2023 ENGINEERING INSTITUTION OF ZAMBIA SYMPOSIUM

Trends in materials science based computational models for fatigue behaviour of high temperature alloys

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DATE : **Friday 19th April 2024**

Avani Victoria Falls Resort, Livingstone, Zambia

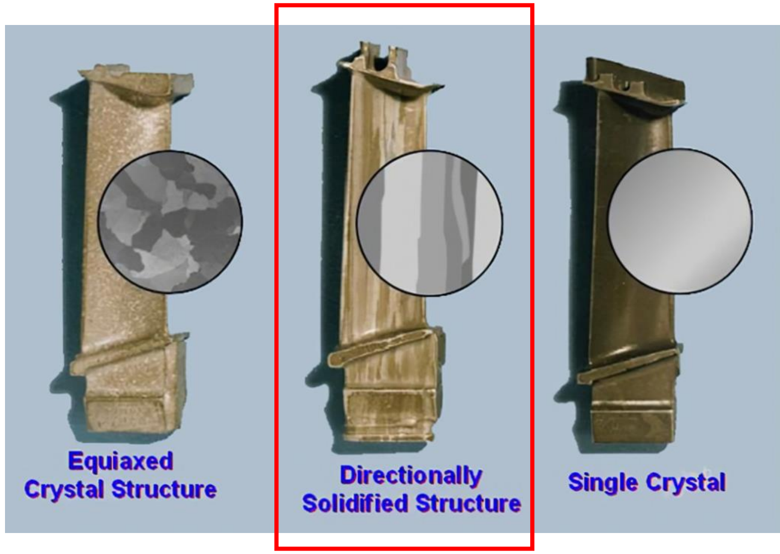
Introduction

Innovative Engineering curricula to suit existing and future demands and problems

- What are the problems that need solutions from engineers, in todays world??
- What does it take to train an engineer who can solve problems in todays world??
- Is the training being provided in the nation sufficient for engineers??
- What are the challenges?
- How can we improve??

- Training in computational mechanics requires improvement

- We look at analysis of failure in a directionally solidified nickel-based superalloy

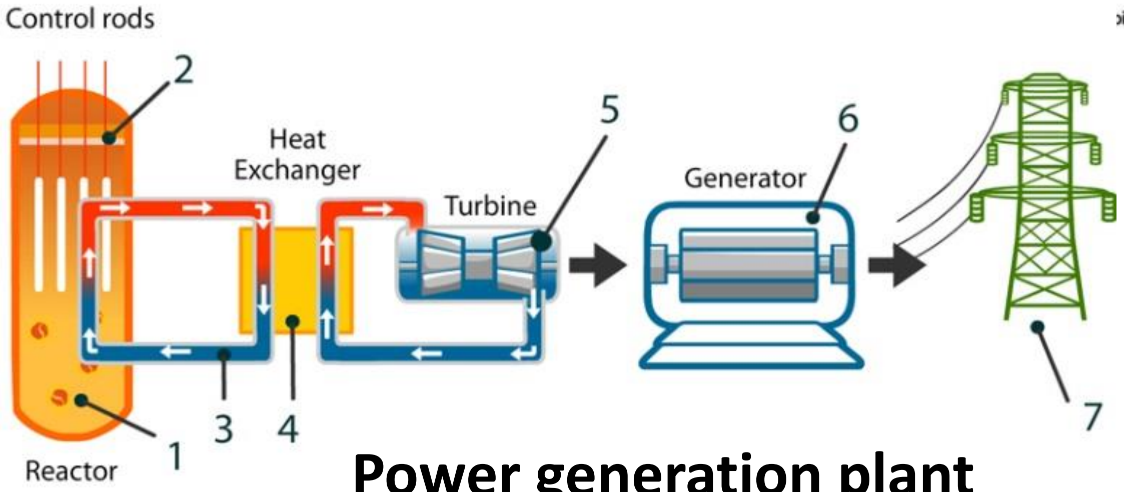


Introduction

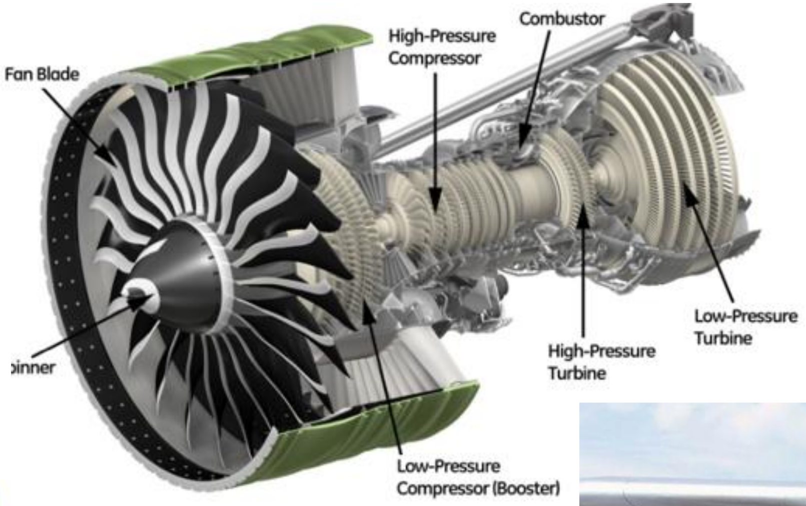
- Ni-based superalloys are materials with unique properties – high temperatures

- Widely used as turbine-engine materials.

- Turbines are widely applied in
  - Power generation
  - Jet engines



Power generation plant



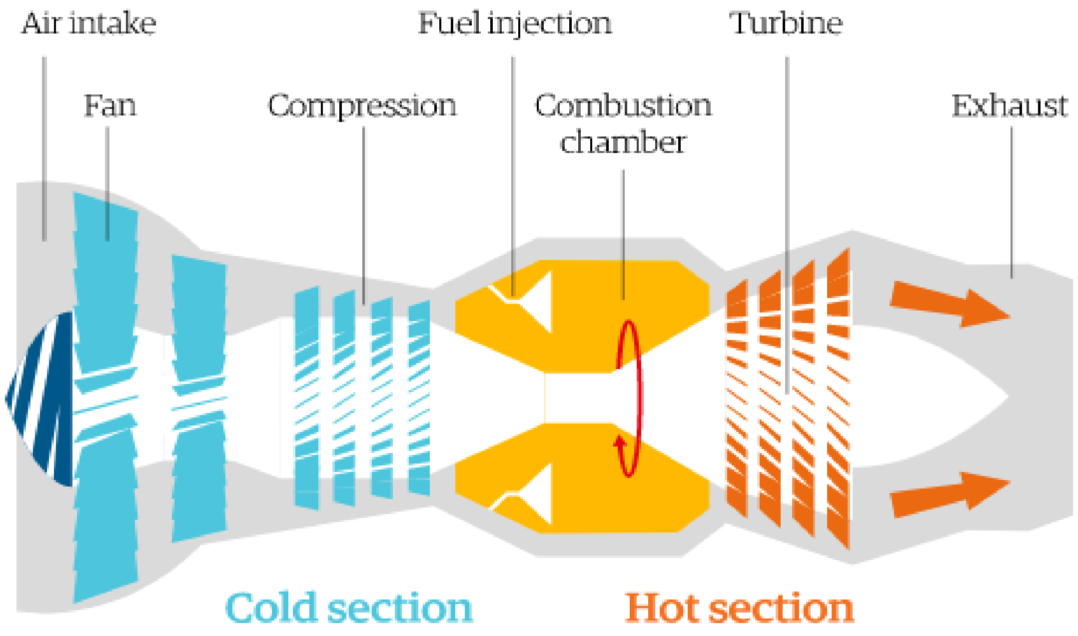
Jet engine

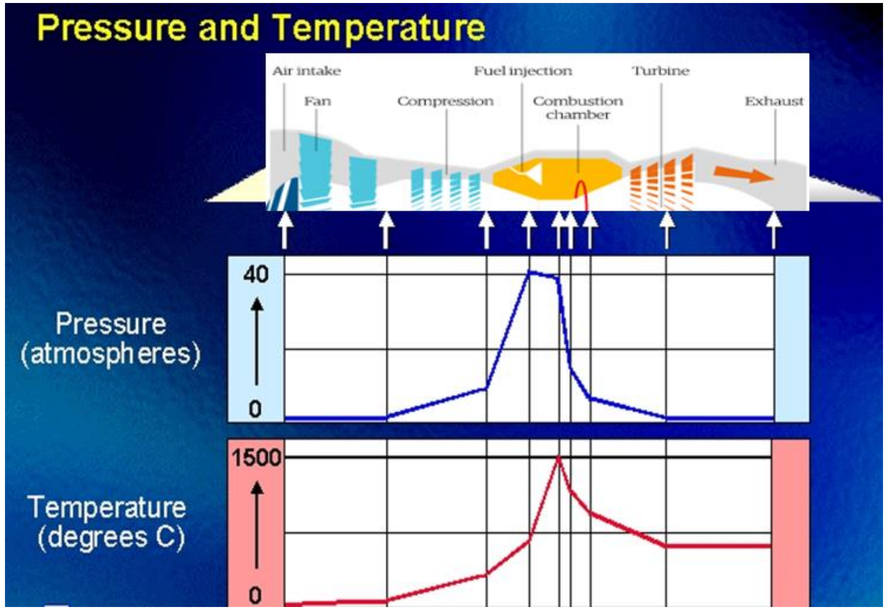
Introduction

- Current requirements:- fuel economy, low CO_2/NOx and low noise

- Essentials include high:-
  - ❖Compressor exit pressures
  - ❖Turbine temperatures

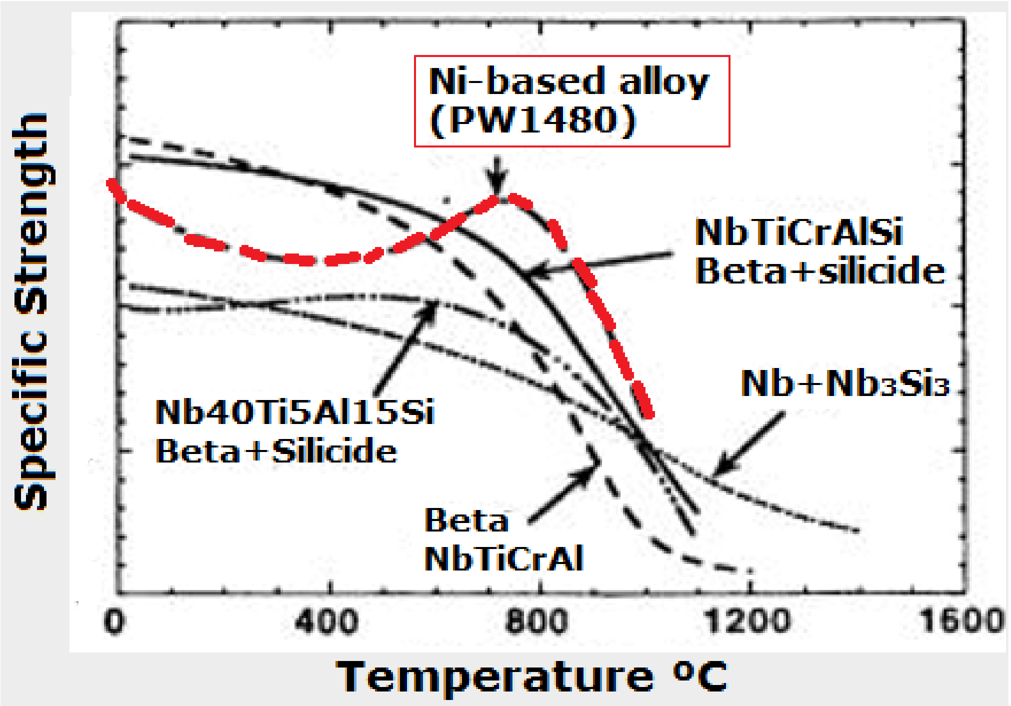
- Materials design is a big challenge.

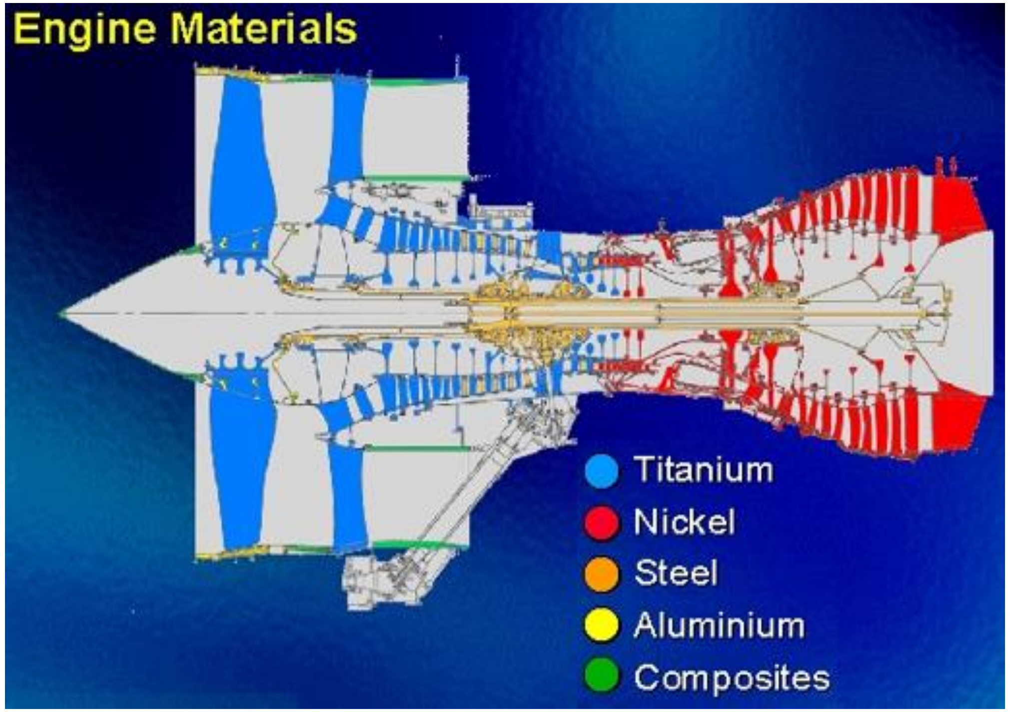




Introduction

- Steels – historically
- Superalloys – Co-, Ni- and Fe-Ni-based
- Ni-based - extensively applied in hot sections

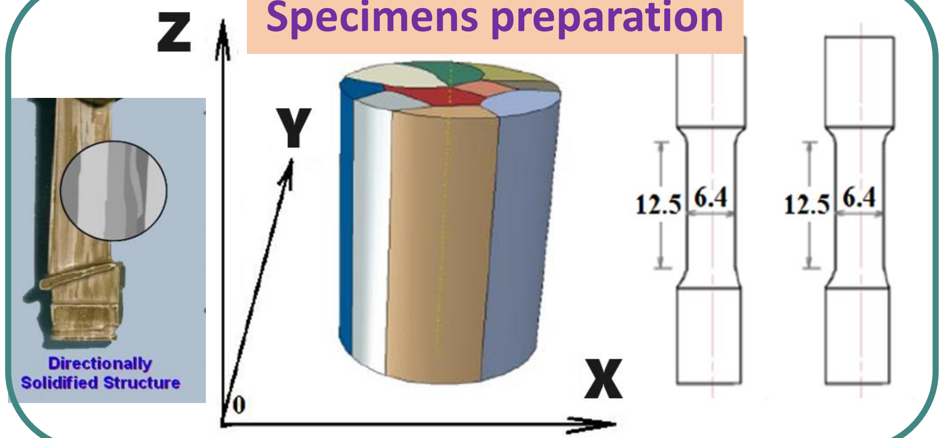


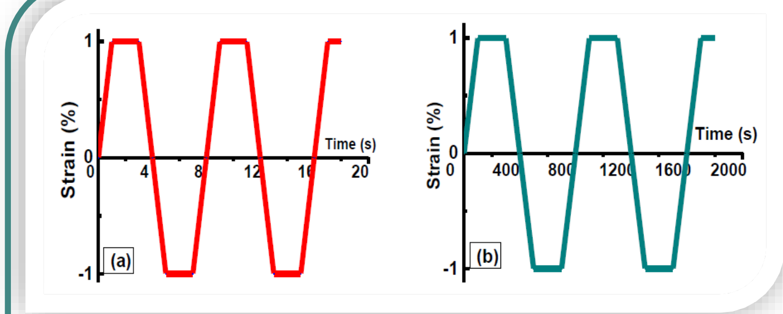


Strain-controlled fatigue tests

- Two specimens machined from the same sample
- Subjected to fatigue loading, at high temperature
- Results show different number of cycles to failure in the specimens, WHY???
- Investigation, using computational mechanics

Specimens preparation

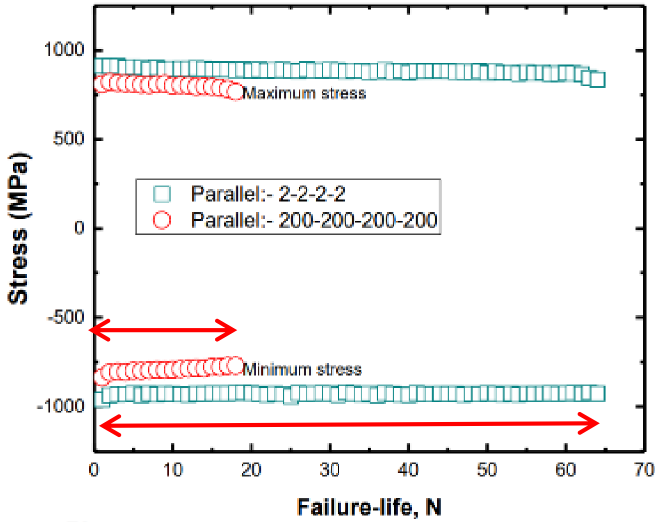


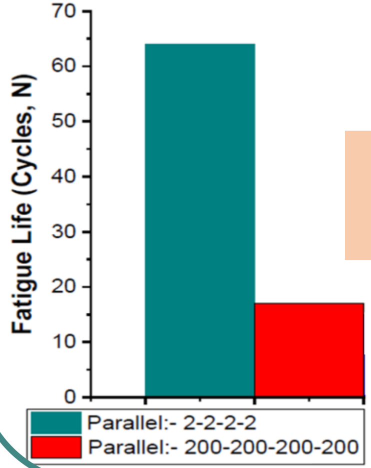


Fatigue loading waveforms

Fatigue testing machine (Strain-controlled)

Fatigue life (cycles, N)



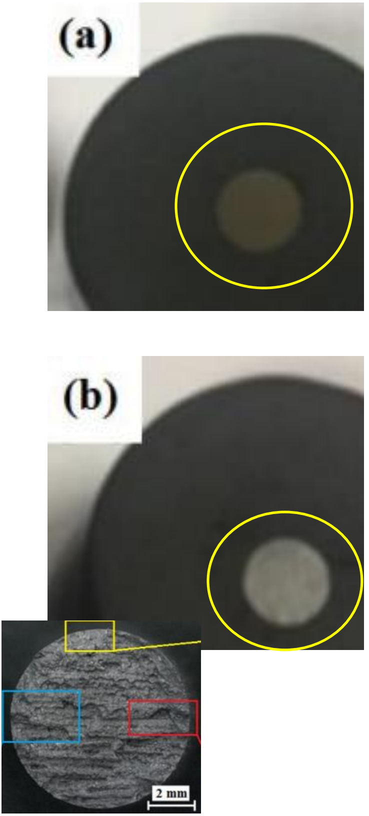


Fatigue life (cycles, N)

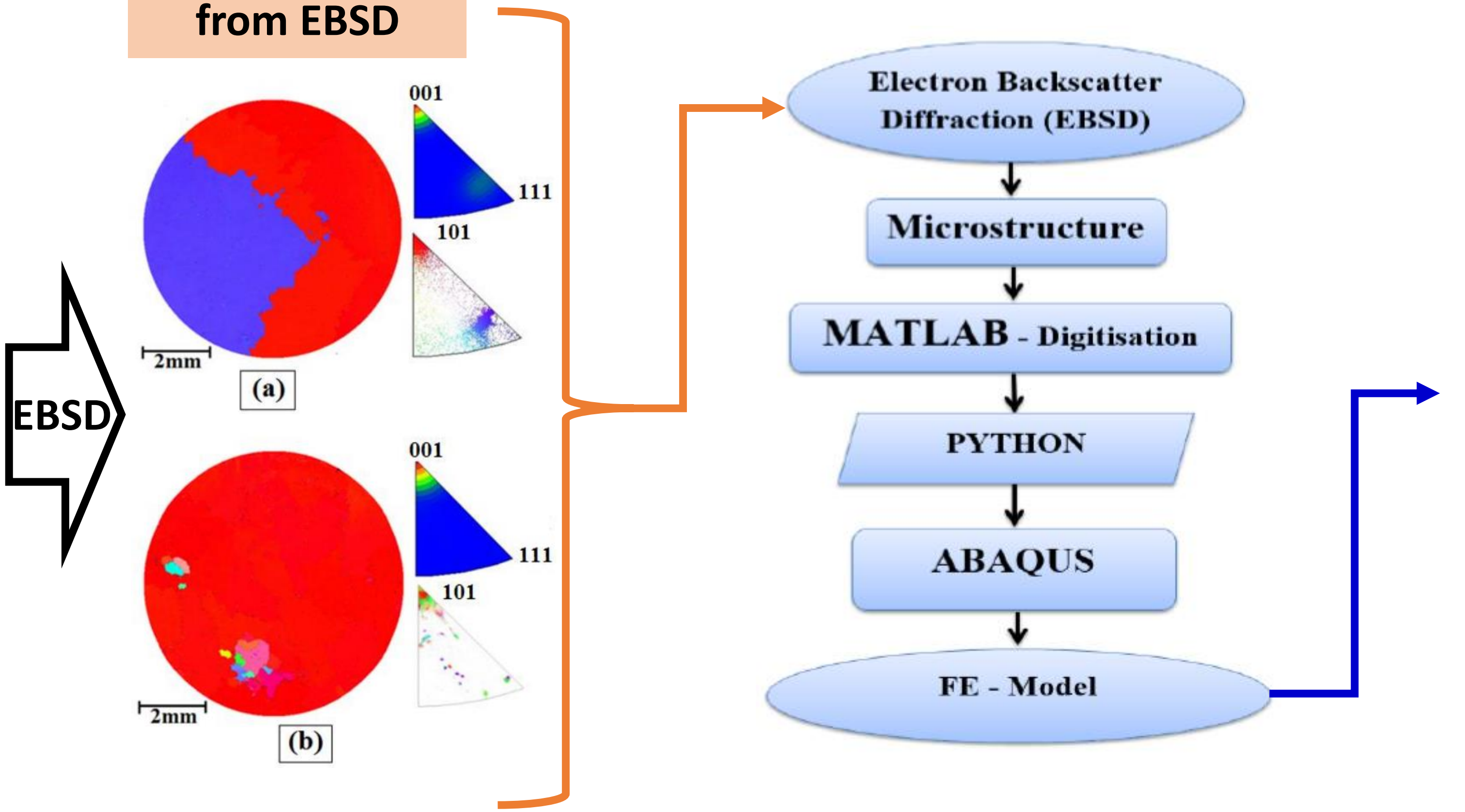
FE model generation - ABAQUS

- Two FE models were generated based on the methodology in the flow chart
- Due to curved geometries, mesh was tetrahedral elements
- These are C3D10 with full integration
- Non-uniform mesh size – due to variable grain size

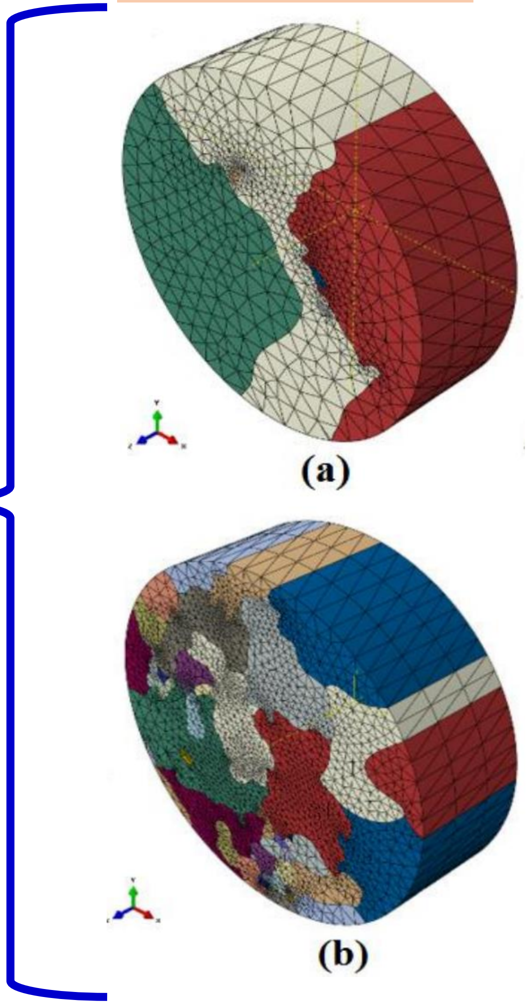
Failed fatigue samples



Microstructure from EBSD



FE models



FE modelling - ABAQUS

- ABAQUS simulations with mechanical deformations – Crystal plasticity model
- Loading & boundary conditions based on experimental tests
- Results post processing: stress/strain loops & stabilised stress evolution to failure
- Hence we can use these results to elucidate Fatigue life difference

Crystal Plasticity Model

Based on multiplicative decomposition of the total deformation gradient:

$$F = \frac{\partial x}{\partial X} = F^{e} F^{p}$$

Octahedral and cubic slip systems control plastic deformation.
For each slip system α, shear strain rate is given by:

$$\dot{\gamma}^{\alpha} = \dot{\gamma}_0 \exp\left[-\frac{F_0}{\kappa\theta}\left\langle 1-\left\langle\frac{\left|\tau^{\alpha}-B^{\alpha}\right|-S^{\alpha}\,\mu/\mu_0}{\hat{\tau}_0\,\mu/\mu_0}\right\rangle^{p}\right\rangle^{q}\right]\mathrm{sgn}(\tau^{\alpha}-B^{\alpha})$$

$$\dot{B}^{\alpha} = h_B\dot{\gamma}^{\alpha} - r_D B^{\alpha}\left|\dot{\gamma}^{\alpha}\right|$$

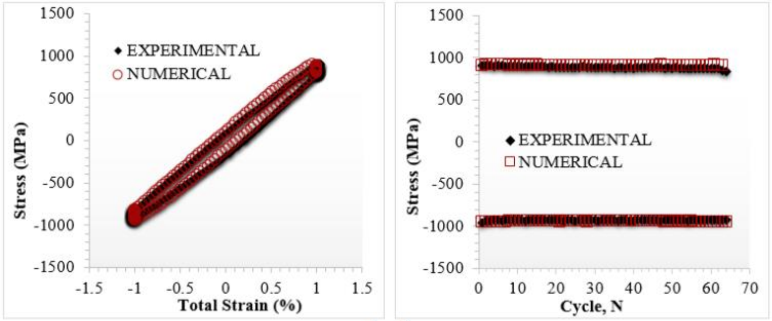
Back stress evolution

$$\dot{S}^{\alpha} = \left[h_S - d_D(S^{\alpha}-S_0^{\alpha})\right]\left|\dot{\gamma}^{\alpha}\right|$$

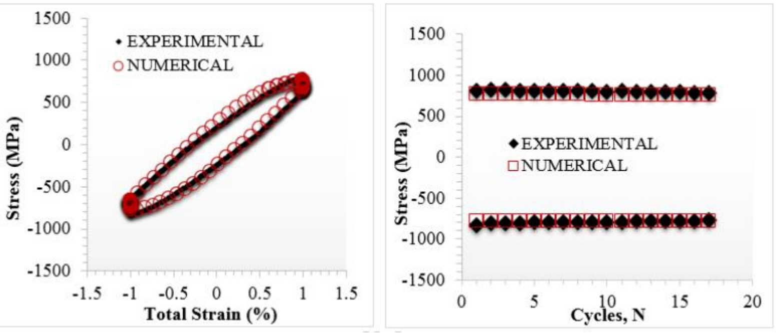
Slip system resistance evolution

Finite element model implemented in ABAQUS as a UMAT, via Fortran

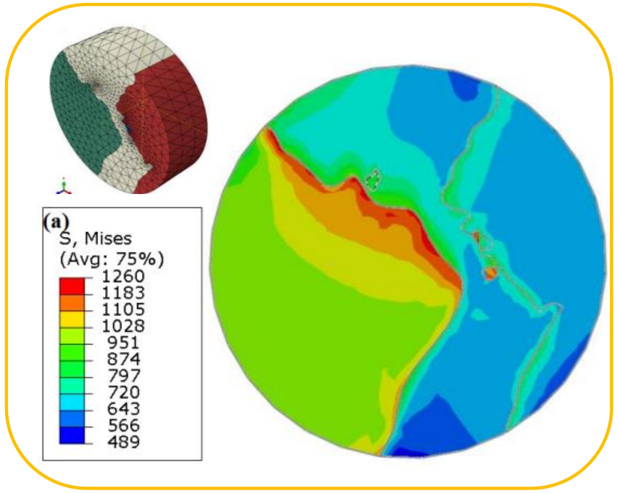
Simulation vs test comparison

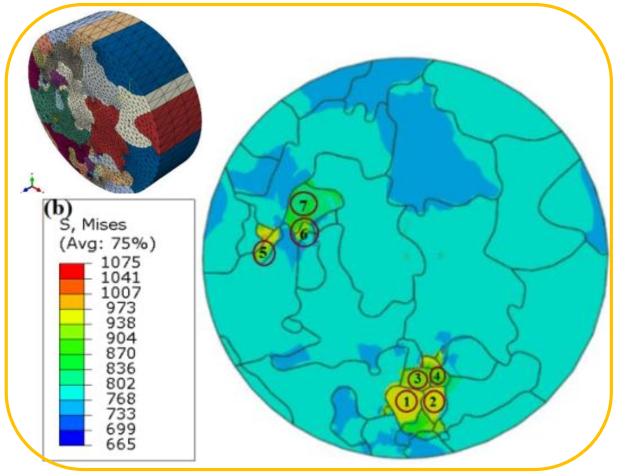


(a)



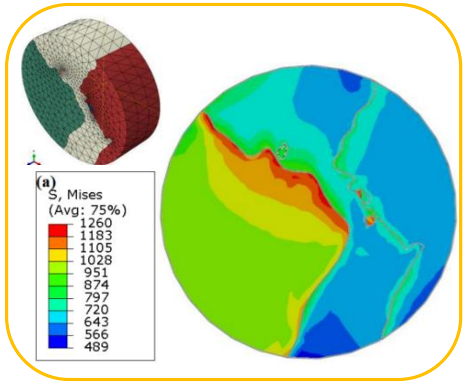
Stress distributions

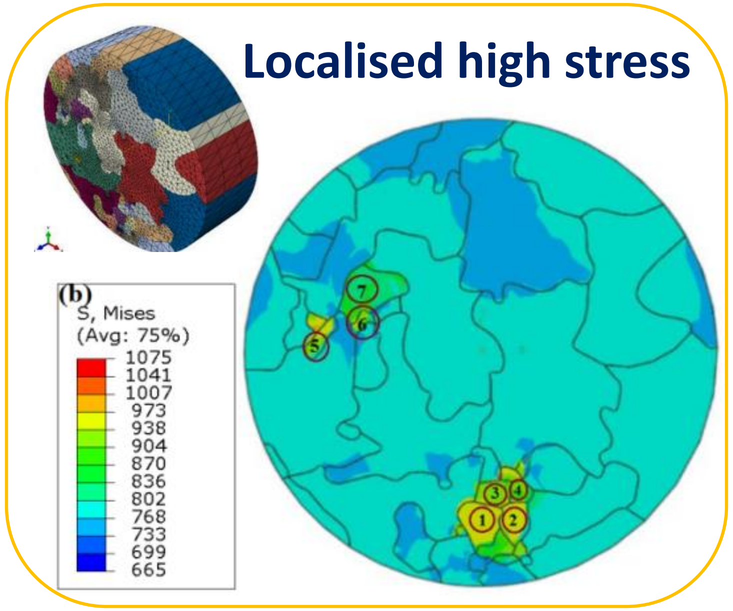


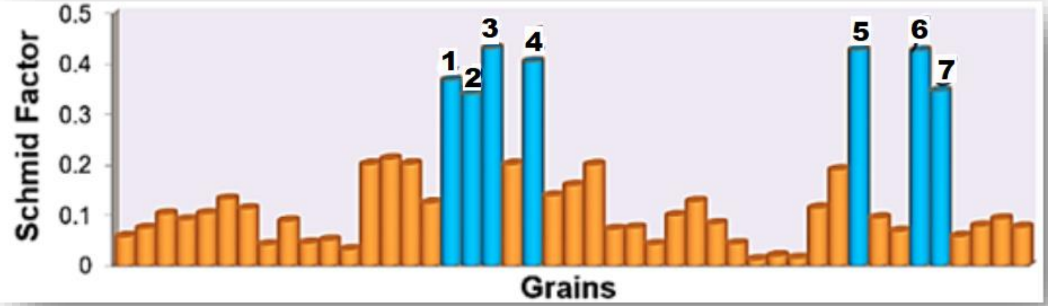


FE modelling - ABAQUS

- **Need to investigate localised high stress in model (b)**
- **Grains with high stress are numbered i.e., 1 - 7**
- **Orientations for all grains in model (b) was considered**
- **Based on the orientations, Schmid factors for each grain were calculated**







Grain	ϕ_1 (°)	Φ (°)	ϕ_2 (°)	Schmid factor
1	21.91	43.5	42.19	0.335184
2	38.63	41.27	40.85	0.324106
3	136.32	35.07	71.91	0.446824
4	125.45	31.87	68.97	0.418316
5	335.28	45.09	60.74	0.436073
6	61.26	33.58	73.57	0.441784
7	268.81	19.08	86.71	0.308274

$$(\tau_{RSS}) = (\sigma) \underbrace{\sin\Phi \sin\phi_2 \cos\Phi}_{\text{Schmid factor}}$$

- **Since shear is proportional to Schmid factor**
- **The 7 grains yielded and failed before the rest**
- **Hence, this led to the reduced fatigue**
- **Failure was caused by missorientations generated at casting stage**
- **Such defects are normally common in engineering components**

Conclusions

- **Illustration of capability of FEM as a tool for solving existing and future (mechanics) engineering problems.**
- **Results were used to elucidate difference in LCF life**
- **Methodology can be applied to study other alloys**
- **Method is useful to solve other complex engineering problems, including:**
  1) Sheet metal forming deep- and cup-drawing,
  2) Extrusion and process/product design
  3) Failure due to mechanical and diffusion interaction

Recommendations

- Since such tools are available for various engineering disciplines, local engineers need to be trained
- Investment in the state-of-the-art equipment and modern engineering software, in research centres.
- Continuous curricula review, to train engineers to innovatively solve local challenges in health, energy, agriculture, transport, and others.

The End

THANK YOU FOR YOUR ATTENTION.