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Understanding Fatigue Performance of Additive Layer Manufactured (ALM) Titanium Alloy

Dr A Halfpenny, Director of Technology
R Plaskitt, Principal Engineer
Dr M Hill, Head of Materials Testing

nCode

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Empowering the engineering community through **software, services, and solutions** to convert engineering data into **actionable information** to improve efficiency, simulation, reliability, safety, durability…

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ALTA
Accelerated life testing

BlockSim
RBDs, Fault Trees or Markov diagrams

RENO
Probabilistic event and risk analysis

RGA
Reliability growth analysis

λPredict
Standards based reliability prediction

XFMEA
FMEA and related analyses

RCM++
Reliability centered maintenance

RBI
Risk based inspection analysis

MPC
MSG-3 Maintenance program creation

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Acoustics and vibration analysis

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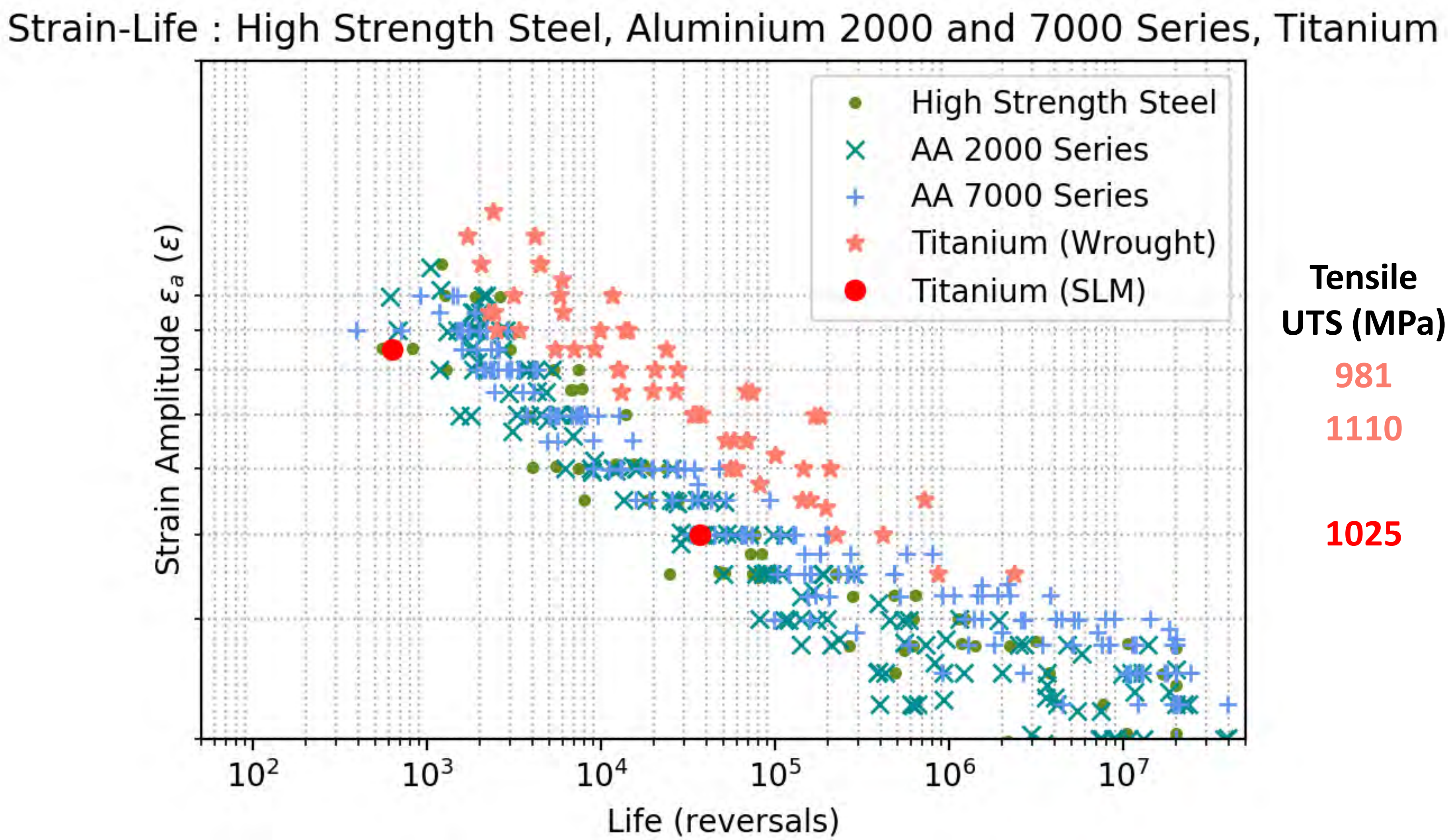
"it is pretty good in Tensile, but it is * (not very good) in Fatigue"***



Tensile UTS (MPa)

981

1110

1025

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ICAF 2019

36th Conference & 30th Symposium of the International Committee on Aeronautical Fatigue and Structural Integrity

Poland, Kraków 2- 7 June 2019

International Committee on Aeronautical Fatigue and Structural Integrity

Agenda

1. **Additive Introduction**
2. Specimen Manufacture
3. Fatigue Testing
4. Fatigue Characterisation
5. Fatigue Test Results
6. Conclusions and Further Work

- **Airbus** completed installation of titanium 3D-printed bracket on an in-series production A350 XWB.
- Built using additive-layer manufacturing (ALM).

News

First titanium 3D-printed part installed into serial production aircraft

For the first time Airbus has completed the installation of a titanium 3D-printed bracket on an in-series production A350 XWB.

The bracket, built using additive-layer manufacturing (ALM) technologies (also known as 3D printing), is part of the aircraft pylon, the junction section between wings and engines. This is the first step toward qualification of more complex 3D-printed parts to be installed on production aircraft.

Additive-layer manufacturing 'grows' products from a fine base material powder – such as aluminum, titanium, stainless steel and plastics – by adding thin layers of material in incremental stages, which enables complex components to be produced directly from computer-aided design (CAD) information.

Aerospace Testing International, September 2017
https://www.aerospacetestinginternational.com/news/industry-news/first-titanium-3d-printed-part-installed-into-serial-production-aircraft.html

- Norsk Titanium to deliver world's first FAA-approved, 3D-printed, structural titanium components to **Boeing**.
- Built by Norsk Titanium using wire-based Rapid Plasma Deposition (RPD) process.

News

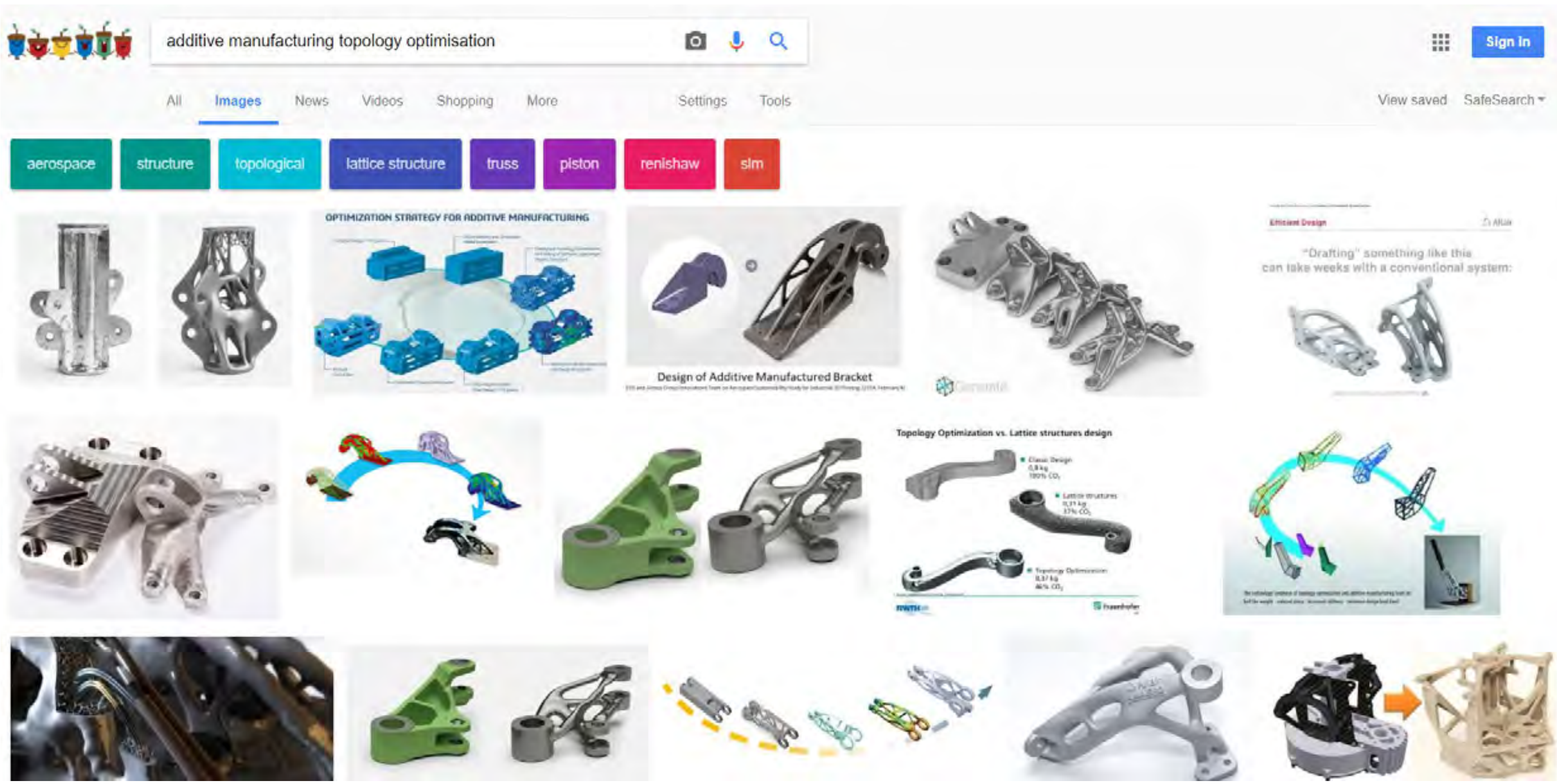
Norsk Titanium to deliver world's first FAA-approved, 3D-printed, structural titanium components to Boeing

Norsk Titanium, a leading supplier of additive-manufactured structural titanium components, has received a production purchase order for 3D-printed structural titanium components from Boeing that are being produced by Norsk's proprietary Rapid Plasma Deposition (RPD) process.

Aerospace Testing International, April 2017
https://www.aerospacetestinginternational.com/news/industry-news/norsk-titanium-to-deliver-worlds-first-faa-approved-3d-printed-structural-titanium-components-to-boeing.html

Introduction

- Additive manufacturing ➔ increase design freedom + reduce need for machining
- Many organisations present tools for structural topology optimisation

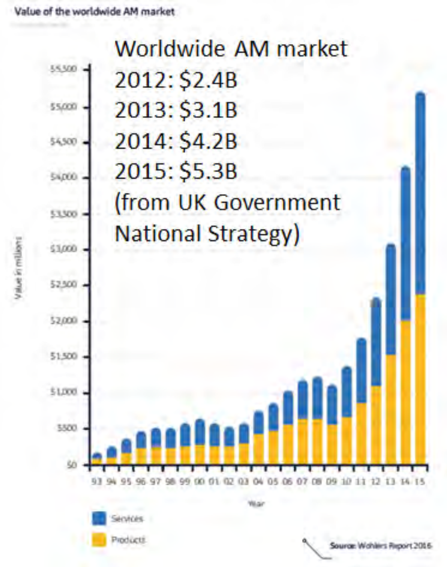


...it is not all about shape

– material strength, and particularly fatigue performance are crucial!

Introduction

- Worldwide AM business sector valued at **$5.3B** in 2015 and increasing rapidly.
  - UK National Strategy for Additive Manufacturing / 3D Printing, September 2016 http://www.amnationalstrategy.uk/



- *"**Fatigue** is a **principal failure mode** of structural AM components and is a hurdle to its general acceptance."*
  - Lloyd's Register Foundation
    Foresight Review of Structural Integrity and Systems Performance, November 2015
    http://www.lrfoundation.org.uk/publications/structural-integrity-and-systems-performance.aspx

- ***"Additive manufacturing (AM) techniques have significant barriers to overcome in delivering a manufacturing process that produces consistent quality and safety."***
  - Lloyd's Register and TWI, March 2017
    Example Guidance Notes for certification and qualification
    http://www.lr.org/en/services/additive-manufacturing/additive-manufacturing-guidance-notes.aspx

Military Aircraft Structural Airworthiness Advisory Group
MASAAG Paper 124 Issue 1
Guidance Note on the Qualification and Certification of AM Parts for Military Aviation

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- *"It has been emphasised that the **sources of scatter in both static strength and deformation, and fatigue properties could be high in AM parts**; higher than is usual for those from conventional manufacturing."*

- *"Further the **properties of an AM part are affected by**, amongst many other things, its **size, geometry, location in the build volume and orientation to the build direction**."*

- *"For Grade A metallic aircraft structures, until such time that AM is sufficiently mature, **it is recommended that both the AM process AND the part are qualified and certified** as a way of establishing and guaranteeing variability."*

GOV.UK MASAAG Documents
https://www.gov.uk/government/publications/military-aircraft-structural-airworthiness-advisory-group-masaag-documents

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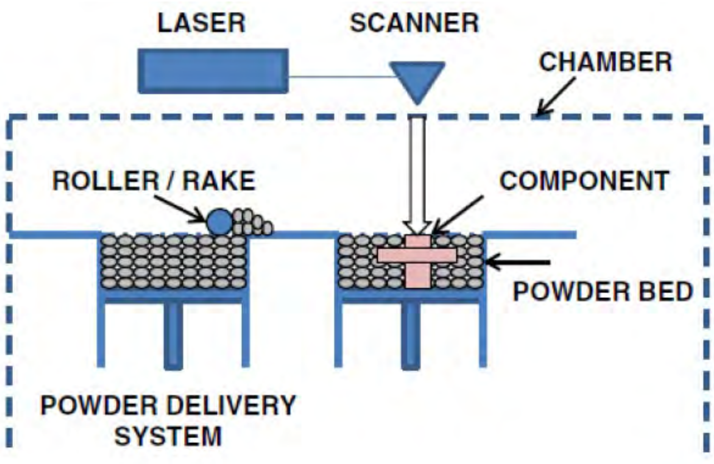
Specimen Manufacture

- Powder Bed Fusion (PBF)
  - Thermal energy selectively fuses regions of a powder bed
  - Two common heat sources:
    - o ***Electron Beam (EB-PBF) – electron beam melting "EBM"***
    - o *Laser (L-PBF) – selective laser melting "SLM"*

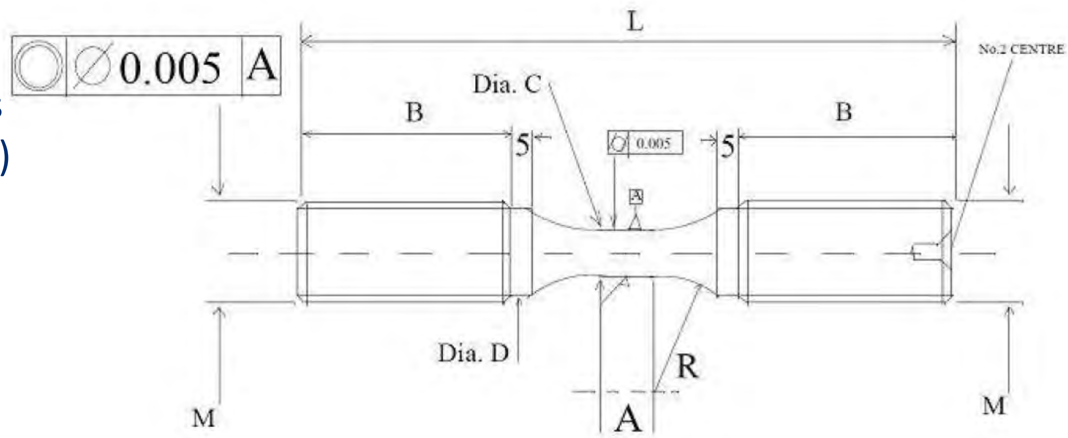


"SI Performance of AM Ti Alloys", Zhang RAeS Conference, AMRC Sheffield, 5 April 2017

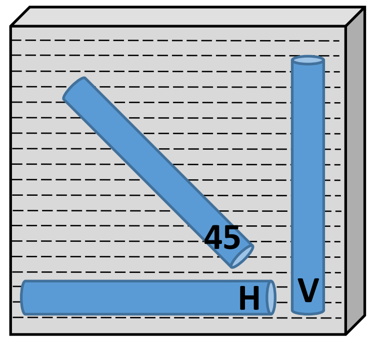
- Hot Isostatic Pressing (HIP)
  - A manufacturing and heat treatment process to reduce porosity and improve a material's mechanical properties, particularly fatigue resistance.
  - It is used to densify powders or cast and sintered material in a furnace at high pressure and at high temperature.
  - "PM HIP case studies.pdf" - from https://www.epma.com/hot-isostatic-pressing

Specimen Manufacture

- Material : Titanium Ti-6Al-4V alloy
- Geometry
  - Machined from cylindrical blanks (*except Wrought Sheet Annealed*)
  - Polished gauge section
    6 mm diameter, 10 mm length



- EBM specimens in 3 build orientations and 2 post manufacture conditions:
  - Vertical build orientation, with no post manufacturing treatment
  - Three build orientations, with post manufacturing HIP
    - Vertical, Horizontal and
      45 Degrees build orientations
- SLM specimens
  - Vertical build orientations, and stress relieved
- PM HIP specimens
  - Cut and machined from a large block



Specimen Manufacture : Titanium Alloy Ti-6Al-4V Conditions

Material Condition	Manufacturing Description	UTS (MPa)
EBM As-Built (V)	Cylindrical blanks, EBM, built vertically, with no post-manufacturing heat treatment.	1133

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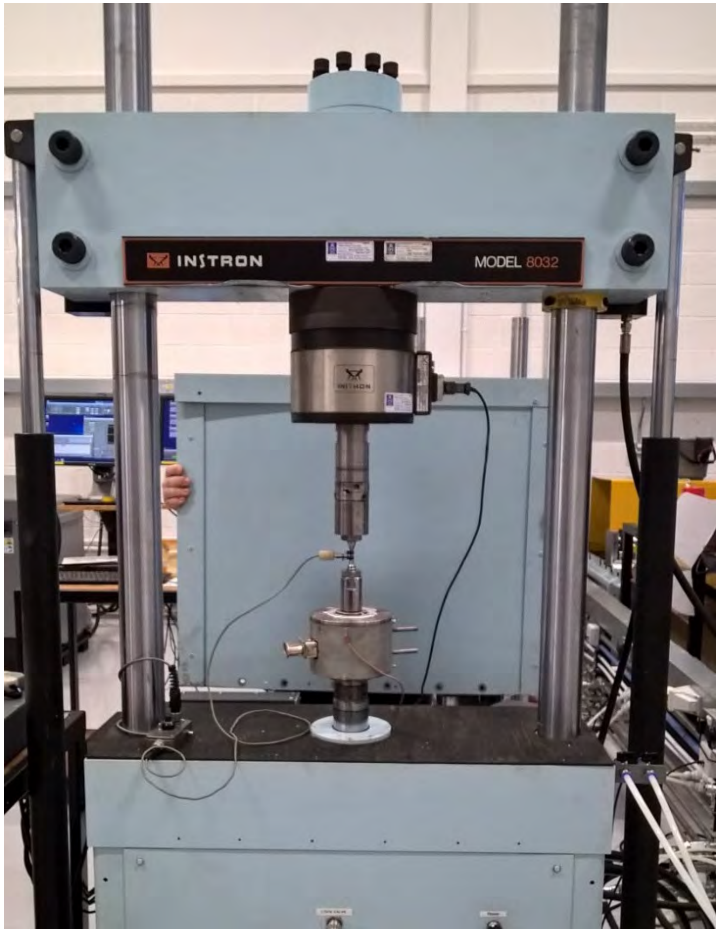
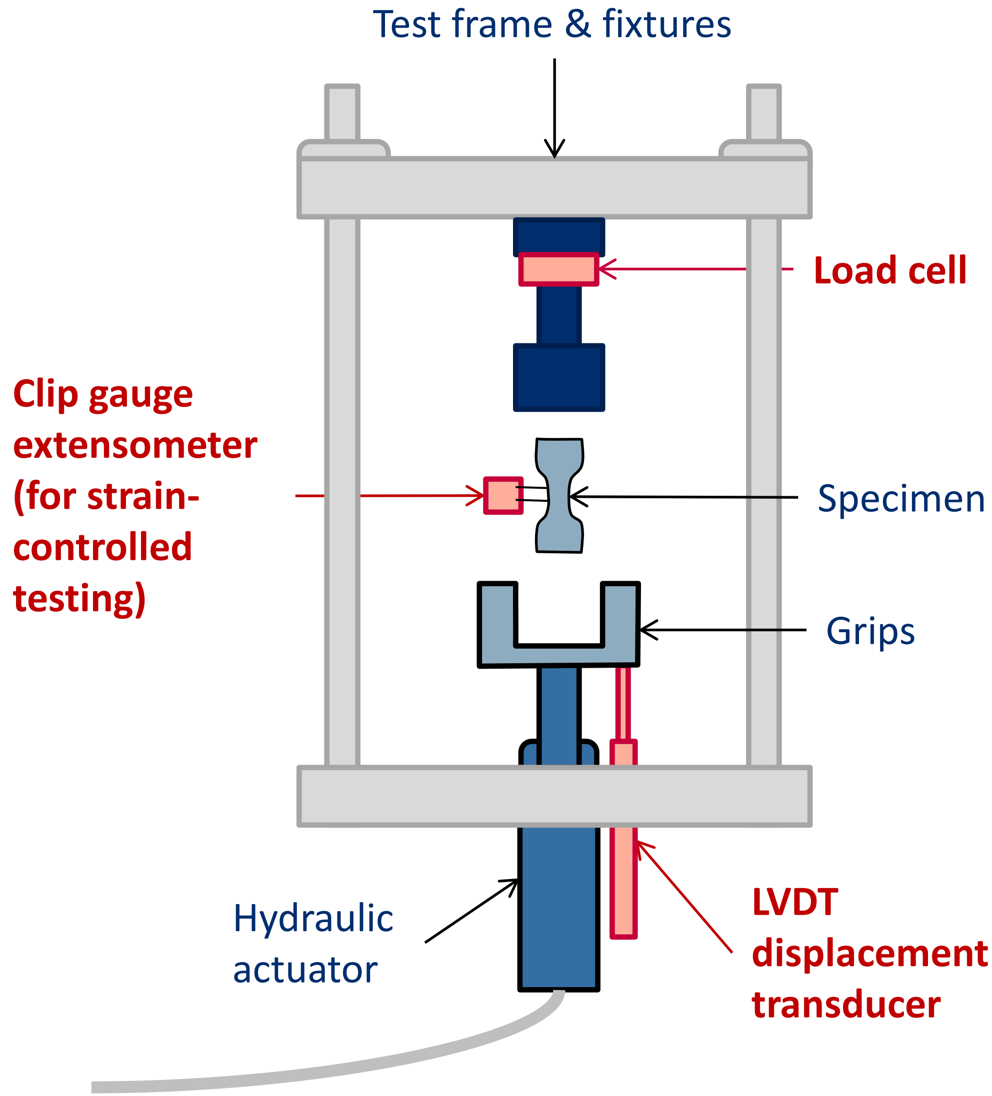
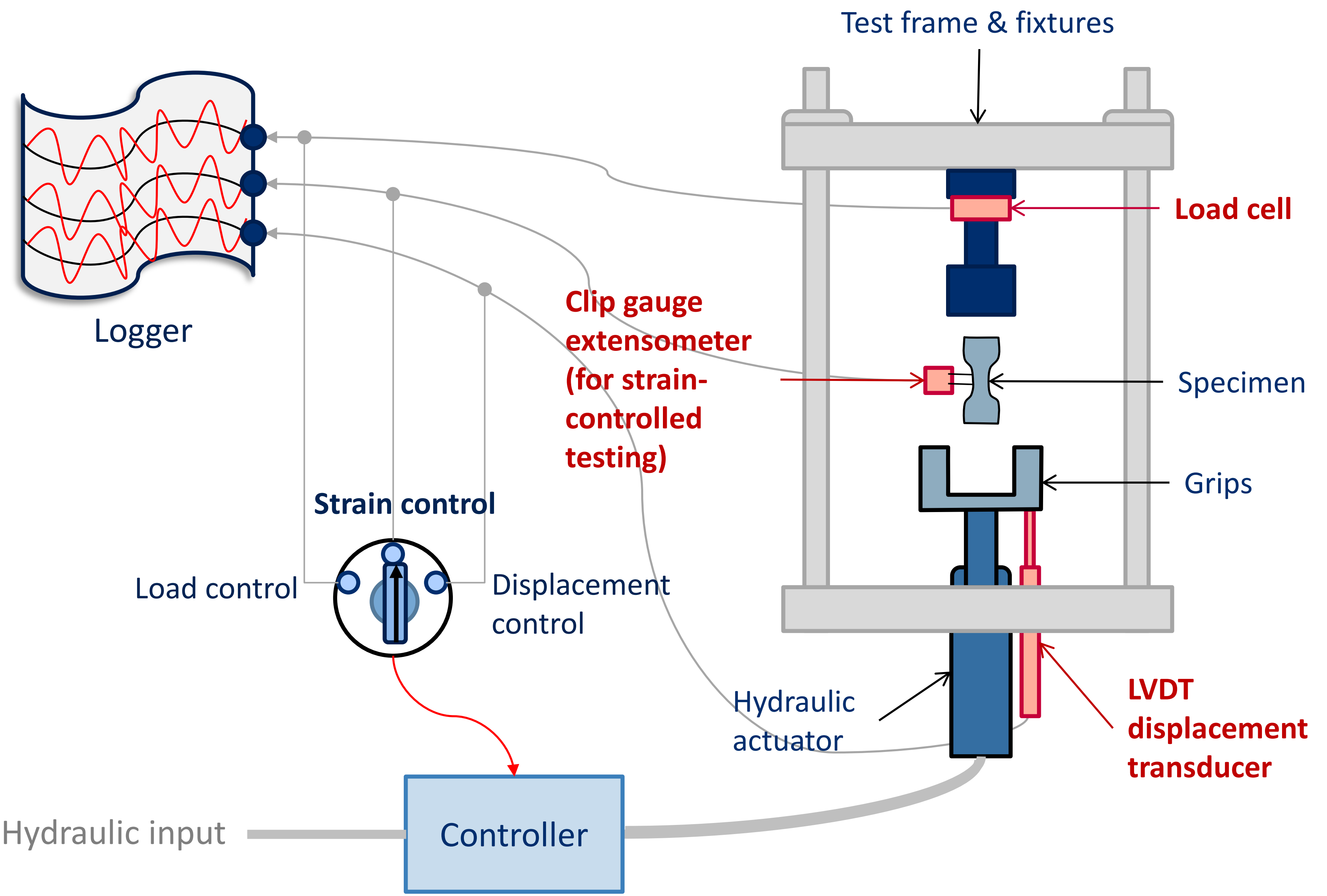
Fatigue Testing : Axial Fatigue Test Rig





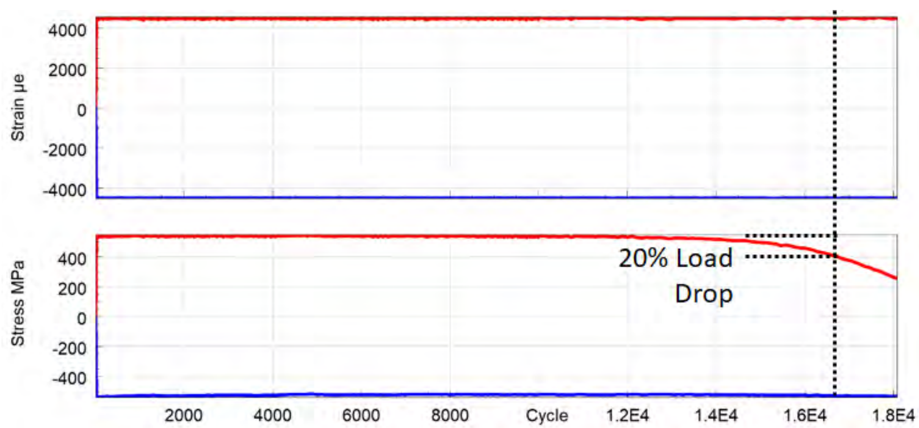
Fatigue Testing : Axial Fatigue Test Rig



Fatigue Testing : Test Conditions, Test Monitoring and Failure Criteria

- Test Condition
  - Room temperature
  - Strain controlled
  - Triangular waveform (EBM)
    Sinusoidal waveform (all others)
  - Fully reversed (R = -1)
  - Soft start – a slow increase to target strain in first few cycles
  - 0.5 Hz for first 43200 cycles (= 1 day) increased if/when appropriate

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



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

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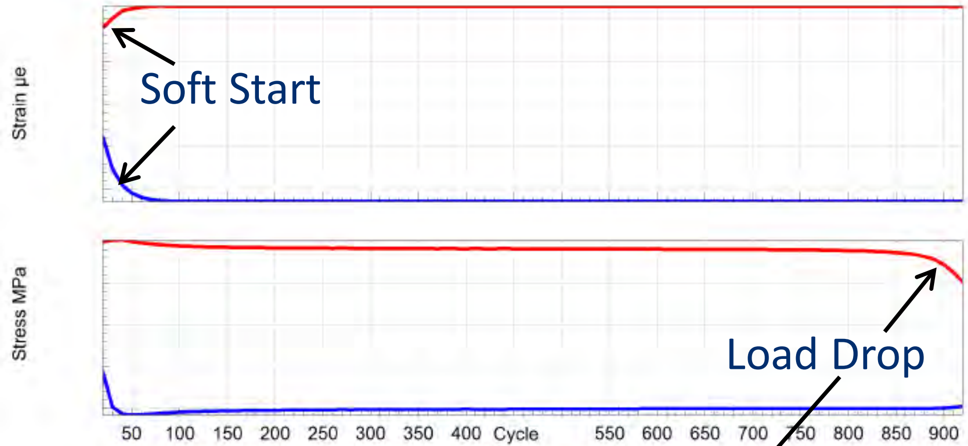
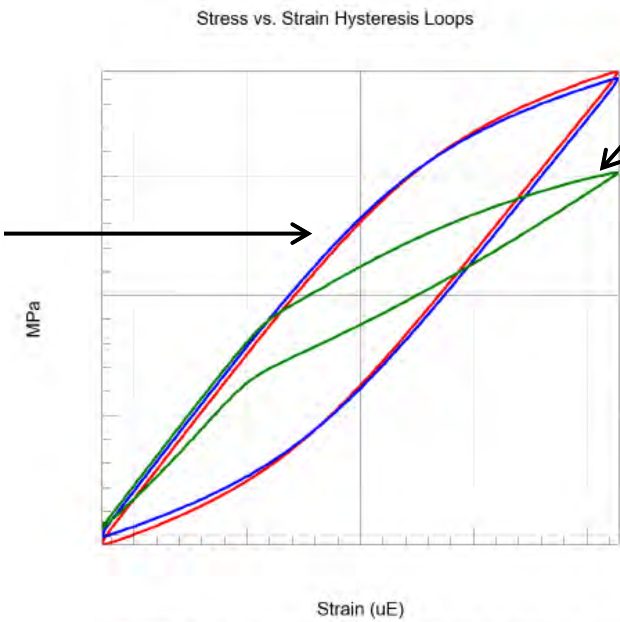
Fatigue Testing : Post-Test Analysis

Strain

Stress



Hysteresis
Loops



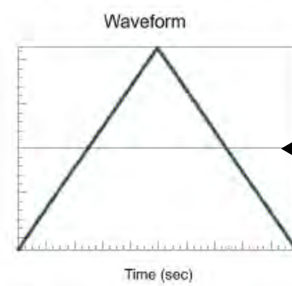
..	Cycle Nu...	Total Stress	Total Strain	Elastic Str...	Plastic Str...
	100				
	460				
	910				

Cross sectional area = 19.55649 mm²
Cycles Gate = 92
Separation Cycles = 926

Number of cycles = 920
Stable loop = 100 cycles
5% load drop = 430 cycles
10% load drop = 870 cycles
20% load drop = 910 cycles
50% load drop = 920 cycles

Cycle rate = 0.5011 Hz
Sample rate = 308 points/loop

Cycles to Failure
at different
Failure Criteria



Waveform

Total Stress
Total Strain
Elastic Strain
Plastic Strain

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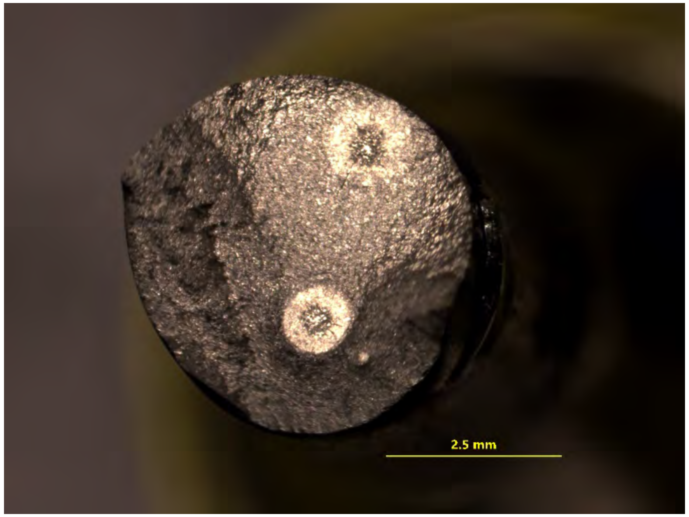
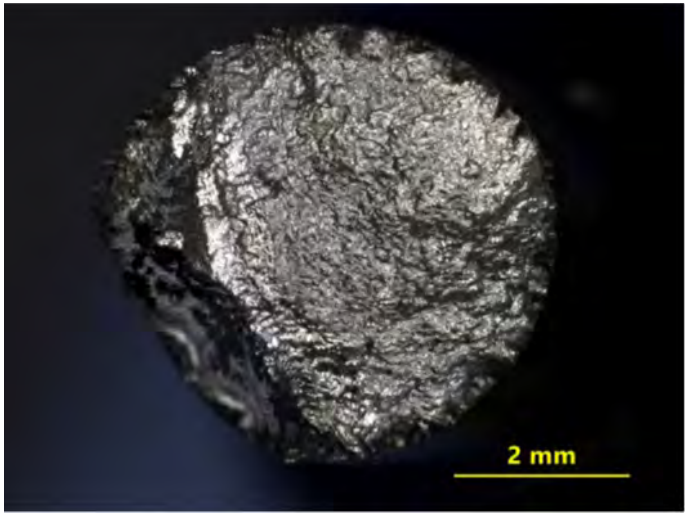
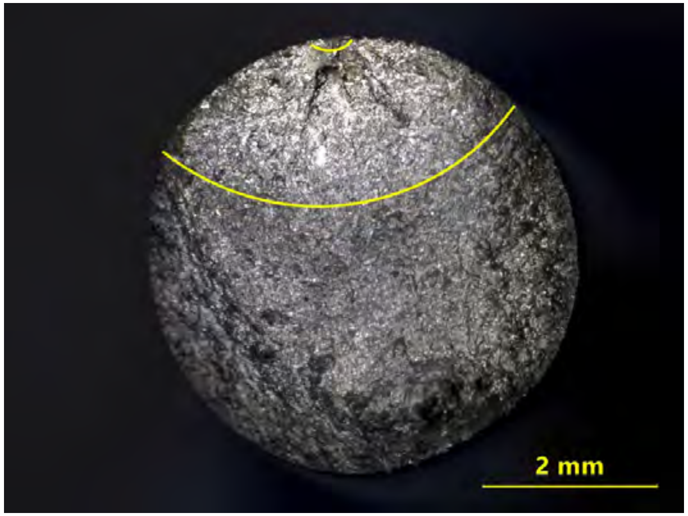
- Failure Surfaces
  - Predominantly plastic
  - Predominantly elastic
    (crack nucleated at surface)
  - “Double Fish Eye”
    (two cracks nucleated internally)







Agenda

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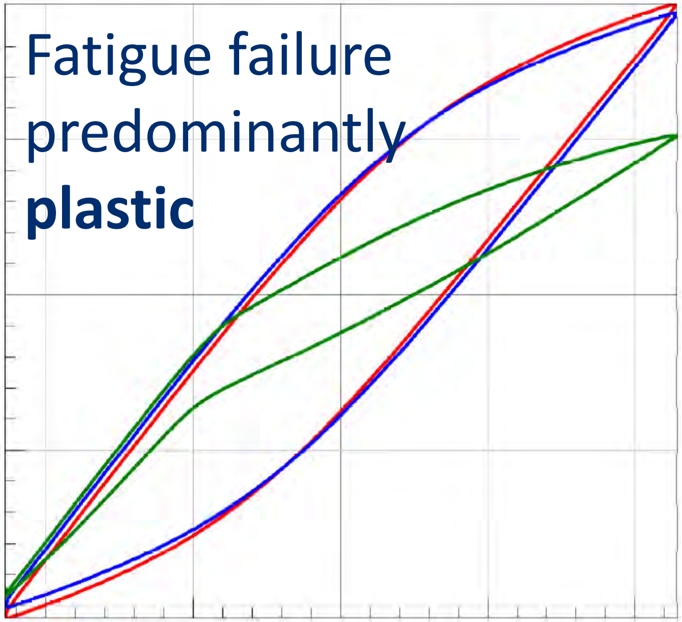
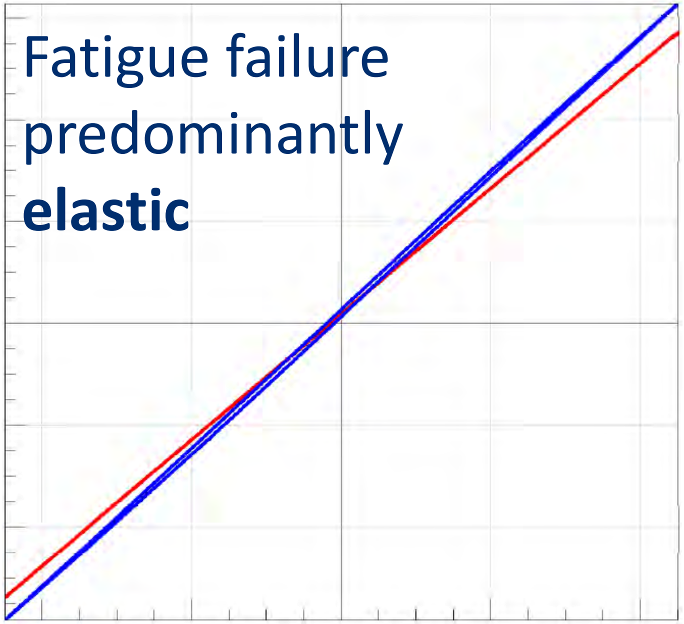
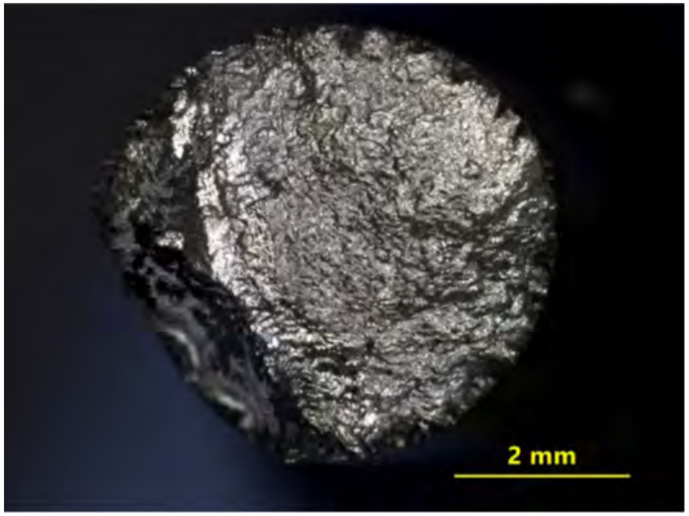
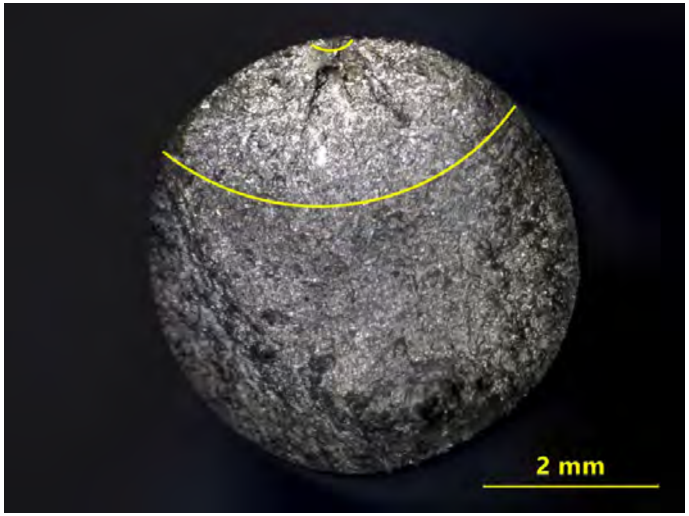

Fatigue failure
predominantly
plastic


Fatigue failure
predominantly
elastic

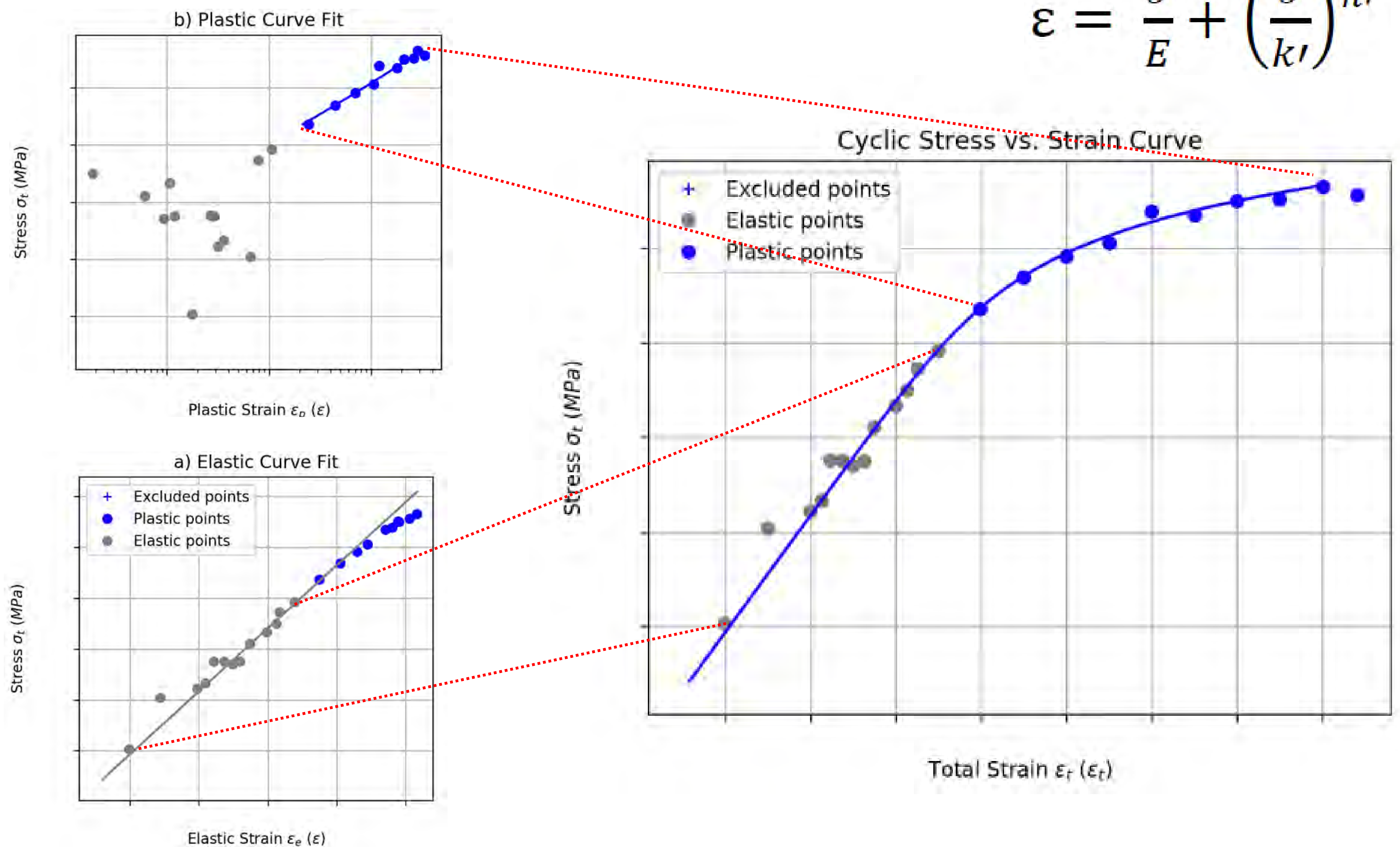

2 mm


2 mm

Fatigue Characterisation : Cyclic Stress-Strain Curve

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

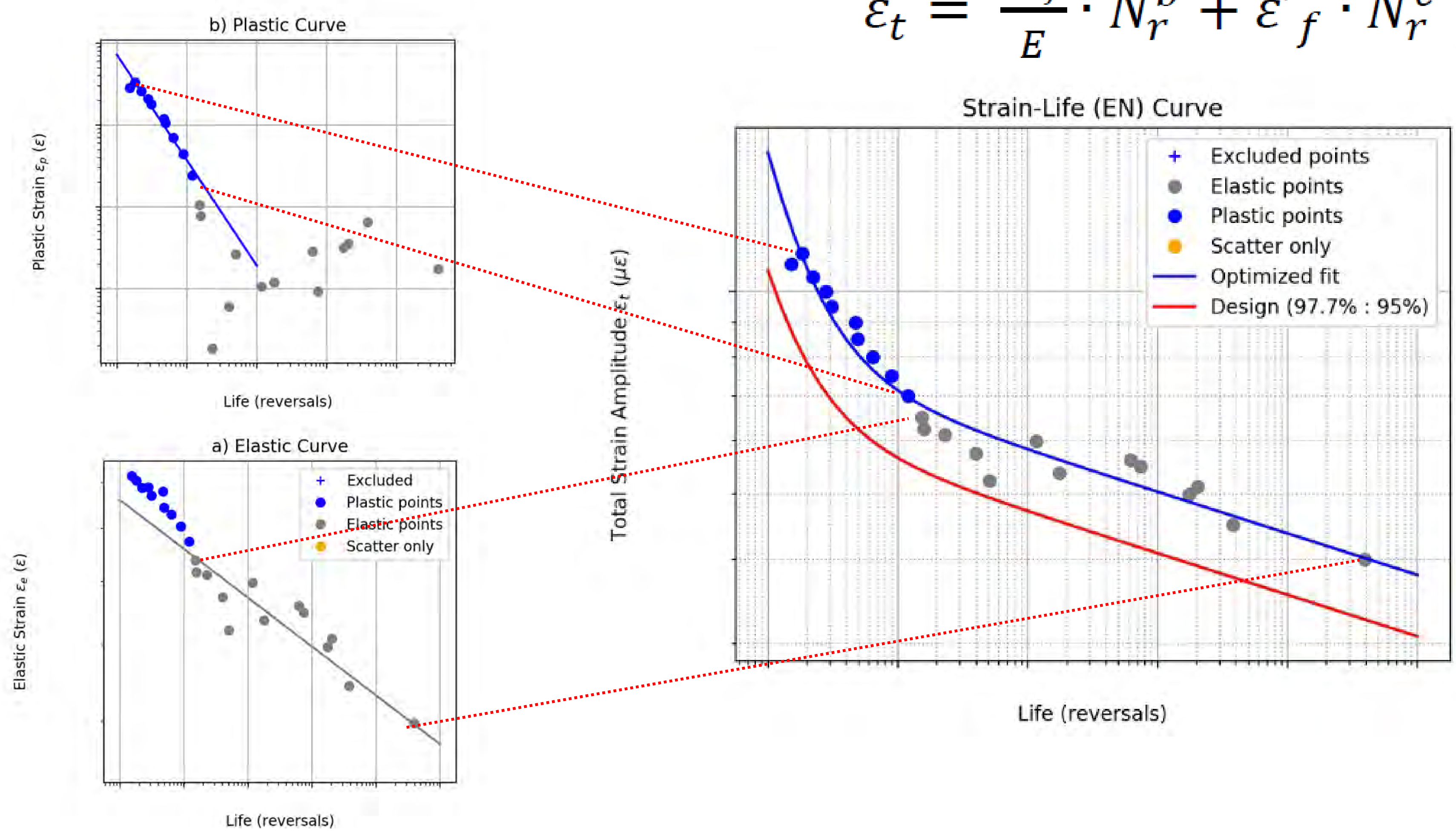
$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{k'}\right)^{\frac{1}{n'}}$$



Fatigue Characterisation : Strain-Life Curve

- Fitting the Basquin and Coffin-Manson parameters for the strain-life curve

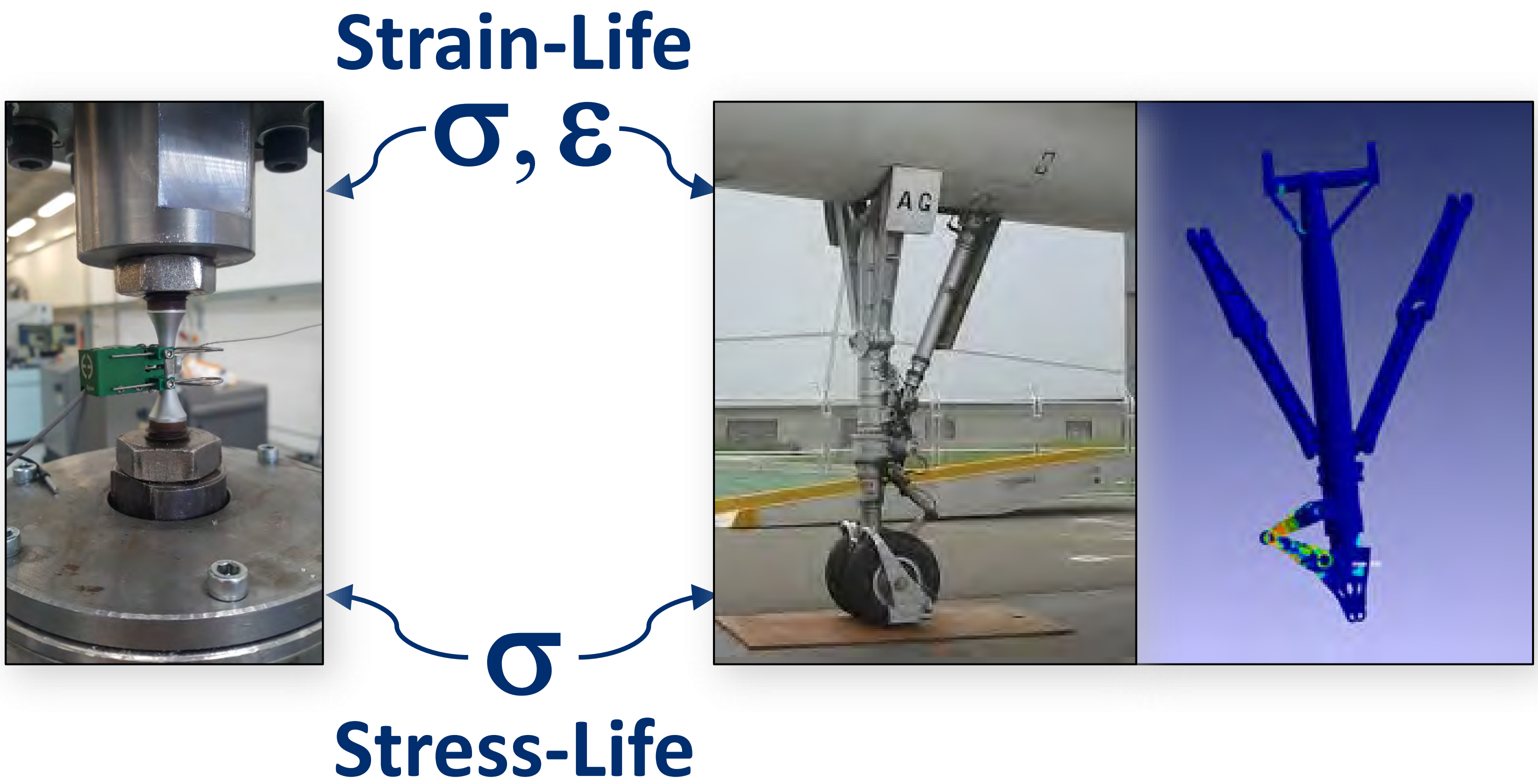
$$\varepsilon_t = \frac{\sigma'_f}{E} \cdot N_r^b + \varepsilon'_f \cdot N_r^c$$



Fatigue Characterisation : 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

- Virtual fatigue testing



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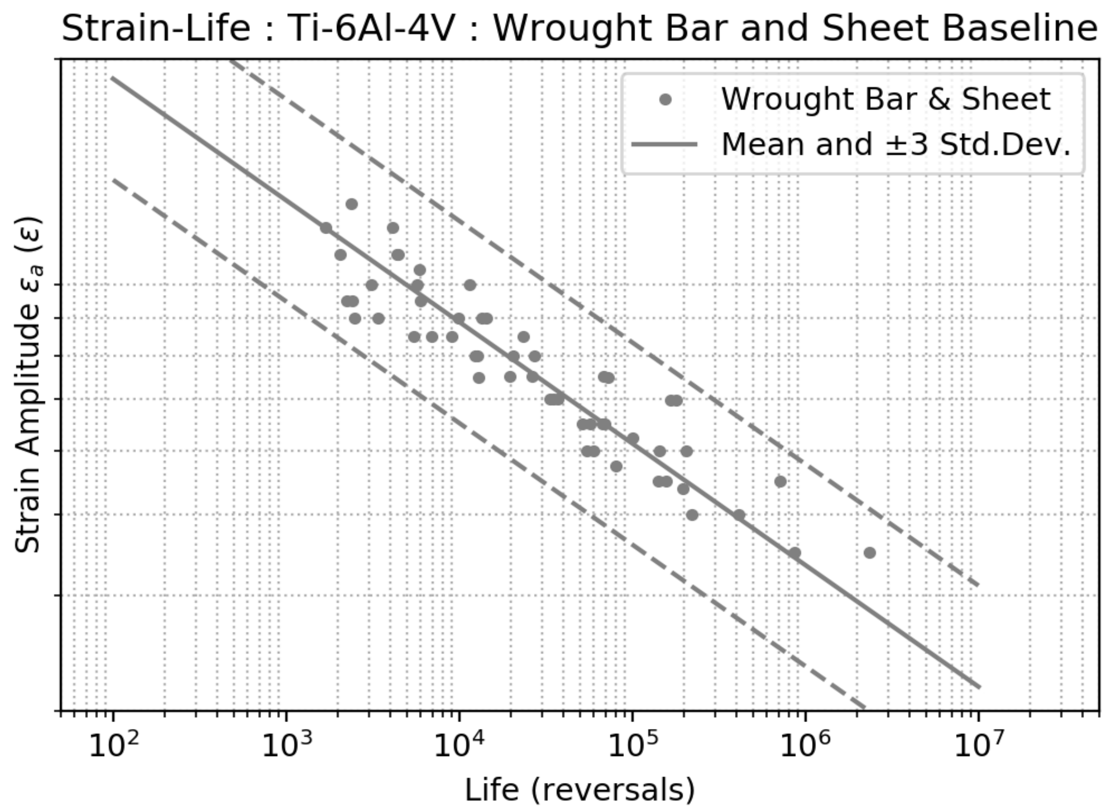
Fatigue Test Results : Wrought Bar and Sheet Baseline

- Wrought Bar and Sheet Baseline
  - High scatter – because combined results
  - Two batches of wrought bar
  - One batch of wrought sheet (longitudinal & transverse rolling directions)



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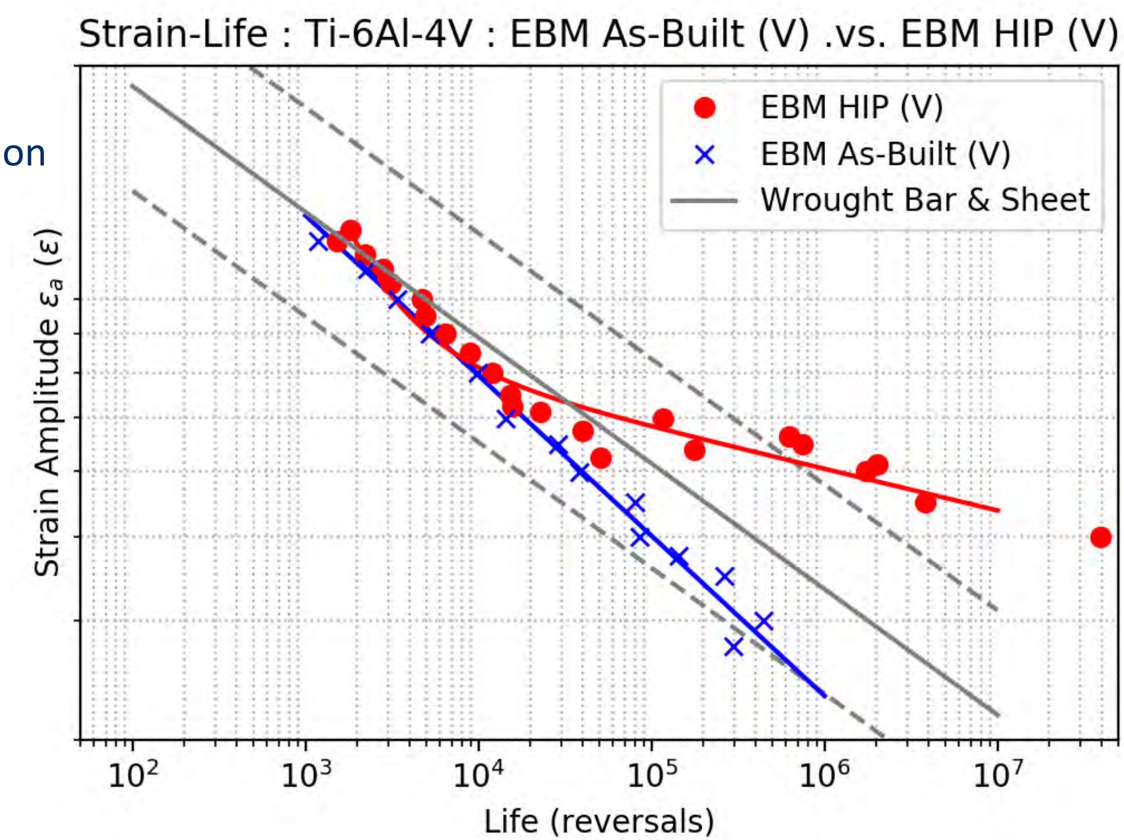
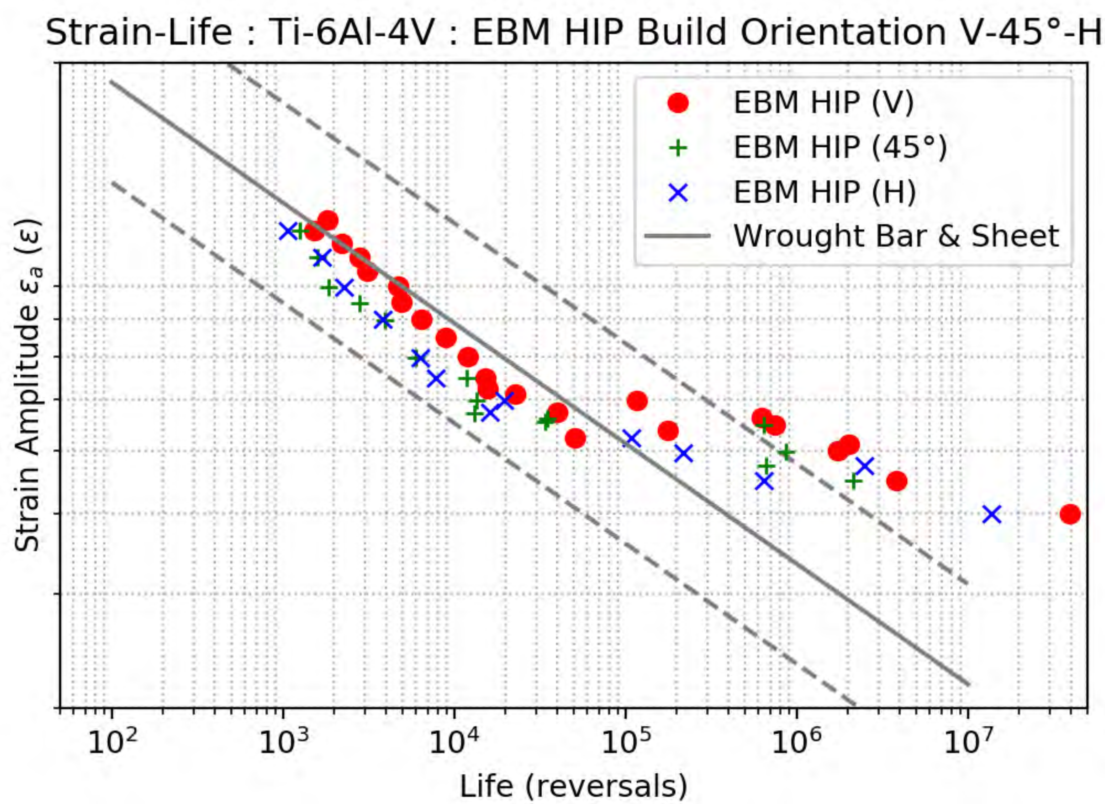
Fatigue Test Results : Compare vertical build EBM, with and without HIP treatment

- Wrought Bar and Sheet Baseline
- EBM As-Built (V) : 15 samples (*with no post heat treatment*)
  - Low scatter
  - Lower life than baseline but generally within 3σ
  - Increase in slope
- EBM HIP (V) : 27 samples
  - Low scatter in low cycle region
  - Notable increase in life in high cycle region
  - …, but with high scatter in this high cycle region
  - Expected as a result of the HIP post manufacture heat treatment - reducing porosity and potential fatigue crack nucleation sites has most effect in high cycle region



Fatigue Test Results : Compare EBM build orientations, all with HIP treatment

- Wrought Bar and Sheet Baseline
- EBM HIP (V) : 27 samples
- EBM HIP (45°) : 15 samples
- EBM HIP (H) : 16 samples
  - All three build orientations show similar characteristics
  - Low scatter in low cycle region
  - Notable increase in life in high cycle region
  - …, but with high scatter in this high cycle region
  - Vertical build generally has longer fatigue lives (built in one build)
  - 45° and horizontal build are very similar (built together in one build)



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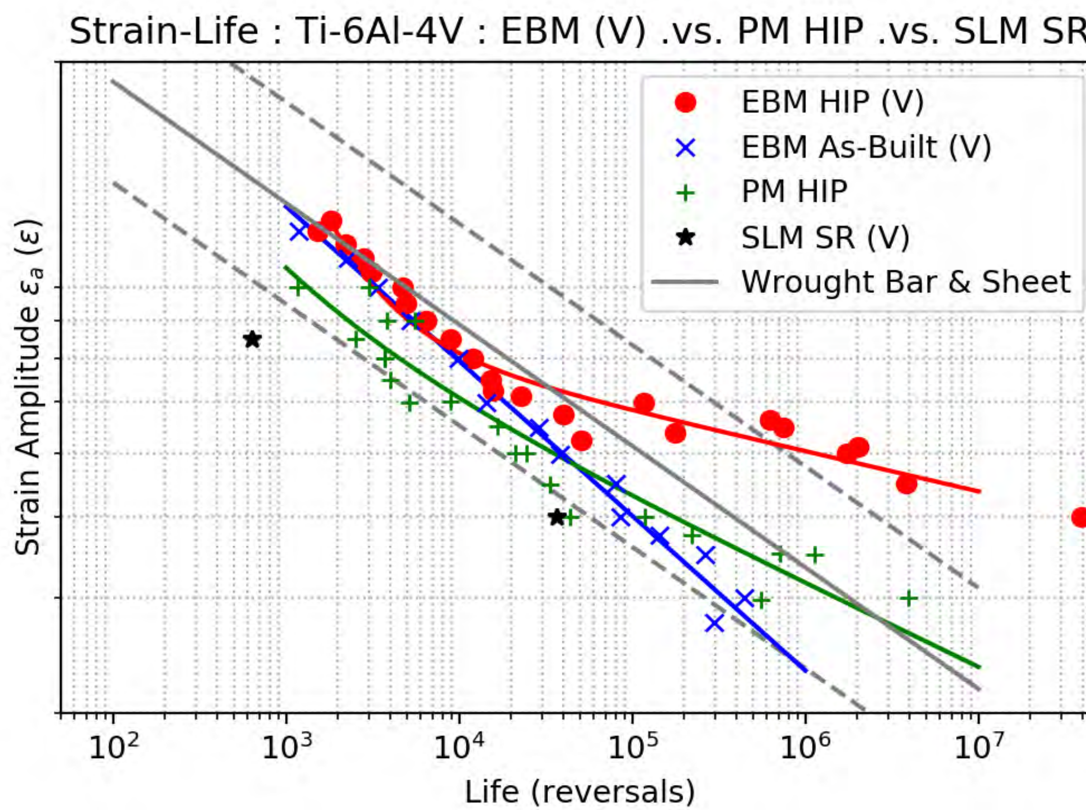
Fatigue Test Results : Compare vertical build EBM, w/wo HIP, PM HIP & SLM

- Wrought Bar and Sheet Baseline
- EBM As-Built (V) : 15 samples
- EBM HIP (V) : 27 samples
- PM HIP : 25 samples
  - Shorter life than both EBM As-Built and HIP in low cycle region
  - Fatigue life becomes better than As-Built in high cycle region as a result of HIP benefits
- SLM SR : 2 samples
  - Much shorter fatigue life
  - SLM testing program was delayed by a year
  - SLM program has now starte optimising build parameters, building density test blocks



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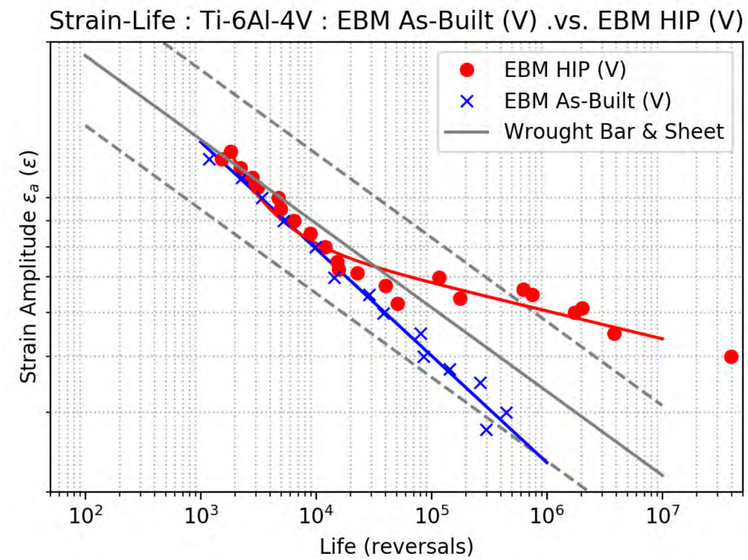
Conclusions

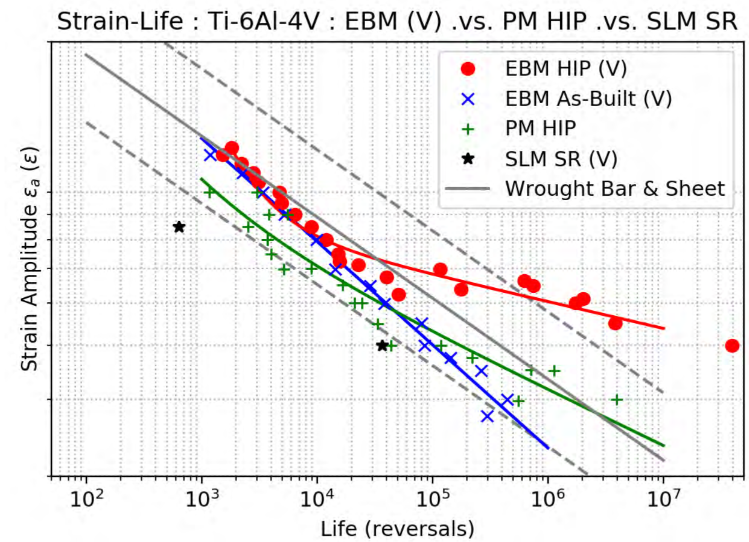
1. The Strain-Life fatigue damage model is applicable for EBM additive manufacturing of this titanium alloy Ti-6Al-4V.

2. Post-manufacturing HIP treatment improves high cycle fatigue performance, though scatter is increased.

3. Fatigue tests on additive manufactured material is considered essential because the fatigue performance cannot be inferred from the wrought material.

4. The material condition tested needs to include both manufacturing process and any post manufacturing treatment.





MASAAG Paper 124 Issue 1
Guidance Note on the Qualification and Certification of Additive Manufactured Parts for Military Aviation

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GOV.UK MASAAG Documents
https://www.gov.uk/government/publications/military-aircraft-structural-airworthiness-advisory-group-masaag-documents

- **Work Completed : Strain-life characterization of base material**

  - PM HIP Powder Metallurgy Hot Isostatic Pressing
  - EBM Electron Beam Powder Bed Fusion
  - SLM Laser Powder Bed Fusion
    Testing was due to start in August 2018, but was delayed 1-year.
    Supporting a 3-year research programme (2019-2022),
    to include titanium, aluminium and nickel alloys
  - WAAM Wire Arc Additive Manufacturing
    Supporting a 5-year Cranfield / Coventry University NEWAM research programme (2018-2023), to include titanium, aluminium and steel alloys

- **Further Work : Component validation**
  - Small component test cases to physically test and compare with strain-life fatigue prediction

Further information

30th ICAF Symposium – Kraków, 5 – 7 June 2019

Strain controlled fatigue testing of additive manufactured titanium alloy Ti-6Al-4V

Mr. Rob Plaskitt[1], Dr. Andrew Halfpenny[2] and Dr. Michelle Hill[3]

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[3]Head of Materials Testing, HBM Prenscia, United Kingdom

ABSTRACT

This paper describes strain controlled fatigue testing of a titanium Ti-6Al-4V alloy, additive manufactured by "electron beam melting" (EBM). The EBM material is manufactured in two conditions; with no post-manufacture heat treatment ("As-Built") and after a hot isostatic pressing (HIP) treatment. The EBM HIP treatment condition is manufactured in three build orientations; vertical, horizontal and at 45°. The fatigue test results for these EBM material conditions are compared with those for similar titanium Ti-6Al-4V alloy powder, manufactured by powder metallurgy hot-isostatic pressing (PM HIP), and for similar titanium Ti-6Al-4V alloy manufactured by traditional wrought mill into bar and sheet material.

The strain-life fatigue damage model and fatigue characterisation method used to fit fatigue test results from traditional manufacturing methods (wrought and PM HIP) appears to be applicable to the additive layer manufacturing method (EBM) for this titanium Ti-6Al-4V alloy material.

The EBM As-Built and HIP conditions in the low-cycle region all show similar fatigue performance. This is expected given their similarity in tensile strength. The effect of the HIP on the EBM additive manufactured material is seen in the high-cycle region with much better fatigue performance. This is expected as the HIP treatment reduces porosity in the material and improves the fatigue life. The three EBM HIP build orientations all show very similar fatigue performance, though the vertical has slightly longer lives than the corresponding horizontal and 45° build orientations. It is not possible to identify whether these slightly longer lives are because of a build orientation difference, a build-to-build difference, or an effect of powder recycling

In conclusion, fatigue tests on additive manufactured material, including both manufacturing process and any post manufacturing treatment, is considered essential because the fatigue performance of additive manufactured material cannot be inferred from tensile tests or from comparable wrought material.

Keywords: strain controlled fatigue testing, additive manufacturing. titanium

Rev. 10/2016

MATERIAL CONDITIONS

Table 1 details the material and manufacturing conditions of the source "blank" titanium Ti-6Al-4V alloy material. All powder-based material conditions were manufactured from plasma atomized Ti-6Al-4V (grade 5). The same powder batch was used for all EBM conditions. The SLM and PM HIP material conditions were manufactured by different suppliers and so each used different powder batches.

Where:
- "EBM" – electron beam melting, an electron-beam powder bed fusion method
- "SLM" – selective laser melting, a laser powder bed fusion method
- "PM HIP" – powder metallurgy hot isostatic pressing

Most additive manufactured blanks (EBM and SLM in Table 1) were manufactured in vertical (V) orientation, with the long axis perpendicular to the deposition layers. To assess material property anisotropy, some EBM HIP treatment conditions were manufactured in horizontal (H) and 45 degrees (45°) build orientation. The vertical EBM blanks were manufactured together in one build, and the horizontal and 45 degrees blanks manufactured in a following build.

The EBM material conditions were manufactured by Arcam EBM® using an Arcam Q20plus, in the UK National Centre for Additive Manufacturing, at the Manufacturing Technology Centre, and further described in (Plaskitt, et al, 2018). The supplier manufacturing details for the SLM, PM HIP and wrought material conditions are confidential.

Table 1. Description of the material conditions.

Material Condition	Description
EBM As-Built (V)	Cylindrical blanks additive manufactured by EBM, with deposition layers perpendicular to the long axis (built vertically), with no post-manufacturing heat treatment
EBM HIP (V)	Cylindrical blanks additive manufactured by EBM, with deposition layers perpendicular to the long axis (built vertically), with post-manufacturing HIP; 2 hours at 920 °C, with 100 MPa pressure and cooled in an inert argon atmosphere to below 425 °C
EBM HIP (H)	Cylindrical blanks additive manufactured by EBM, with deposition layers parallel to the long axis (built horizontally), with post-manufacturing HIP; 2 hours at 920 °C, with 100 MPa pressure and cooled in an inert argon atmosphere to below 425 °C
EBM HIP (45°)	Cylindrical blanks additive manufactured by EBM, with deposition layers 45° to the long axis (built at a 45° angle), with post-manufacturing HIP; 2 hours at 920 °C, with 100 MPa pressure and cooled in an inert argon atmosphere to below 425 °C

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Additive Manufacturing

*"it is pretty good in Tensile, but it is **** (not very good) in Fatigue"*

"can fatigue performance meet qualification reliability requirements"

Questions

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