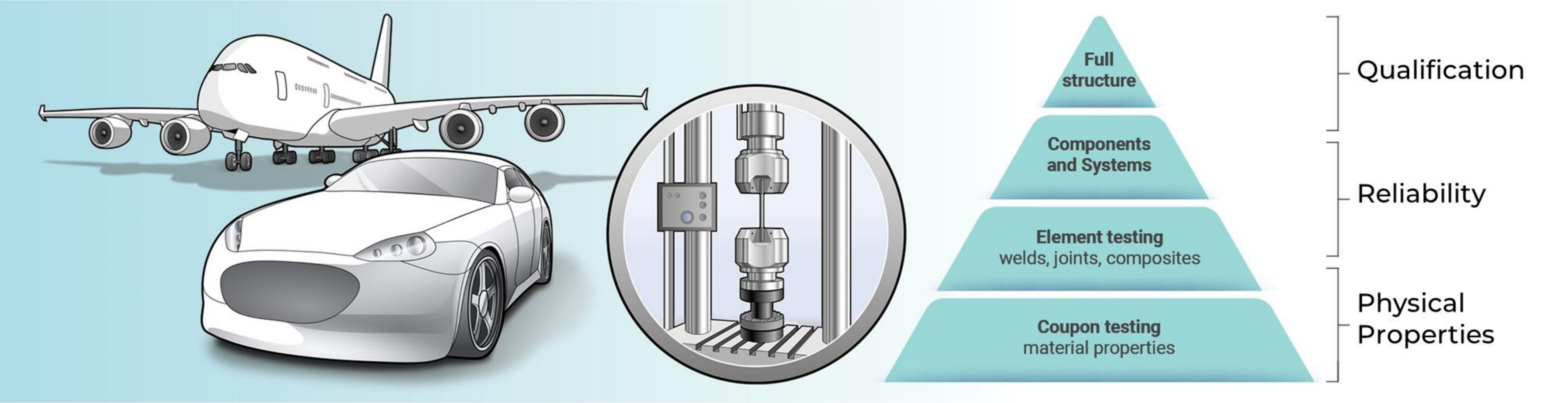
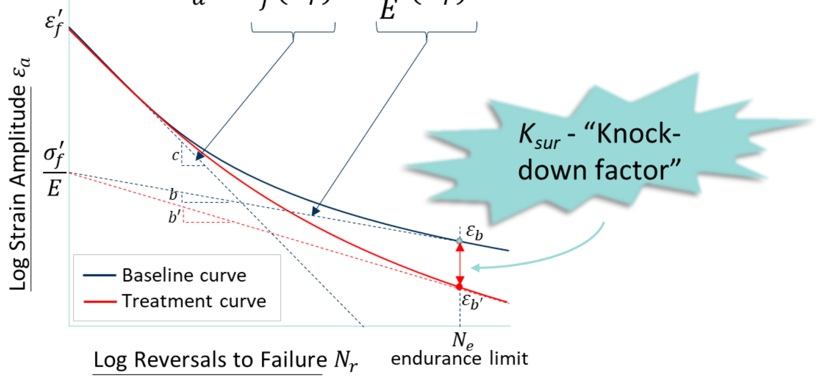


2023 HBK Technology Days

14 November 2023

Plastic line | Elastic line

$$\varepsilon_a = \underbrace{\varepsilon_f'(N_r)^c}_{\text{Plastic line}} + \underbrace{\frac{\sigma_f'}{E}(N_r)^b}_{\text{Elastic line}}$$



$$K_{sur} = \frac{\varepsilon_{b'}}{\varepsilon_b} = (N_e)^{b'-b}$$

- **Fatigue methodology for combining surface treatment factors in strain-life fatigue**

Dr. Andrew Halfpenny,
Director of Technology – nCode Products, HBK

Fatigue methodology for combining surface treatment factors in strain-life fatigue

Abstract

- The strain-life fatigue method is generally preferred for military aircraft landing gear fatigue life predictions because at the higher strain levels they experience, the stress-life fatigue method breaks down. The strain-life fatigue method requires strain controlled fatigue testing over a range of strain amplitudes and wide range of fatigue cycles to failure, followed by characterisation to fit parameters for the Ramberg-Osgood-Neuber cyclic plasticity model and Coffin-Manson-Basquin strain-life model. A minimum of 25 fatigue tests are recommended to characterise baseline material fatigue performance for a full range (102 to 107 cycles) equally biased low to high cycle strain-life curve.

- The K_{sur} method for surface treatment factors models the fatigue effect of a surface treatment with a single K_{sur} parameter to adjust the slope of a stress-life fatigue curve in the high cycle region. This method was originally derived for stress-life fatigue curves and assumes that surface effects are mostly confined to the high cycle fatigue region. It is reasoned that under high cycle fatigue loading, the applied loads are relatively low and localised fatigue initiation sites are dependent on the surface condition. Fatigue testing can be reduced to a minimum of 12 because there is only a single K_{sur} factor parameter to fit, and tests can be biased for results in the mid to high cycle fatigue region.

- This presents how strain-life fatigue parameters can be combined with K_{sur} surface treatment factors, including sample results and fatigue methodology validation.

Fatigue methodology for combining surface treatment factors in strain-life fatigue

- About the presenter, Dr. Andrew Halfpenny, Director of Technology – nCode Products, HBK

  - Dr. Halfpenny has a PhD in Mechanical Engineering from University College London (UCL) and a Master’s in Civil and Structural Engineering. With over 25 years of experience in structural dynamics, vibration, fatigue and fracture, he has introduced many new technologies to the industry including: FE-based vibration fatigue analysis, crack growth simulation and accelerated vibration testing. He holds a European patent for the ‘Damage monitoring tag’ and developed the new vibration standard used for qualifying UK military helicopters.

  - He has worked in consultancy with customers across the UK, Europe, Americas and the Far East, and has written publications on Fatigue, Digital Signal Processing and Structural Health Monitoring. He sits on the NAFEMS committee for Dynamic Testing and is a guest lecturer on structural dynamics with The University of Sheffield.

Materials and Surface Coatings and Processes

2023 HBK TECHNOLOGY DAYS

Presenters:

Dr Michelle Hill, Head of Materials testing, HBK

Mr Ben Griffiths, Chief Engineer, Select Engineering Services

Dr Andrew Halfpenny, Director of Technology – nCode products, HBK

Agenda

1. Materials and surface coatings and processes
   - Introduction
   - USAF Project Background and Significance

2. **Fatigue methodology for combining surface treatment factors in strain-life fatigue**
   - **Strain-Life Testing**
   - **Theory and Calculations**

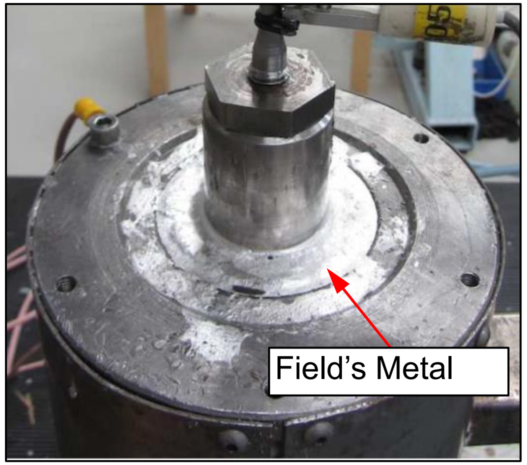
3. Application of the Material Assessment and Predictive Analysis (MAPA) Tool for Fatigue Data Management
   - Tested Results
   - MAPA Data Manager
   - Ongoing Efforts

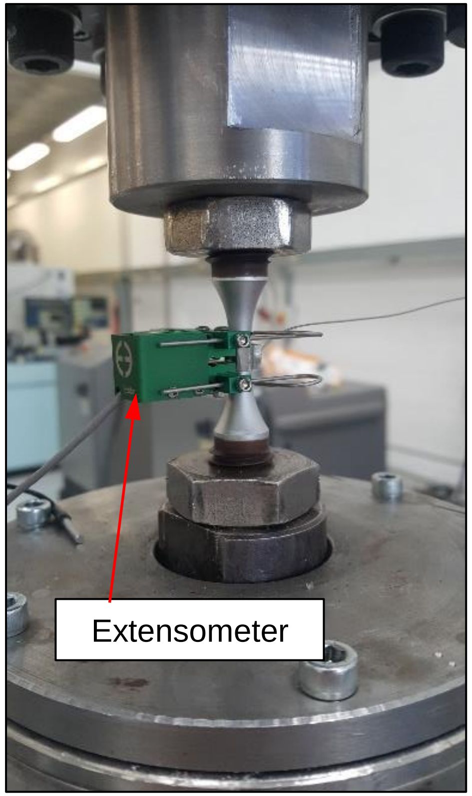
SES Select Engineering Services

HBK HOTTINGER BRÜEL & KJÆR

Strain-life Testing

- Conducted at the AMCT Facility (HBK)
  - **Fully reversed** uniaxial strain – ASTM E606
  - **Strain-control** maintained for entire test
  - **Field's metal pot** for specimen alignment
- Specimen Fabrication
  - **Baseline** (ideal) specimens longitudinally polished
  - **Surface treated** specimens fabricated to USAF landing gear specs



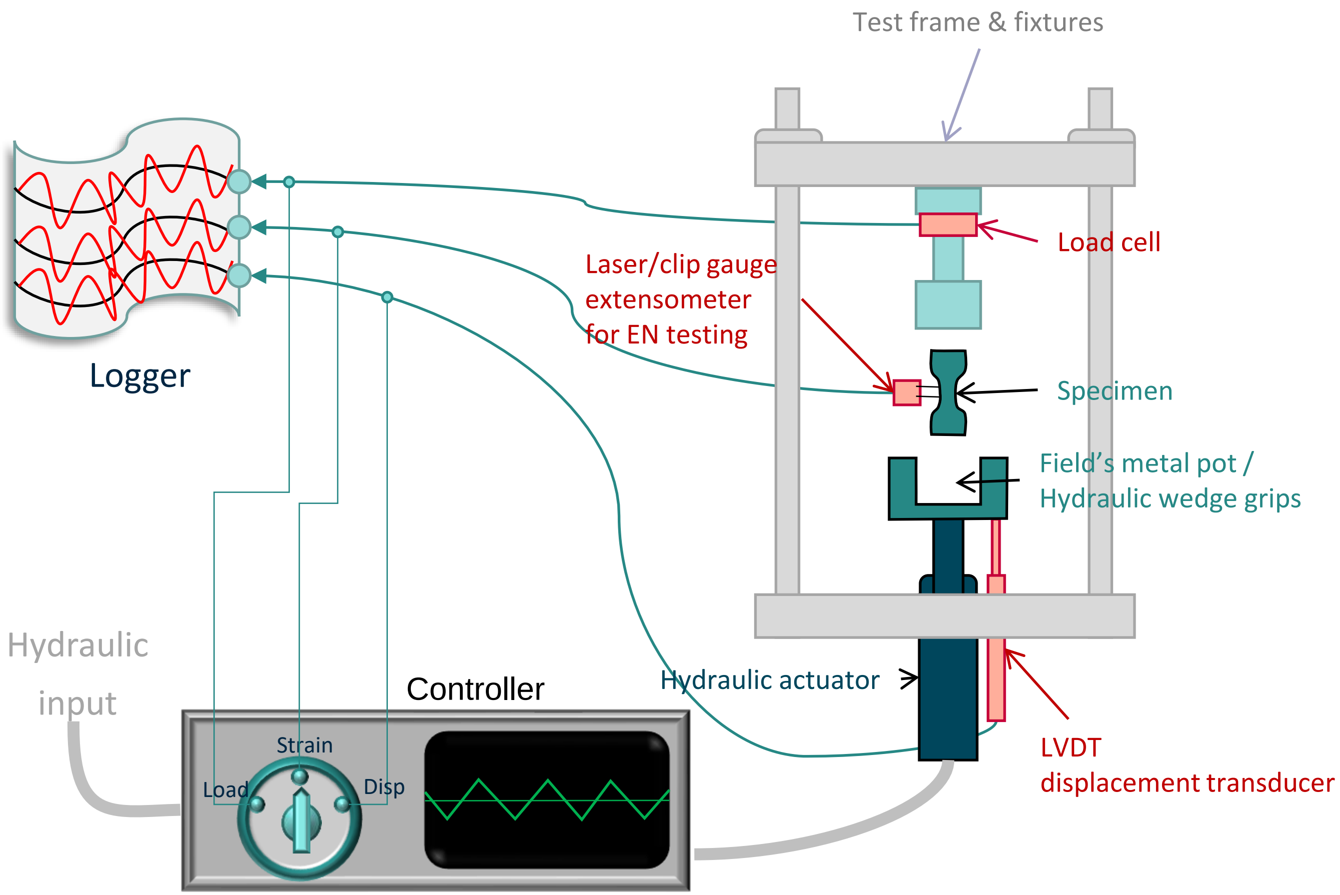


Fatigue Test Setup

Longitudinal Polish

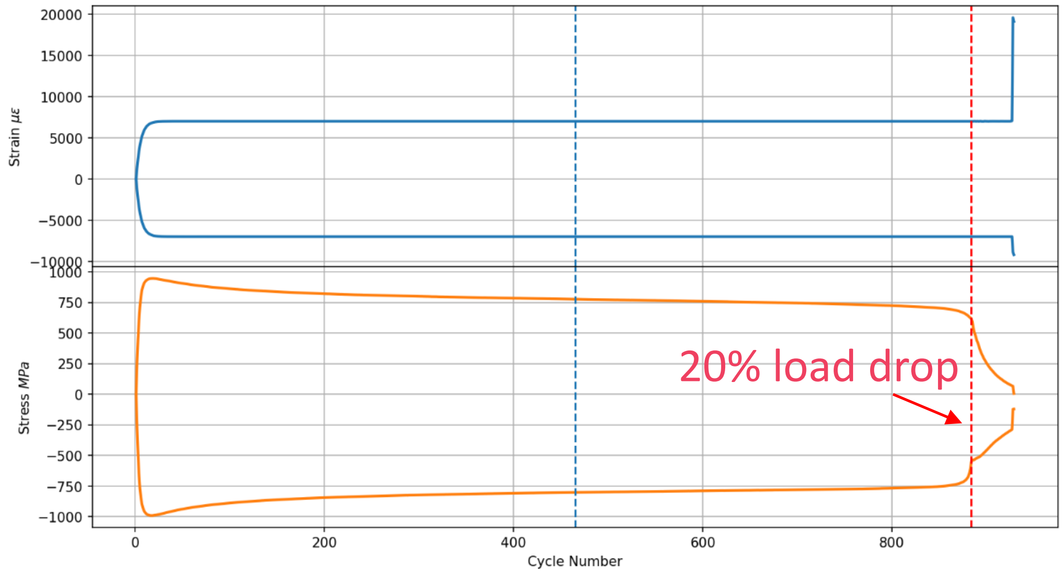
HBK HOTTINGER BRÜEL & KJÆR

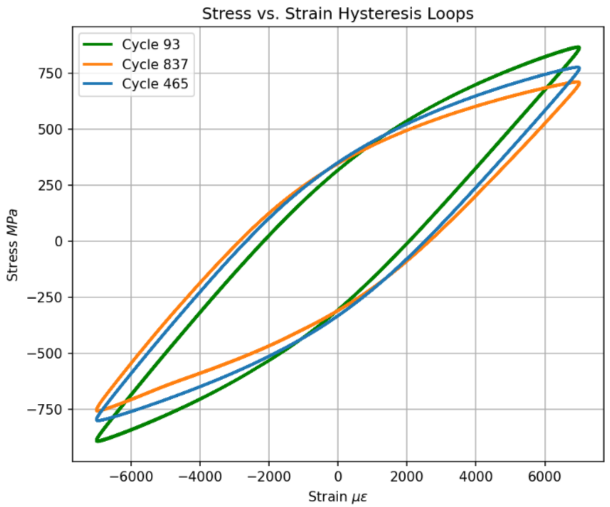
Cyclic & Fatigue Parameters



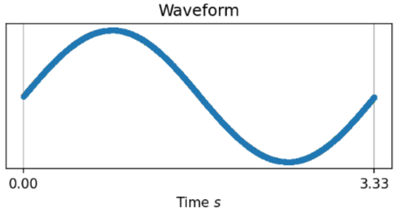
Strain Controlled Fatigue Test Report

Job reference:	C12345	Material:	Sample Material
Test number:	11	Customer:	HBK AMCT
Test date:	21/10/2020	Engineer:	MC
Software version:	3.0.1	Test rig:	Emily (Tiab)



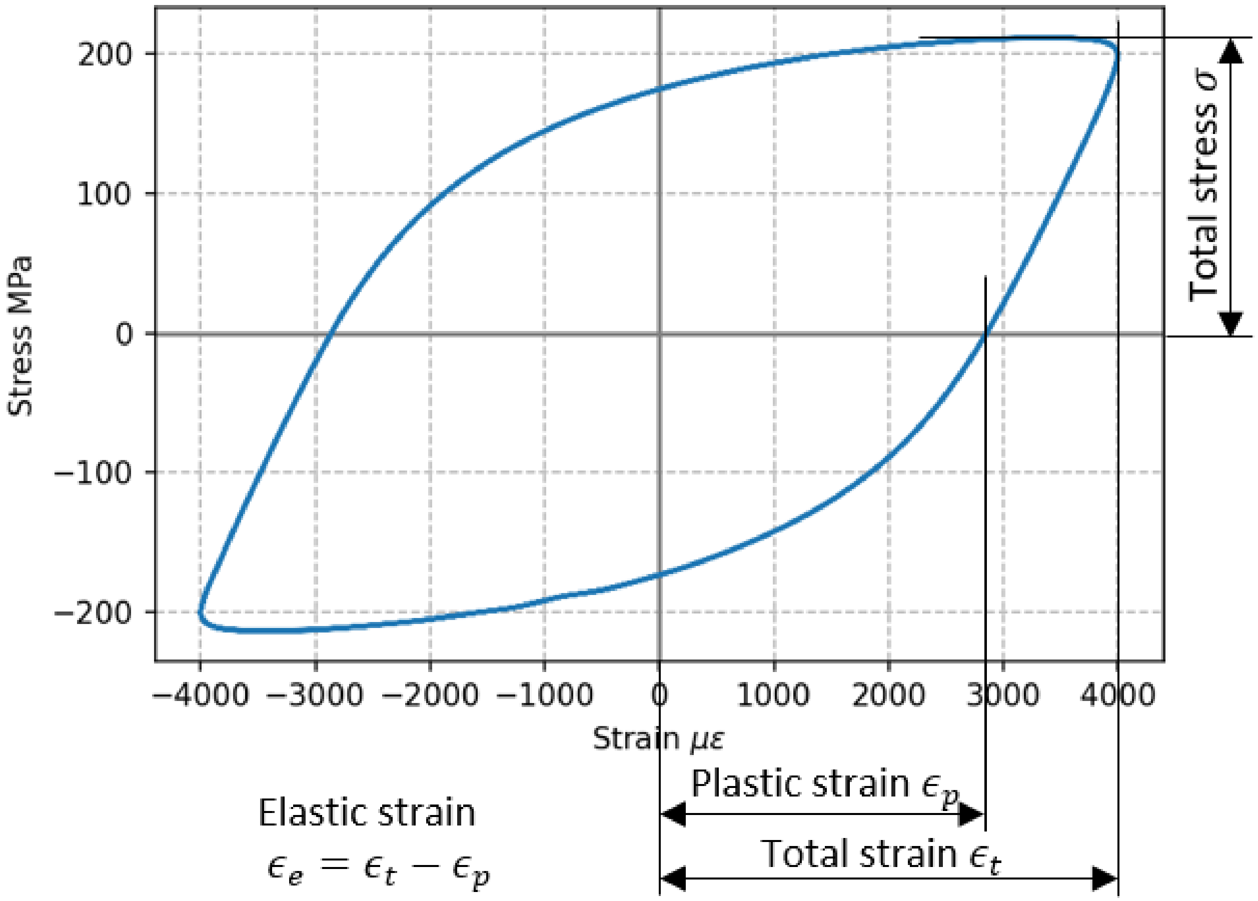


Cross sectional area:	16.100 mm^2
Test temperature:	Ambient
Test frequency:	0.3 Hz
Stable loop:	465
Cycles to separation:	929
5% load drop:	740
10% load drop:	858
20% load drop:	884
50% load drop:	893



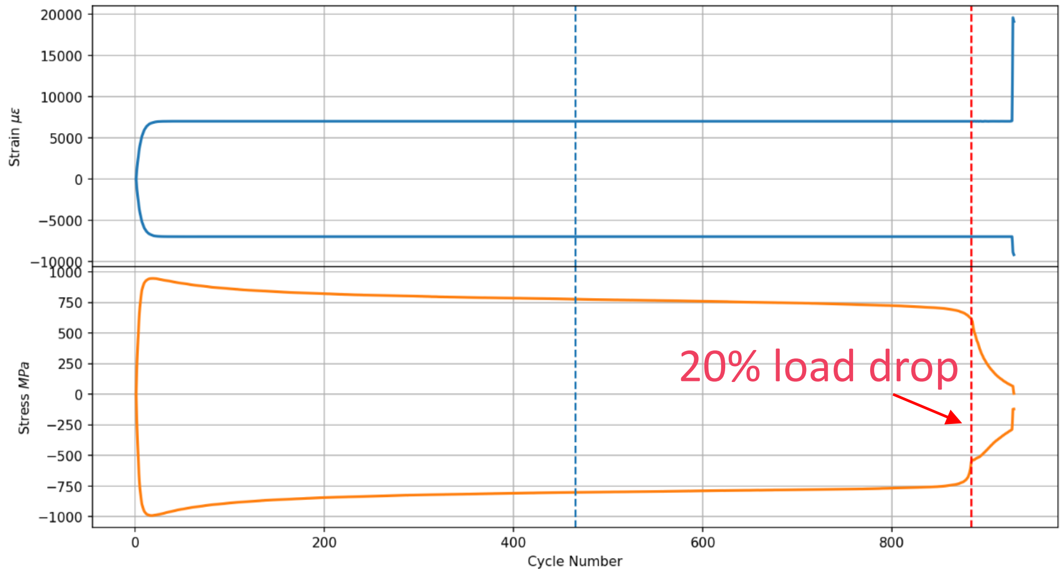
Cycle No.	Total Stress	Total Strain	Elastic Strain	Plastic Strain
93	1758.5 MPa	14000	9780	4220
465	1577.1 MPa	13999	8817	5182
837	1468.4 MPa	14000	8496	5504

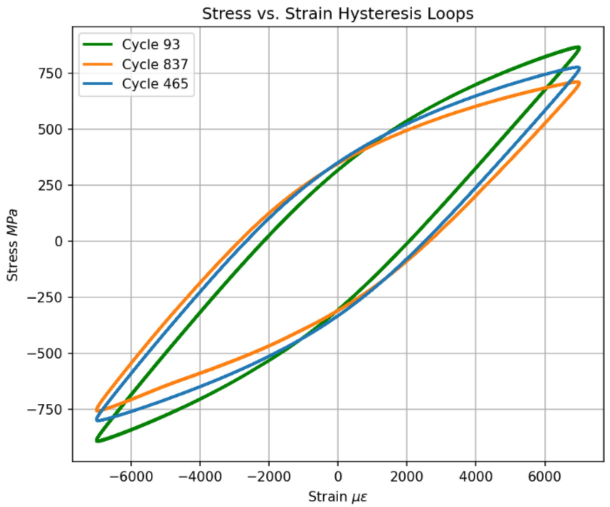
Cyclic & Fatigue Parameters



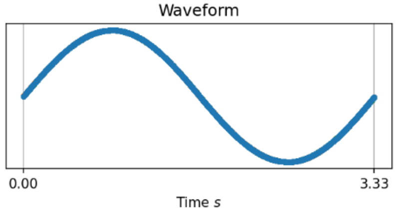
Strain Controlled Fatigue Test Report

Job reference:	C12345	Material:	Sample Material
Test number:	11	Customer:	HBK AMCT
Test date:	21/10/2020	Engineer:	MC
Software version:	3.0.1	Test rig:	Emily (Tiab)



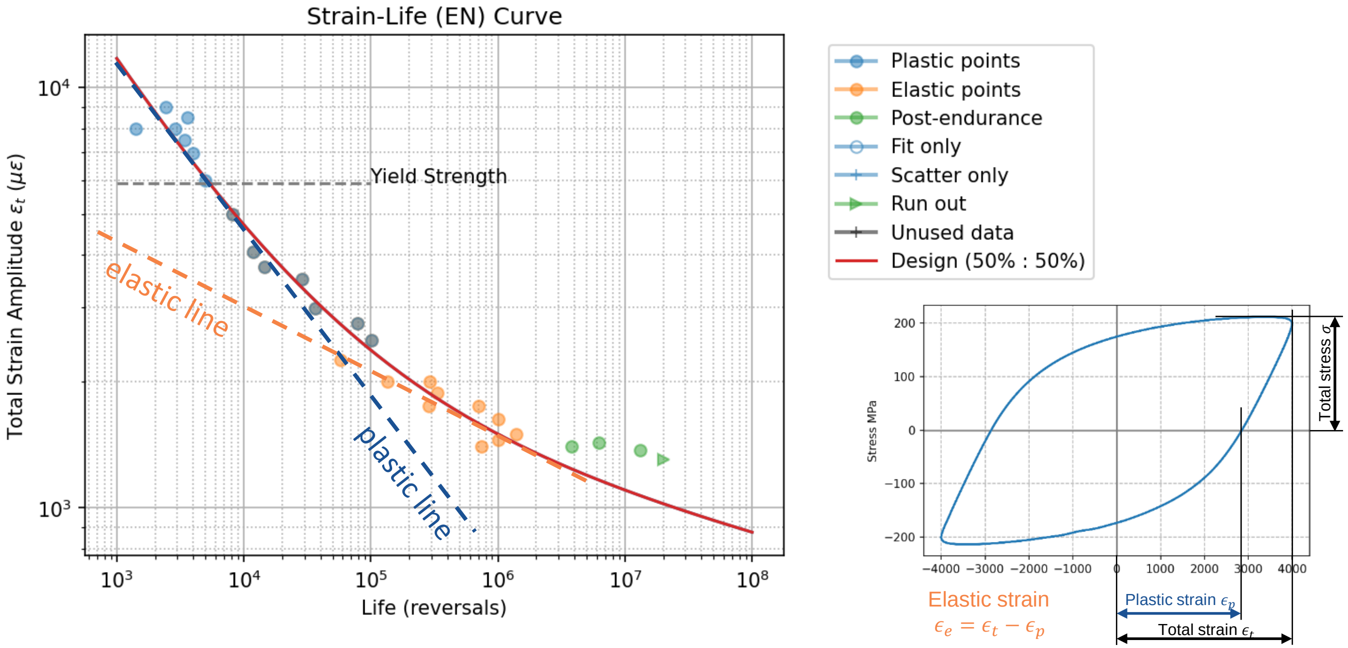


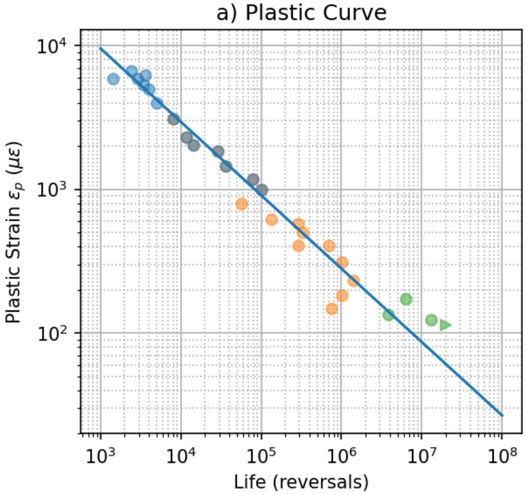
Cross sectional area:	16.100 mm^2
Test temperature:	Ambient
Test frequency:	0.3 Hz
Stable loop:	465
Cycles to separation:	929
5% load drop:	740
10% load drop:	858
20% load drop:	884
50% load drop:	893

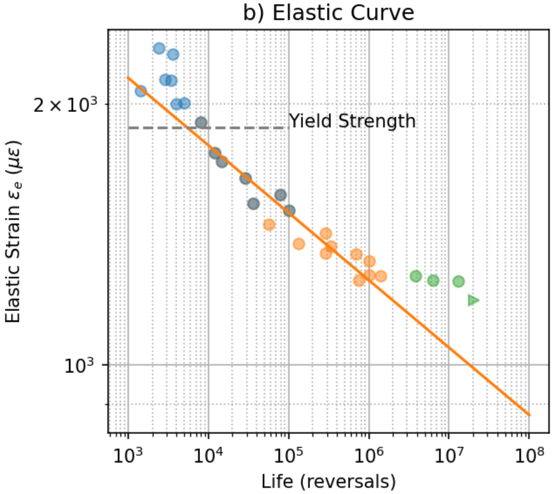


Cycle No.	Total Stress	Total Strain	Elastic Strain	Plastic Strain
93	1758.5 MPa	14000	9780	4220
465	1577.1 MPa	13999	8817	5182
837	1468.4 MPa	14000	8496	5504

Cyclic & Fatigue Parameters – *EN characterisation analysis*







1. Plot Total strain amplitude ϵ_t vs. reversals to failure N_r for the specified load-drop.
2. Fit **plastic line** using plastic strain ϵ_p

$$\epsilon_p = \epsilon_f' N_r^c$$

3. Fit **elastic line** using elastic strain

$$\epsilon_e = \frac{\sigma_f'}{E} N_r^b$$

4. Parameter re-optimisation

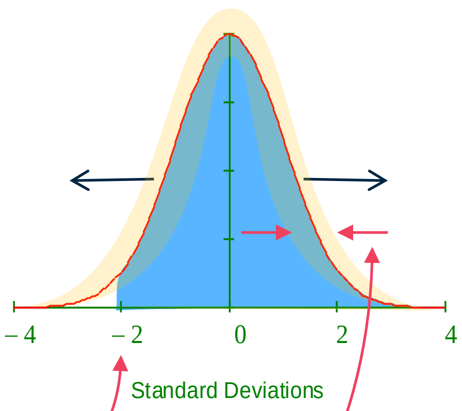
$$\epsilon_t = \frac{\sigma_f'}{E} N_r^b + \epsilon_f' N_r^c$$

5. Outlier analysis

Cyclic & Fatigue Parameters – *Uncertainty Quantification*

Deterministic design approach:

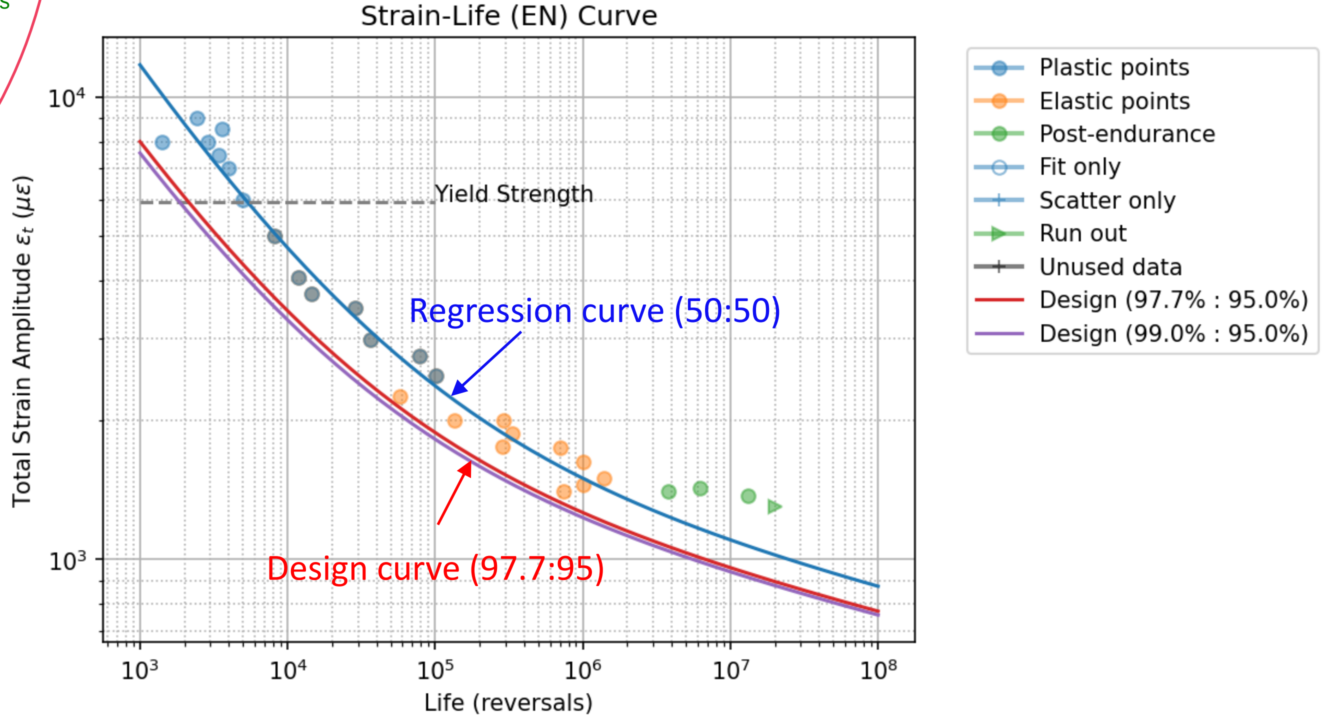
Design curve(reliability % : confidence %)



$$\epsilon_t = \frac{\sigma'_f}{E}10^{k_{Ue}\cdot SEe}N^b + \epsilon'_f 10^{k_{Up}\cdot SEp}N^c$$

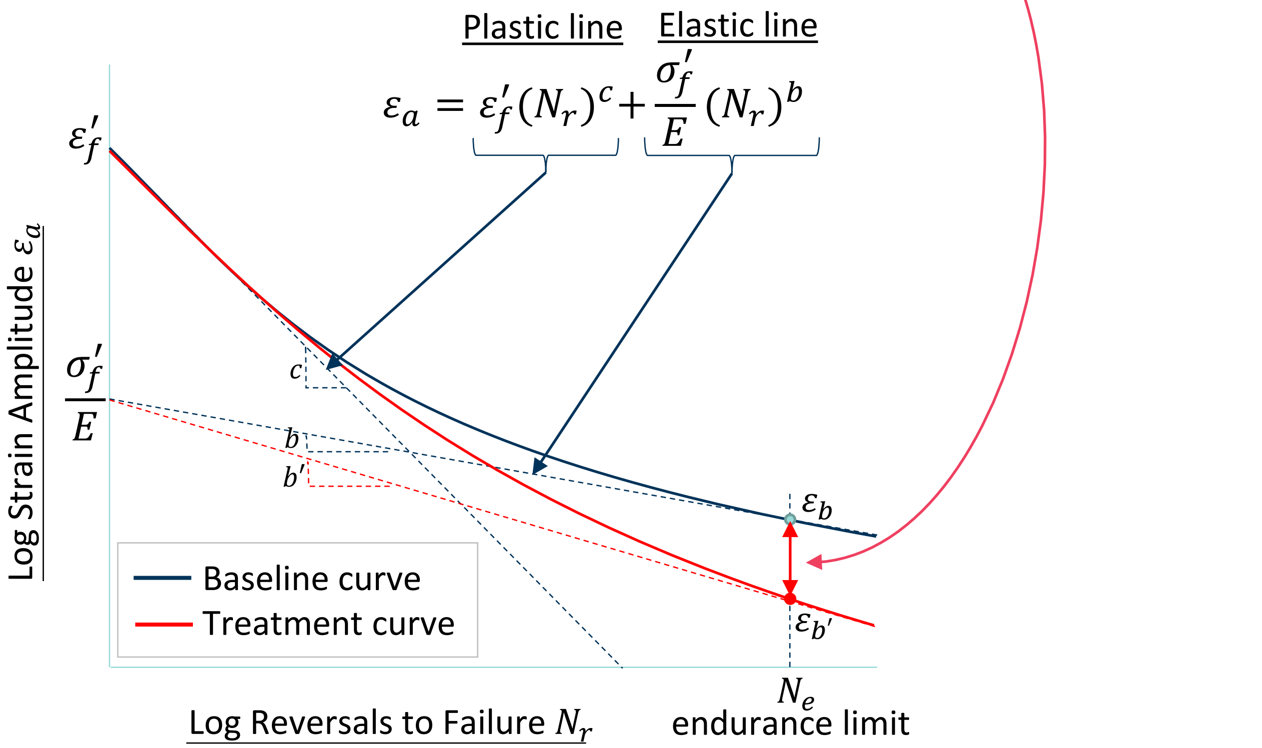
$$k_U = \frac{z_\rho + \frac{z_\gamma}{\sqrt{n}}\sqrt{1-\frac{z_\gamma^2}{2(n-1)}+\frac{nz_\rho^2}{2(n-1)}}}{1-\frac{z_\gamma^2}{2(n-1)}}$$

- Reliability statistic:
  (acceptable number of failures)
  - 50% (mean expected life)
  - 95% (5 failures in 100)
  - 97.7% (2 sigma)
  - 99% (1 failure in 100)
- Confidence statistic:
  (sensitivity to sample size)
  - 50% (mean expected life)
  - 90 – 95% (typical design curves)



Surface Treatment Factors – k_{SUR} METHOD

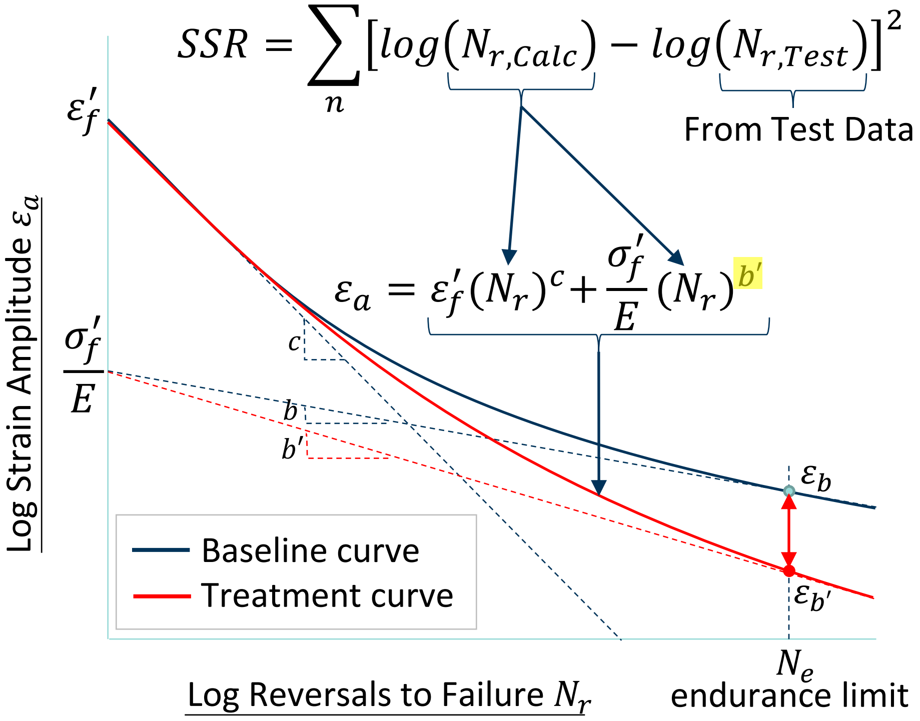
- Baseline curve (5 parameters)
  - 25 data points, fully reversed strain (R=-1)
  - High & low-cycle characterization
- Surface treatment test data
  - 12 data points, fully reversed strain (R=-1)
  - Focused on high-cycle fatigue
- Attributes of K_{sur}
  - Single parameter treatment characterization
  - Similar statistical significance to 25-point curve
  - Compare different treatments on same material
  - Compare same treatments on different material
  - Assumes treatment effects greater at high cycles



$$K_{sur} = \frac{\varepsilon_{b'}}{\varepsilon_b} = (N_e)^{b'-b}$$

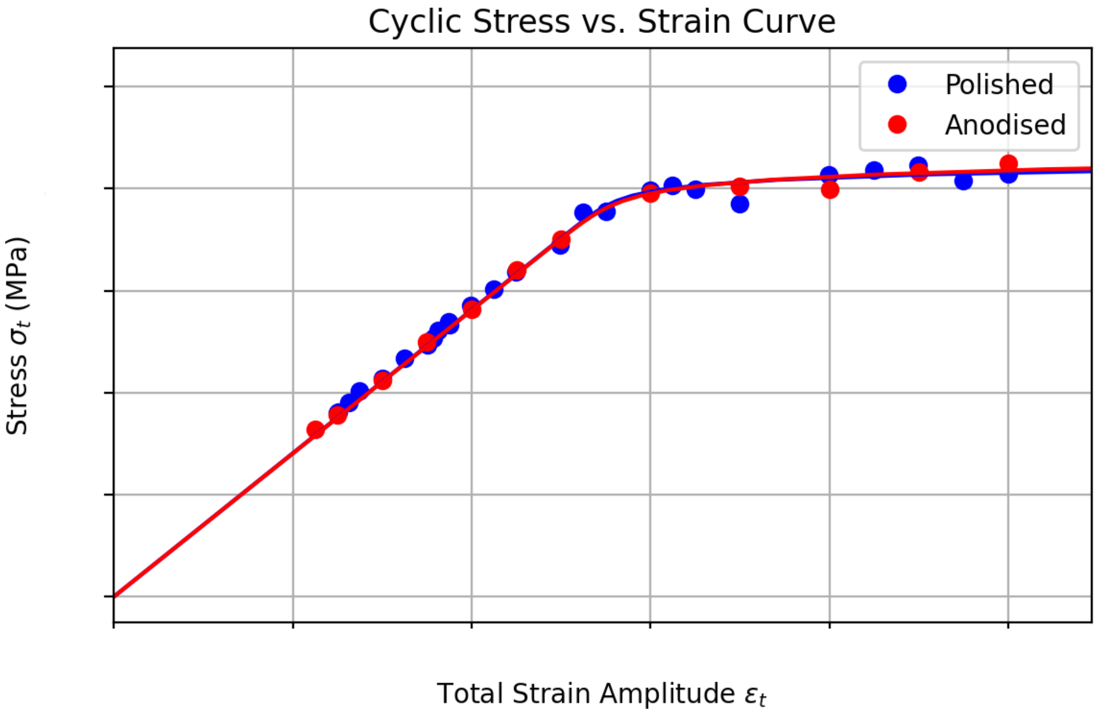
k_{SUR} Numerical calculations

- K_{sur} is a function of b', b, and N_e $\longrightarrow$ $K_{sur} = (N_e)^{b'-b}$
  - b' - slope of elastic line for surface treatment curve
  - b - slope of elastic line calculated with baseline (ideal) curve
  - N_e - selected endurance limit
    - Does not affect surface treatment curve
- b' calculated iteratively to minimize sum of squared residuals (SSR)
  - Cycles to failure considered dependent variable
  - Equation for SSR must be solved using numerical methods

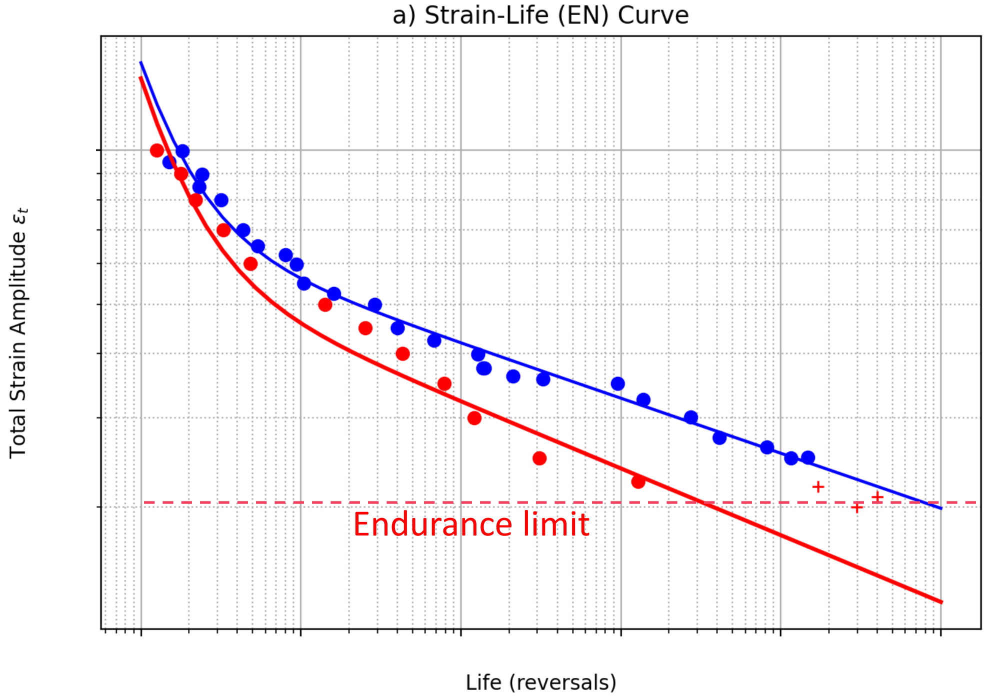


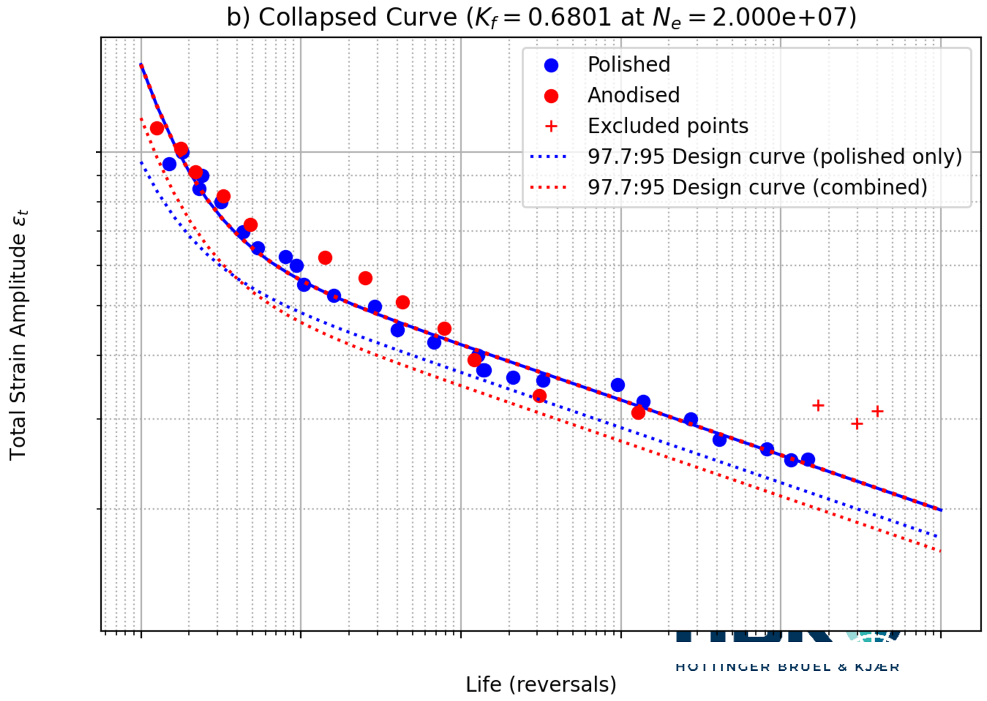
HOTTINGER BRÜEL & KJÆR

E.g. 7075 – Anodised vs. Polished

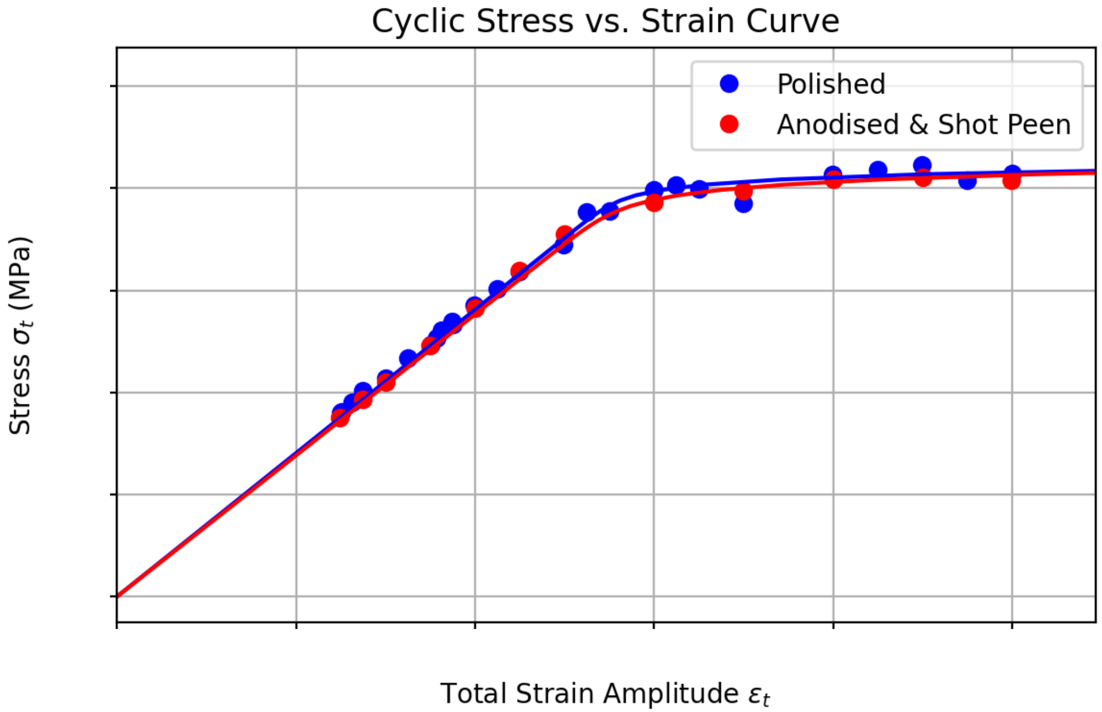


- No change in stiffness between baseline and treated
- Significant change in high-cycle fatigue life $K_{sur} = 0.6801$
- Ksur method offers reasonable fit to material
- Endurance (fatigue strength) unmodified by treatment

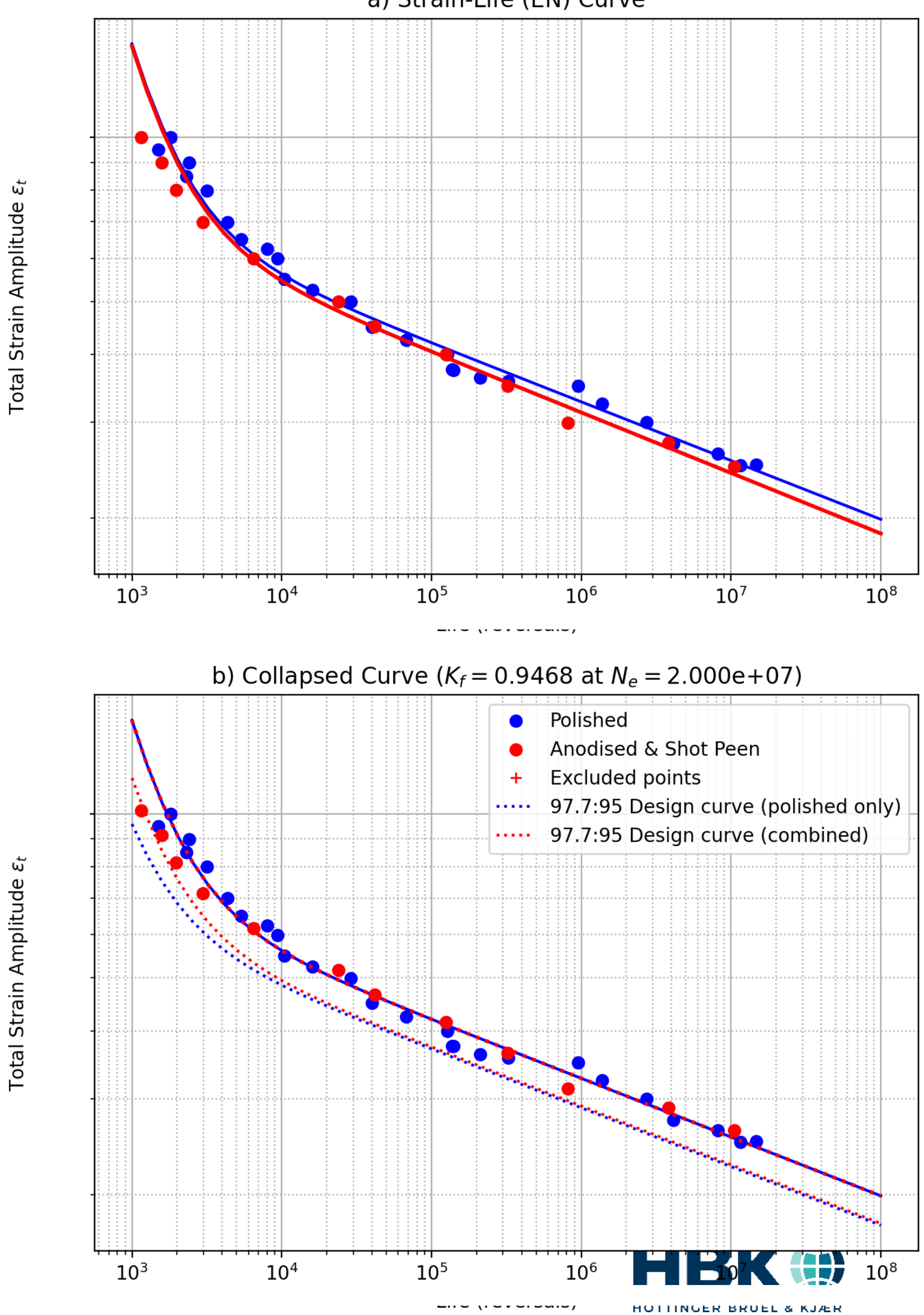




E.g. 7075 – Shot peen & Anodised vs. Polished



- No change in stiffness between baseline and treated
- Little change in high-cycle fatigue life $K_{sur} = 0.9468$
- Shot peening effectively negates effect of anodising

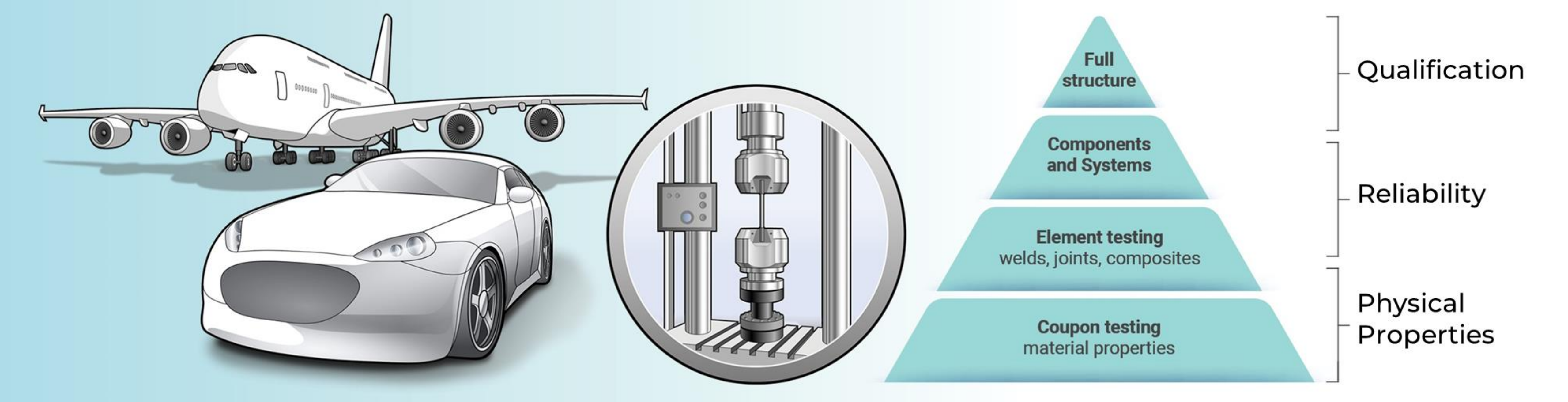


Agenda

1. Materials and surface coatings and processes
   - Introduction
   - USAF Project Background and Significance

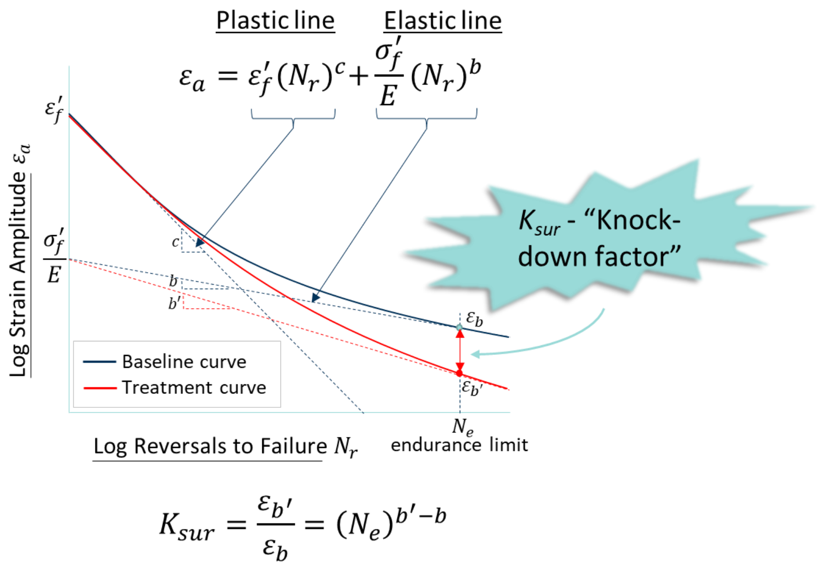
2. Fatigue methodology for combining surface treatment factors in strain-life fatigue
   - Strain-Life Testing
   - Theory and Calculations

3. **Application of the Material Assessment and Predictive Analysis (MAPA) Tool for Fatigue Data Management**
   - **Tested Results**
   - **MAPA Data Manager**
   - **Ongoing Efforts**



2023 HBK Technology Days

14 November 2023



- **Fatigue methodology for combining surface treatment factors in strain-life fatigue**

Dr. Andrew Halfpenny,
Director of Technology – nCode Products, HBK