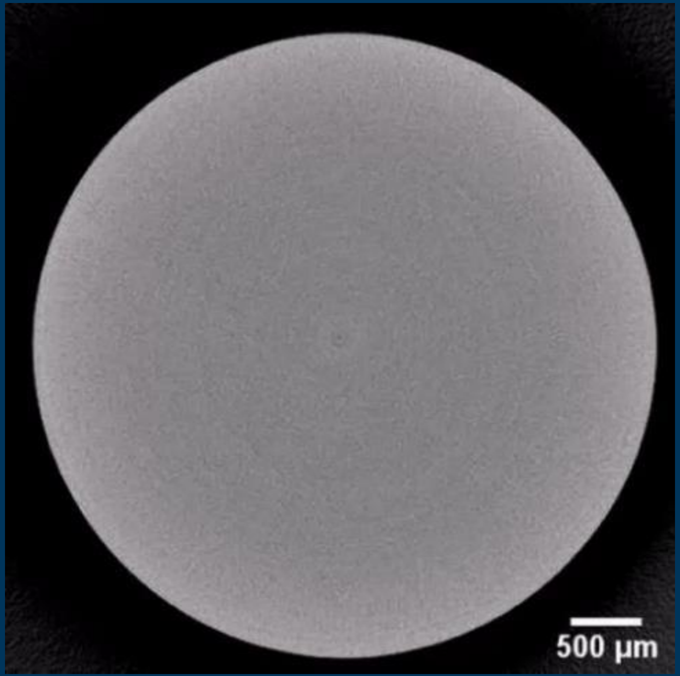
Virtual Seminar Series – Tuesday 2, 9, 16 November



Cyclic Deformation and Fatigue Behaviour of Titanium Ti-6Al-4V additively manufactured by w-DED

Presented by Mr. Rob Plaskitt, *Prenscia (HBK)*
Dr. Abdul Khadar Syed, *Coventry University*

Tuesday, November 9, 2021

Cyclic Deformation and Fatigue Behaviour of Titanium Ti-6Al-4V additively manufactured by w-DED

Abstract

This joint presentation describes the fatigue initiation and microstructure research for the high strength titanium alloy Ti-6Al-4V material additively manufactured by w-DED for the NEWAM research programme. This includes the material behaviour and properties in fully reversed low cycle fatigue (LCF) and high cycle fatigue (HCF) regimes in as-deposited condition. X-ray computed tomography was used to detect defects in the test samples. A detailed microstructure and fractography was performed to understand the role of microstructure on crack initiation and fracture. The following findings are presented with respect to the characteristics of the microstructure:

- Wider columnar primary β grains consisting α+β in Widmanstätten and colony morphology.
- Cyclic stress-strain curves obtained from fatigue hysteresis loops show typical cyclic softening. Horizontal build orientation samples, with the loading axis perpendicular to the columnar β grains, showed higher material performance. This finding aligns with static tensile test data where horizontal samples showed higher yield and tensile strengths.
- In the LCF region (<104 cycles), vertical build orientation samples, loaded along the columnar β grains, is superior. This is considered to be linked to the microstructure along the grain boundary α.
- In the HCF region (>104 cycles), vertical and horizontal build orientation sample performance is similar, though with considerable scatter in the data.

Cyclic Deformation and Fatigue Behaviour of Titanium Ti-6Al-4V additively manufactured by w-DED

About the presenter, Mr. Rob Plaskitt, Prenscia (HBK)

Rob Plaskitt is an application engineer for Prenscia with a degree in Mechanical Engineering (Loughborough) and a masters in Structural Integrity (Sheffield). He has over 30 years of experience working as an engineer at Prenscia (formerly nCode) in areas of automotive, aerospace, defence and power generation. He has applied nCode software and technology in these industries from CAE concept design through full-scale testing, fleet monitoring, structural durability and vibration qualification.

Prenscia became involved in additive manufacturing in 2017 after testing some material and discovering that its fatigue performance was different to similar and previously tested wrought material. Since then, Prenscia have become involved in commercial AM material fatigue testing, and Rob has supported their research programmes for electron beam and laser beam powder bed fusion, and wire-arc directed energy deposition - the subject of this presentation.

About the presenter, Dr. Abdul Khadar Syed, Coventry University

Abdul Khadar Syed obtained his MSc in Advanced Materials Science and Engineering (Erasmus Mundus joint master’s degree) from Luleå University of Technology, Sweden and Universität des Saarlandes, Germany between 2006-2008. He received the PhD in 2014 from The Open University, UK. During the Ph.D, he investigated the application of bonded crack retarders for life enhancements and improving airframe structural integrity and damage tolerance of the critical aircraft structures. In November-2014, he joined Faculty of Engineering and Environment and Computing at Coventry University as a Research Fellow. He has been promoted to Assistant Professor in Aug-2019.

Currently his research centres around structural integrity and damage tolerance assessment of additive manufactured high strength alloys and to provide a fundamental understanding on the relation between additive manufacturing process-microstructure-mechanical properties relation under static and cyclic loading conditions. Alongside, he is also an active user of neutron and synchrotron X-ray diffraction facilities in UK and across Europe to understand the residual stress and damage development in metallic materials and components under in-service conditions.

Fatigue Behaviour of Titanium Ti-6Al-4V additively manufactured by wire-DED

Presenter: Rob Plaskitt

Agenda

1. Defects and CT Scan
2. Walls ➔ Blanks ➔ Specimens
3. Fatigue Testing
4. Reporting and Characterisation
5. Comparison with Wrought
6. ➔ the role of microstructure

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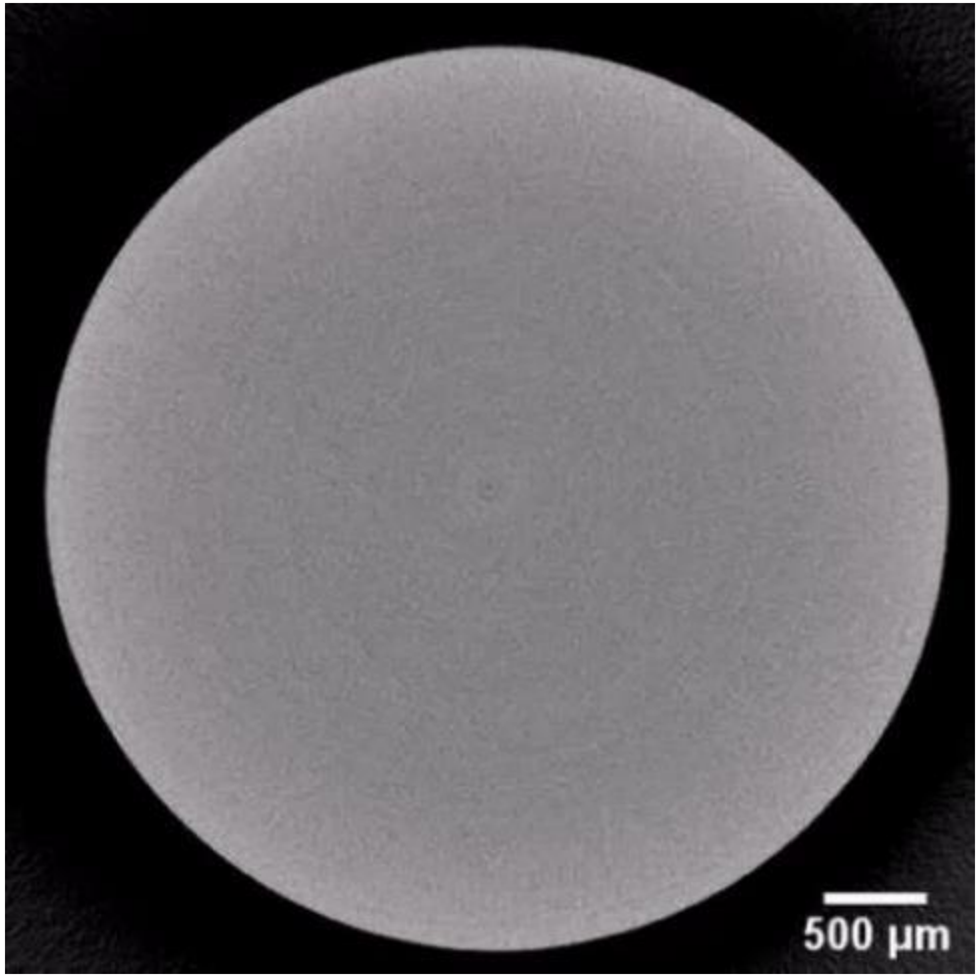
Defects and CT Scan

- Prenscia within HBK – a Spectris plc company

- Malvern Panalytical – a Spectris plc company
  - Manufacture and supply laboratory equipment for materials characterisation.

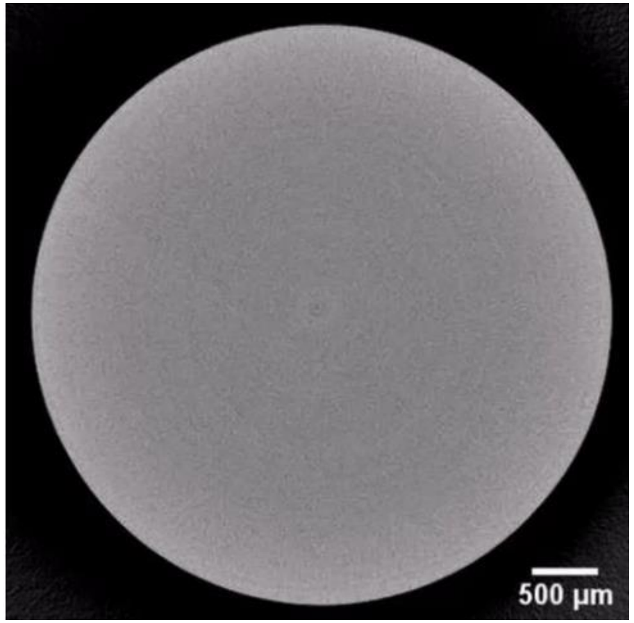
- CT scan at Empa
  - (Swiss Federal Laboratories for Materials Science and Technology)
  - RX Solutions Easy Tom XL system.

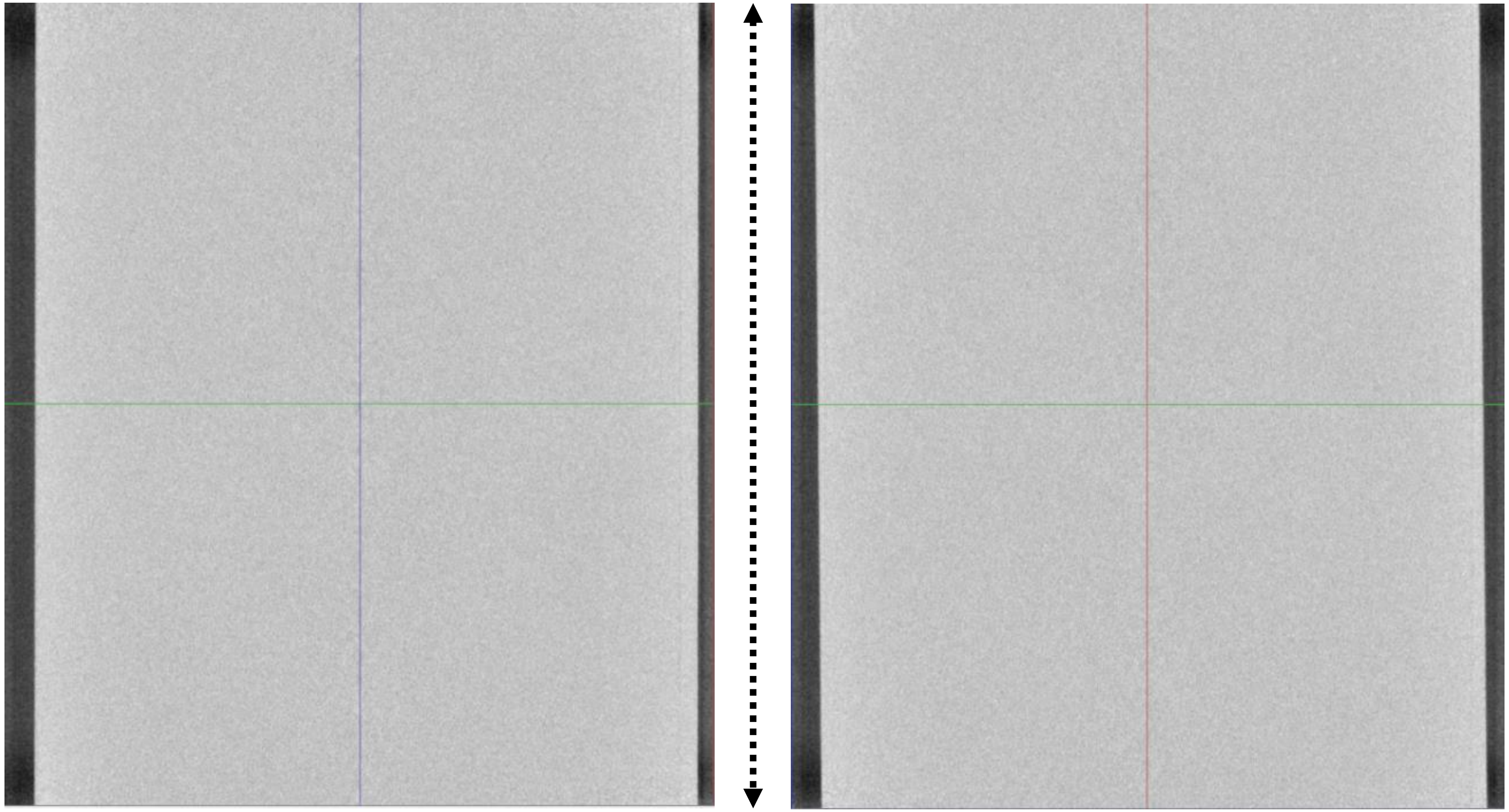
- Cone beam CT of the central 6mm in the gauge length (voxel size 3.7um):
  - ***“Sample looks very homogeneous no signs of cracks or porosity above the resolution limit (~7.4um)”***



Defects and CT Scan

- **"… very homogeneous no signs of cracks or porosity above the resolution limit (~7.4um)"**
- 6 mm orthogonal slice

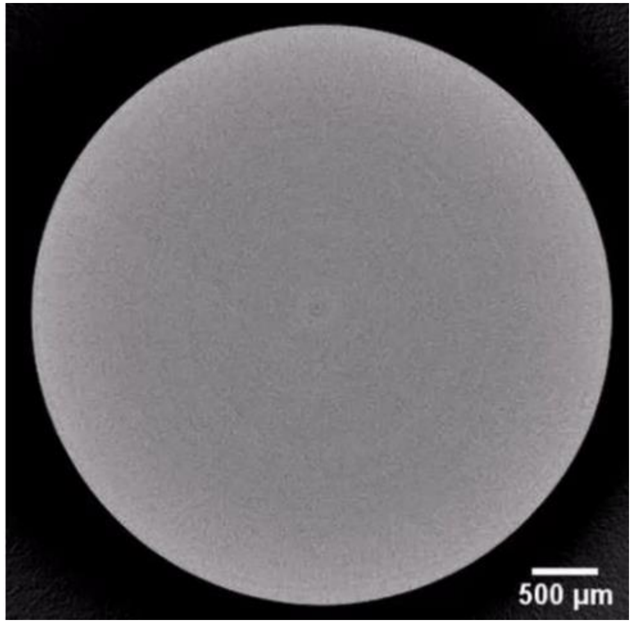




6 mm

Defects and CT Scan

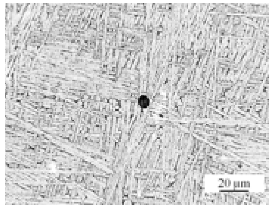
- "… very homogeneous no signs of cracks or porosity above the resolution limit (~7.4um)"**
- recalling Zhang: "S-N Behaviour (fatigue crack initiation) - Effect of defects and microstructure"



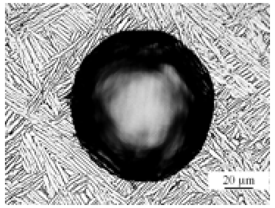
Critical pore size

In another batch of samples,

- Larger pores were purposely embedded using contaminated wires (dia.100-200 µm; vol. fraction 0.04% = fully dense)
- Critical pore diameter ~ 100 µm
- Spherical pores:
  Stress concentration factor = 2.1
  Fatigue strength reduction factor ~ 2



Inherent pore < 100 µm



Anomaly pore > 100 µm

Biswal, Zhang, Syed et al. Int J Fatigue, 2019; https://doi.org/10.1016/j.ijfatigue.2019.01.017

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- Columnar primary beta grains did not cause property anisotropy.
- Fatigue strength is comparable with wrought and greater than cast alloys.
- Gas pores (50-70 µm typical) were crack initiation sites.
- Small pores did not reduce fatigue strength (mean value), but cause larger scatters.

Syed, Zhang, Shamir et al. Int J Fatigue, 2021; https://doi.org/10.1016/j.ijfatigue.2021.106268

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WAAM Walls ➔ Cylindrical Blanks ➔ Machined Specimens

Wall 1

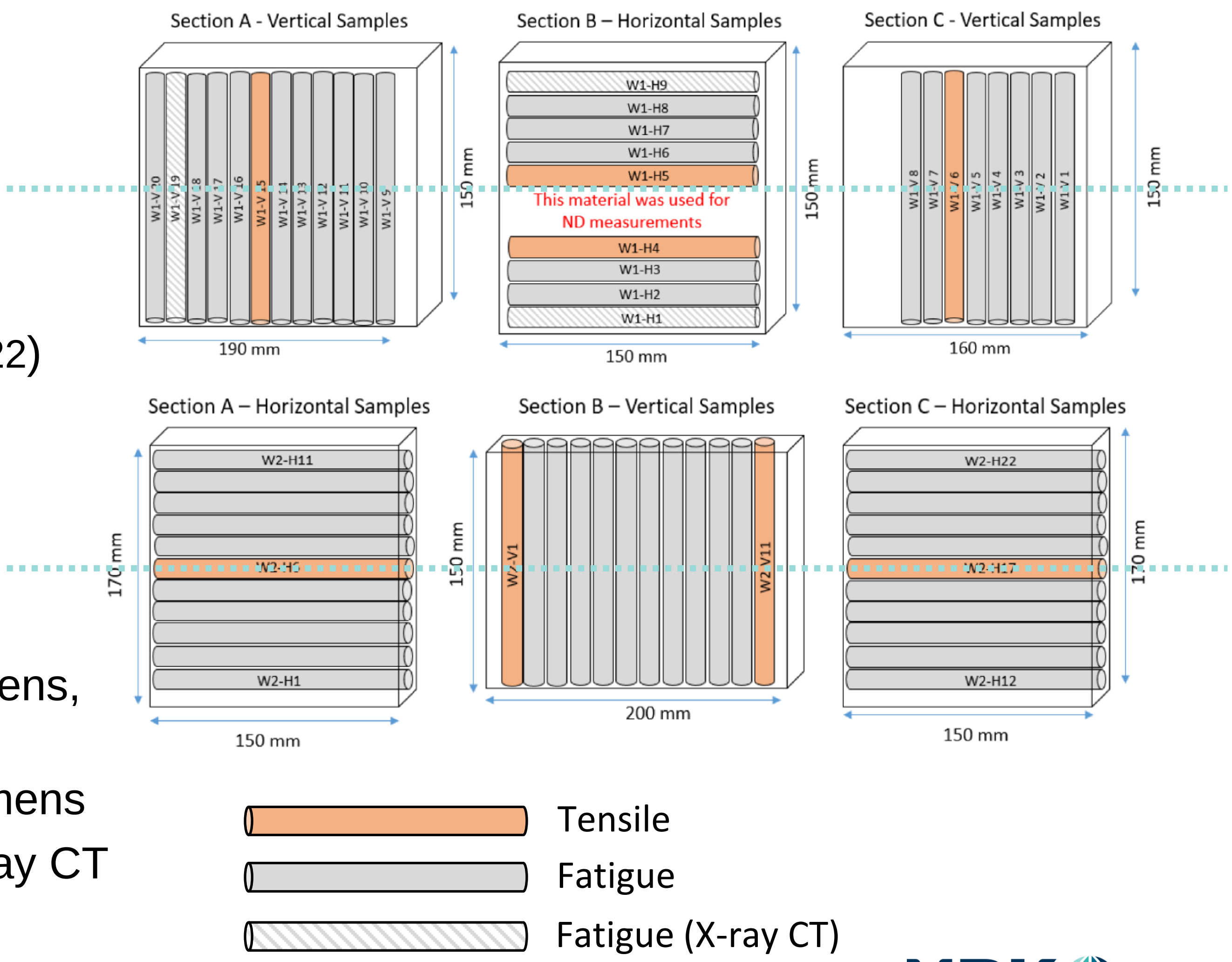
- 9 horizontal cylindrical blanks (W1H1 to W1H9)
- 20 vertical cylindrical blanks (W1V1 to W1V20)

Wall 2

- 22 horizontal cylindrical blanks (W2H1 to W2H22)
- 11 vertical cylindrical blanks (W2V1 to W2V11)

Total

- 33 horizontal and vertical cylindrical blanks
- 4 H&V selected & machined to tensile specimens, all with gauge length close to mid wall height
- 29 H&V remaining machined to fatigue specimens
- 3 fatigue specimens selected for *potential* X-ray CT



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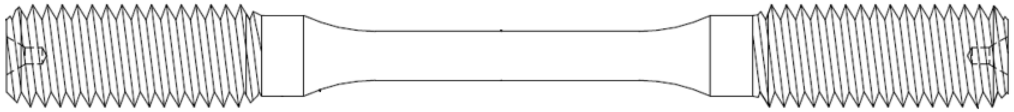
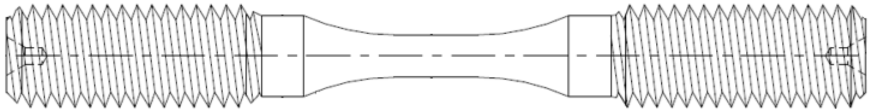
Machined Specimens ➔ Tensile & Fatigue Test Specimens

- Tensile Test Specimens
  - 118 mm total length, 31 mm gauge length, 5.75 mm gauge diameter



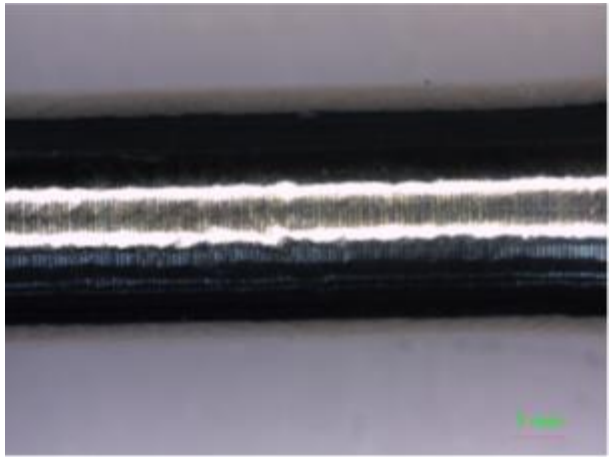
- Fatigue Test Specimens
  - 101 mm total length, 10 mm gauge length, 5.00 mm gauge diameter



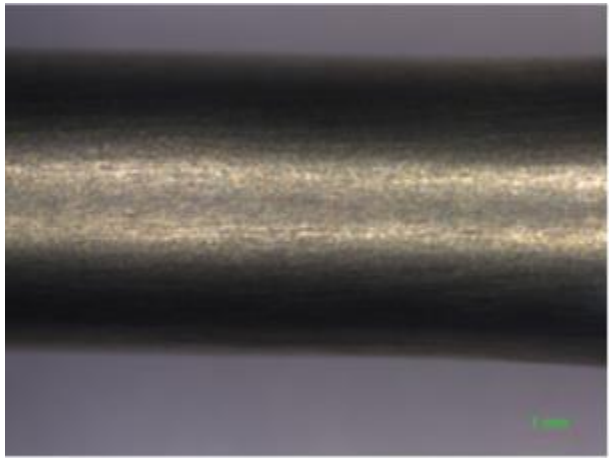
  - Polished to Ra < 0.2

- *(to ASTM E606, BS 7270, ISO 12106)*

Machined Surface



Polished Surface



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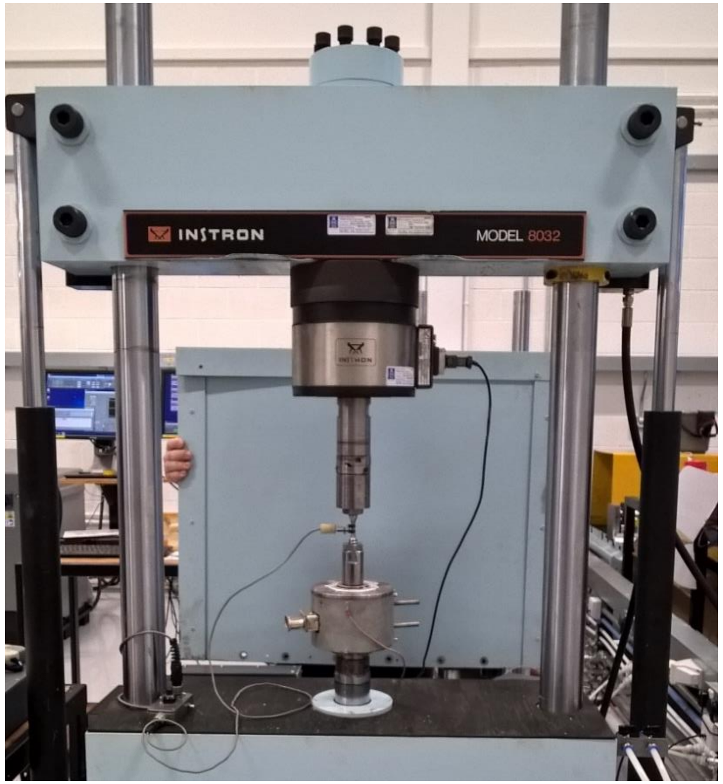
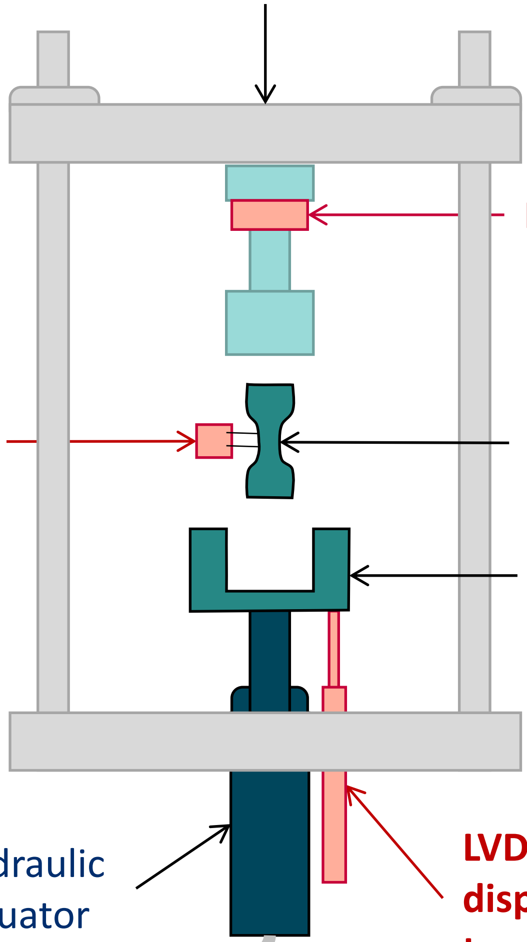
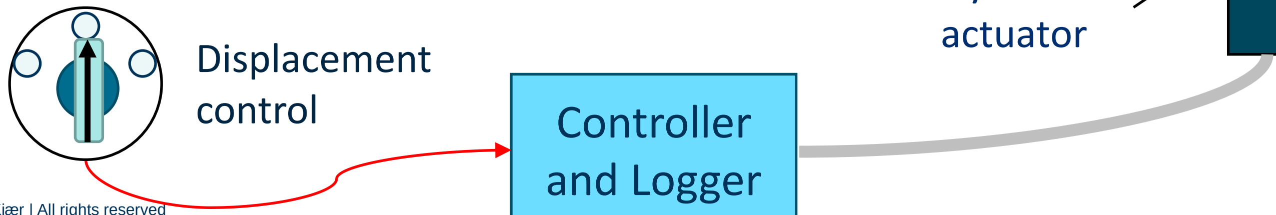
Axial Fatigue Test Rig







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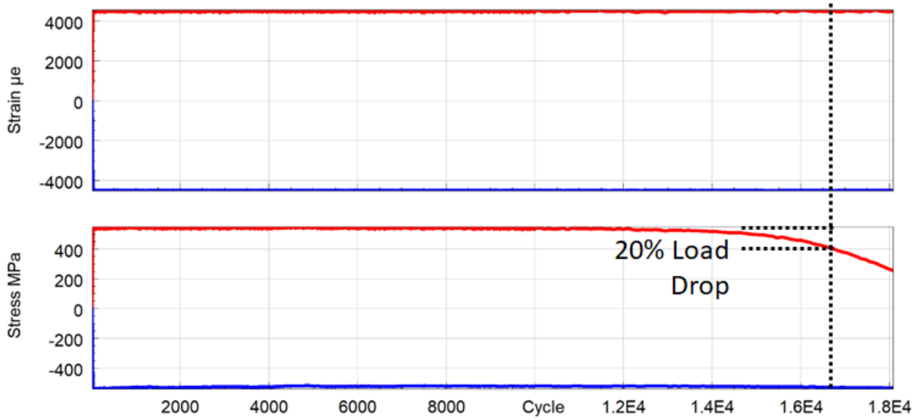
Fatigue Test Conditions, Monitoring and Failure Criteria

Test Condition

- Room temperature
- Strain controlled
- Sinusoidal waveform
- Fully reversed (R = -1)
- Soft start – a slow increase to target strain in first few cycles
- Cycle rate 0.25 to 5.0 Hz depending on strain magnitude

Test Monitoring

- All cycles recorded
- Strain in the gauge length
- Load to maintain waveform
- Test stopped at separation
- 20% load drop failure criteria applied during post-test analysis
- Stress calculated from load and gauge cross sectional area



Failure Criteria	Cycles to Failure
Separation	19136
50% load drop	18195
20% load drop	16620
10% load drop	15675
5% load drop	14625

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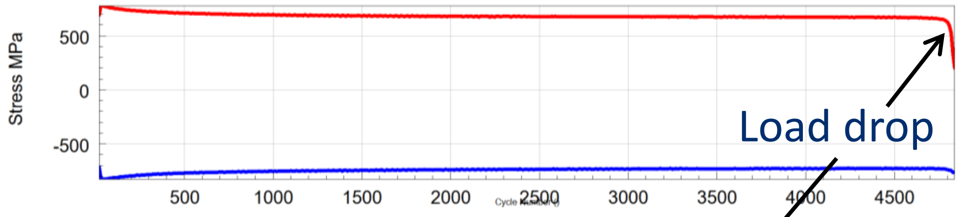
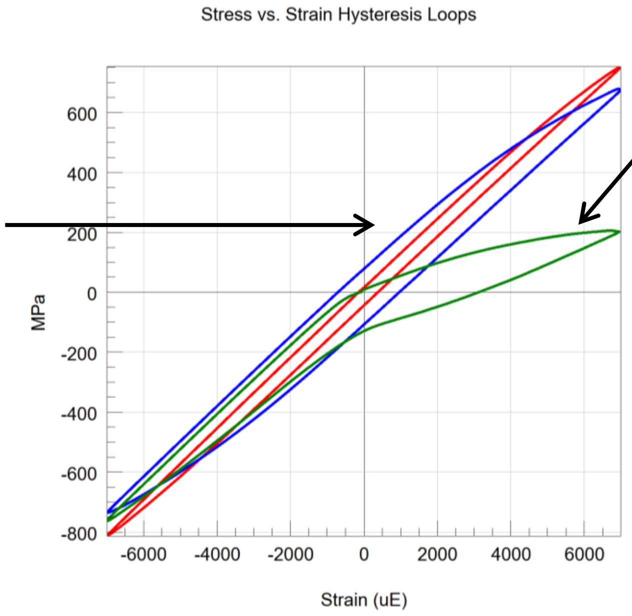
Post-Test Analysis, Specimen Report

Strain

Stress



Hysteresis loops
100 cycles (red)
stable loop (blue)
failure (green)

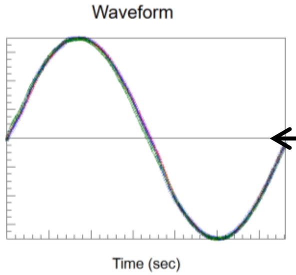


Cross sectional area = 19.40 mm²
Cycles Gate = 484
Separation Cycles = 4842

Number of cycles = 4840
Stable loop = 2390 cycles
5% load drop = 4800 cycles
10% load drop = 4820 cycles
20% load drop = 4830 cycles
50% load drop = 4840 cycles

Cycle rate = 1.510 Hz
Sample rate = 299 points/loop

Cycles to failure
at different
failure criteria



Waveform

Total Stress
Total Strain
Elastic Strain
Plastic Strain

..	Cycle Nu...	Total Stress	Total Strain	Elastic Str...	Plastic Str...
(red)	100	1566	1.399E4	1.364E4	344
(blue)	2420	1414	1.395E4	1.238E4	1570
(green)	4830	968.2	1.394E4	1.088E4	3054

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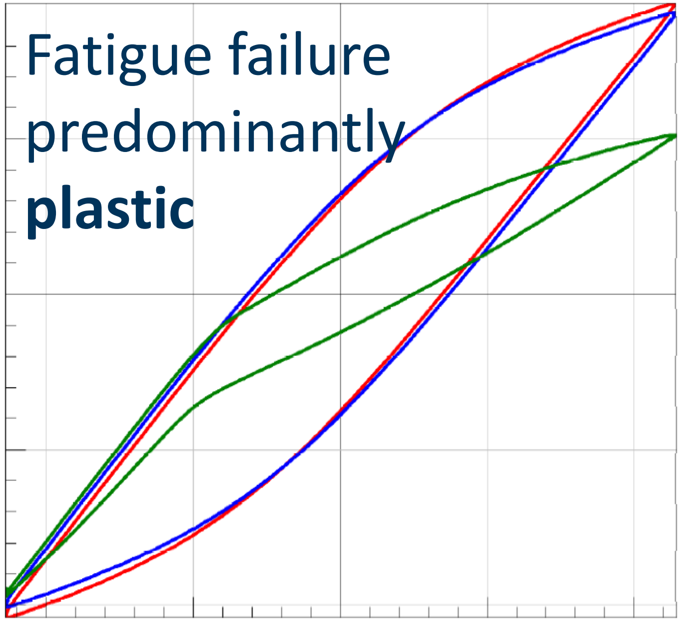
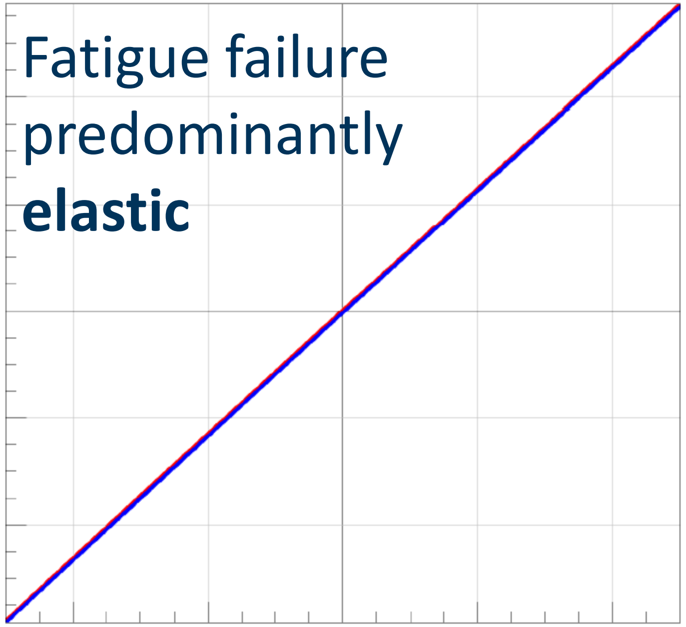
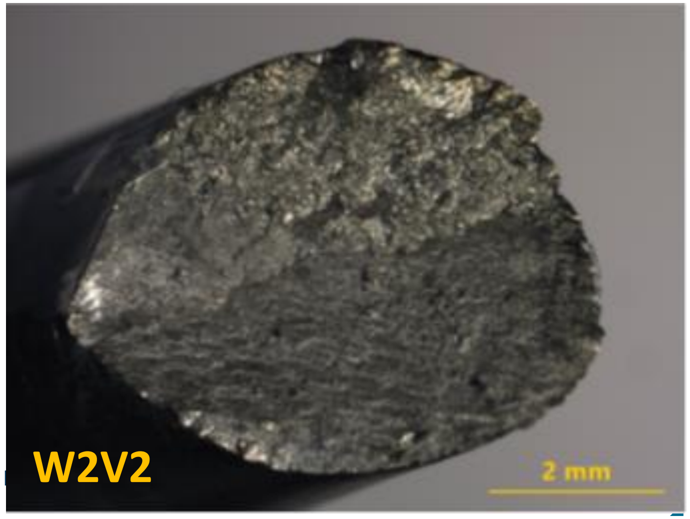
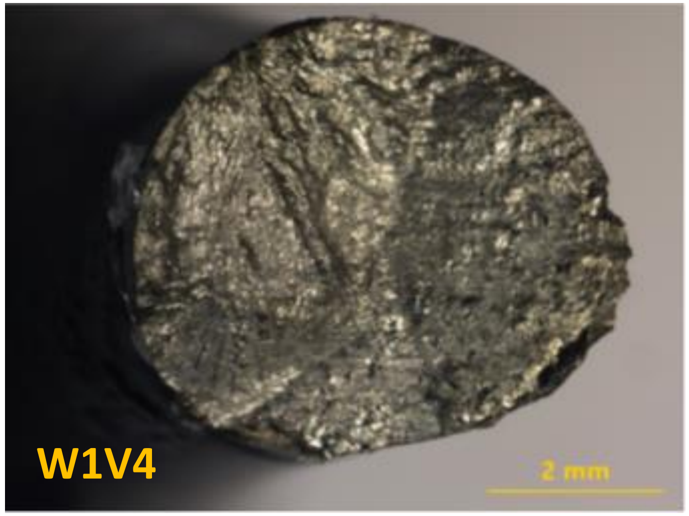
Fatigue Characterisation : Plastic or Elastic





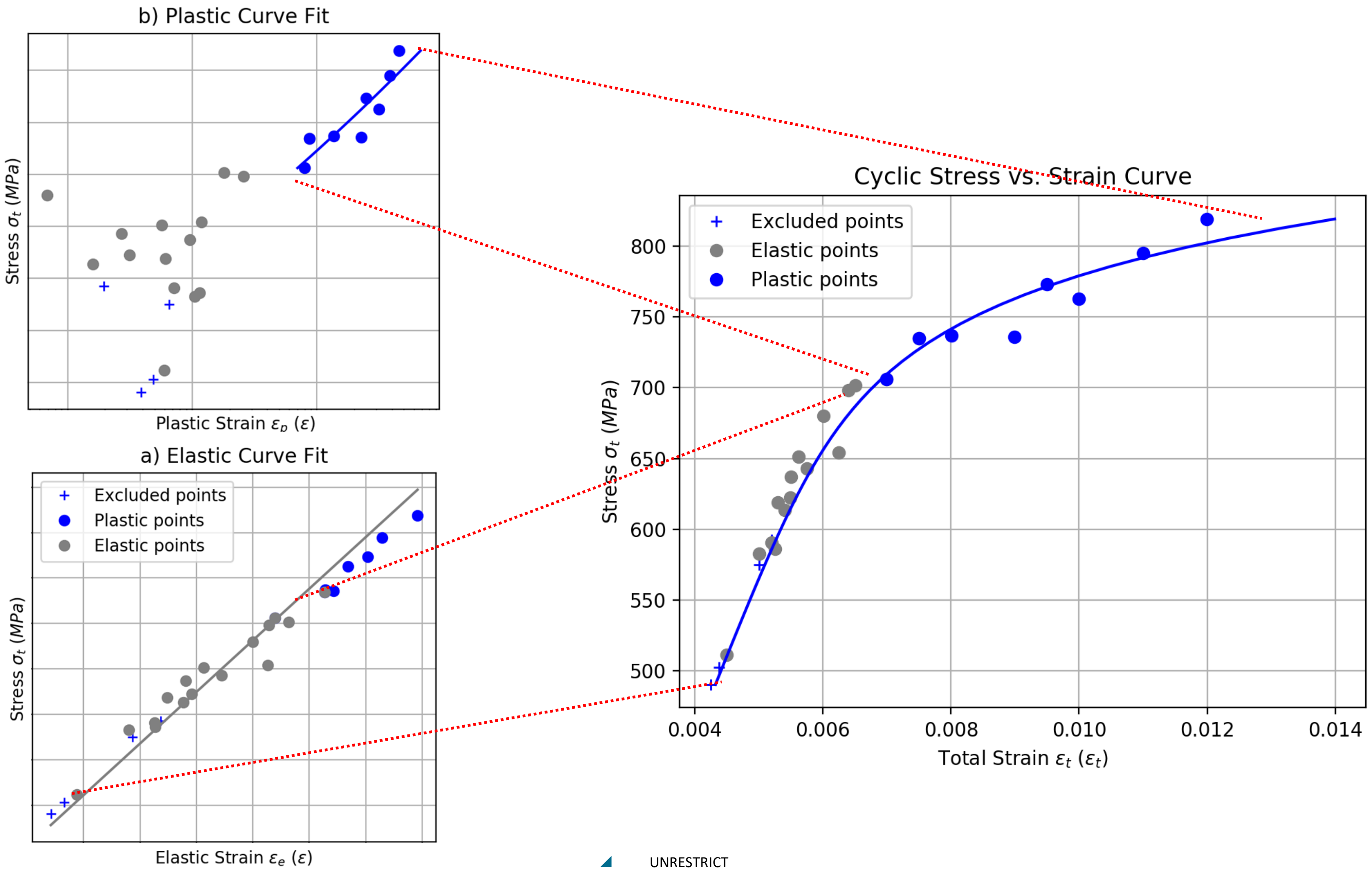




Fatigue Characterisation : Cyclic Stress-Strain Curve

- Fitting the Ramberg-Osgood parameters for the cyclic stress-strain curve

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{k'}\right)^{\frac{1}{n'}}$$



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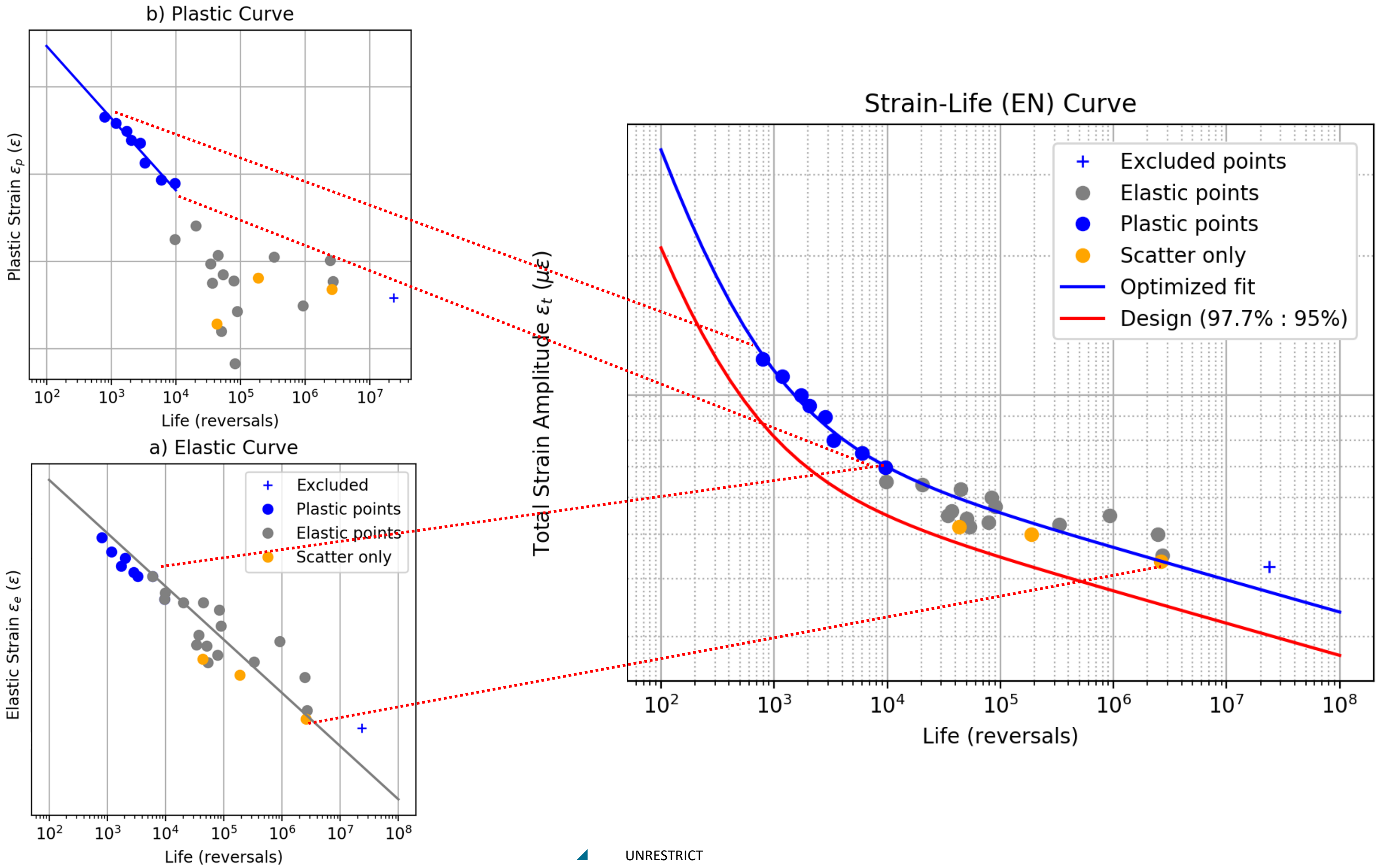
Fatigue Characterisation : Cyclic Stress-Strain Curve

- Fitting Basquin and Coffin-Manson parameters for strain-life curve $\varepsilon_t = \frac{\sigma'_f}{E} \cdot N_r^b + \varepsilon'_f \cdot N_r^c$

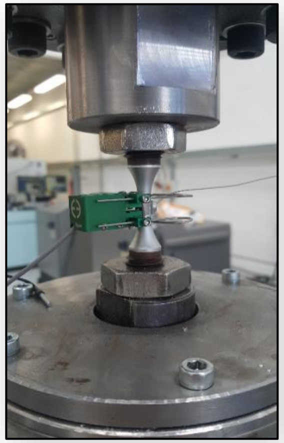


Fatigue Characterisation : Strain-Life Design Curves

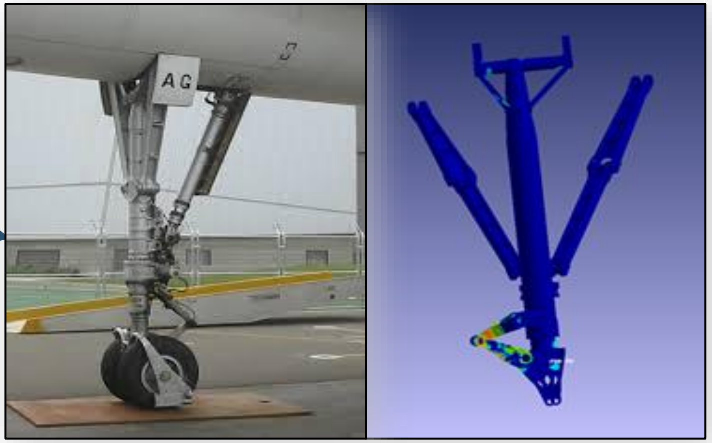
- Strain-Life Design Curves
  - are very sensitive to scatter and number of test points
  - are specific to the source material and manufacturing process

- Strain-Life Fatigue Damage Model - if the stresses and strains are similar:
  - Cycles to Failure in the Test Specimen **==** Cycles to Failure in the Component and Model
  - applies through a wide cycles to failure region, from low cycle fatigue through high cycle fatigue

- Virtual fatigue testing
  - for fatigue life prediction from finite element stress analysis results

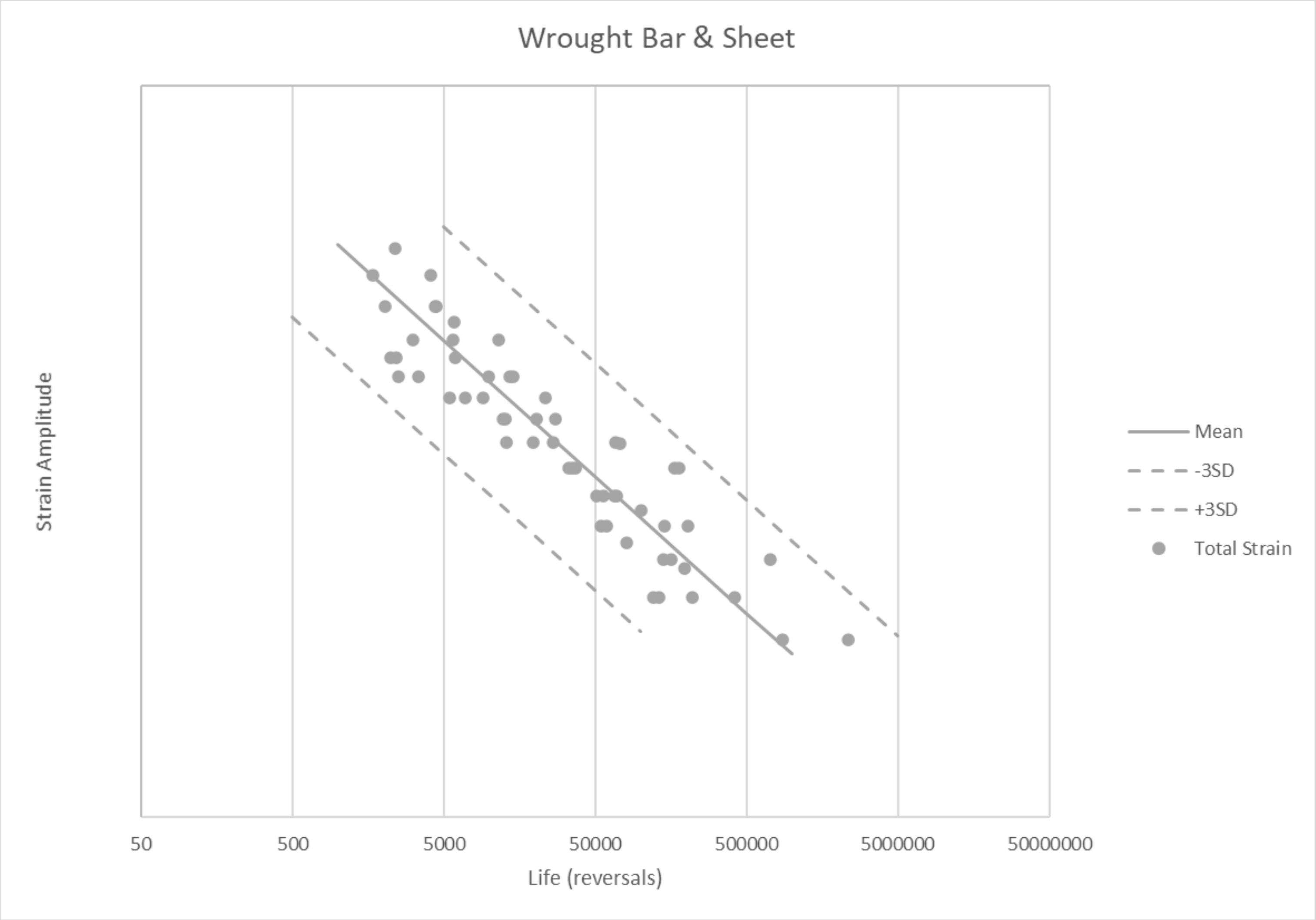


similar
σ, ε



Fatigue Test Results : Wrought Bar and Sheet Baseline

- Ti-6Al-4V wrought bar and sheet baseline
  - Mean & ±3 standard deviation
  - High scatter – because combined results from three batches
  - Two batches of wrought bar
  - One batch of wrought sheet (both longitudinal & transverse rolling directions)



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Fatigue Test Results : Compare wire-DED with Wrought

- Ti-6Al-4V wrought bar and sheet baseline

- wire-DED (H) & (V)
  - strain-life characterisation
  - mean strain-life curves

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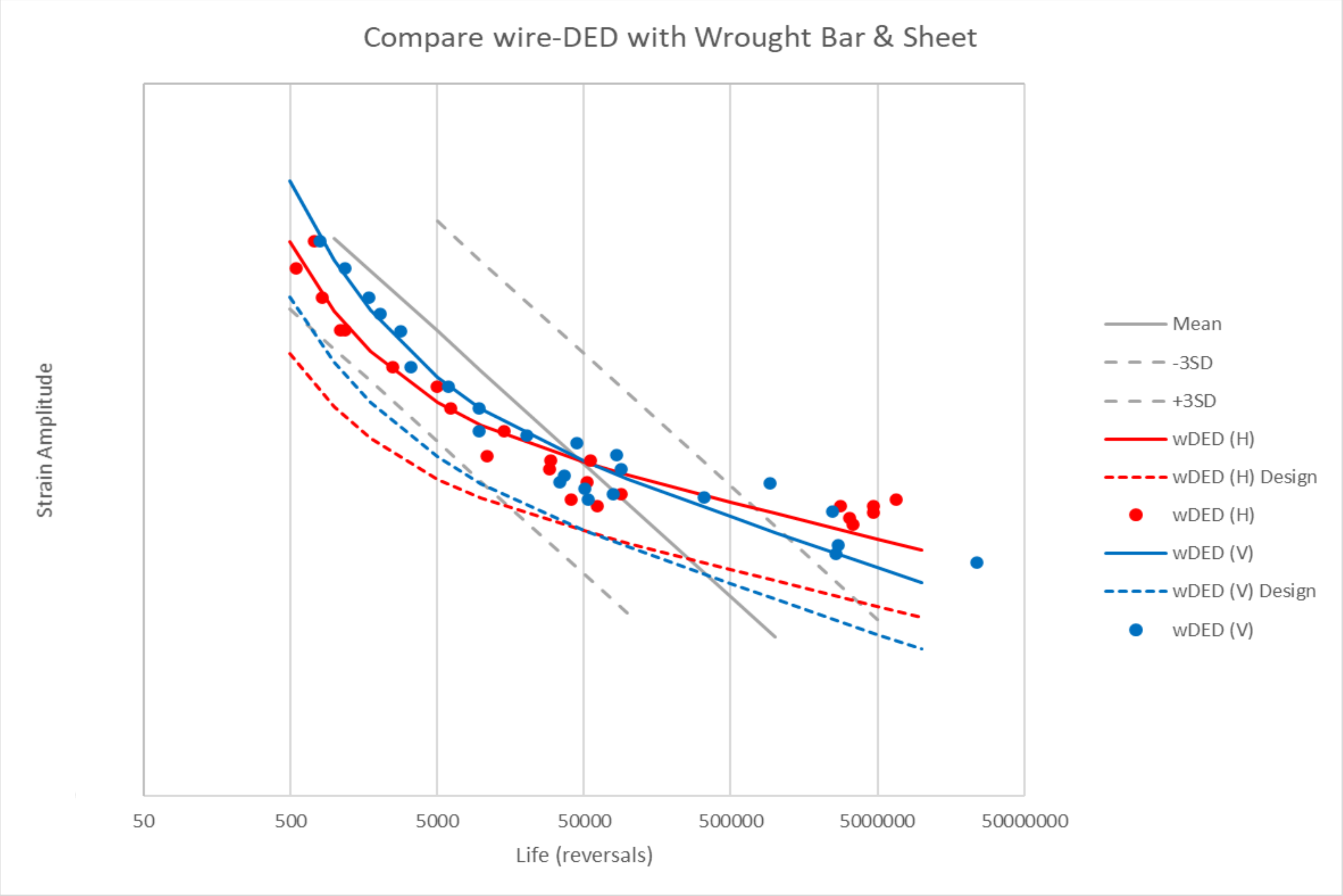
Fatigue Test Results : Compare wire-DED with Wrought

- Ti-6Al-4V wrought bar and sheet baseline

- wire-DED (H) & (V)
  - strain-life characterisation
  - mean strain-life curves
  - design strain-life curves
  - 97.7% certainty of survival (-2 standard deviation)
  - 95% confidence

- *Session #5 seminar next week will present the strain-life characterisation method and explain certainty of survival and confidence.*



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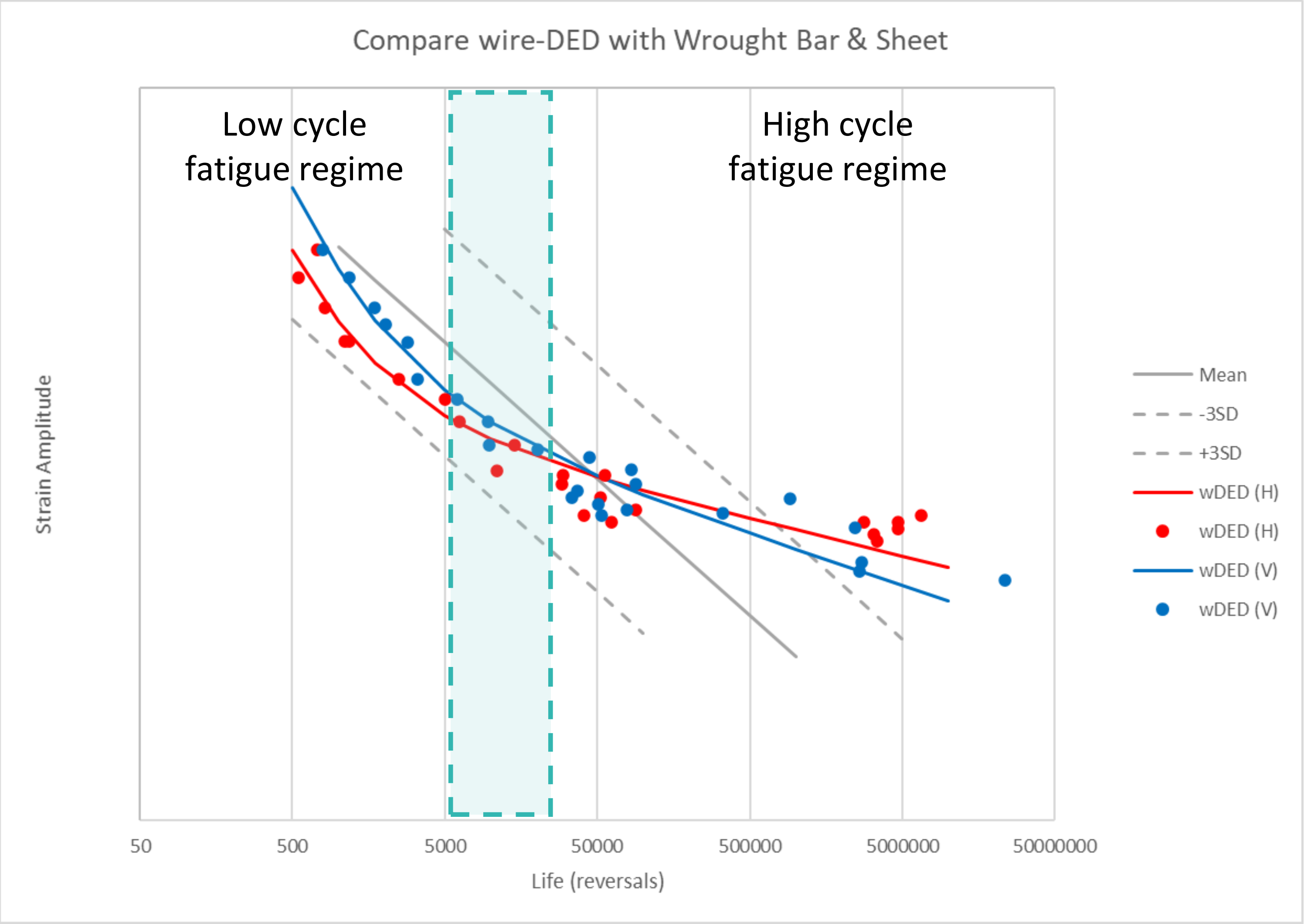
Fatigue Test Results : Compare wire-DED with Wrought

- Ti-6Al-4V wrought bar and sheet baseline
- wire-DED (H) & (V)
- Low cycle fatigue regime
- High cycle fatigue regime
- All fatigue tests strain-controlled for consistency and continuity of test results and strain-life curve through this transition
- ➔ role of microstructure ...



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Questions

Thank You

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Clean Growth & Future Mobility

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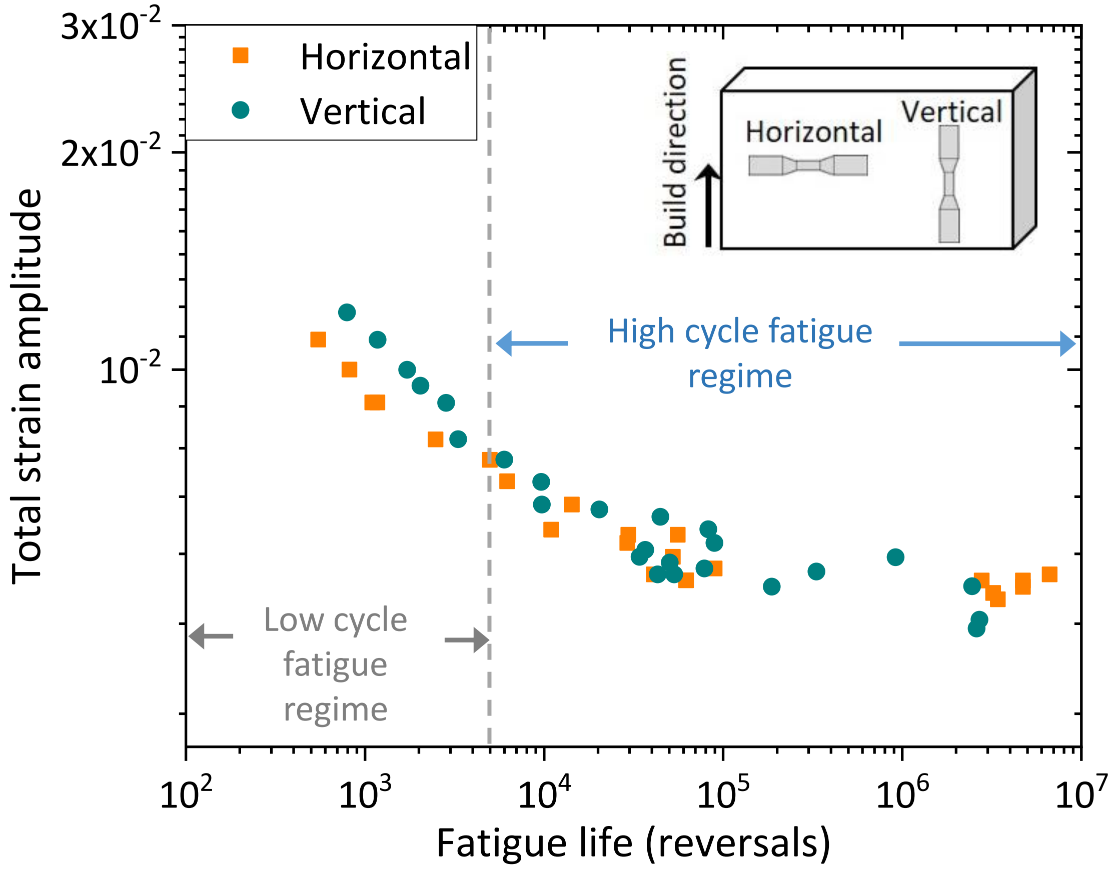
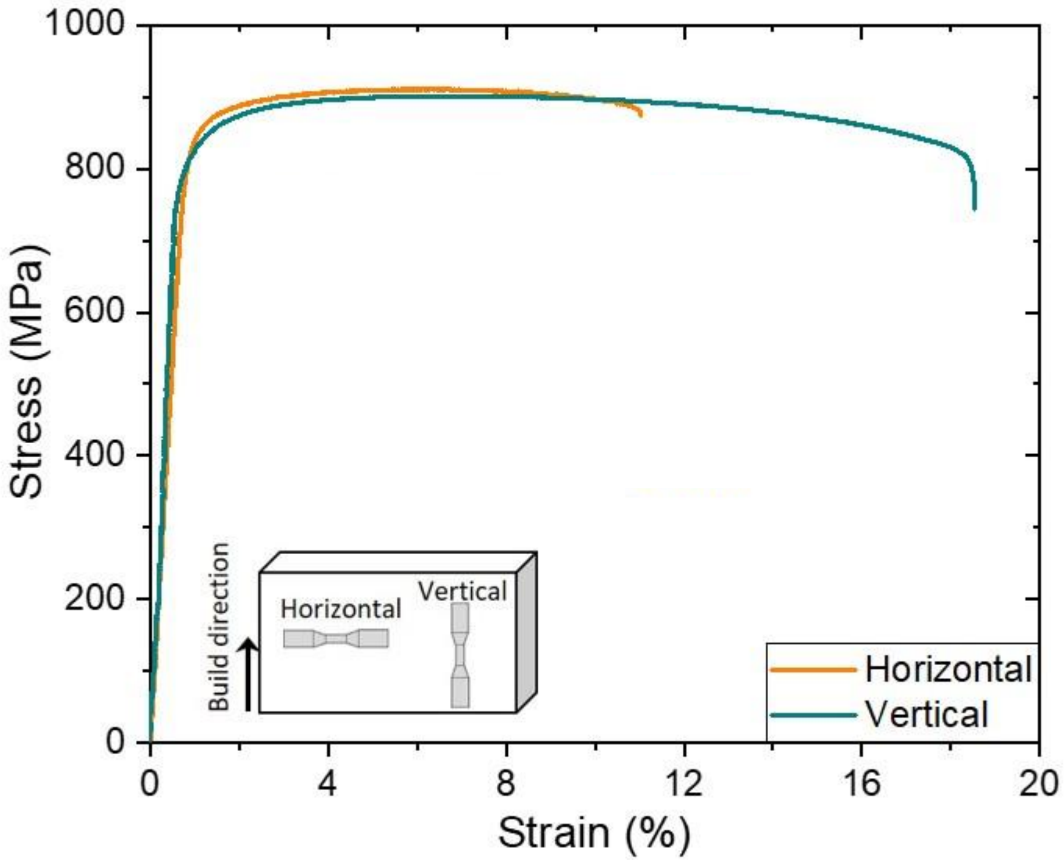
The role of microstructure on cyclic deformation and damage mechanisms

A.K. Syed[1], M. Hill[2], R. Plaskitt[2], S. Williams[3], X. Zhang[1]

[1]Centre for Manufacturing and Materials, Coventry University, UK
[2]HBK world
[3]Welding Engineering and Laser Processing Centre, Cranfield University, UK

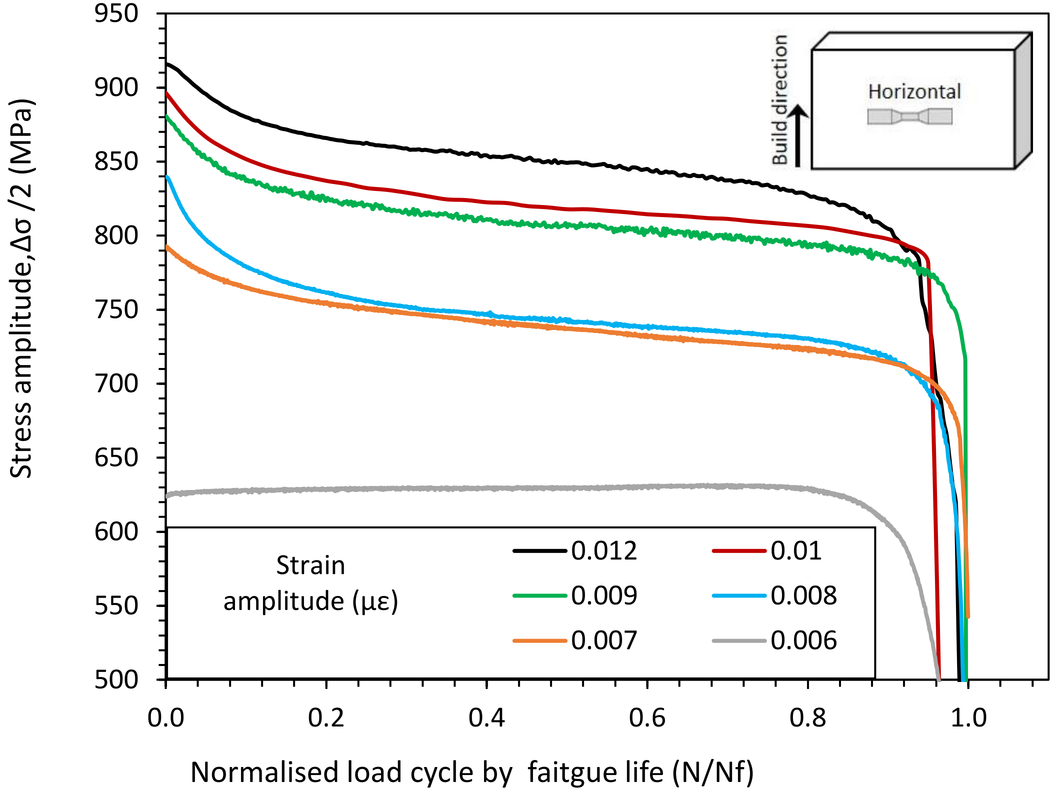
Strain vs. life (ε-N)

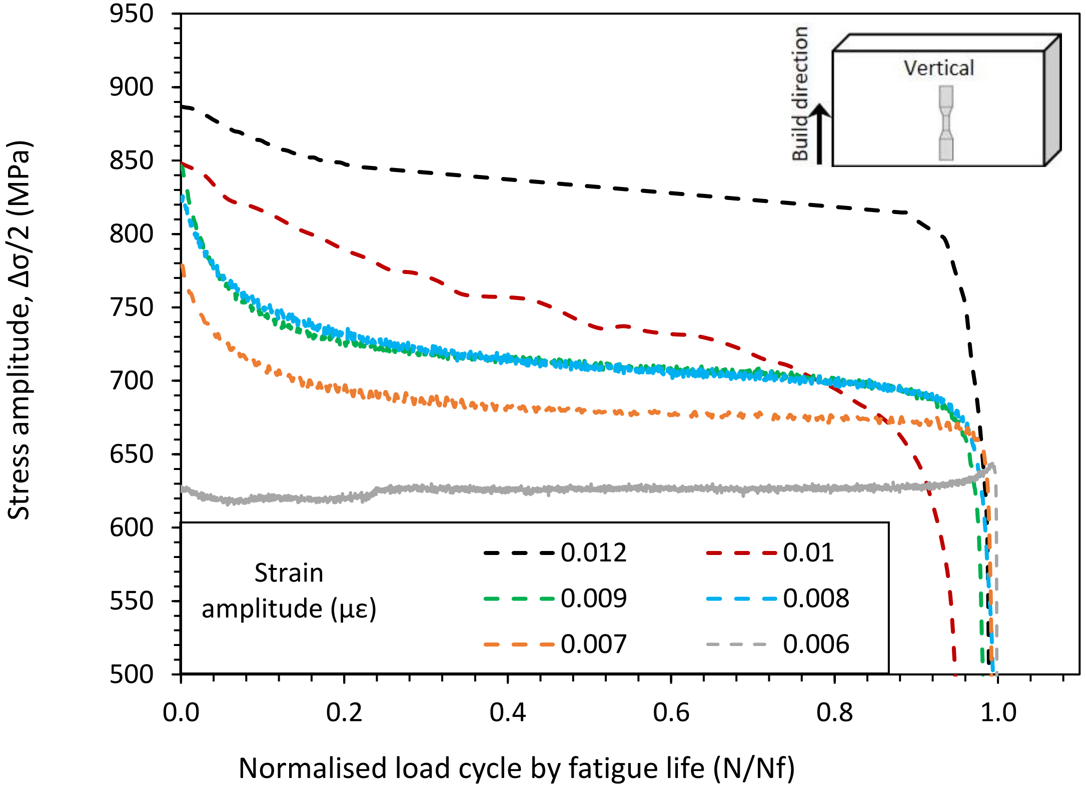




- Higher fatigue strength in vertical samples in LCF regime owing to higher ductility?
- Isotropic property in HCF regime (strain amplitude < 0.006)

Cyclic deformation behaviour





- A continuous cyclic softening due to change in dislocation substructure until a stable configuration is reached
- Softening is apparent in both sample orientations at higher strain amplitudes (Δε/2> 0.006 με)

Cyclic deformation: Horizontal vs Vertical

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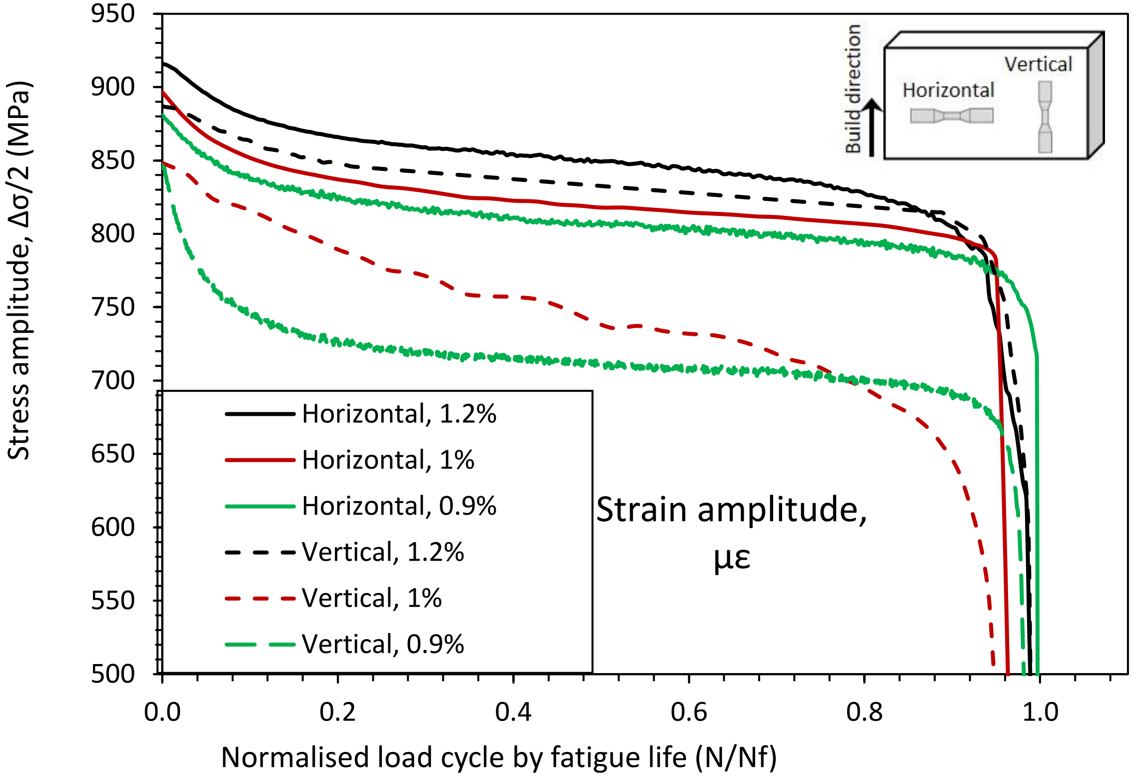
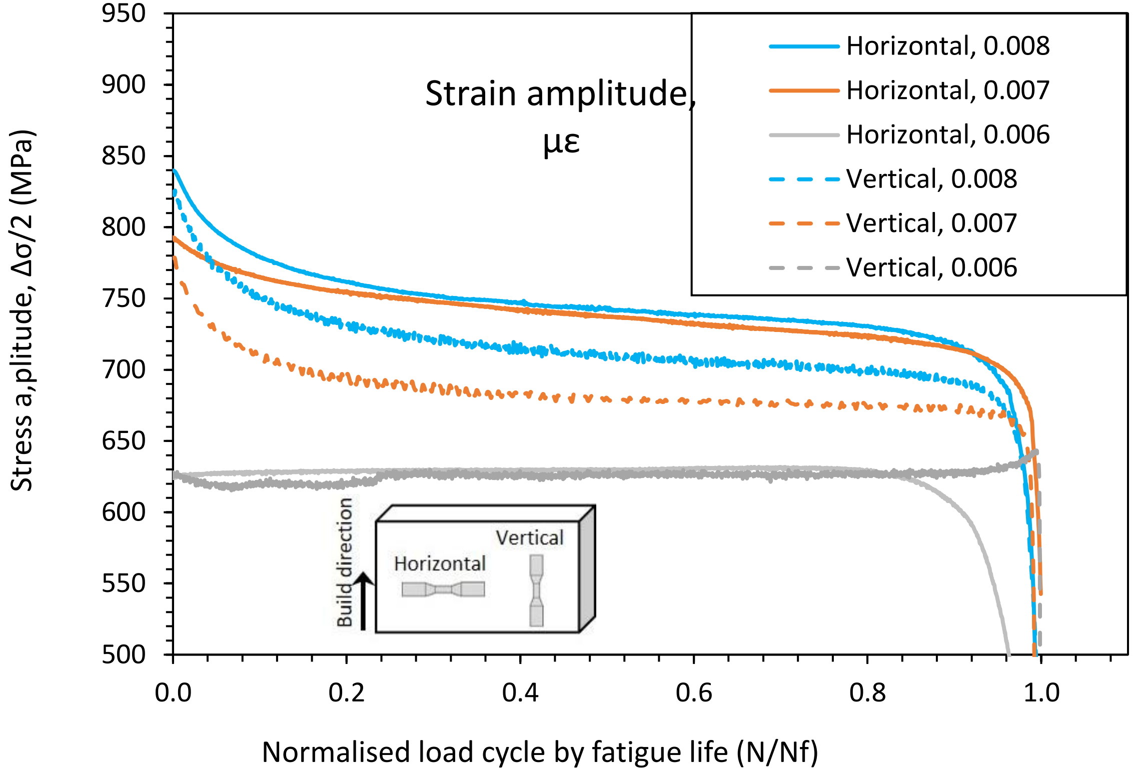
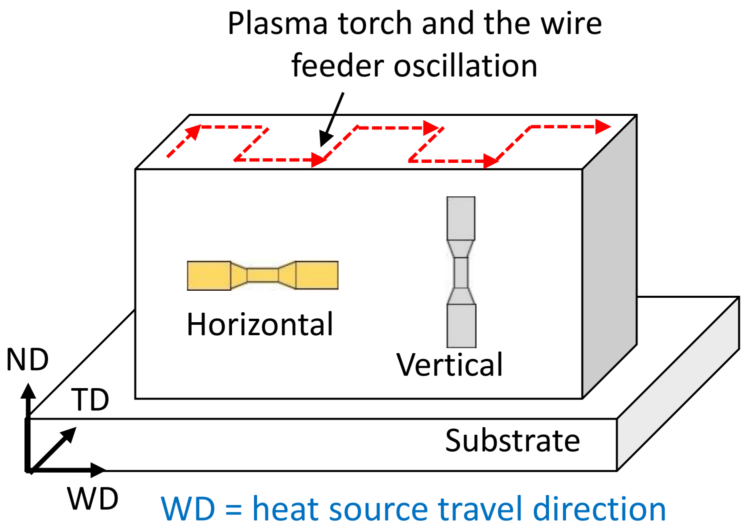


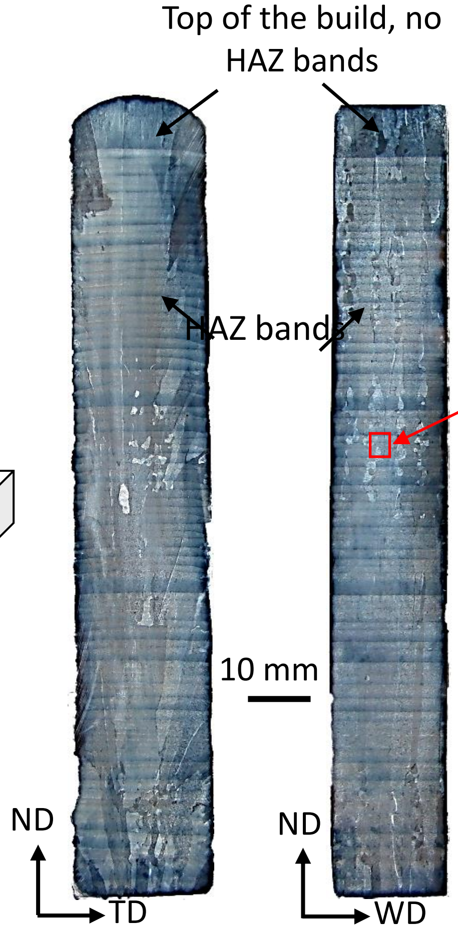


- For the same applied strain, horizontal samples showed a marginal higher stress
- Difference in maximum stress (between Horizontal and Vertical) reduced with $\Delta\varepsilon/2$
- No anisotropy when applied strain amplitude is near or in the elastic region ($\Delta\varepsilon/2 < 0.006$)

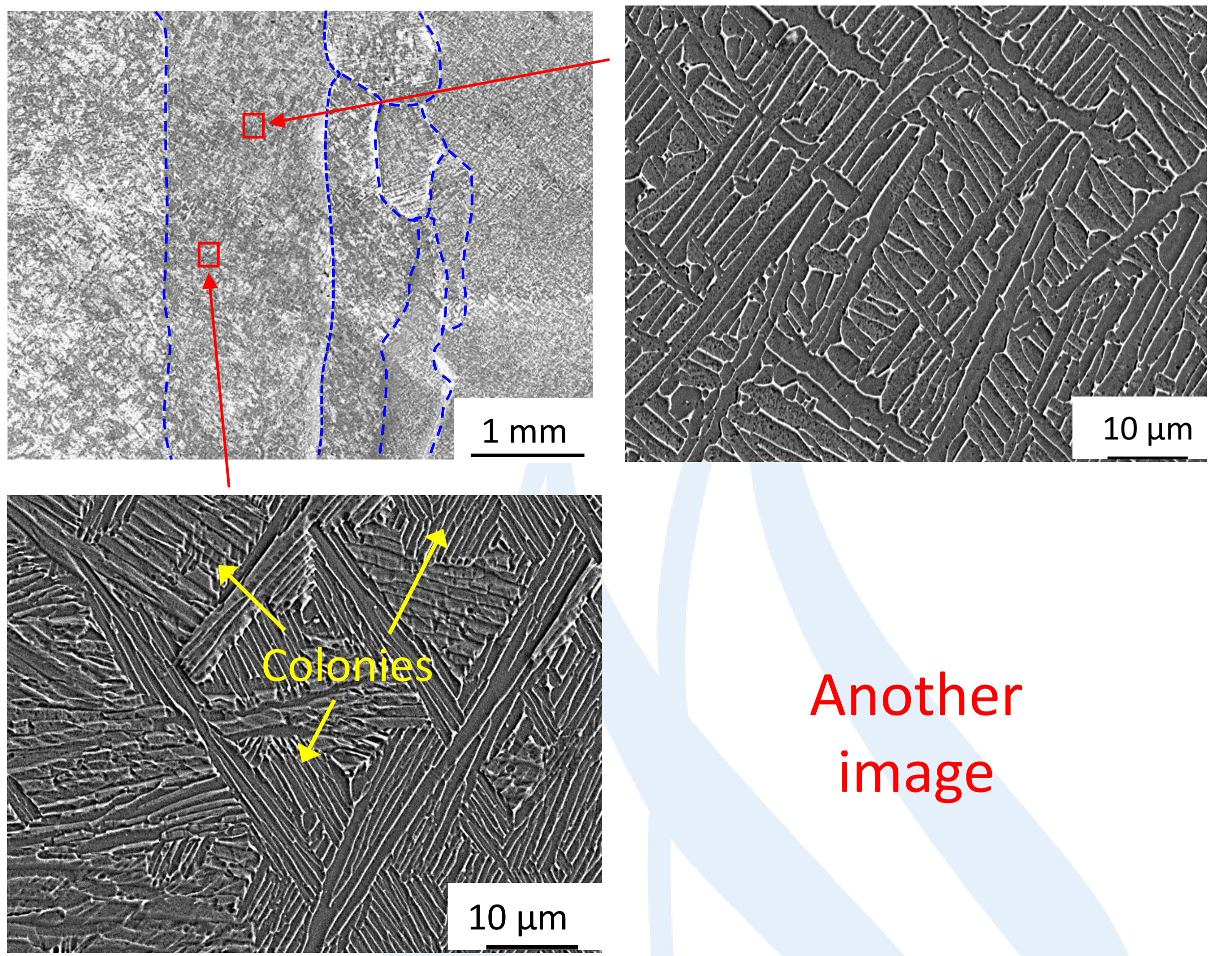
Microstructure



WD = heat source travel direction
TD = wall thickness direction
ND = build height direction



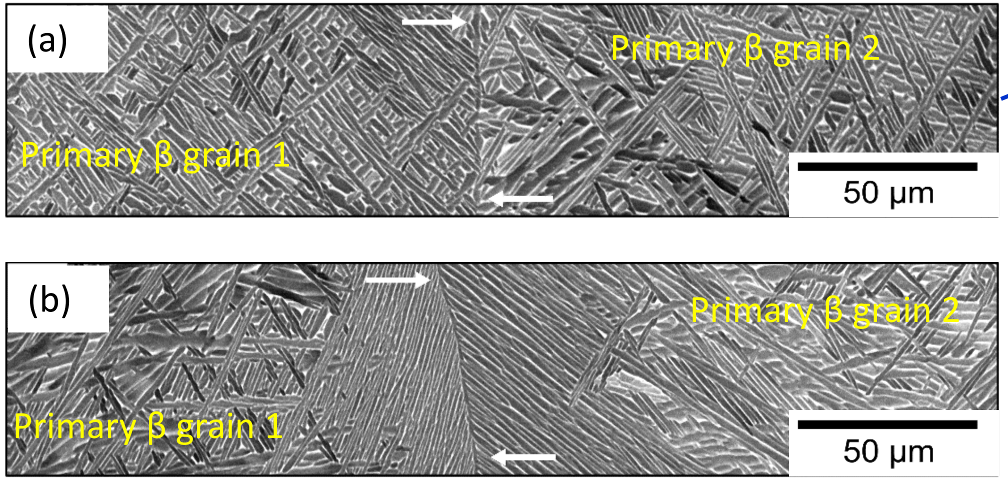
Optical macrograph



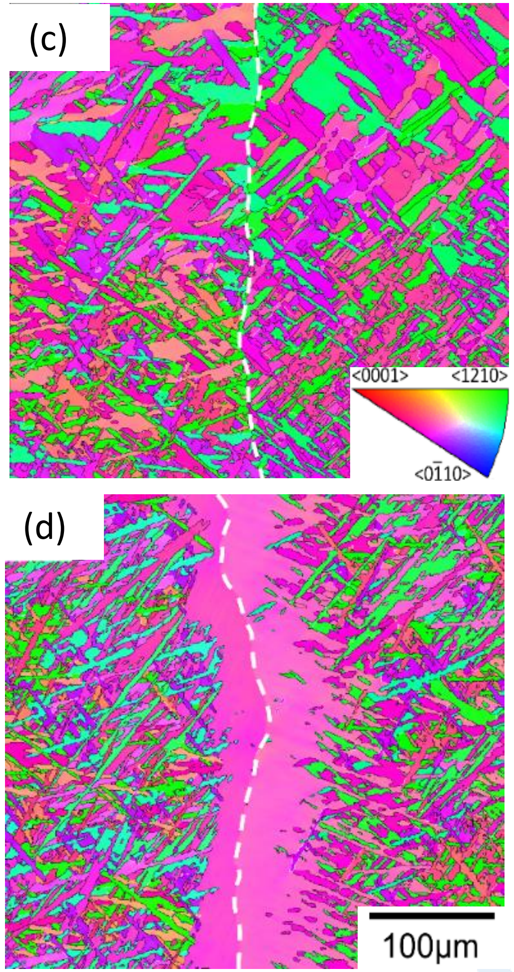
Another image

- Columnar primary β grains are the consequence of steep thermal gradient
- Classical lamellar α+β with Widmanstätten and single variant colony morphologies
- Repeated thermal cycles lead to heterogeneous microstructure

Microstructure effect



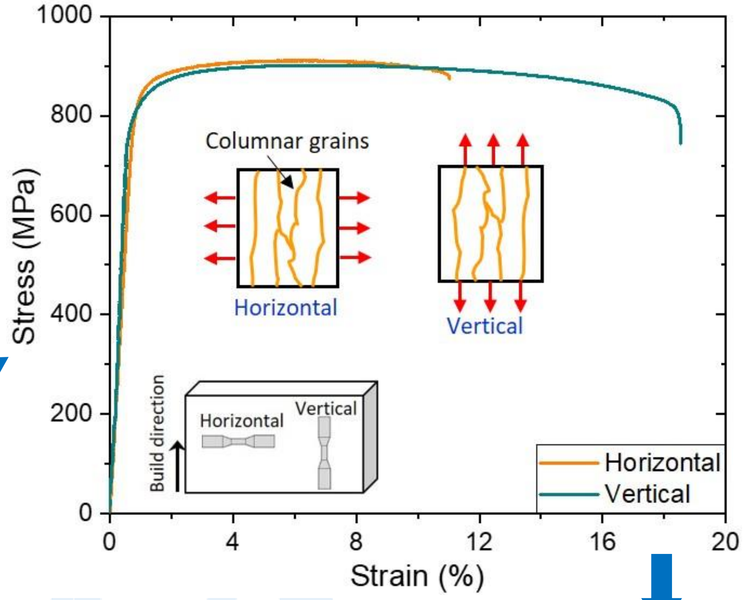
SEM, back scattered micrographs



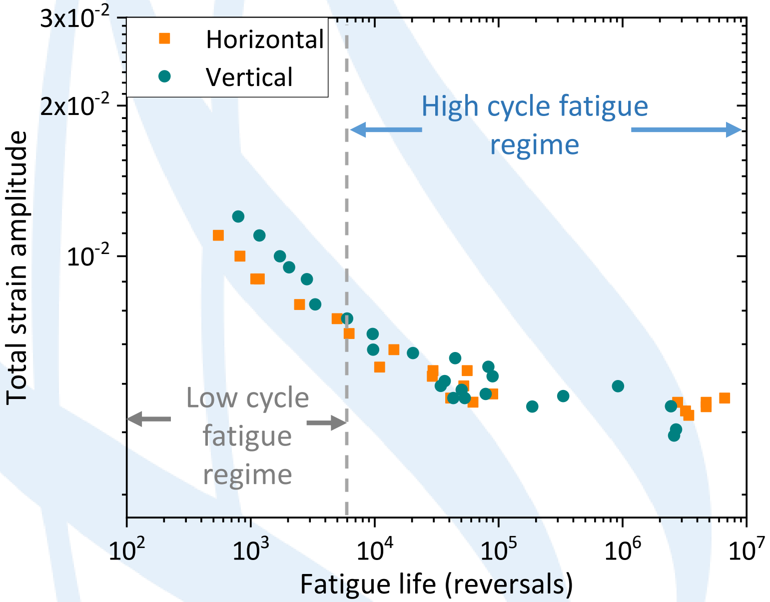
EBSD, IPF maps

- 83% α_{GB} have large colonies and 17% have basket-weave microstructure
- Single variant large colonies leads to strong texture along α_{GB}
- Horizontal sample: applied load is perpendicular to α_{GB} and strong texture along α_{GB} separate adjacent β grains. **Hence, lower ductility and lower fatigue life in LCF regime**

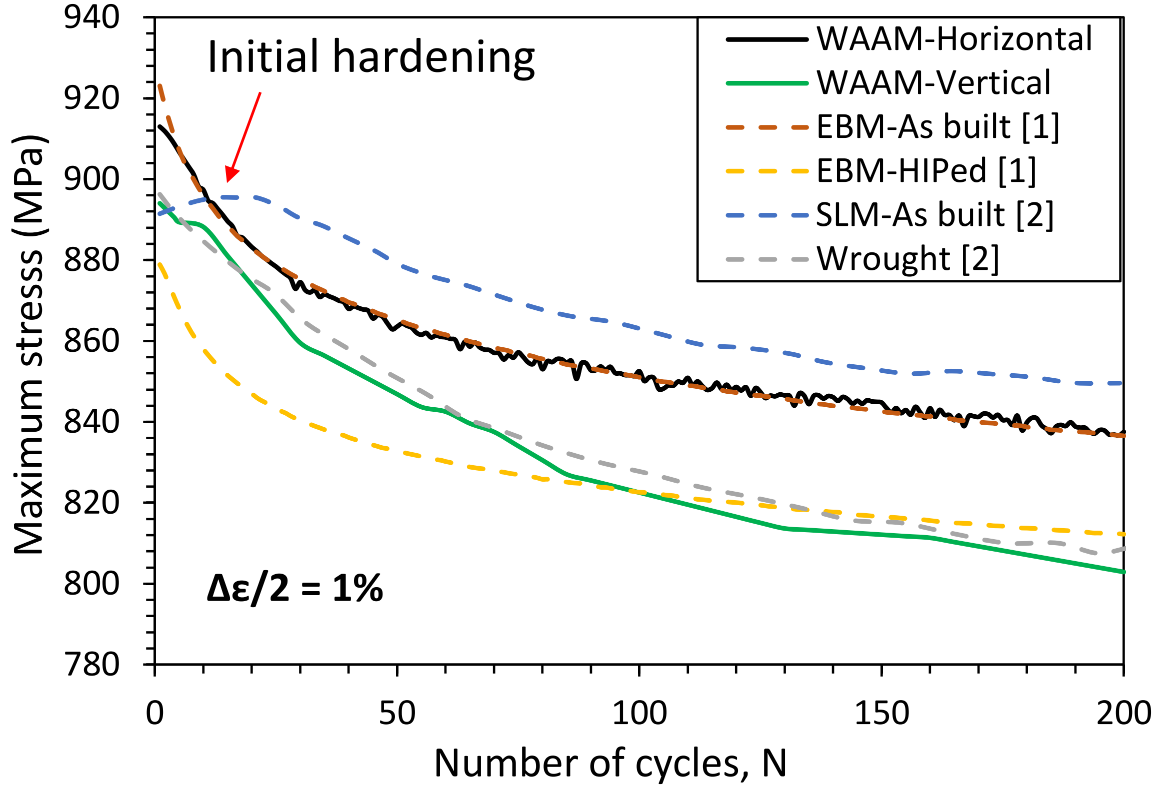
Anisotropy in ductility

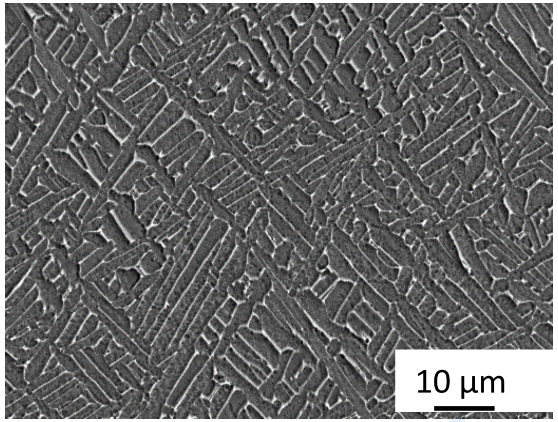


Marginal anisotropy in LCF regime

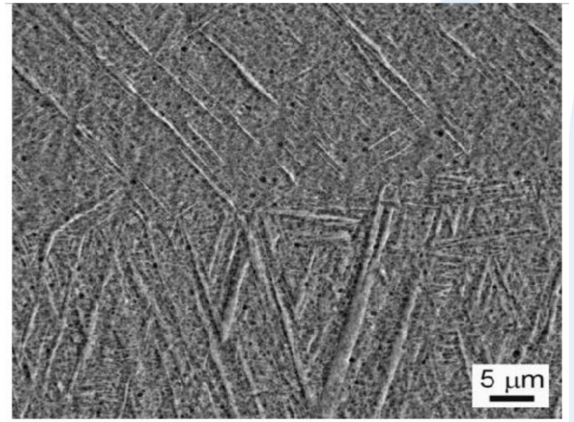


Cyclic deformation: Current study vs literature

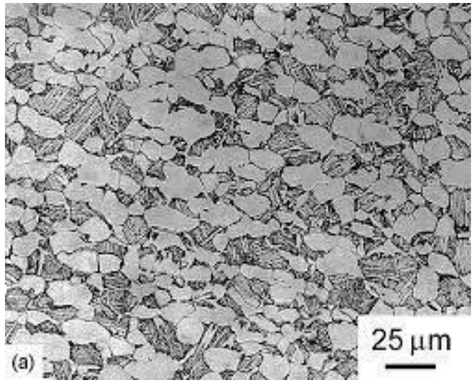




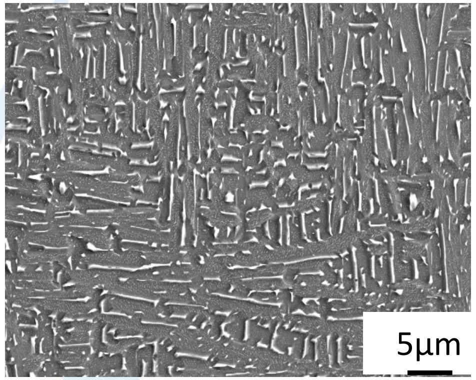
WAAM



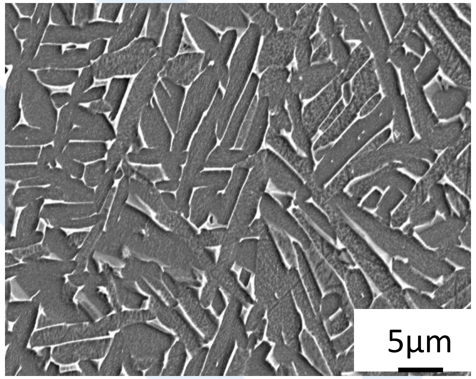
SLM-as built



Wrought (mill annealed)



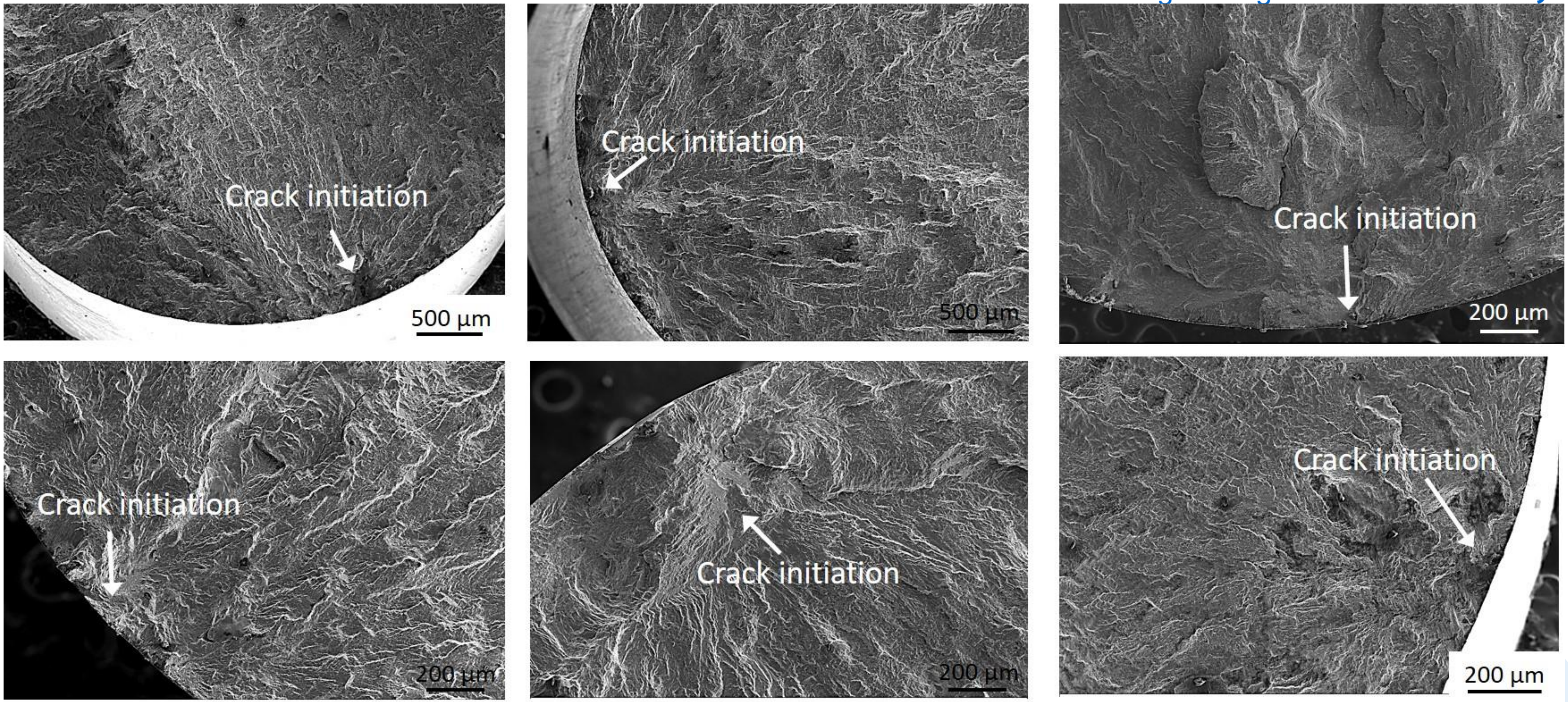
EBM-as built



EBM-HIPed

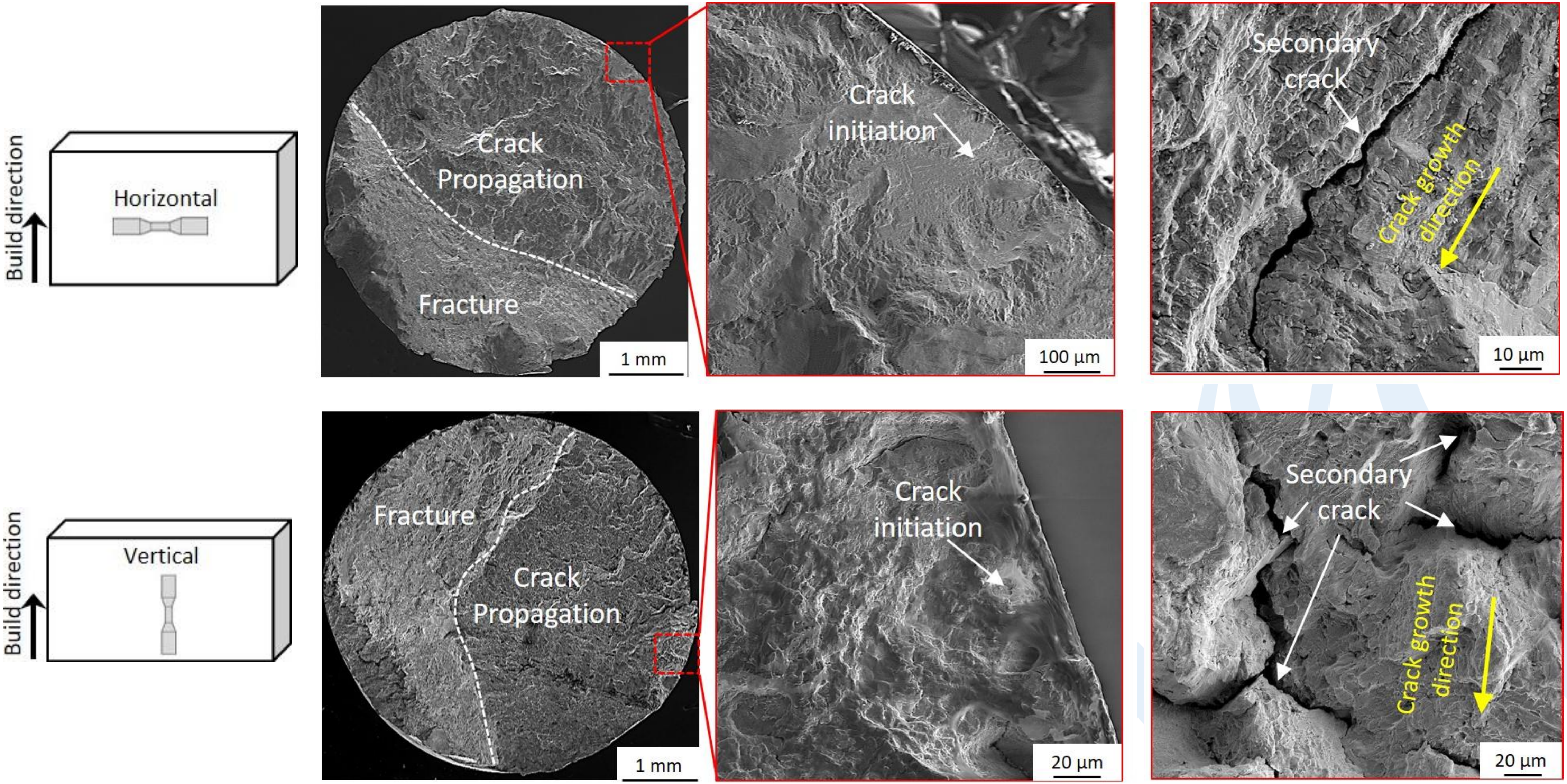
- Similar cyclic deformation as other counterparts
- Higher plasticity in Wrought and EBM HIPed led to lower peak stress
- Acicular α′ in SLM have high dislocation density and twin structures, causing dislocation tangling at GB’s and leading to initial cyclic hardening

Crack initiation sites



- Fracture surface of more than 50 samples were studied
- **No defects were found. Cracks initiated from microstructure feature(s).**

Failure mechanisms in strain controlled fatigue



Conclusions

1. Classical lamellar α+β with Widmanstätten and single variant colony morphologies
2. Microstructure along the α_{GB} largely consists of single variant α colonies
3. Property anisotropy in low cycle fatigue region is marginal (horizontal samples had lower fatigue strength due to lower ductility)
4. No defects; crack initiated from microstructure feature(s)
5. Numerous secondary cracks is the consequence of the colony microstructure

Acknowledgements

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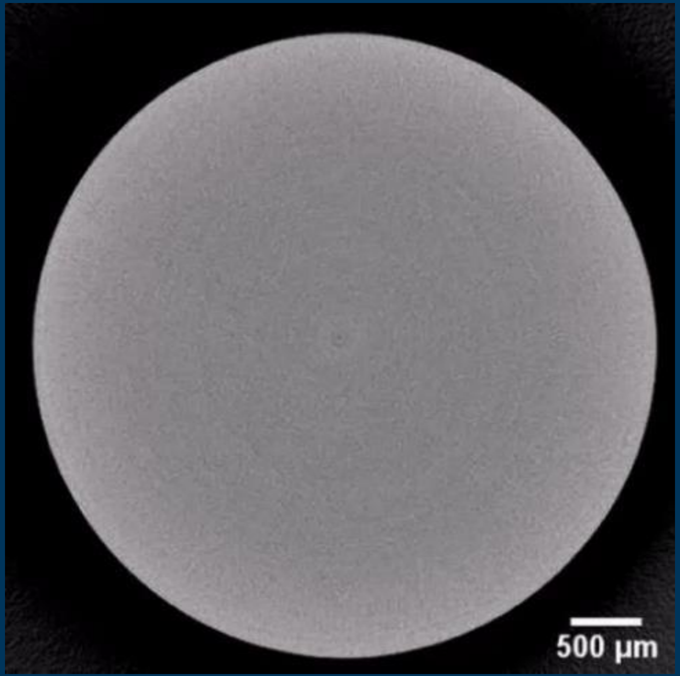
Thank you for your attention

Virtual Seminar Series – Tuesday 2, 9, 16 November



Cyclic Deformation and Fatigue Behaviour of Titanium Ti-6Al-4V additively manufactured by w-DED

Presented by Mr. Rob Plaskitt, *Prenscia (HBK)*
Dr. Abdul Khadar Syed, *Coventry University*

Tuesday, November 9, 2021