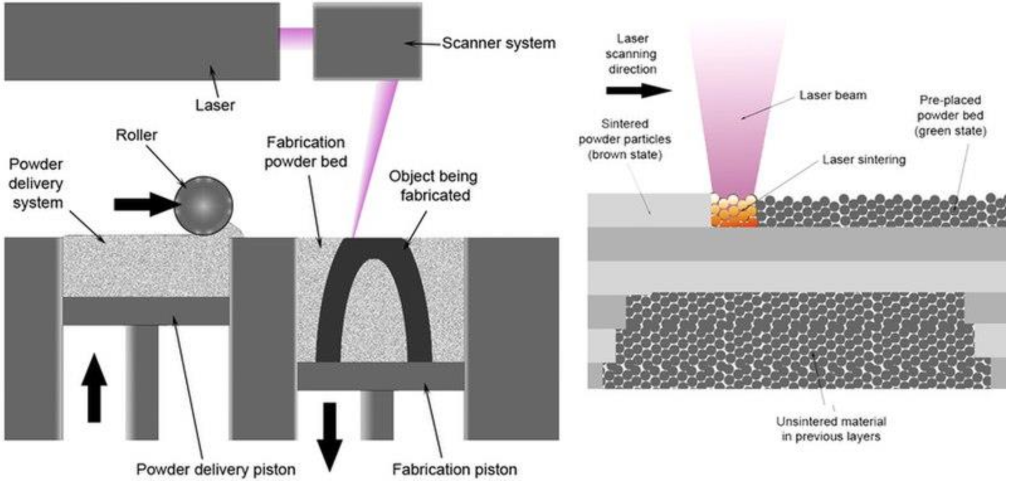
Laser Powder Bed Fusion

L-PBF process. Laser-material interaction

https://www.twi-global.com/media-and-events/insights/a-more-holistic-approach-in-l-pbf-process-optimisation



Light optical micrographs of longitudinal cross sections of as-printed L-PBF 316L SS cylinders.
H. Choo et al. (2019), licensed by CC BY 4.0
https://doi.org/10.1016/j.matdes.2018.12.006



Laser powder bed fusion process.
Materialgeeza, CC BY-SA 3.0, via Wikimedia Commons
https://commons.wikimedia.org/wiki/File:Selective_laser_melting_system_schematic.jpg

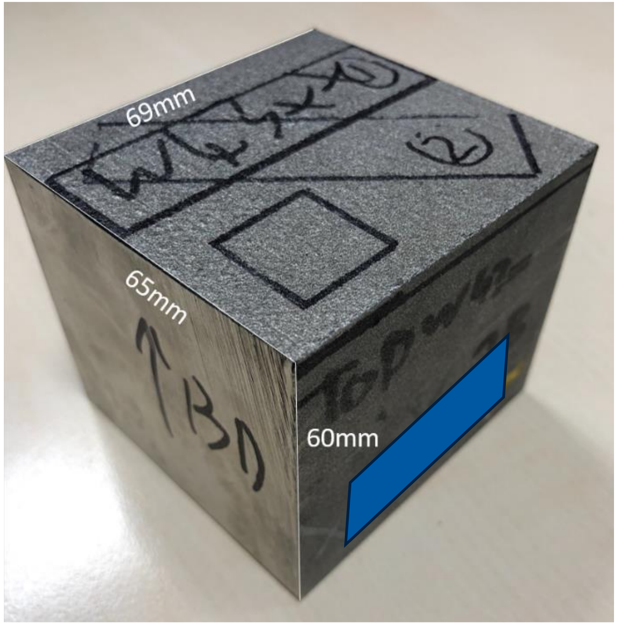
Sample and Specimen

Composition

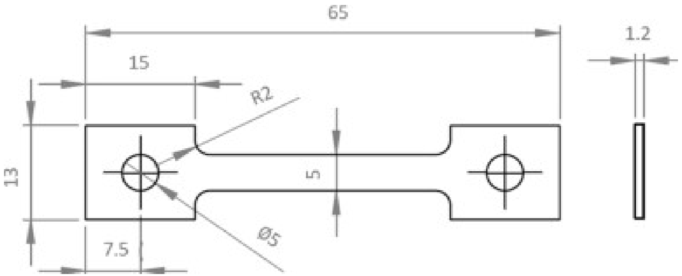
	Elements (wt%)									
	C	Cr	Mn	Mo	Ni	P	S	Si	N	O
W43	0.02	17.6	0.57	2.3	12.9	0.011	0.009	0.73	0.086	0.024
Wrought	0.065	16.35	1.72	2.15	10.11	<0.005	0.003	0.53	0.0052	0.0016

Process parameters

Scanning speed	Hatch space	Laser power	Layer thickness	Laser spot size	Energy density	Normalised enthalpy	Heat treatment
mm/s	mm	W	mm	µm	J/mm³		
1037	0.09	280	0.04	100	75.0	2.92	As Built



Sample Block, Specimen extracted from blue box



Test Specimen, dimensions in mm

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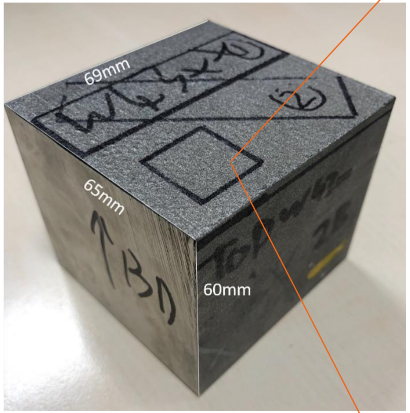
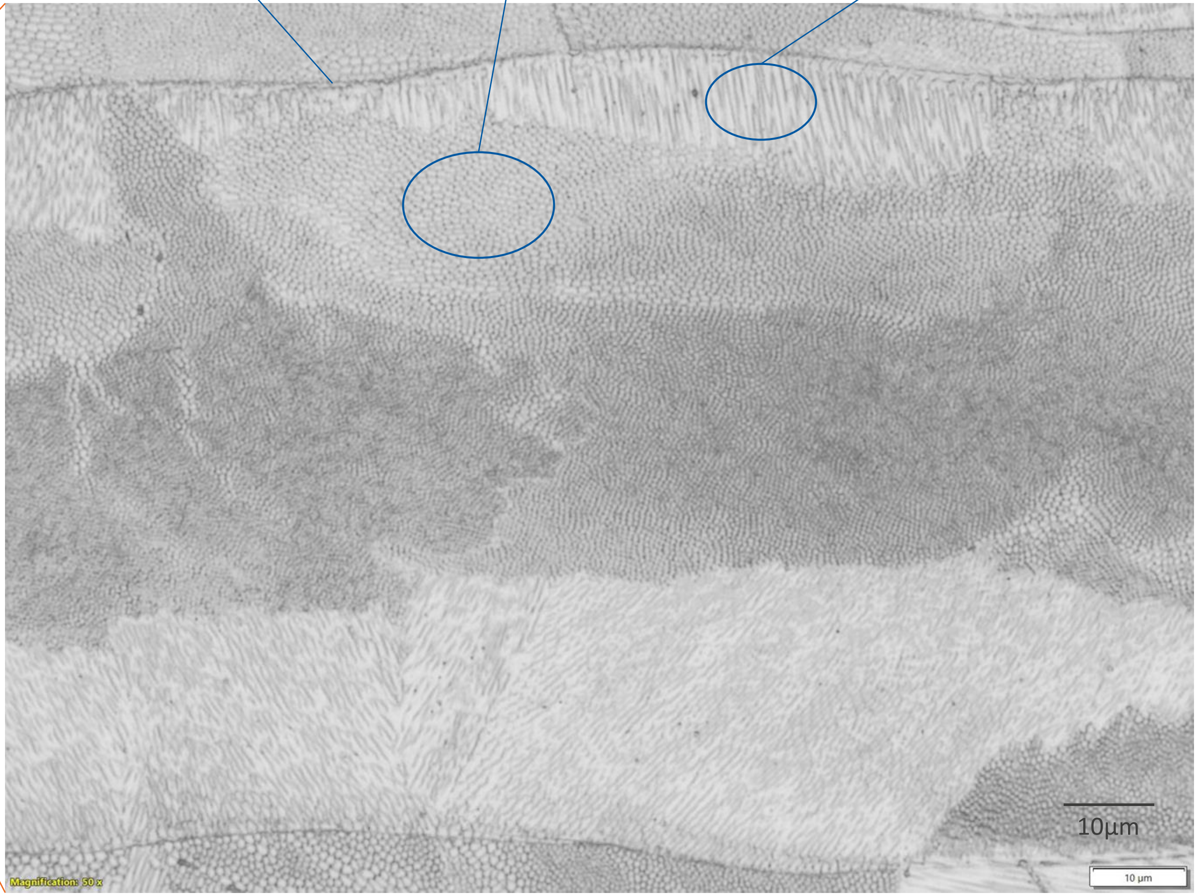
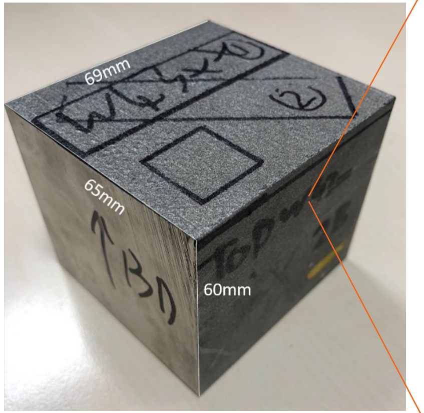
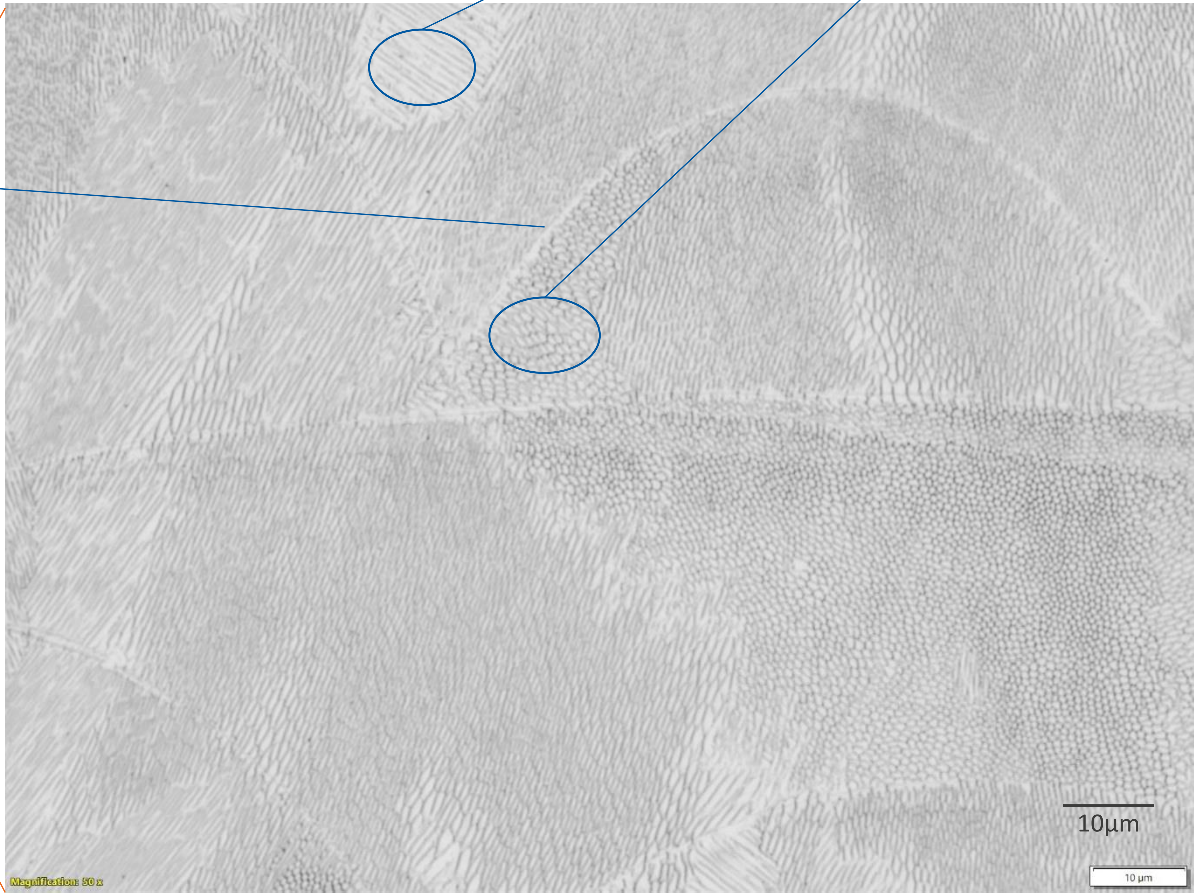
Sample and Specimen





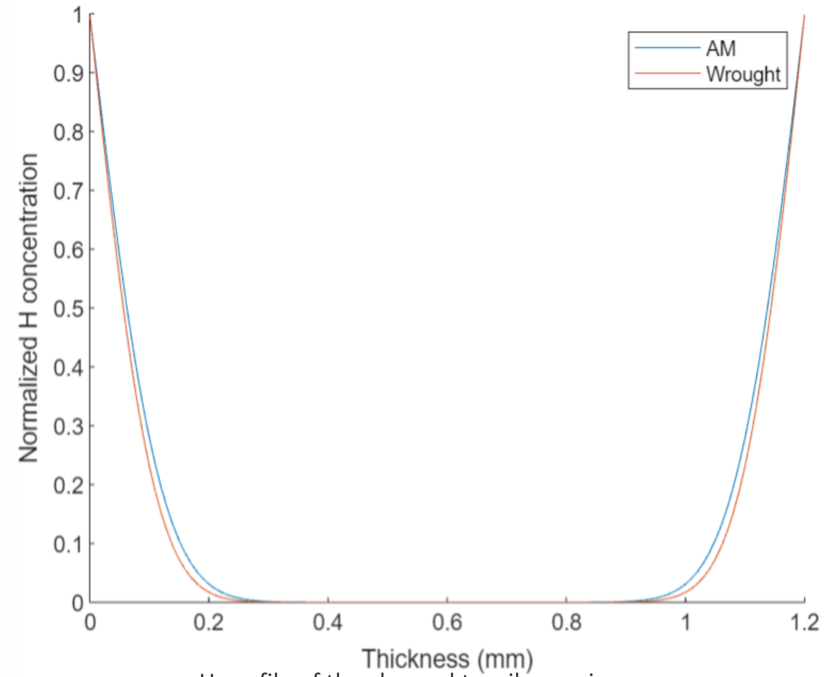
Sample and Specimen





Hydrogen Charging Conditions for Tensile Specimens

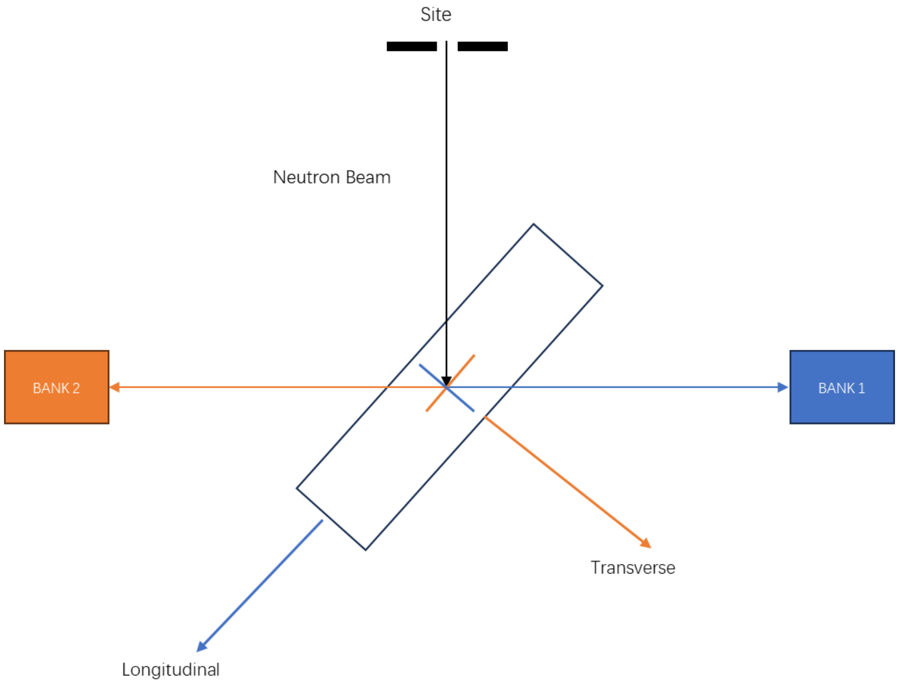
- Temperature: 80 °C
- Reference electrode: Calomel
- Counter electrode: Pt
- Solution: 3.5 wt% NaCl
- Potential (V.S. RE): -1050 mV
- Charging time: 10 days



H profile of the charged tensile specimen

Slow Strain Rate Tensile Test with In-situ Neutron Diffraction

ISIS EngX

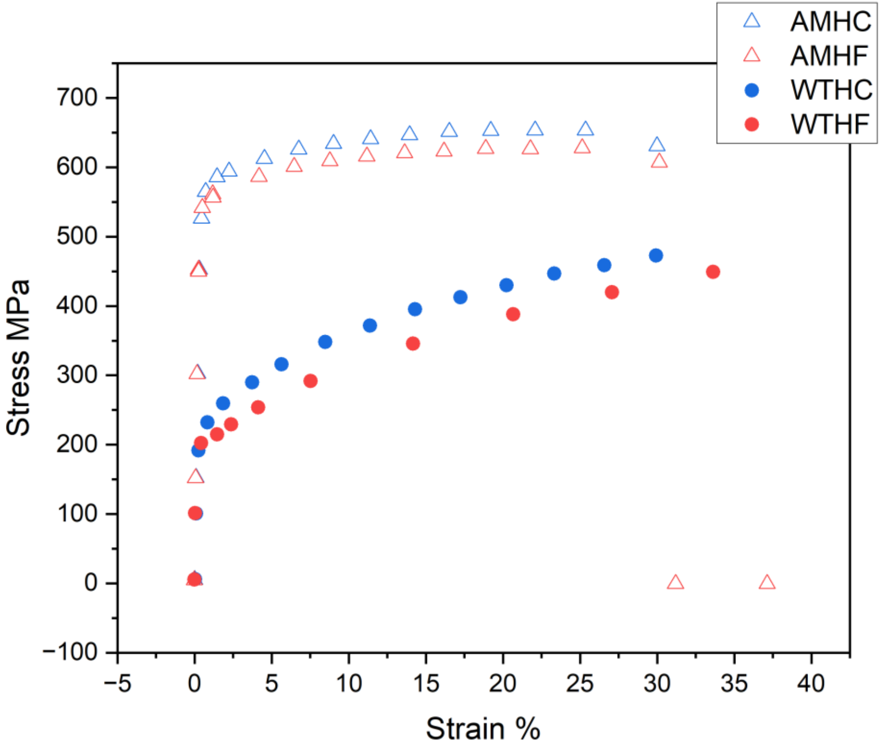


Neutron diffraction experiment set up

Specimen has to be static to take neutron diffraction measurement.

Tensile Test

- Strain rate: 8*10^-5 s^{-2}
- Stress data from static sampling points of neutron diffraction
- Both AM specimens failed at 30% elongation
- Wrought specimens were not tested to failure



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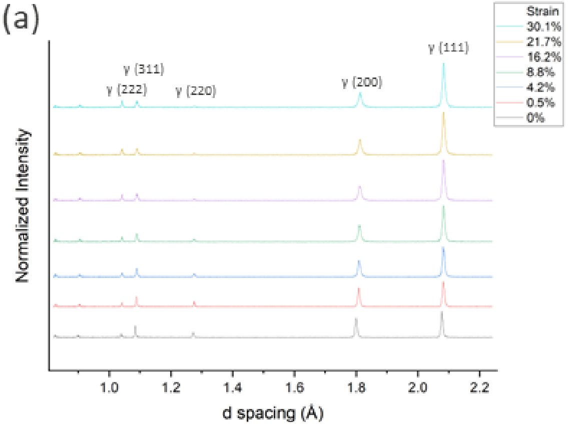
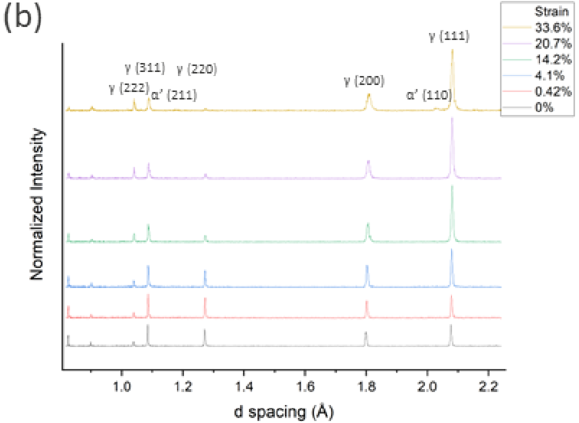
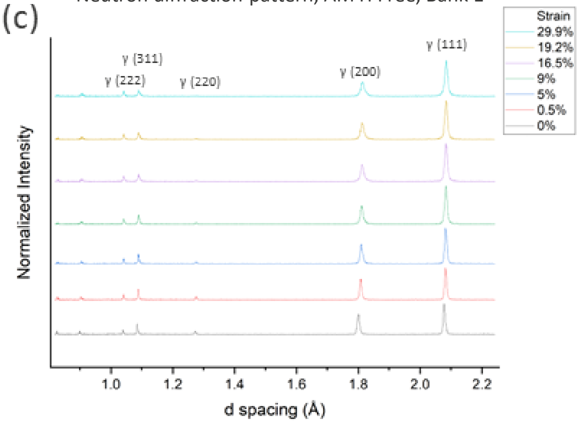
Diffraction Pattern
Bank 1
Longitudinal Direction



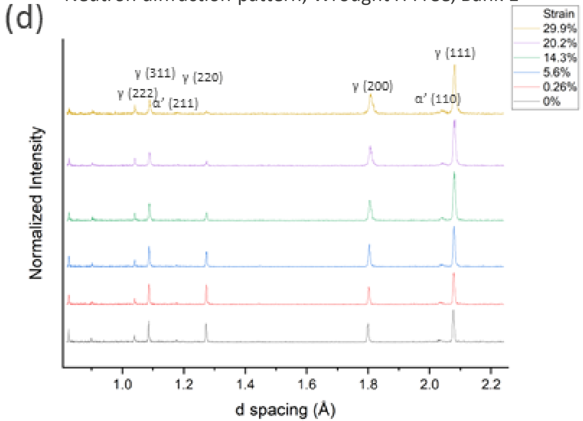
Neutron diffraction pattern, AM H Free, Bank 1



Neutron diffraction pattern, Wrought H Free, Bank 1



Neutron diffraction pattern, AM H Charged, Bank 1



Neutron diffraction pattern, Wrought H Charged, Bank 1

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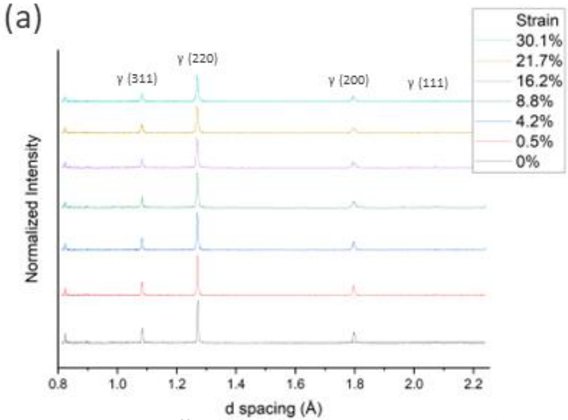
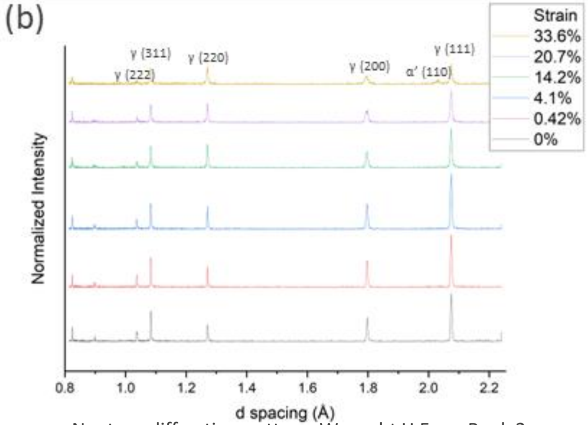
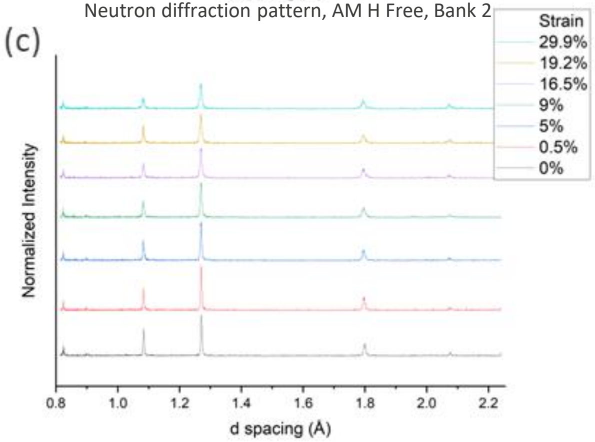
Diffraction Pattern
Bank 2
Transverse Direction



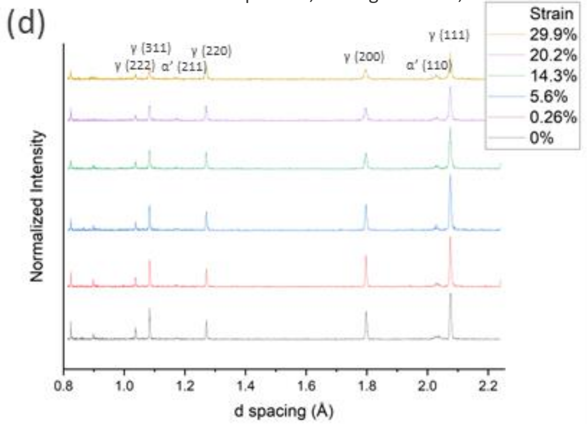
Neutron diffraction pattern, AM H Free, Bank 2



Neutron diffraction pattern, Wrought H Free, Bank 2



Neutron diffraction pattern, AM H Charged, Bank 2



Neutron diffraction pattern, Wrought H Charged, Bank 2

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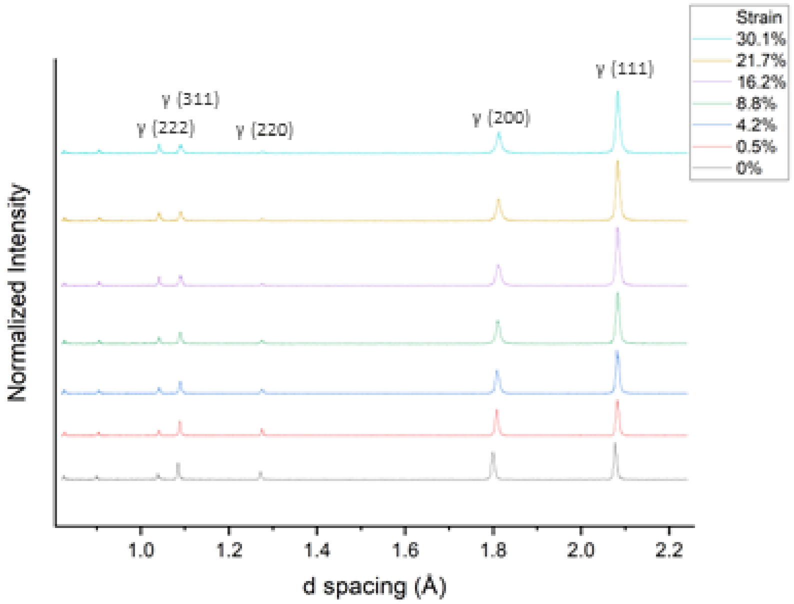
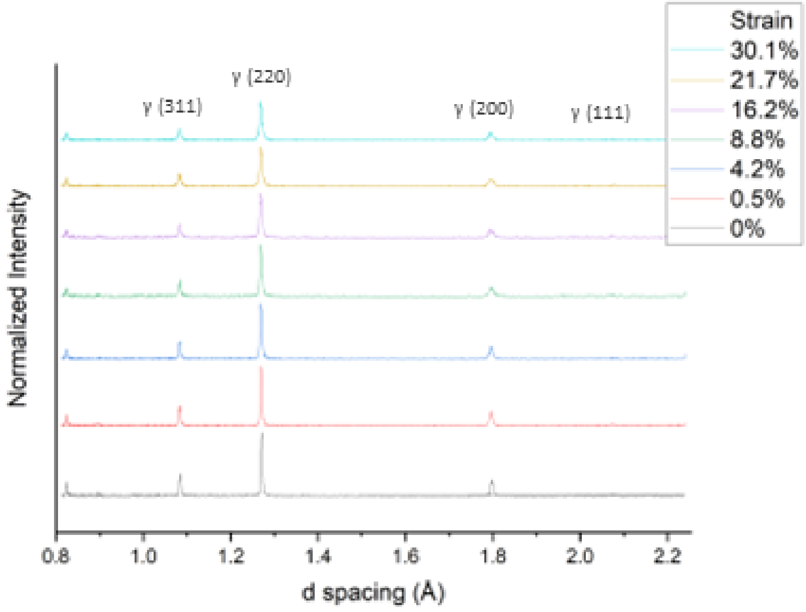
Diffraction Pattern



Neutron diffraction pattern, AM H Free, Bank 1



Neutron diffraction pattern, AM H Free, Bank 2

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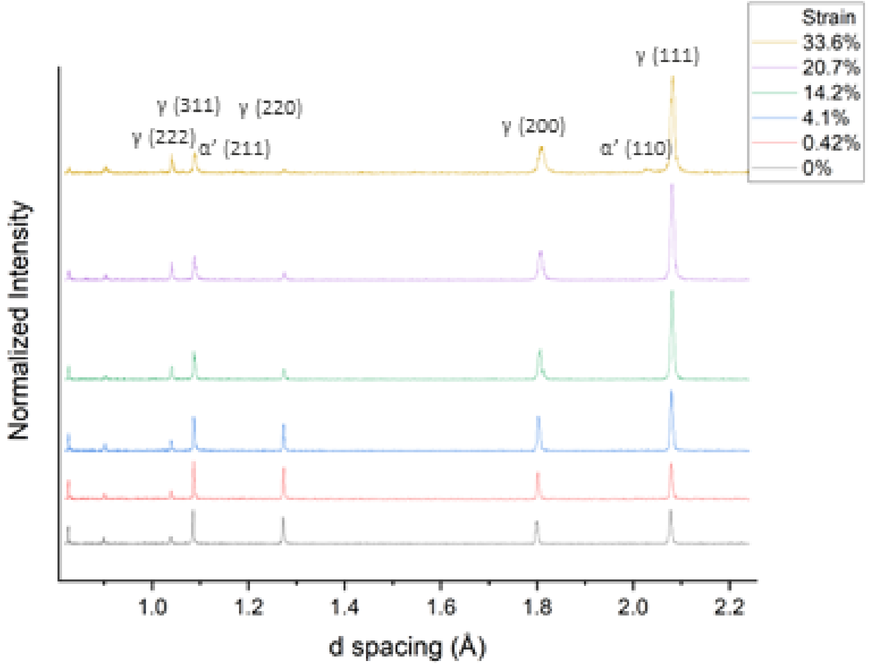
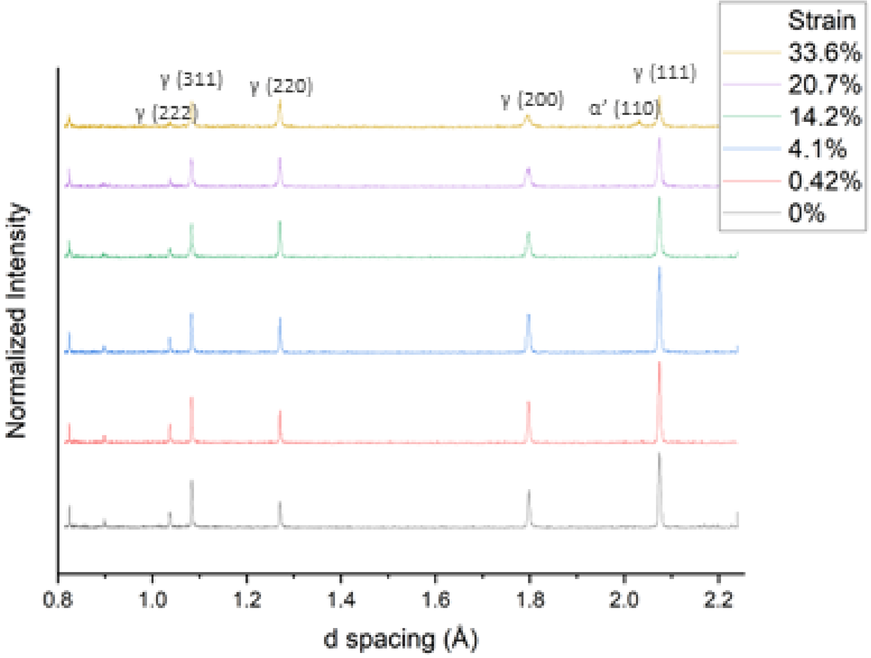
Diffraction Pattern

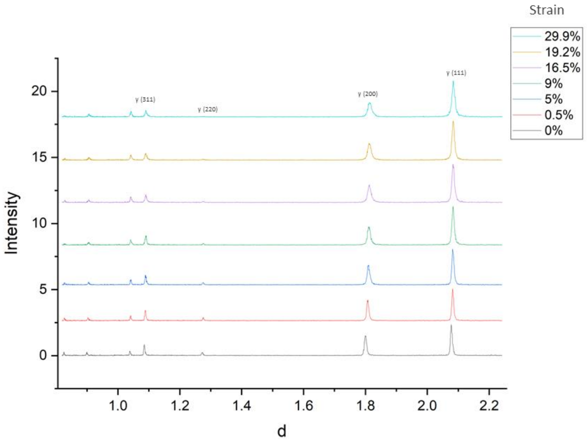


Neutron diffraction pattern, Wrought H Free, Bank 1

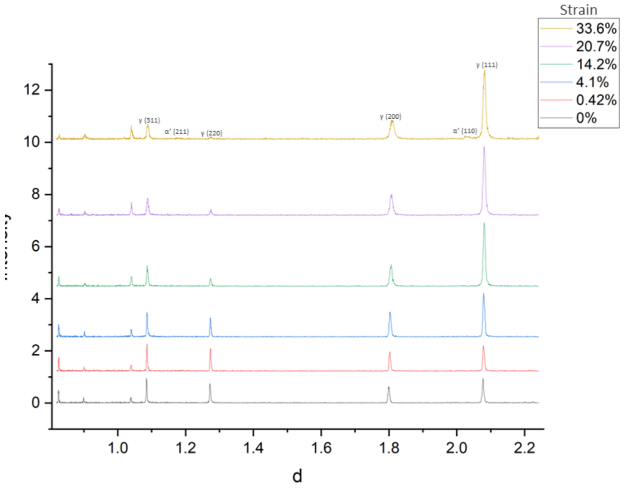


Neutron diffraction pattern, Wrought H Free, Bank 2

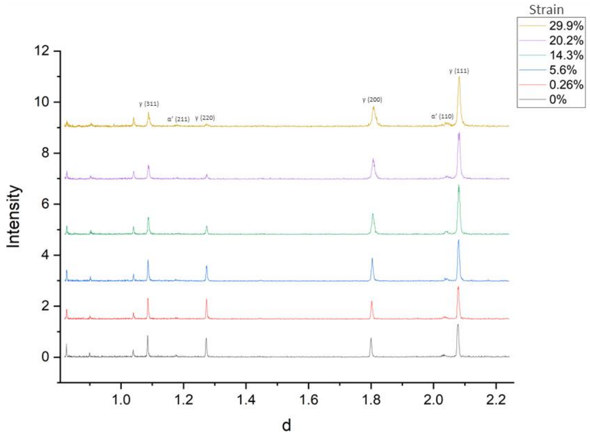
Diffraction Pattern



Neutron diffraction pattern, AM H Charged, Bank 1



Neutron diffraction pattern, Wrought H Free, Bank 1

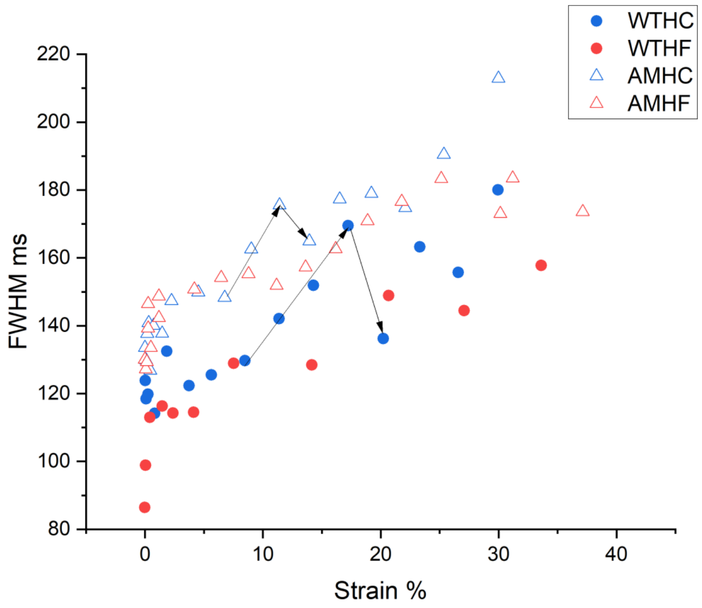


Neutron diffraction pattern, Wrought H Charged, Bank 1

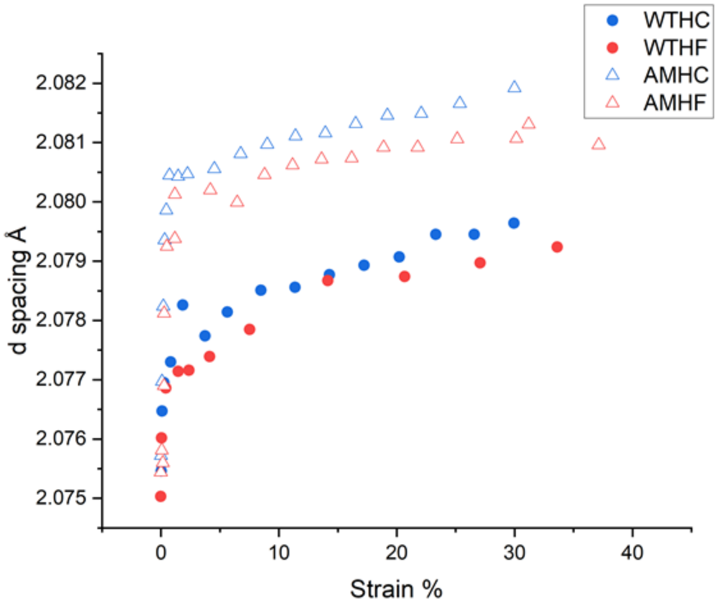
Diffraction Pattern

- AM specimens showed strong texture;
- Inhibition of formation of strain induced martensite (SIM) observed in AM specimens;
- Promotion of formation of SIM observed in H charged wrought specimens.

Diffraction Pattern

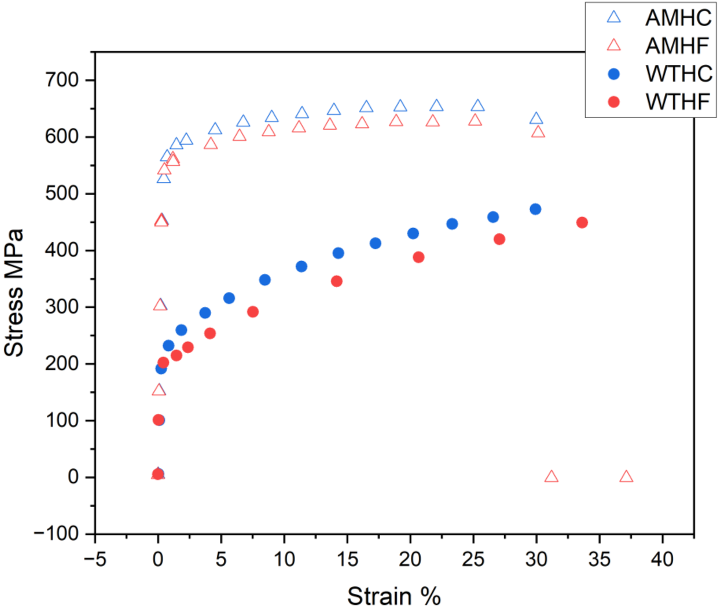


111 plane, FWHM vs strain

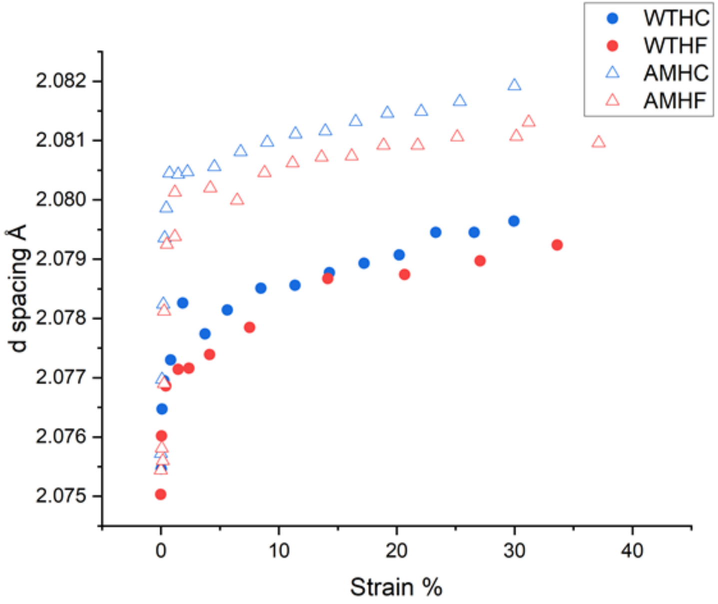


111 plane, d spacing vs strain

Diffraction Pattern

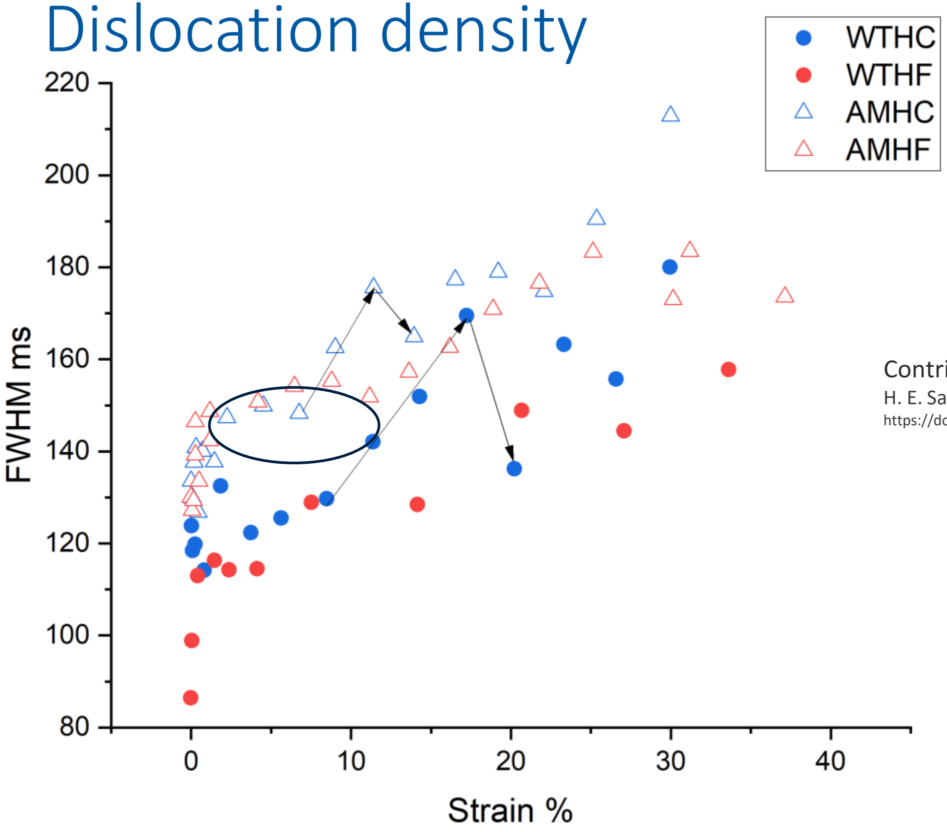


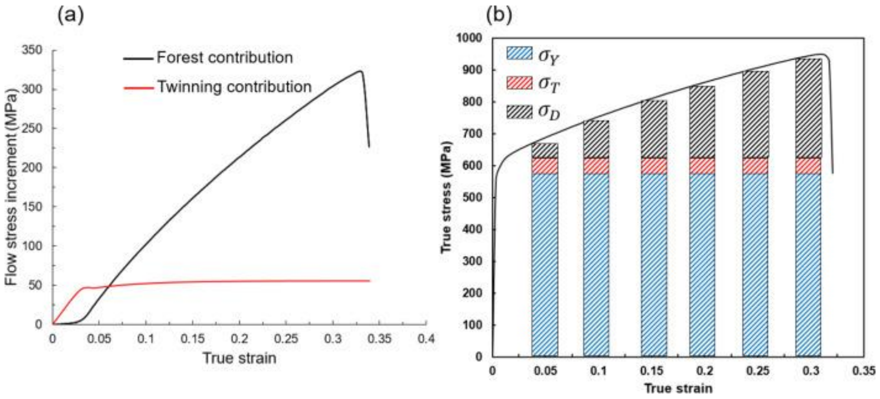
Stress-strain curve



111 plane, d spacing vs strain

Dislocation density

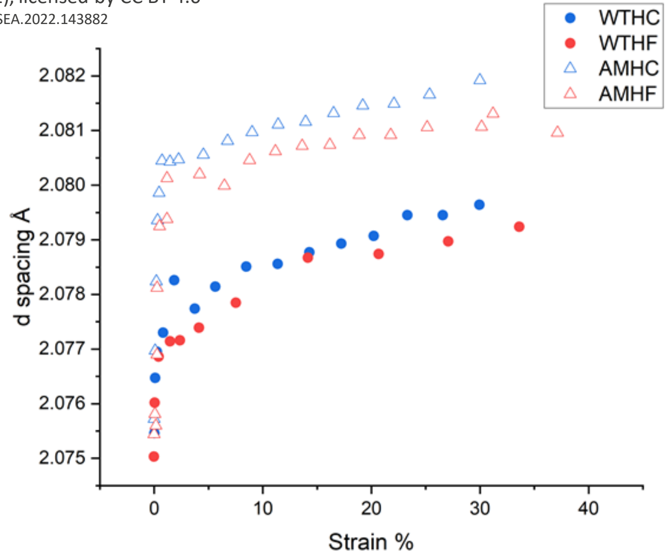




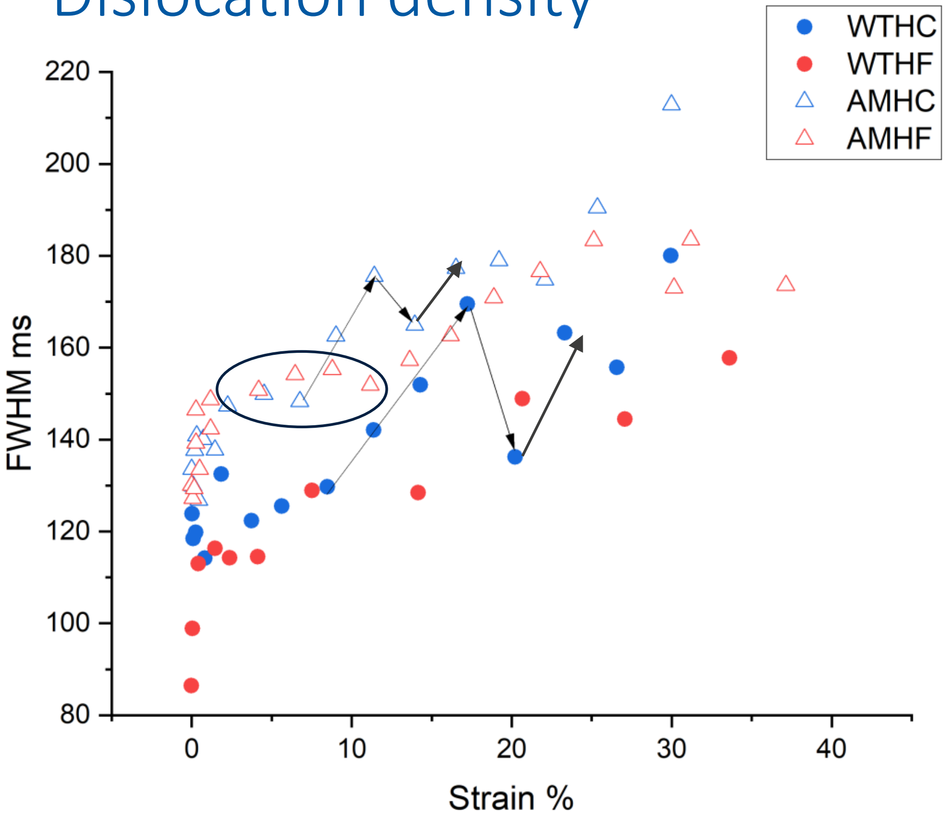
Contribution of dislocation and twinning in strained L-PBFed 316L

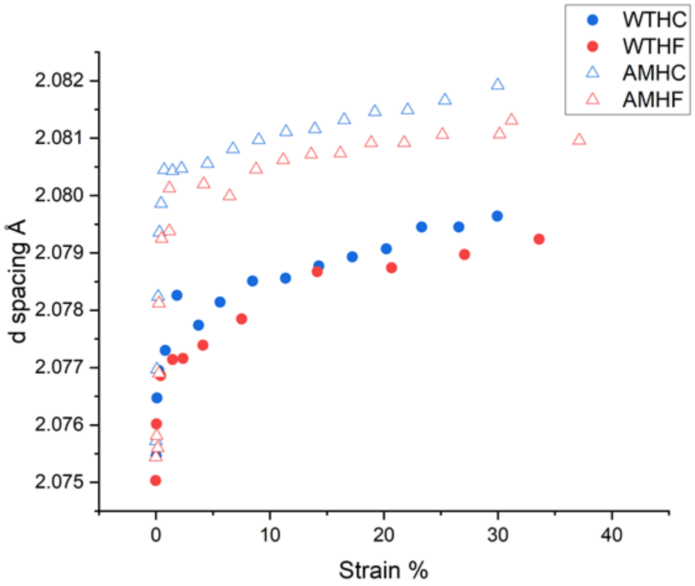
H. E. Sabzi et al. (2022), licensed by CC BY 4.0

https://doi.org/10.1016/J.MSEA.2022.143882



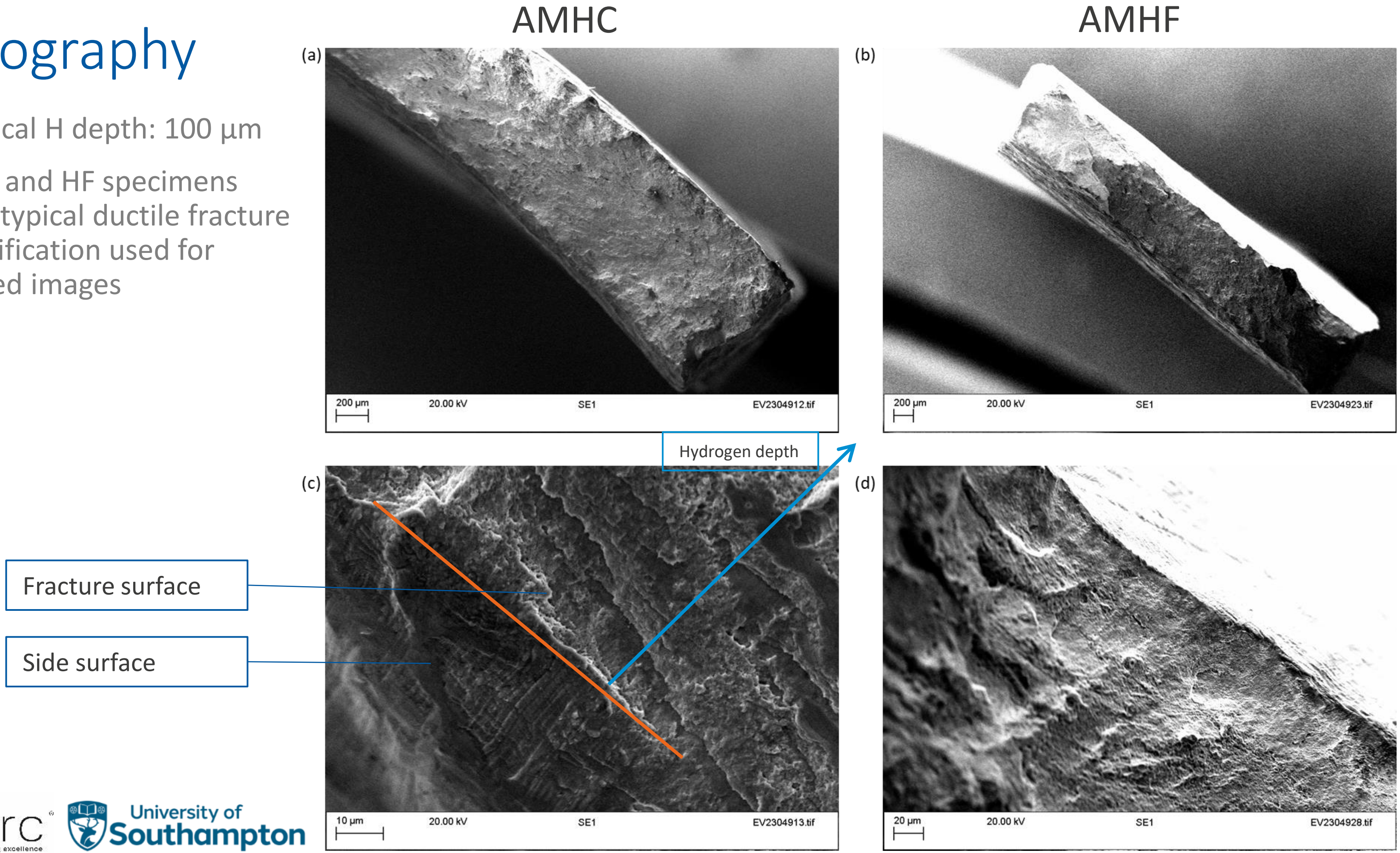
Dislocation density





Fractography

- Theoretical H depth: 100 µm
- Both HC and HF specimens showed typical ductile fracture at magnification used for presented images



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Preliminary Conclusions

- Inhibition of formation of strain induced martensite (SIM) observed in AM specimens;
- Promotion of formation of SIM observed in H charged wrought specimens;
- Dislocation activation during deformation in AM materials was delayed;
- Faster dislocation multiplication observed in H charged specimens;
- No obvious hydrogen embrittlement in AM specimens was observed.

Future work

- Tensile test with lower strain rate;
- Hydrogen trapping and diffusion analysis with thermal desorption spectroscopy;
- Modelling of hydrogen migration with dislocations, and accumulation of hydrogen at sub grain walls.

Acknowledgements

- This project is sponsored by Lloyd's Register Foundation and carried out in NSIRC.