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High temperature thermo-mechanical fatigue in polycrystalline nickel base superalloy RR1000: Material model development

B. Engel, J. P. Rouse and C.J. Hyde
University of Nottingham

S. Stekovic, D. Leidermark, V. Norman
Linkoping University

M. Whittaker, J. P. Jones
Swansea University

S. J. Pattison
Rolls Royce

DevTMF Project

- Funded by the European Union and Cleansky2 in cooperation with University of Linköping, University of Swansea and Rolls Royce
- DevTMF = Development of experimental techniques and predictive tools to characterise Thermo-Mechanical Fatigue behaviour and damage mechanisms
- Reducing emissions and fuel usage of gas turbines, especially CO_2 and NO_x (70 % in the next 30 years) with simultaneously increase of efficiency
- Pushing materials and analysis of turbine components to a limit with innovative standardized experimental methods and modelling approaches

Investigated Material RR1000

Composition

- Powder processed polycrystalline nickel base superalloy
- Used for turbine rotor in the hot gas section
- Nominal composition in wt.%

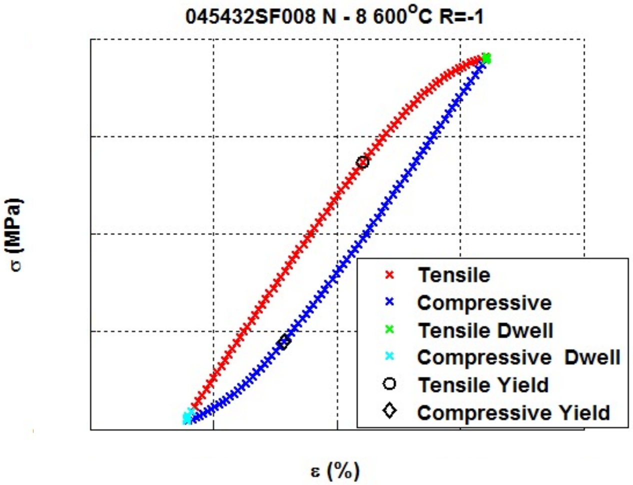
Co	Cr	Mo	Ti	Al	Ta	Hf	Zr	C	B	Ni
18.5	15	5	3.6	3	2	0.5	0.06	0.027	0.015	Bal.

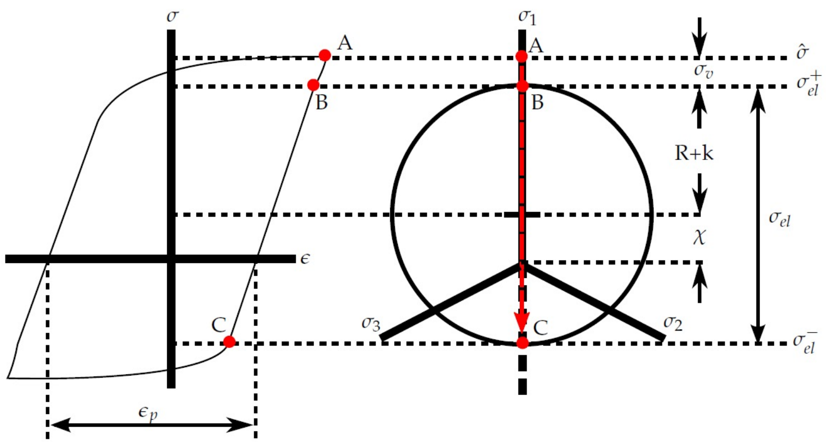
- γ' volume content is up to 50 %, coherently embedded in the γ matrix after a complex multi step heat treatment
- Different size distributions of γ'

Constitutive Model

Elastic viscoplastic model

- Cottrell's stress partitioning was applied to isothermal LCF data





$$\sigma_v = \hat{\sigma} - \sigma_{el}^{+}$$

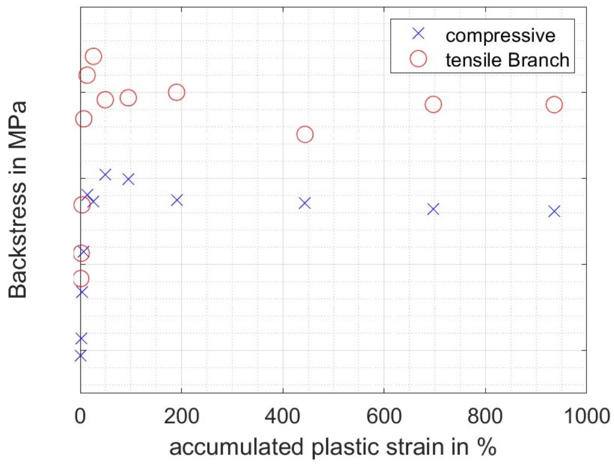
$$R + k = \frac{\sigma_{el}}{2}$$

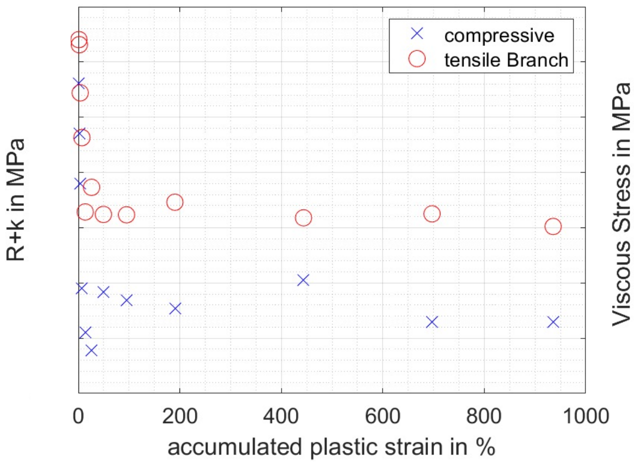
$$\chi = \begin{cases} \sigma_{el}^{+} - \frac{\sigma_{el}}{2}, & \text{if } \sigma_{el}^{+} \geq \sigma_{el}^{-} \\ 0, & \text{if } \sigma_{el}^{+} = \sigma_{el}^{-} \\ \sigma_{el}^{-} + \frac{\sigma_{el}}{2}, & \text{if } \sigma_{el}^{-} \geq \sigma_{el}^{+} \end{cases}$$

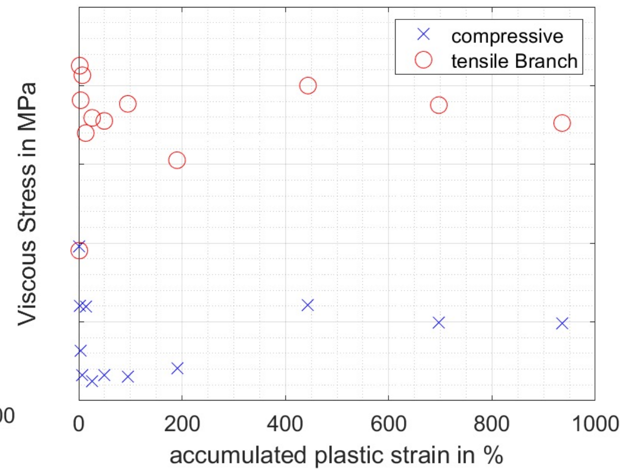
Constitutive Model

Elastic viscoplastic model

- Cottrell's stress partitioning was applied to isothermal LCF data
- Determine the evolution of state variable backstress, dragstress and viscous stress







Constitutive Model

Elastic viscoplastic model

- Cottrell's stress partitioning was applied to isothermal LCF data to estimate state variable evolution
- A elastic-viscoplastic ("Chaboche" type) constitutive model has been applied in order to approximate drag and back stress evolution (for isotropic and kinematic hardening, respectively)

$$\epsilon = \epsilon_e + \epsilon_p$$

$$\sigma = \chi + (R + k + \sigma_v)\frac{\sigma\prime - \chi\prime}{J(\sigma - \chi)}$$

$$dp = \left(\frac{2}{3}d\epsilon_{p^{ij}}d\epsilon_{p^{ij}}\right)^{1/2}$$

$$f = J(\sigma - \chi) - R - k$$

$$J(\sigma - \chi) = \left(\frac{3}{2}(\sigma_{ij}\prime - \chi_{ij}\prime)(\sigma_{ij}\prime - \chi_{ij}\prime)\right)^{1/2}$$

$$d\epsilon_p = d\lambda\frac{\partial f}{\partial \sigma}$$

$$\sigma_v = Z\dot{p}^{1/n}$$

$$d\chi_i = C_i a_i d\epsilon_p + C_i \chi_i p$$

$$\chi = \sum_{i=1}^{2}\chi_i$$

$$R = Q\left(1 - e^{-bp}\right) + Hp$$

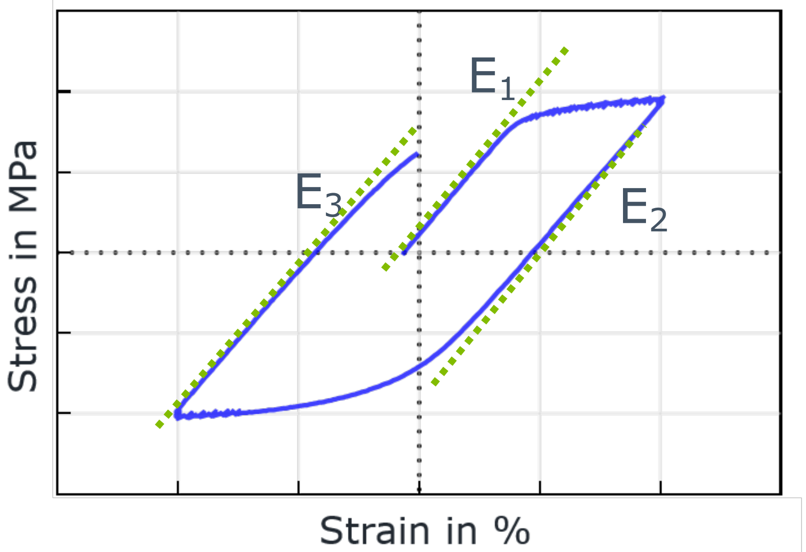
$$\frac{d\epsilon_p}{dt} = \frac{3}{2}\langle\frac{J(\sigma - \chi) - R - k}{Z}\rangle^n \frac{\sigma\prime - \chi\prime}{J(\sigma - \chi)}$$

→ Set of constant material parameters $C_1, a_1, C_2, a_2, Q, b, H$…

Material Behaviour

Investigation of the first cycles

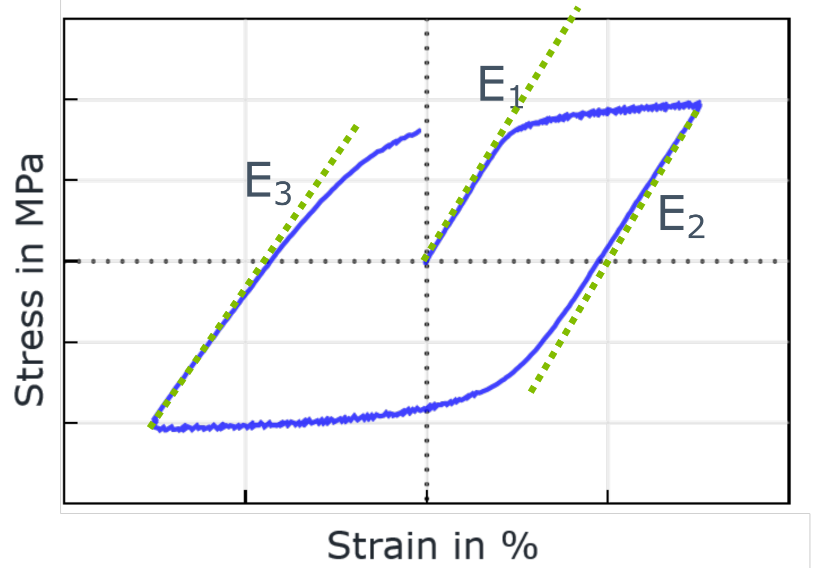
- Test for $\varepsilon_{a,t}$= 1 % and 700 °C
- Decreasing Young's moduli with $E_1 > E_2 > E_3$ for $\varepsilon_{a,t}$= 1 % and $E_3 = 0.9*E_1$
- After stabilization $E_{stab} = E_1*0.87$



Material Behaviour

Investigation of the first cycles

- Test for $\varepsilon_{a,t}$= 1.5 % and 700 °C
- Decreasing Young's moduli with $E_1 > E_2 > E_3$ for $\varepsilon_{a,t}$= 1.5 % and E3 = 0.85*E_1
- After stabilization $E_{stab} = E_1$*0.75
- For tests with $\varepsilon_{a,p} \approx 0$, no measurable changes in Young's modulus

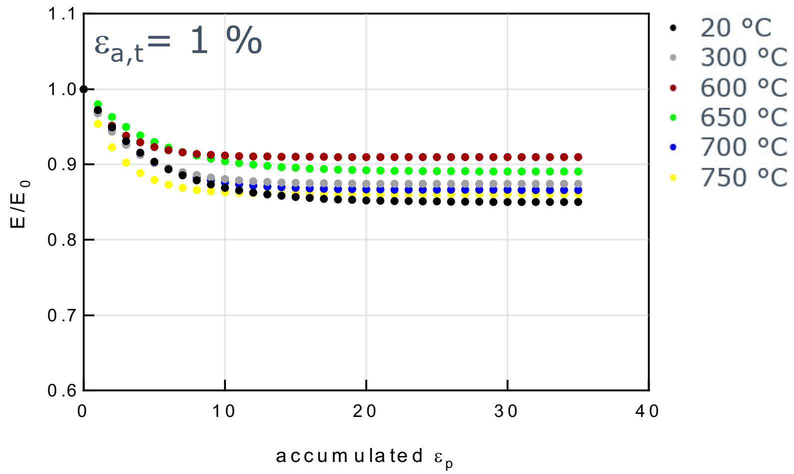


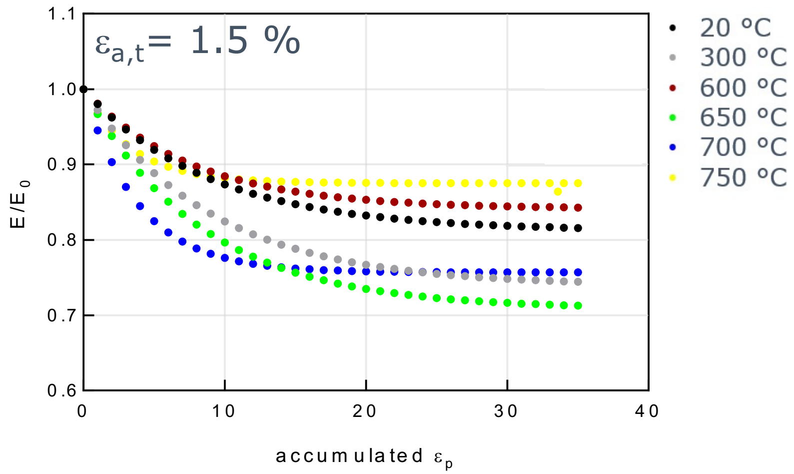
Decrease of Young's moduli is dependent on the apllied plastic strain

Material Behaviour

RR1000 – Young's modulus decrease vs. temperature

- Plotting the relative change $\frac{E}{E_0}$ over the accumulated plastic strain





- No strong correlation between decrease in Young's modulus and temperature

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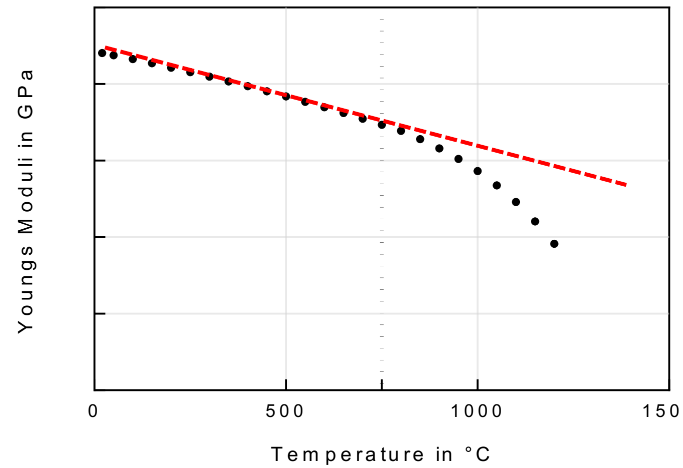
Modelling Approach

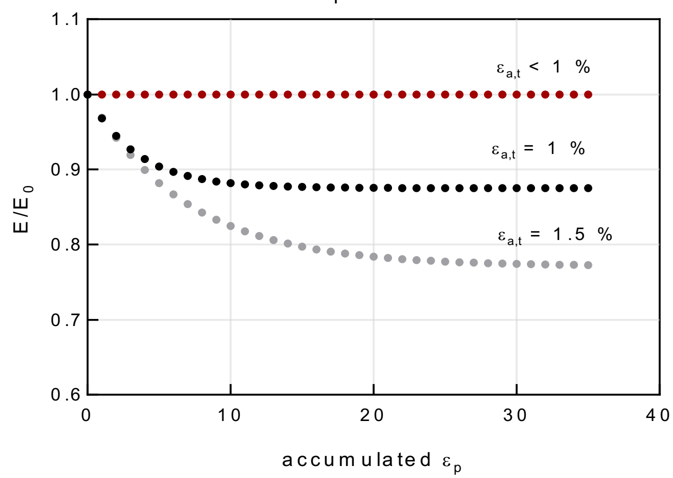
- 1 Step: Calculation of the initial Young's moduli E_0 in dependence of temperature (from tensile test).
  - Up to 750 °C a linear behaviour can be assumed

$$E_0 = \mathrm{a} \cdot \mathrm{T} + \mathrm{b}$$

- 2 Step: Usage of an average function to model the decrease of Young's moduli in dependence of accumulated plastic strain

$$E = 1 - (\mathrm{c} \cdot (1 - \exp(-d \cdot \varepsilon_p)) \cdot E_0$$





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Adding static recovery

- Adding a third term to the decomposed back stress

$$d\chi_i = C_i a_i d\varepsilon_p + C_i \chi_i \mathrm{p} - R_{kin,i}\chi_i$$

- With $R_{kin,i} = B_i \cdot \exp(\frac{-Qm}{RT}) \cdot abs(X_i)^{\ m-1}$
- Independent of plastic strain, dependent on T

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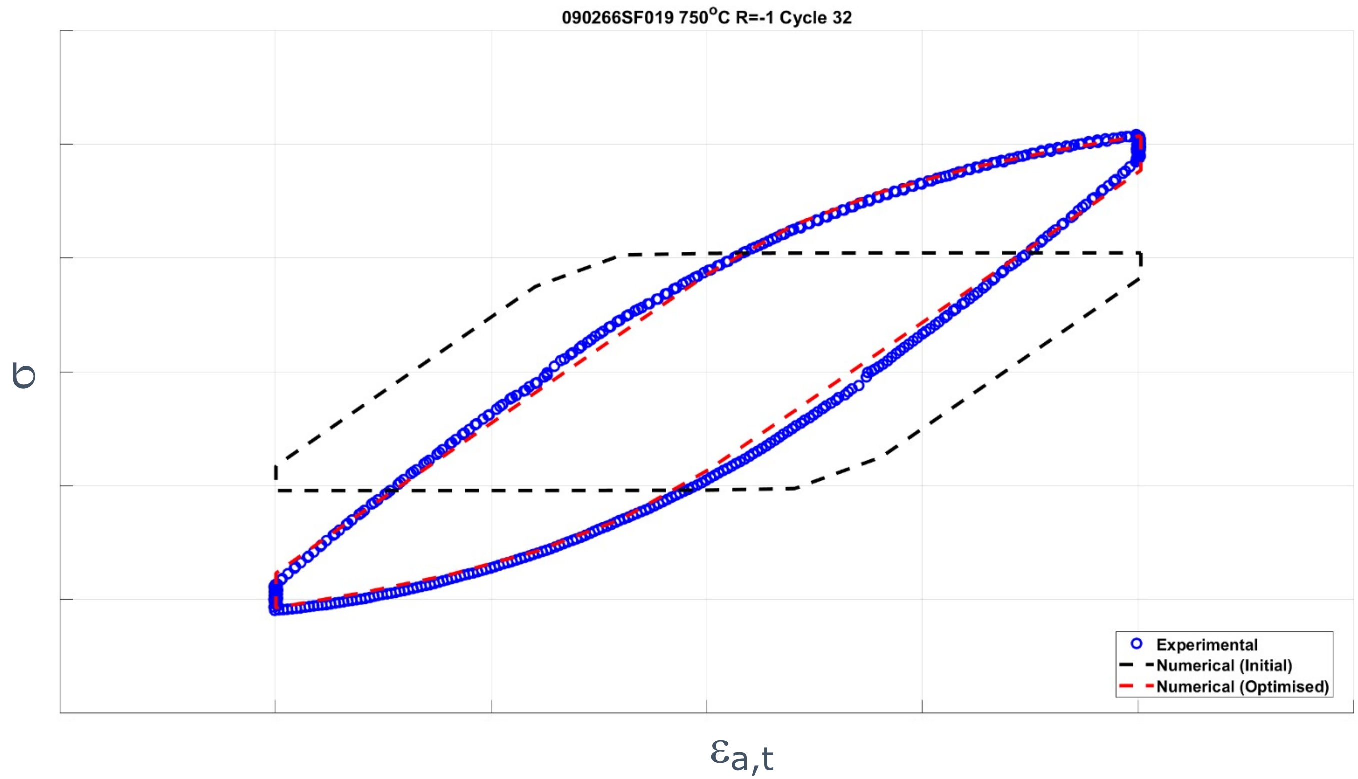
RR 1000 – Results for 1.0 % at 750 °C and optimized parameters



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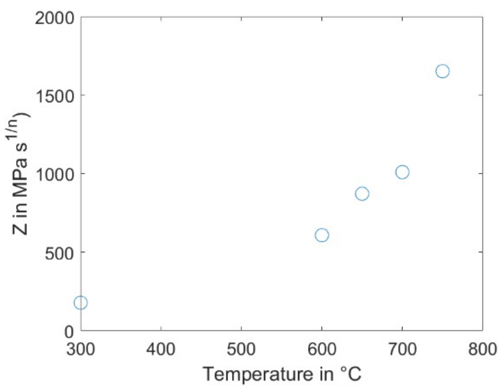
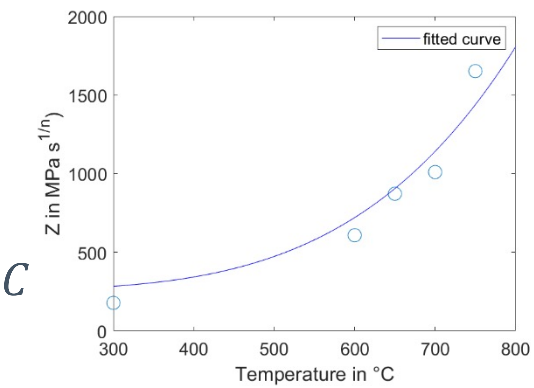
Modell extension for TMF and an-isothermal simulations

- Determining temperature dependent material parameters by fitting a function to the isothermal values



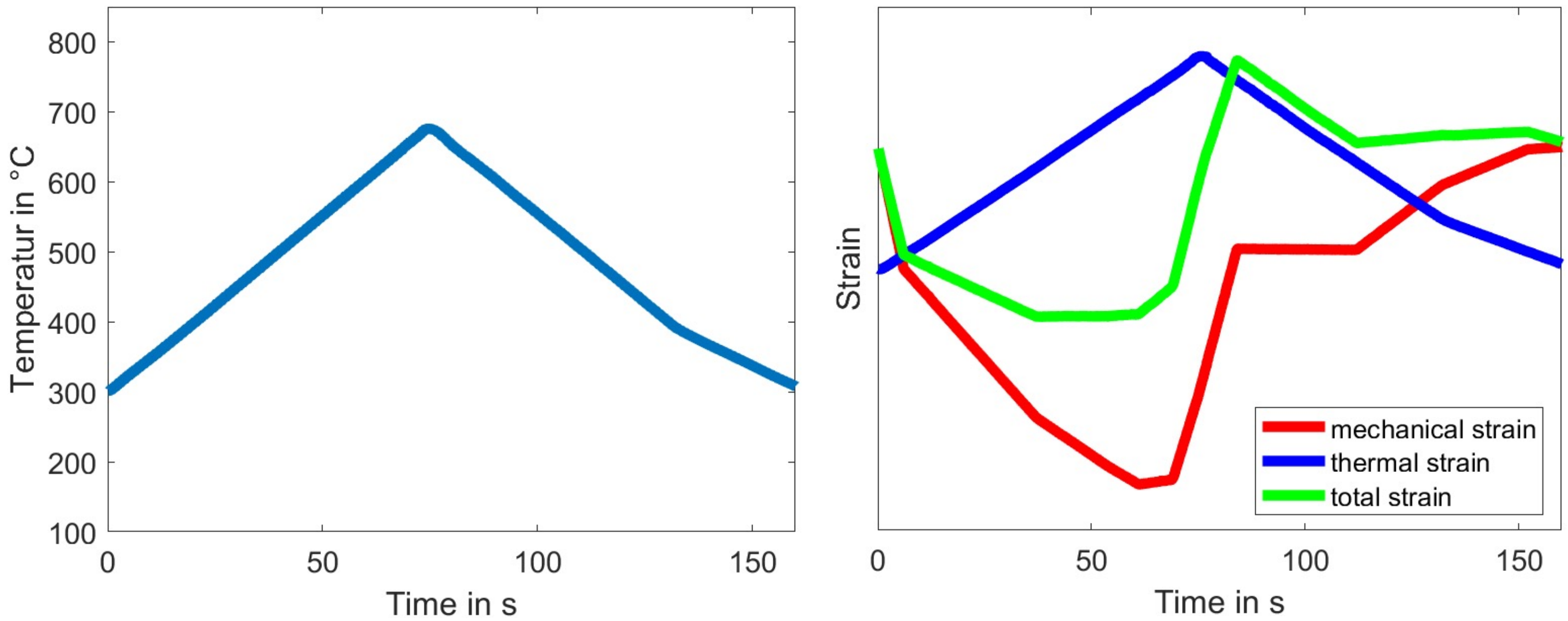
$$y(T) = A \cdot T^{B} + C$$



- Values A,B and C are fitting parameters and describe the material behaviour over the whole temperature range

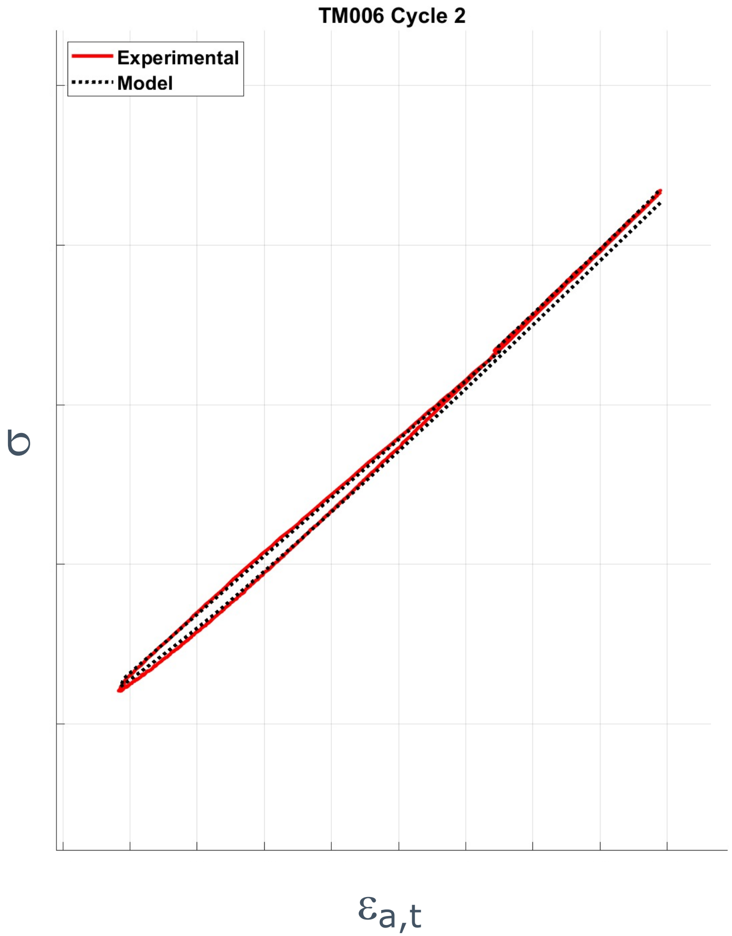
Predicted TMF Tests

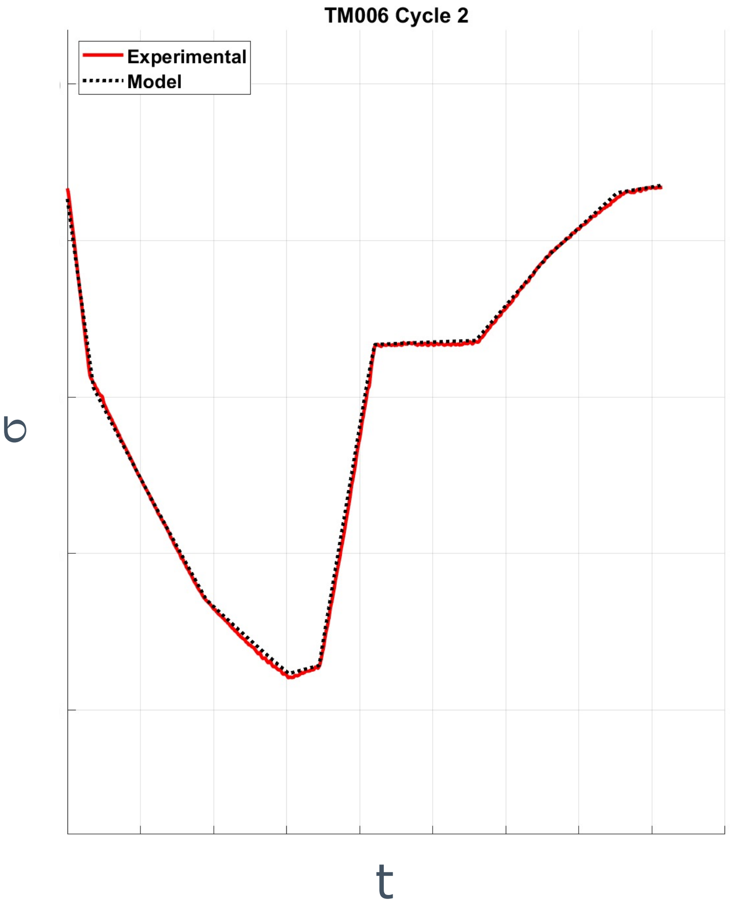
Complex Flight Cycle - Temperature range 300 °C – 675 °C



Predicted TMF Tests

Complex Flight Cycle - Temperature range 300 °C – 675 °C





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Results & Outlook

- The model can predict isothermal LCF-, TMF- and complex an-isothermal tests
- The implementation of a variable Young’s moduli leads to much better predictions especially within the first cycles
- More modifications and optimizations are necessary to improve the predictions (different Young’s modulus in tension and compression)
- Where does the Young’s modulus decrease come from?

Thank You for Your Attention.
Any Questions?

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Where does the decrease come from?

Literature Review

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Literature Review – Changes in Young’s Moduli

- Changes in Young‘s Moduli in dependence of plastic strains up to 15 % are known for:
  - Pure iron, low carbon steels, stainless steel, aluminium, brass, copper, stainless steel
  - At room temeprature and very high plastic strains in tension tests (no cyclic testing)
  - Effects are mostly attributed to dislocation distribution (no effect of texture, resiudal stresses)

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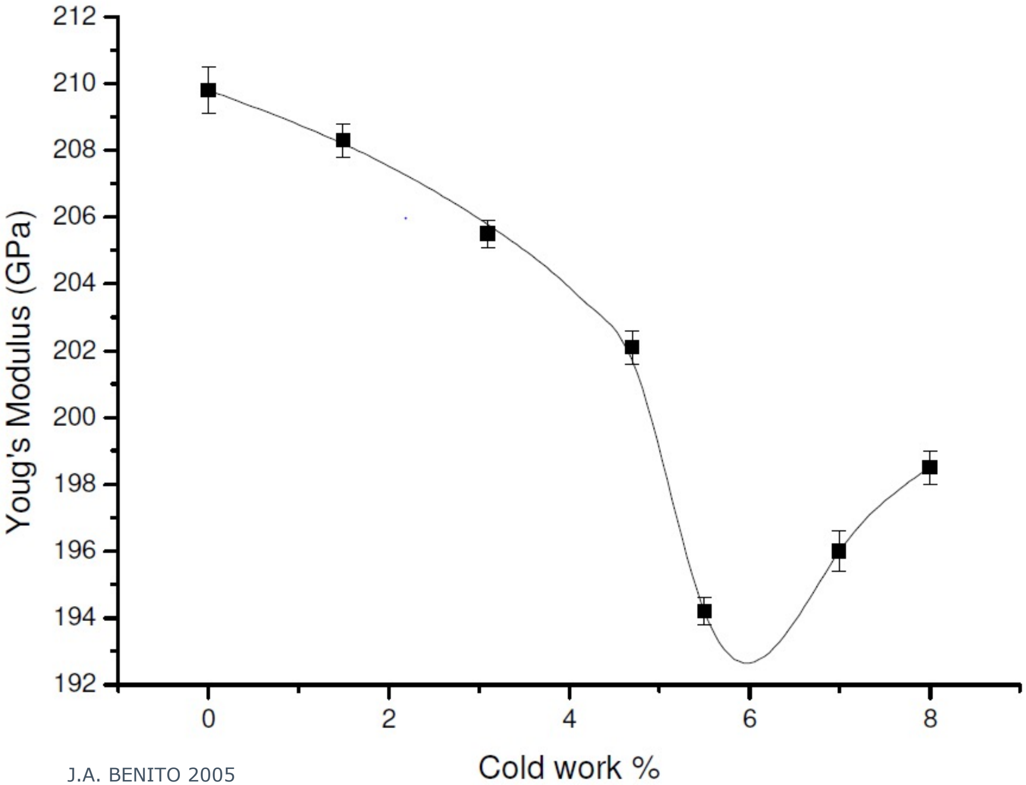
Where does the decrease come from? – Literature Review



J.A. BENITO 2005

$$\frac{\Delta E}{E} = -\rho \cdot \frac{l^2}{6 \cdot \alpha}$$

ρ: dislocation density

l : is the average length line of dislocations between pinning points

α: is a function of l

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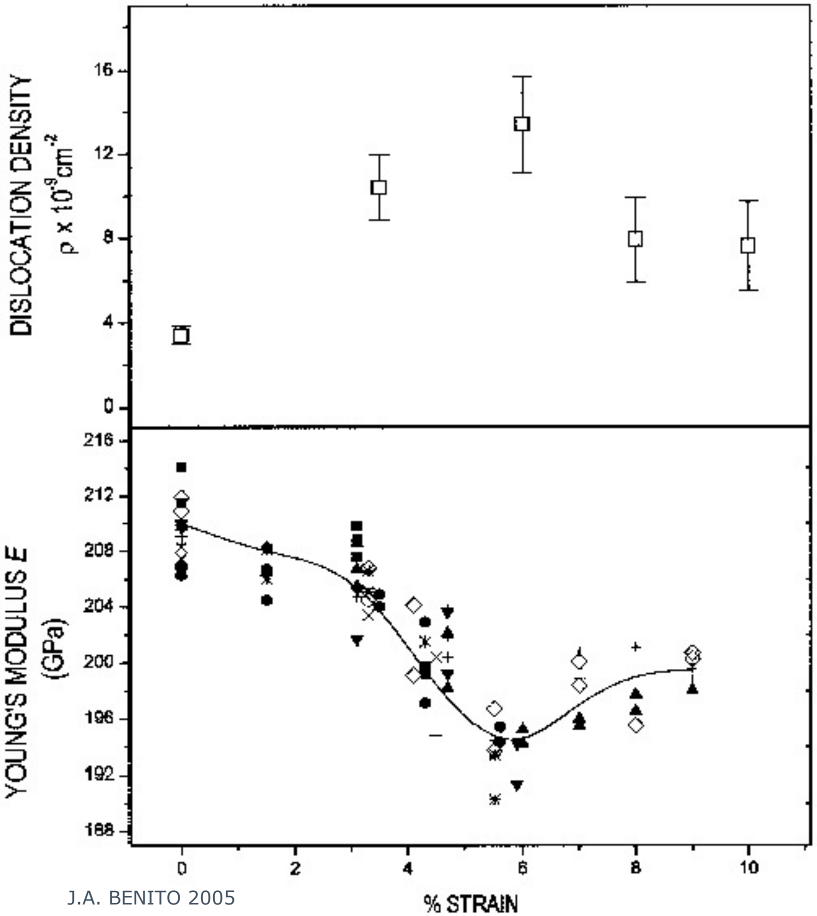
Pure Iron in tensile test



J.A. BENITO 2005

Their conclusion:

Increase of plastic strain leads to increase in dislocation density

Dislocation form a bow out while formation of cellular arrays, which gives additional strain → decreases Youngs Moduli

Recovery attributed to no new formation of cellular dislocation distribution