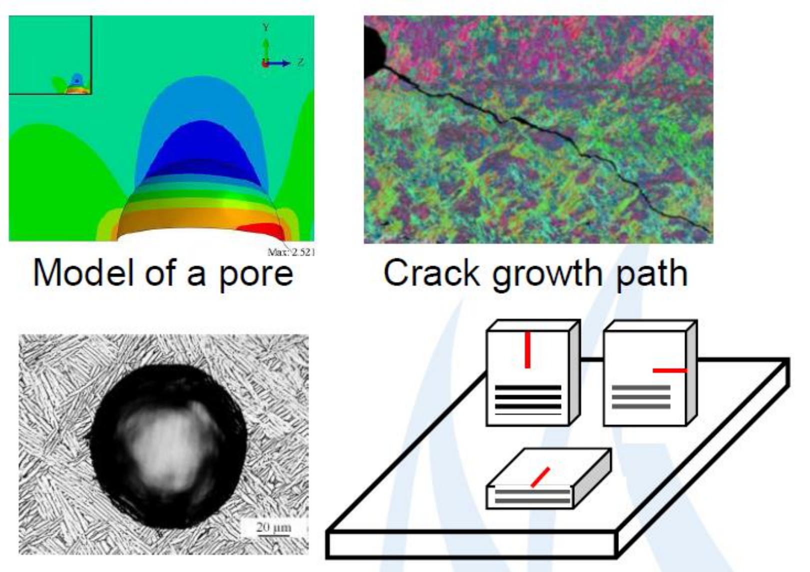
Virtual Seminar Series – Tuesday 2, 9, 16 November



Structural Integrity of Titanium Ti-6Al-4V additively manufactured by w-DED

Presented by Prof. Xiang Zhang
Coventry University

Tuesday, November 9, 2021

Structural Integrity of Titanium Ti-6Al-4V additively manufactured by w-DED

Abstract

Coventry University are leading the “Material Performance and Structural Integrity” of NEWAM, determining structural integrity through:

- residual stress - modelling, contour & diffraction test methods, and residual stress intensity
- fatigue initiation - defects, defect tolerance, testing & characterization and modelling
- fatigue fracture - testing & characterisation, crack growth and fracture mechanics

This presentation describes the process induced residual stress and fatigue crack growth behaviour for the first material, the high strength titanium alloy Ti-6Al-4V. The following presentation presents the fatigue initiation and microstructure research.

Material was manufactured with three different deposition strategies; single pass, parallel pass, and oscillation wave builds. The single pass build is limited to a maximum thickness of around 8 mm, whereas the other two methods can build thicker materials as well as parts with variable thickness. All samples were tested in the as-built condition with standard surface machining and polishing.

About the presenter, Prof. Xiang Zhang, Coventry University

Professor Xiang Zhang has conducted research in aircraft structural integrity for over 30 years, on both metallic and composite material structures. Her research career started from a research associateship at Imperial College London (1987-96), followed by academic faculty appointments at Cranfield University (1997-2014) and Coventry University (since 2015).

Her research interest is focused on the fatigue and fracture problems in lightweight metallic alloys and polymer composite materials, and their applications in the aerospace structures. She has a keen interest in understanding the relationship between manufacturing of structural materials and their performance under the fatigue loads. She is a Fellow of the Royal Aeronautical Society and member of the Society’s specialist group in materials and structures. She is an Associate Editor for the Journal of Aerospace Engineering and editorial board member for the Aerospace journal.

Research Institute
Clean Growth & Future Mobility

Coventry University

Structural Integrity of Titanium Ti-6Al-4V additively manufactured by w-DED (WAAM)

Xiang Zhang, Abdul Khadar Syed, Bilal Ahmed, Michael Fitzpatrick

Centre for Manufacturing and Materials, Coventry University, UK

HBK Prenscia Technology Days

9th November 2021

Research Centre
Manufacturing and
Materials Engineering

Coventry University

Talk content

- **Overview of AM research at Coventry**
- **WAAM Ti-6Al-4V**
  - **Durability**
  - **Damage tolerance**
  - **AM attributes**

    Defects

    Microstructure and Texture

    Residual stress
- **Summary**

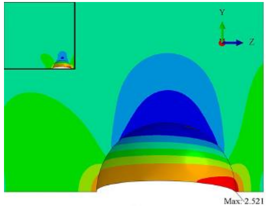
AM projects at Coventry University

Research Centre Manufacturing and Materials Engineering | Coventry University

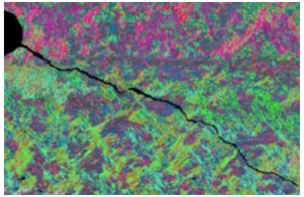
Wire + Arc AM (Ti64, Ti6242, AA5183, AlMgSc)
- Residual stress
- Fatigue and defects
- Fatigue crack propagation

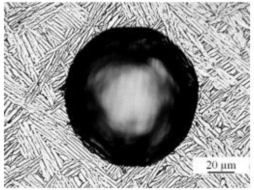
Powder bed fusion (Ti64, SS316L, IN718)
- Porosity effect on fatigue property
- Improvement by heat treatment/HIP
- Residual stress and crack growth behaviour
- Powder re-use (up to 10-14 times)

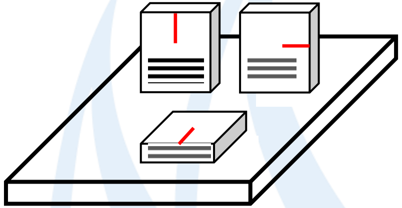
Cold Spray Repairs (Ti64, AA7075)
- Residual stress
- Heat treatment/HIP
  (effects on residual stress and properties)

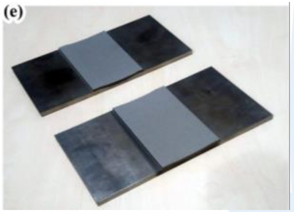


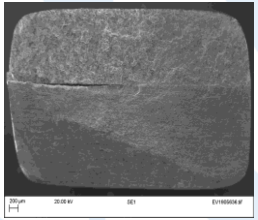
Model of a pore


Crack growth path



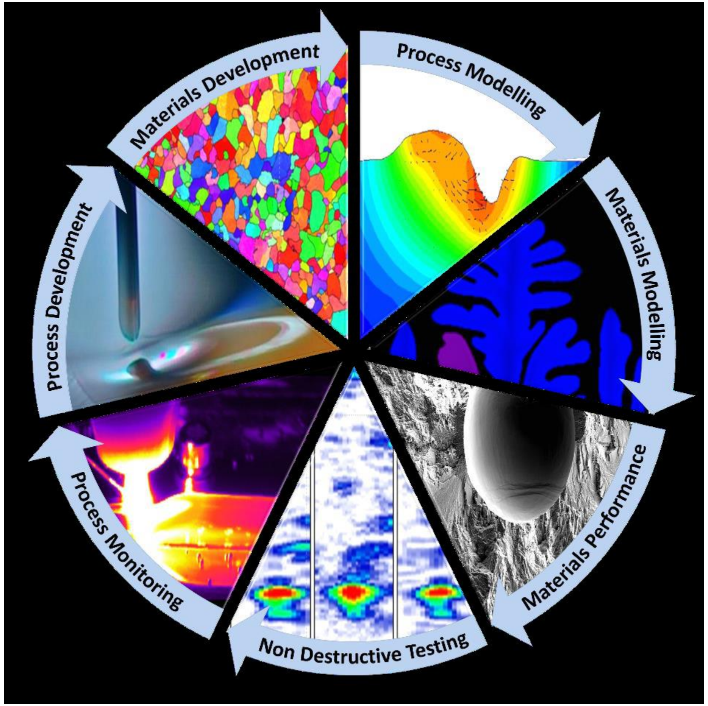






Lloyd's Register Foundation | nsirc Driving engineering excellence | TWI | Prenscia | BAE SYSTEMS | AIRBUS

“New Wire Additive Manufacturing (NEWAM)” Programme, 2018-23



Funded by EPSRC

20 project partners

https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R027218/1

Talk content

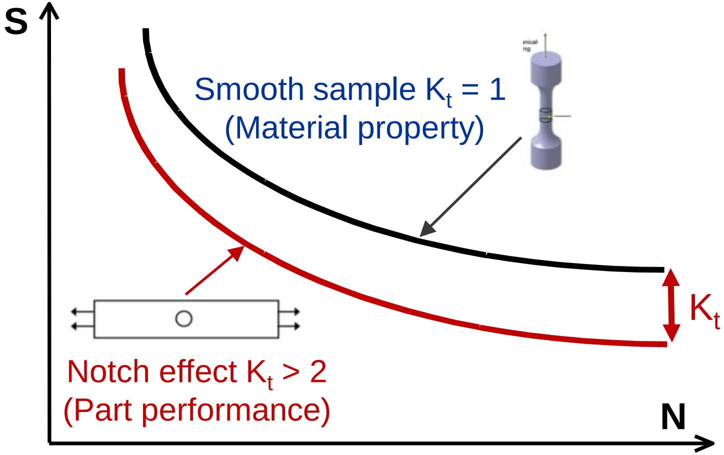
- Overview of AM research at Coventry
- WAAM Ti-6Al-4V
  - Durability
  - Damage tolerance
  - AM attributes

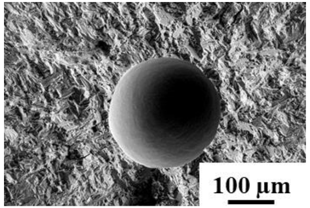
    Defects

    Microstructure and Texture

    Residual stress
- Summary

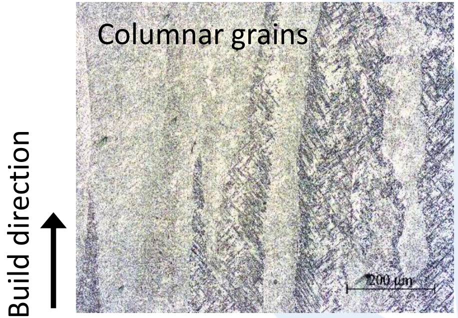
Durability





Gas pores

Surface waviness

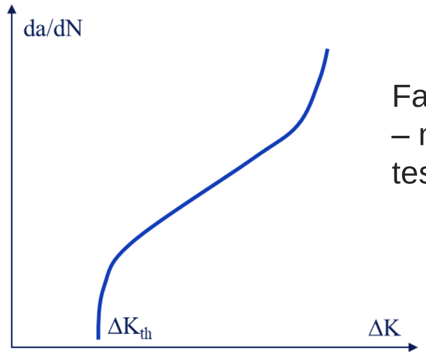


Microstructure anisotropy and heterogeneity

AM attributes

- Defects
- Surface finish condition
- Microstructure/texture
- Sample orientation
- Residual stress

Damage Tolerance



Fatigue crack growth rate – material property by testing small coupons

Crack growth life in components can be predicted based on the **Stress Intensity Factor (ΔK)** (fracture mechanics similitude principle)

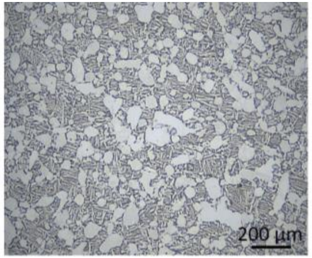
Residual stress in Wall

Residual stresses are very low in test coupons that are extracted from a larger build

AM attributes

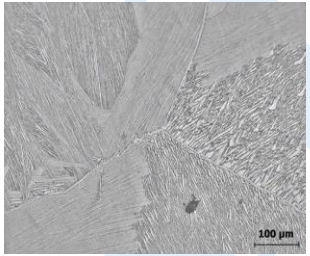
- Residual stress
- Microstructure/texture
- Test sample orientation
- Defects

Wrought (hot rolled milled)



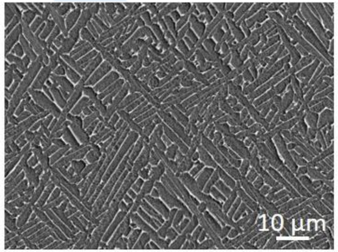
Bi-modal

Cast



Lamellar

WAAM

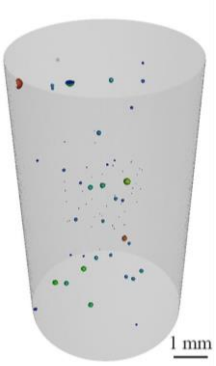


Basket weave and colony

Defect characterisation

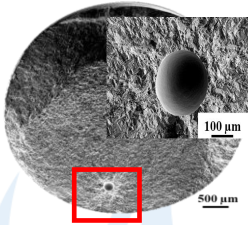
X-ray computed tomography

- Number (volume fraction)
- Morphology
- Proximity
- Size



Fractography (SEM)

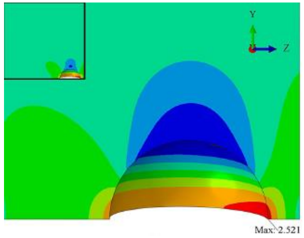
- Crack initiating pore
- Location
- Size

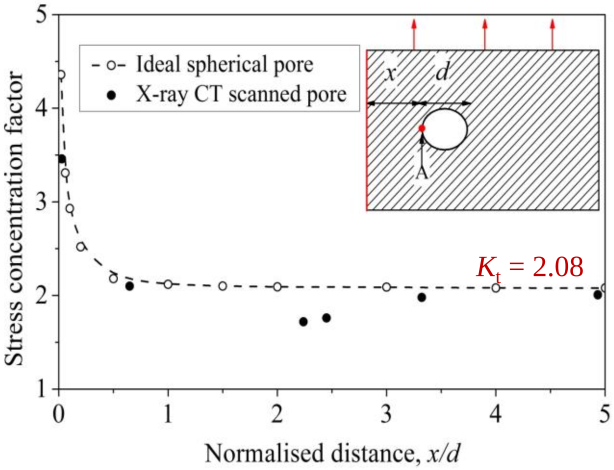


Stress Concentration Factor

- Finite element modelling
- Analytical solutions

K_t = 2.08 for spherical pores





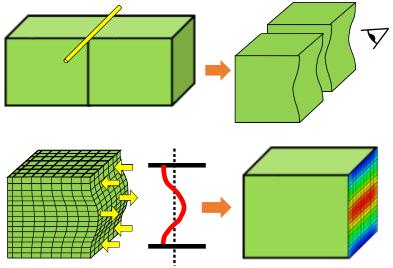
Residual stress evaluation

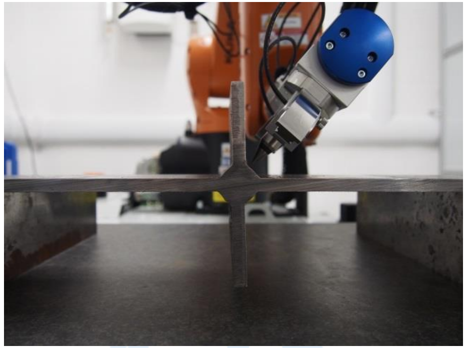
Research Centre
Manufacturing and
Materials Engineering

Coventry University

In-house facilities

- Contour method
- Incremental hole drilling
- Robot-arm X-ray diffractometer

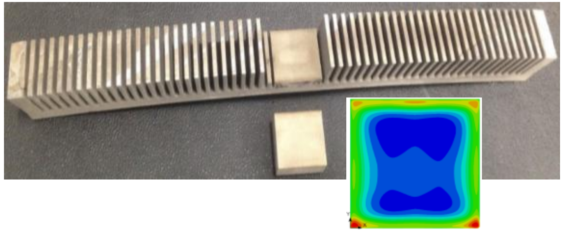




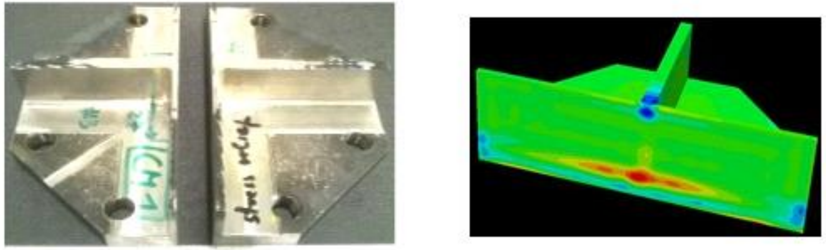
National/international facilities

- Neutron diffraction

Contour measurement examples

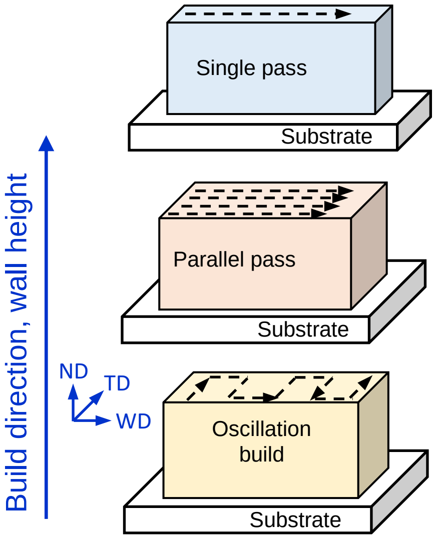


Benchmark beam (SLM Ti-6Al-4V)

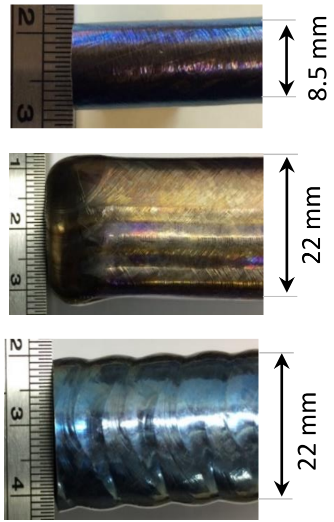


Intersection (WAAM Ti-6Al-4V)

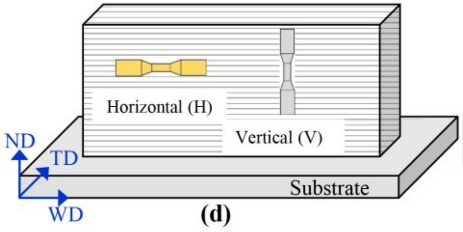
Build strategies and specimen orientations

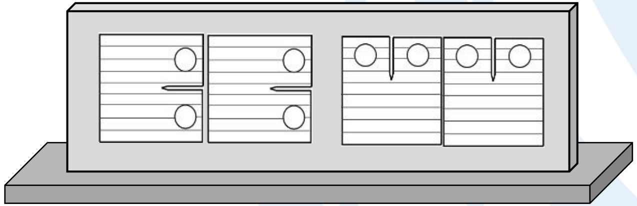


Schematic of deposition strategies



Top view of the walls

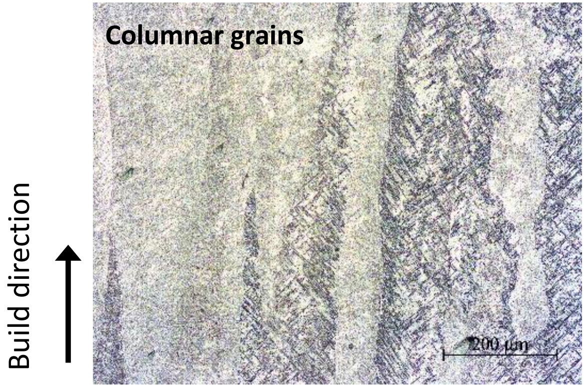


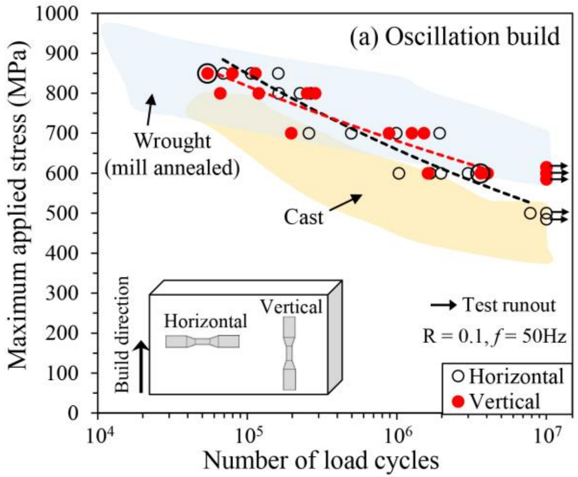


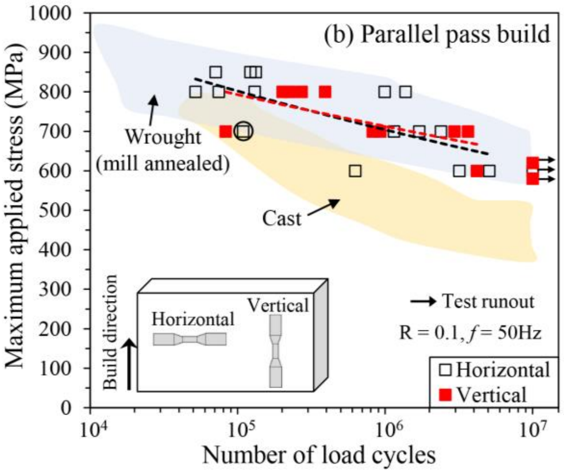
S-N Behaviour (fatigue crack initiation)

- Effect of defects and microstructure

Wire + Arc AM Ti-6Al-4V







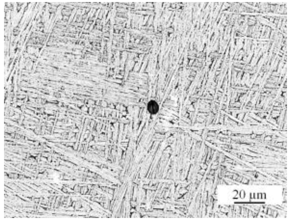
- Columnar primary beta grains did not cause property anisotropy.
- Fatigue strength is comparable with wrought and greater than cast alloys.
- Gas pores (50-70 μm typical) caused crack initiation.
- Small pores did not reduce fatigue strength (mean value) compared to initiation from alpha colony.
- Pores caused larger scatters.

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

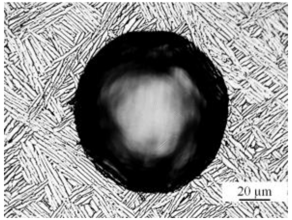
Critical pore size

In another batch of samples,

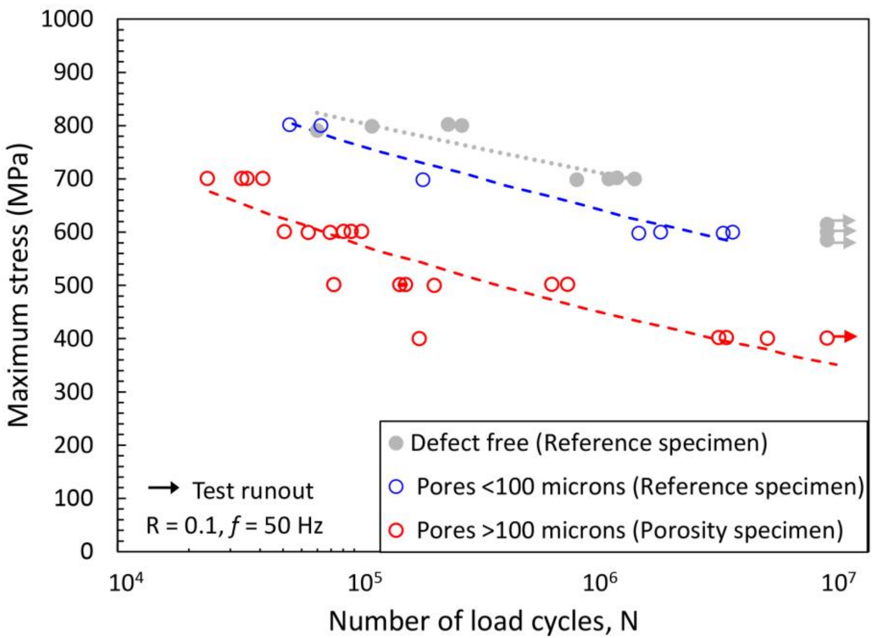
- Larger pores were purposely embedded using contaminated wires (dia.100-200 μm; vol. fraction 0.04% = fully dense)
- Critical pore diameter ~ 100 μm
- Spherical pores:
  Stress concentration factor = 2.1
  Fatigue strength reduction factor ~ 2



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

Summary

- S-N property is comparable with conventional wrought alloys.
- S-N property is isotropic.
- Large scatter in test data is caused by different crack initiation sources (small pores or alpha laths).

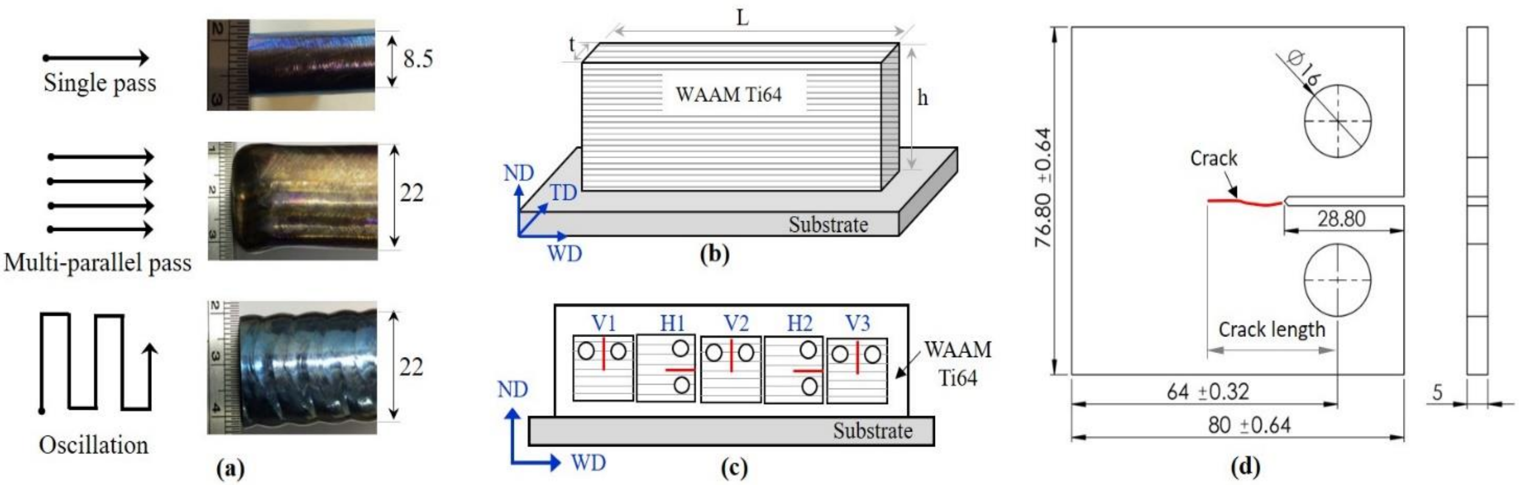
By purposely embedding pores (for damage tolerance study):

- Critical pore size is ~100 μm, fatigue strength reduction by factor ~ 2.
- Surface or sub-surface pores are more critical than internal pores in initiating cracks.

Fatigue Crack Growth Rate

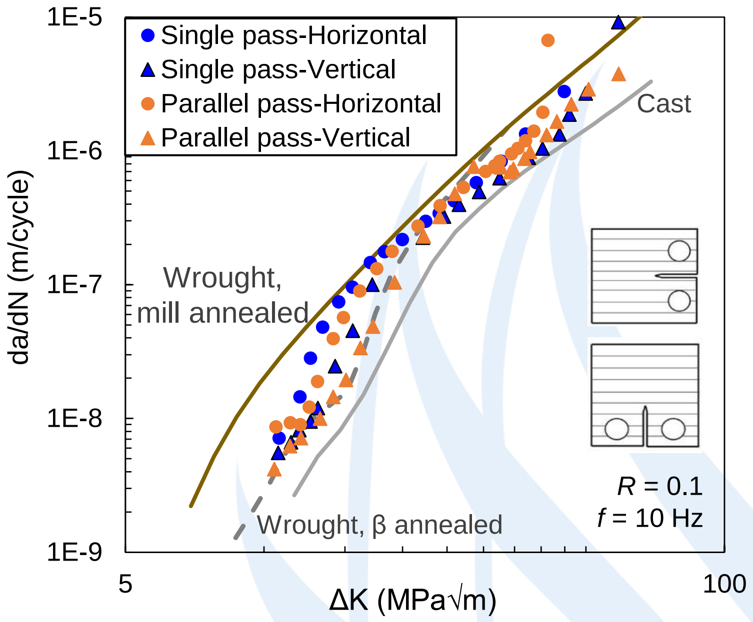
Roles of residual stress and microstructure

Build methods, specimen, and crack orientations



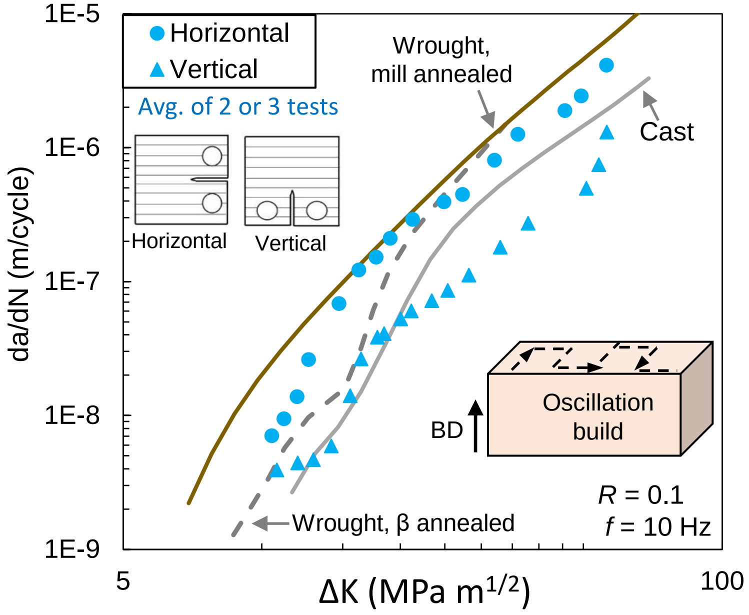
Crack growth rate
(single bead and parallel pass builds)

- Crack growth rate is between two conventional processed alloys
- Wrought mill annealed can be used as the upper bound curve for design of AM parts
- Lamellae microstructure (cast, β-annealed, WAAM) has lower crack growth rate than the equiaxed microstructure (mill annealed)
- Crack orientation effect only seen at lower Δ*K*

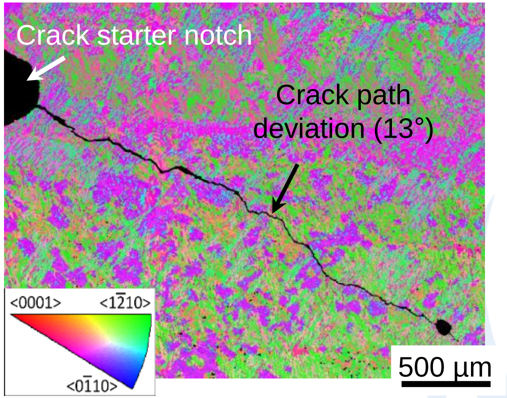


Syed, Zhang, Davis et al. Mater Sci. & Eng. A, 2021; https://doi.org/10.1016/j.msea.2021.141194

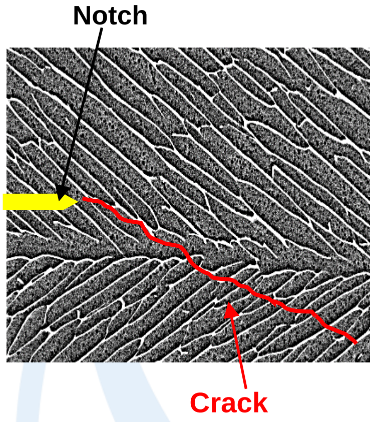
Crack growth rate (oscillation build)



Syed, Zhang, Davis et al. Mater Sci. & Eng. A, 2021; https://doi.org/10.1016/j.msea.2021.141194



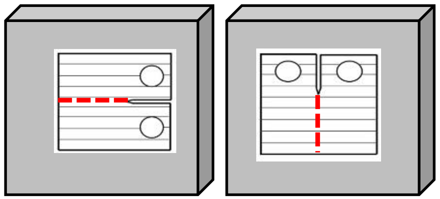
Electron Back Scattered Diffraction map



Schematic of crack deviation

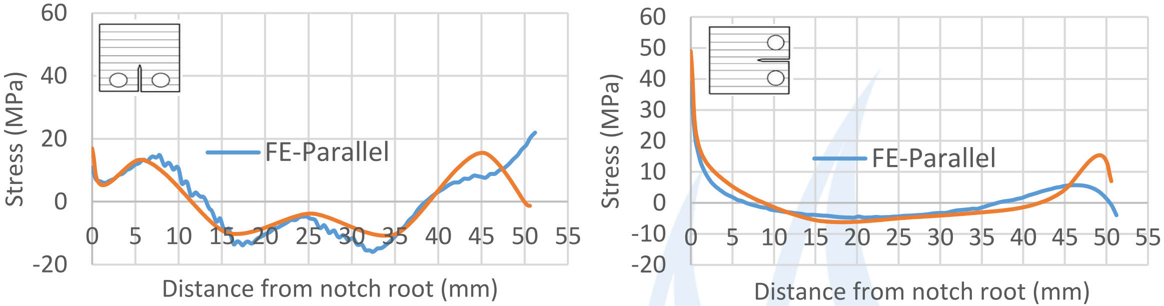
- Crack path deviation was caused by large colonies in β grain matrix.
- Crack path not perpendicular to the applied load reduces the “crack opening” stress intensity factor, decreasing crack growth rate.

Retained residual stress in test coupons (by Contour method)



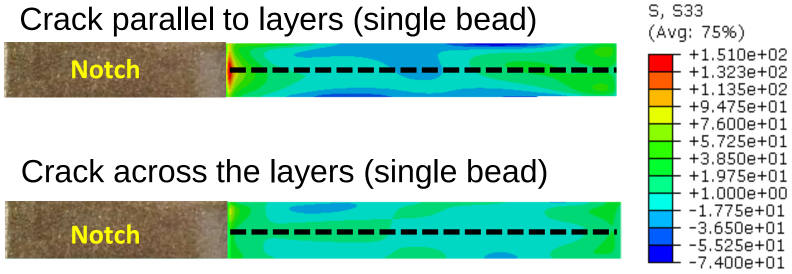
Compact Tension coupons showing a contour cutting line

Average stress



Crack parallel to layers (single bead)

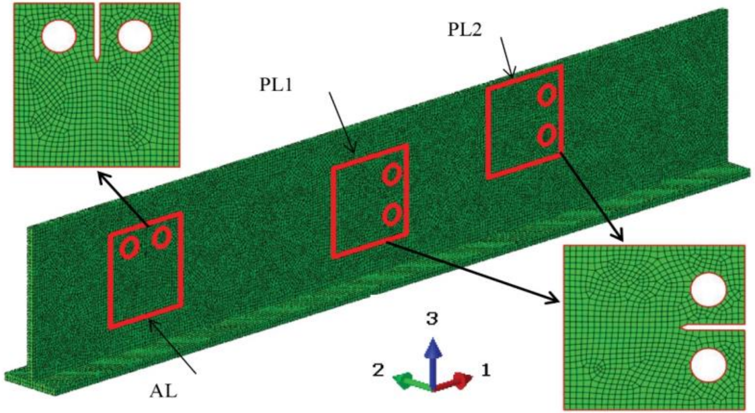
Crack across the layers (single bead)

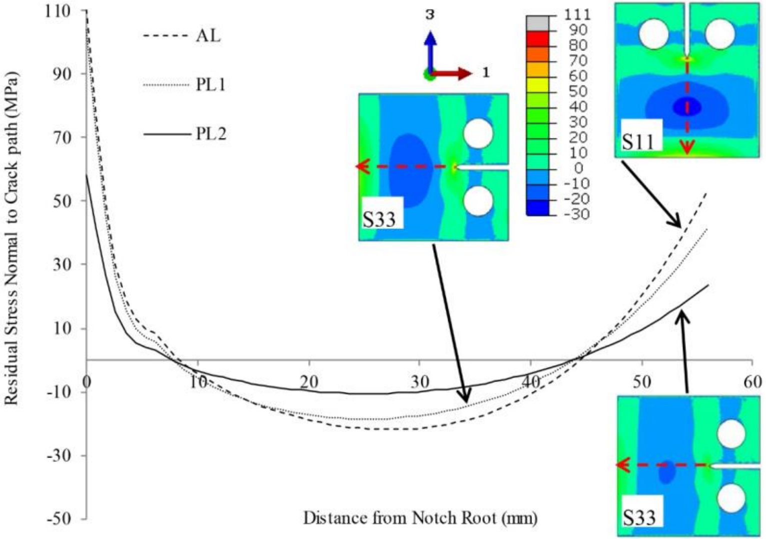


Through thickness stress profile (unit: MPa)

Residual stress in small test coupon is very low. Variations found in crack growth rate are mainly caused by differences in microstructure characteristics

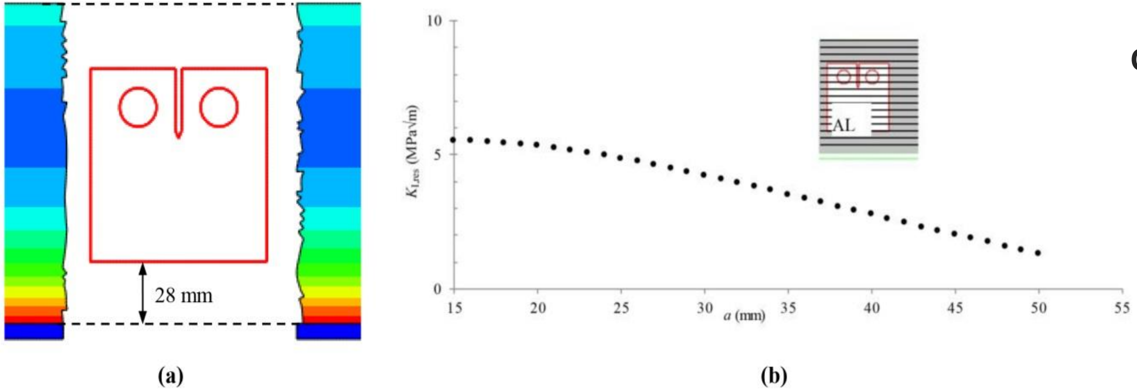
Retained residual stress in test coupons (by FEA)





X Zhang et al. Proceedings of the 29th Symposium of the International Committee on Aeronautical Fatigue (ICAF2017), Nagoya, June 2017

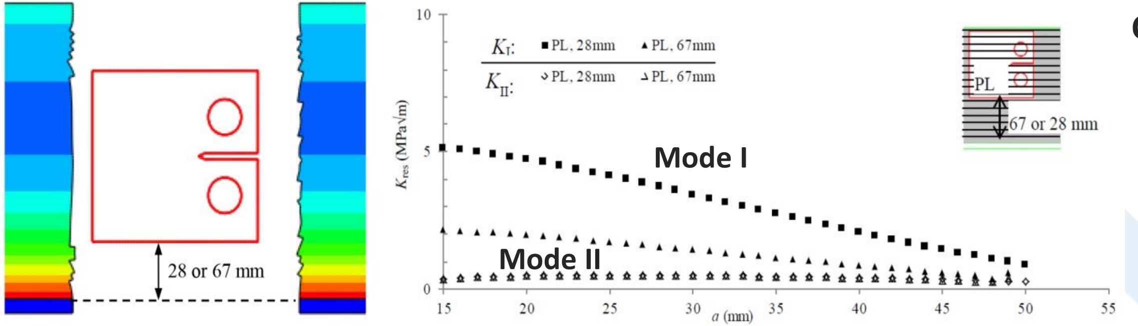
Stress Intensity Factors due to residual stress



Crack across AM layers

Mode-I only

$K_{res} = 5\ \mathrm{MPa}\sqrt{m}$



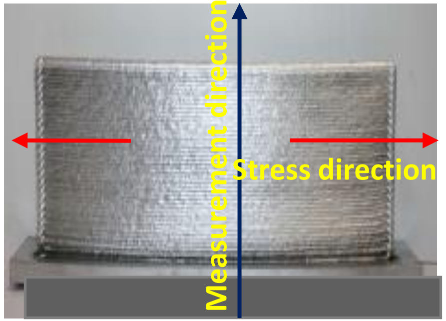
Crack parallel to AM layers

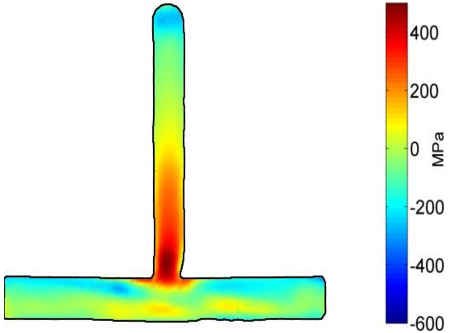
Mode-I $K_{I\text{-}res} = 5\ \mathrm{MPa}\sqrt{m}$

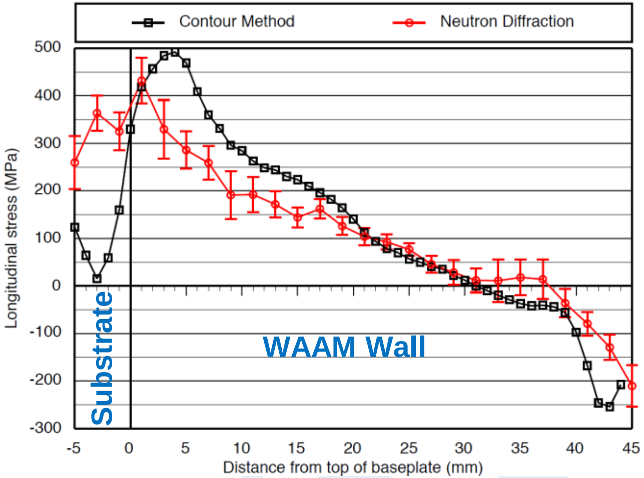
Mode-II $K_{II\text{-}res} = 0.5\text{-}1.5\ \mathrm{MPa}\sqrt{m}$ depending on specimen position

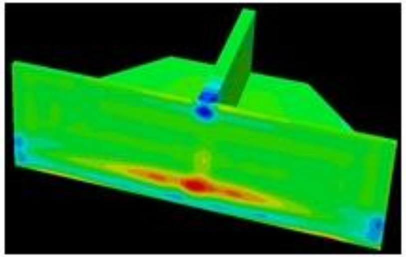
X Zhang et al. Proceedings of the 29th Symposium of the International Committee on Aeronautical Fatigue (ICAF2017), Nagoya, June 2017

Residual stress in larger parts can be high









An intersection made of WAAM Ti-6Al-4V

Max. tensile residual stress in as-built condition ~ 300 MPa, by Contour method

[Hönnige et al. Materials & Design, 2018]

Life Prediction

Research Centre Manufacturing and Materials Engineering | Coventry University

Crack growth law

$$\frac{da}{dN} = C(\Delta K, R_{eff})^n$$

$$K = \sigma\sqrt{\pi a}$$

C **and** ***n*** **are** **<u>material</u>** constants, determined by tests, taking account of:

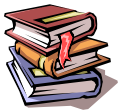
- Microstructure/Texture
- Crank orientation
- *R* ratio (mean stress)

Residual stress effect is accounted for by R_{eff} or K_{max}

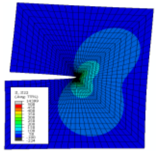
$$R_{eff} = \frac{K_{app\,\min} + K_{res}}{K_{app\,\max} + K_{res}}$$

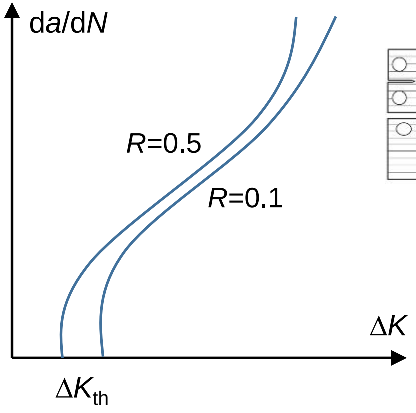
$$K_{\max,\ \mathrm{eff}} = K_{\max,\ \mathrm{app}} + K_{\mathrm{res}}$$

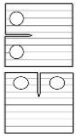
Handbooks of *K* solutions



Computer modelling (FEM)







Standard coupon test

$$\frac{\mathrm{d}a}{\mathrm{d}N} = \frac{C(\Delta K\text{-}\Delta K_{\mathrm{th}})^m}{[(1\text{-}R)K_{\mathrm{c}}\text{-}\Delta K]}$$

Hartman-Schijve (1970)
Priddle E. (1976)

$$\frac{\mathrm{d}a}{\mathrm{d}N} = D\left(\frac{(\Delta K\text{-}\Delta K_{\mathrm{thr}})}{\sqrt{1\text{-}K_{\max}/A}}\right)^p$$

Modified Hartman-Schijve eq.
(Schwalbe KH, 2010)
(Jones R, et al. 2014)

Shamir, Zhang, Syed. Eng Fract Mech., 2021; https://doi.org/10.1016/j.engfracmech.2021.107876

Summary

Fatigue crack growth rate

- between wrought mill-annealed and beta-annealed conventional alloys
- highly dependent on microstructure characteristics
- residual stress is very low in small test samples extracted from a larger build
- in crack growth laws, residual stress is considered in the “mean stress” term, either the R ratio or K_{max}

Acknowledgements

Coventry University

Dr Romali Biswal, Shamir Muhammad, Emre Akgun

Cranfield University

Dr Jialuo Ding, Dr Filomeno Martina, Professor Stewart Williams

Manchester University

Dr Alec Davis, Dr Jacob Kennedy, Professor Phil Prangnell

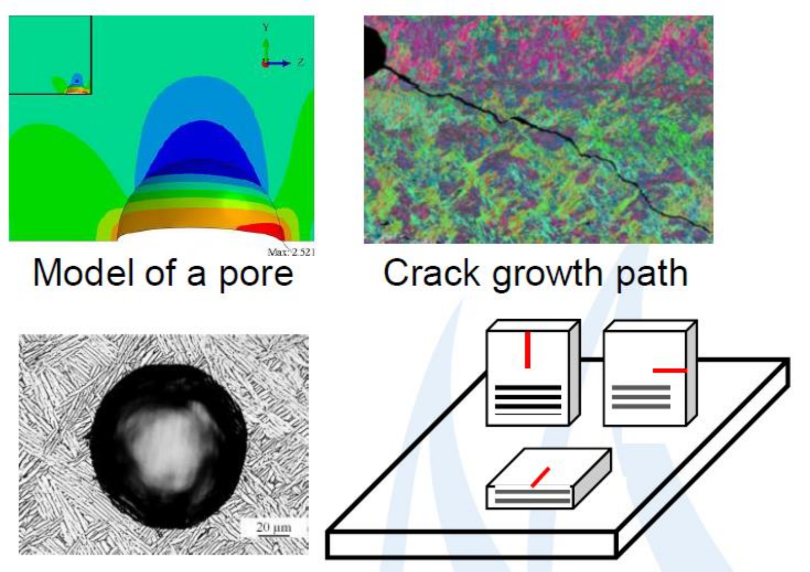
EPSRC

Programme Grant "*New Wire Additive Manufacturing (NEWAM)*": 2018-23

Thank you for your attention!

xiang.zhang@coventry.ac.uk

Virtual Seminar Series – Tuesday 2, 9, 16 November



Structural Integrity of Titanium Ti-6Al-4V additively manufactured by w-DED

Presented by Prof. Xiang Zhang
Coventry University

Tuesday, November 9, 2021