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


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# 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.%

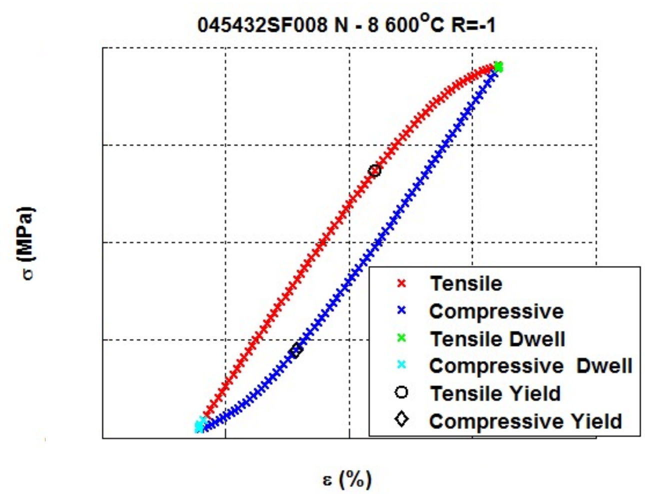
| Co | Cr | Mo | Ti | Al | Ta | Hf | Zr | C | B | Ni |
|---|---|---|---|---|---|---|---|---|---|---|
| 18.5 | 15 | 5 | 3.6 | 3 | 2 | 0.5 | 0.06 | 0.027 | 0.015 | Bal. |

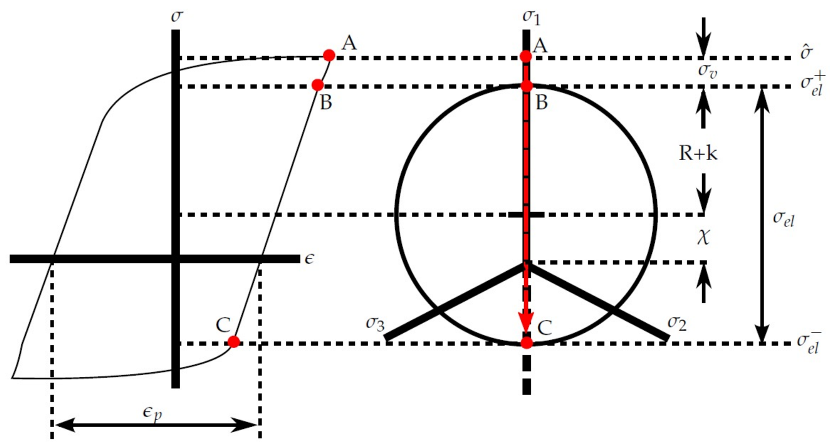
- $\gamma'$ volume content is up to 50 %, coherently embedded in the $\gamma$ matrix after a complex multi step heat treatment
- Different size distributions of $\gamma'$

# Constitutive Model

## Elastic viscoplastic model

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




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

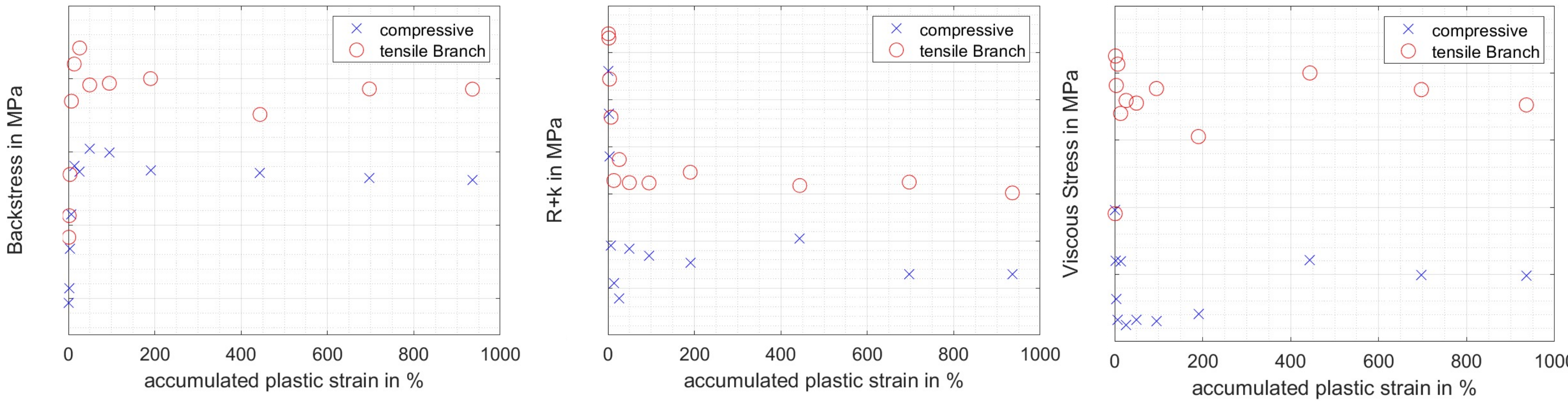
$$R + k = \frac{\sigma_{el}}{2}$$

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

# 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)

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

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

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

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

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

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

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

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

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

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

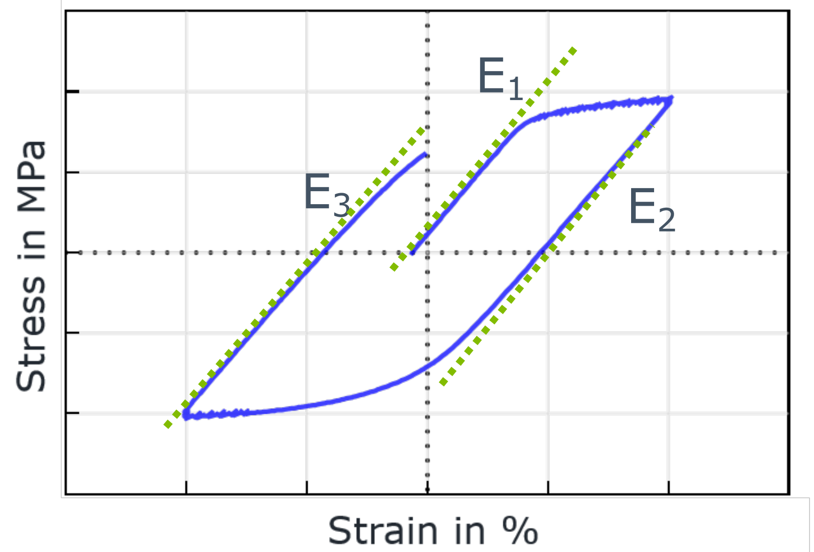
$$\frac{d\epsilon_p}{dt} = \frac{3}{2}\langle\frac{J(\sigma - \chi) - R - k}{Z}\rangle^n \frac{\sigma\prime - \chi\prime}{J(\sigma - \chi)}$$

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

# Material Behaviour

## Investigation of the first cycles

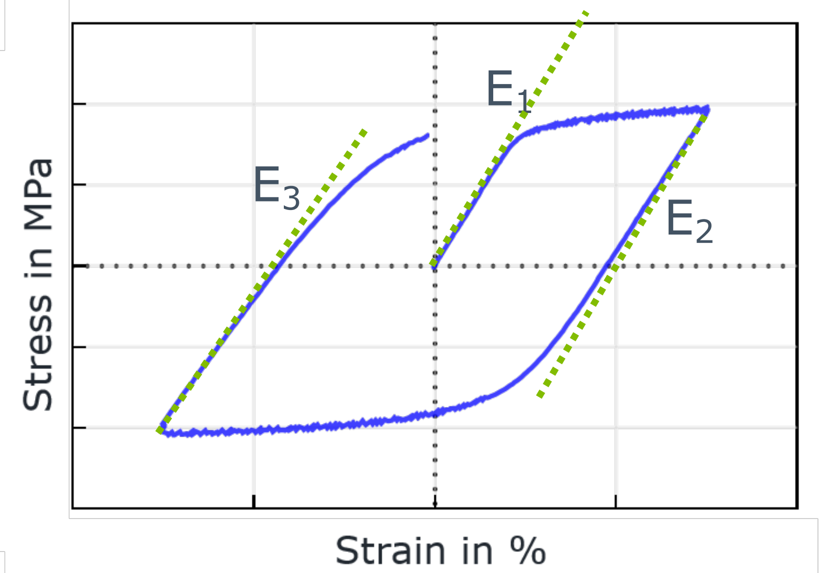
- Test for $\varepsilon_{a,t}$= 1 % and 700 °C
- Decreasing Young's moduli with $E_1 > E_2 > E_3$ for $\varepsilon_{a,t}$= 1 % and $E_3 = 0.9 * E_1$
- After stabilization $E_{stab} = E_1 * 0.87$



# 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

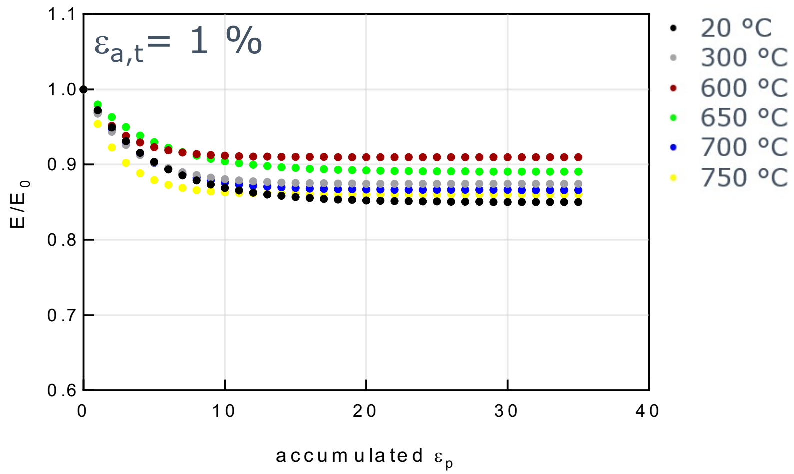


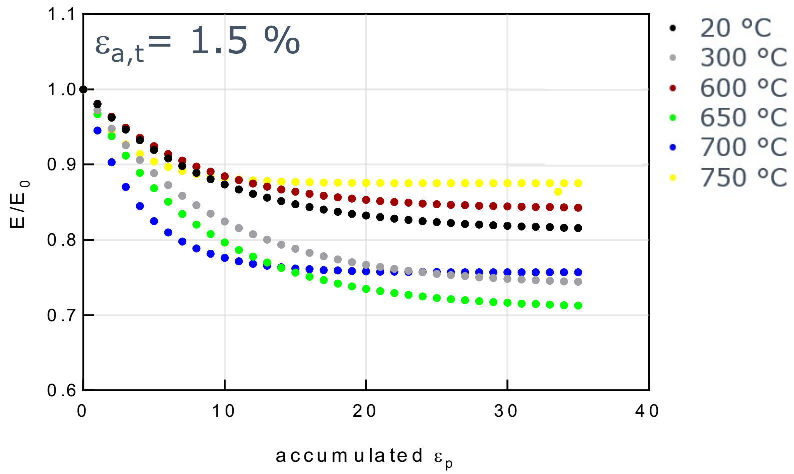

Decrease of Young‘s moduli is dependent on the apllied plastic strain

# 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

# DevTMF

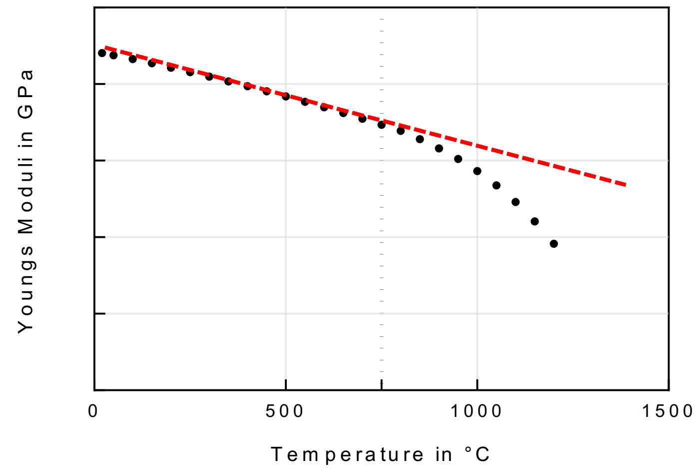
## Modelling Approach

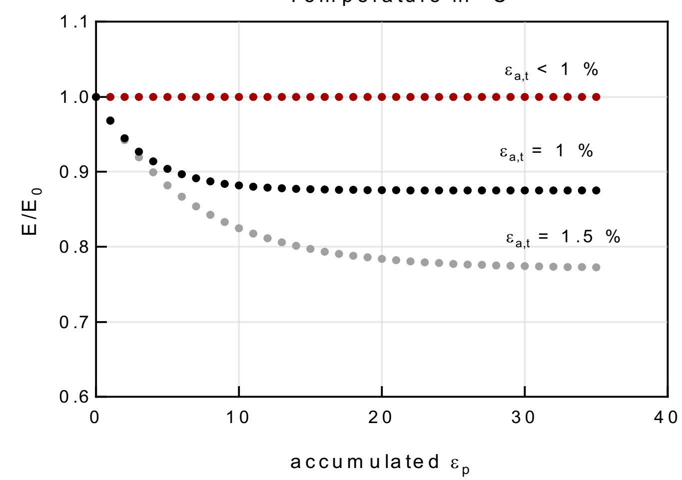
- 1 Step: Calculation of the initial Young's moduli $E_0$ in dependence of temperature (from tensile test).
  - Up to 750 °C a linear behaviour can be assumed

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

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

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



# DevTMF

## Adding static recovery

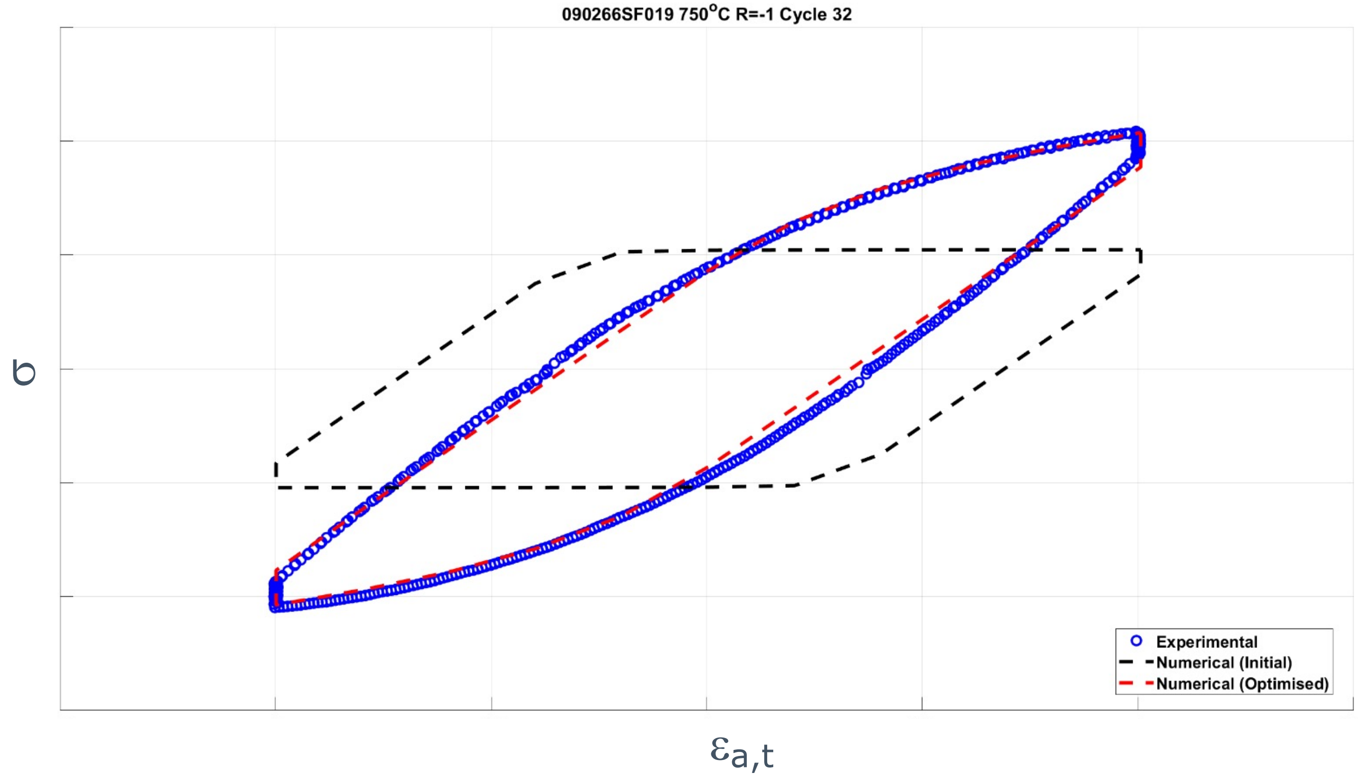
- Adding a third term to the decomposed back stress

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

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

# DevTMF

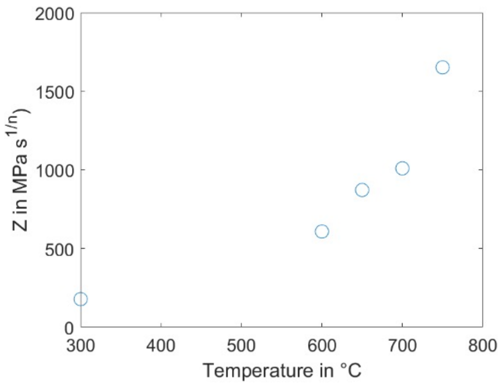
## RR 1000 – Results for 1.0 % at 750 °C and optimized parameters



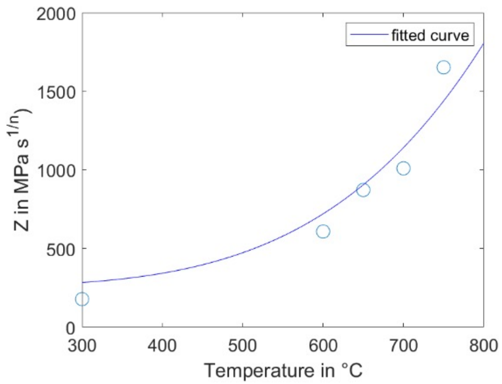
# DevTMF

## Modell extension for TMF and an-isothermal simulations

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



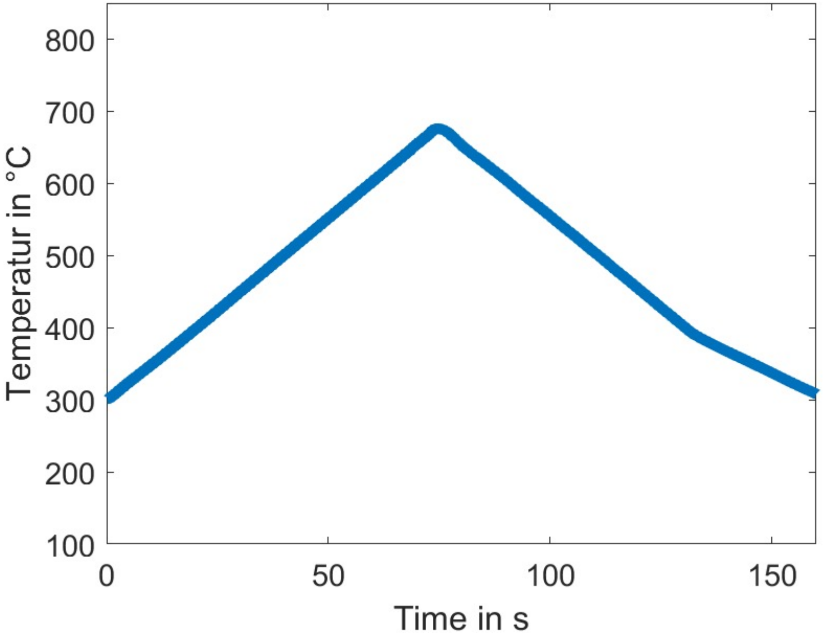

$$y(T) = A \cdot T^B + C$$

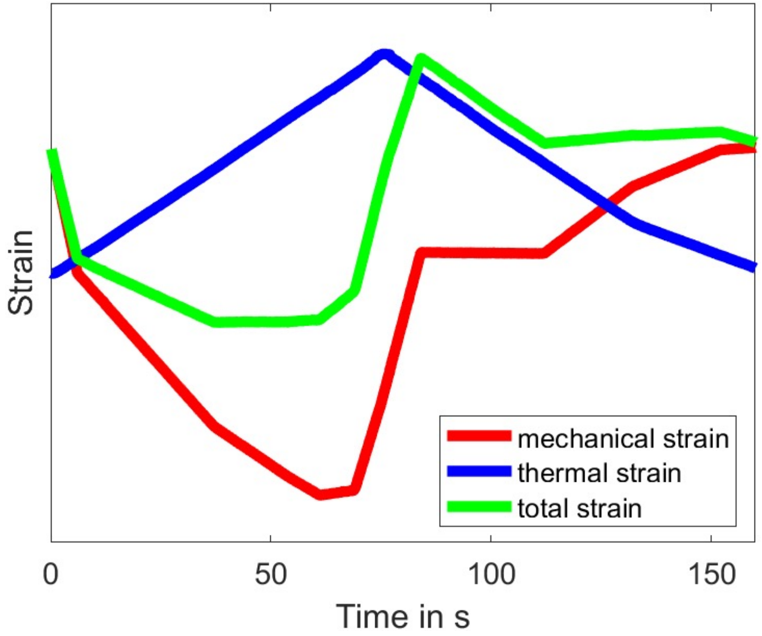



- Values A,B and C are fitting parameters and describe the material behaviour over the whole temperature range

# Predicted TMF Tests

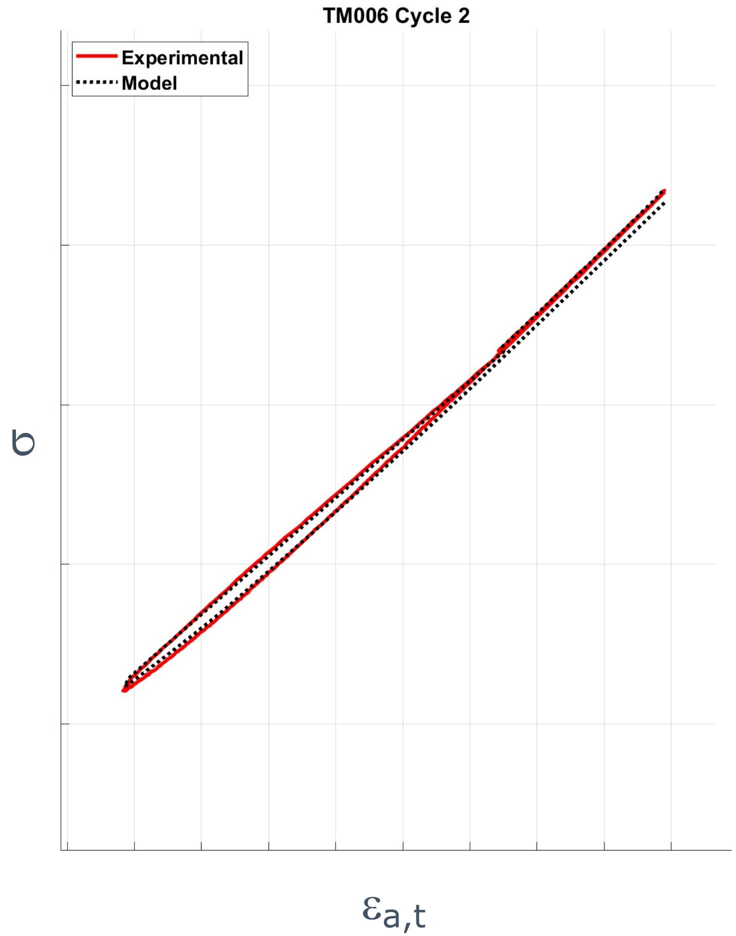
## Complex Flight Cycle - Temperature range 300 °C – 675 °C

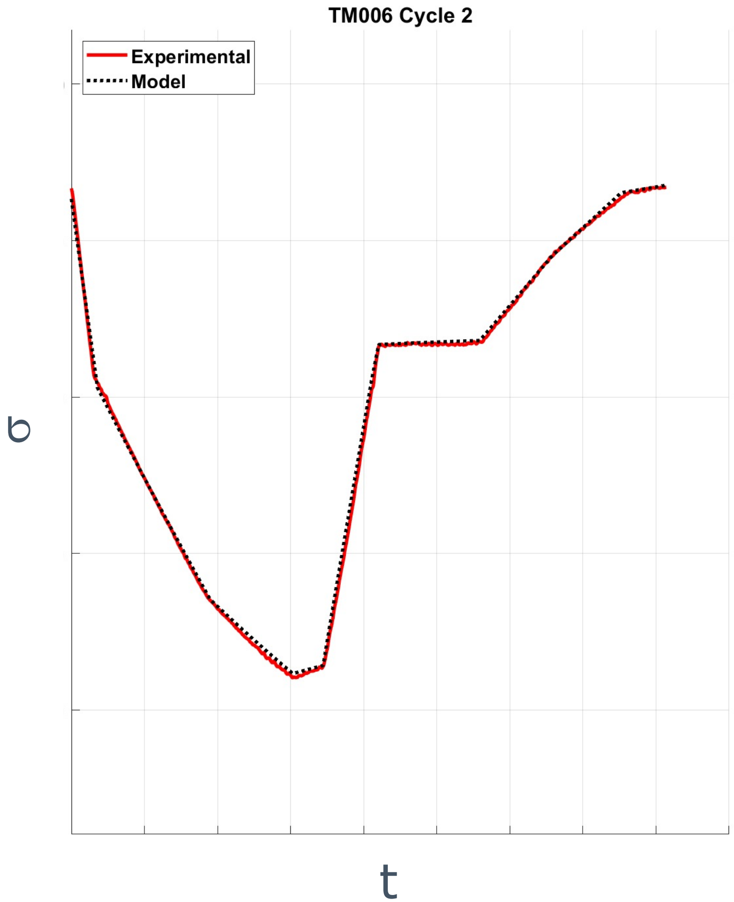


# Predicted TMF Tests

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



# DevTMF

## 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?

# DevTMF

Where does the decrease come from?

Literature Review

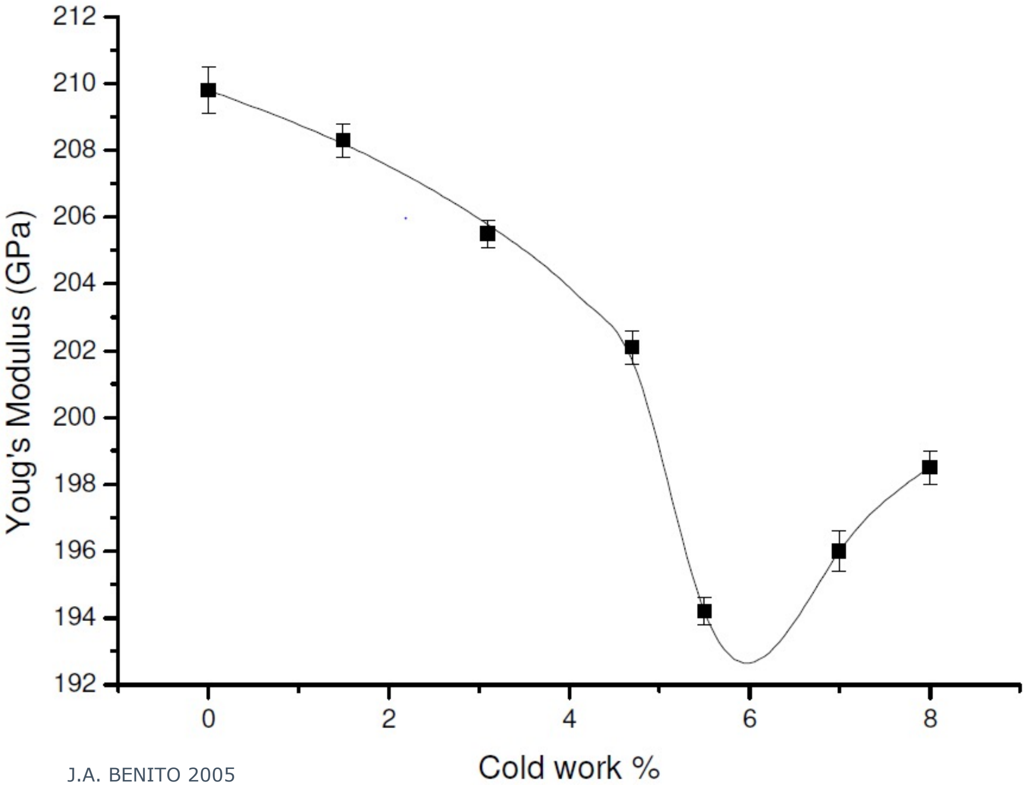
# DevTMF

## 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)

# DevTMF

## Where does the decrease come from? – Literature Review




J.A. BENITO 2005

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

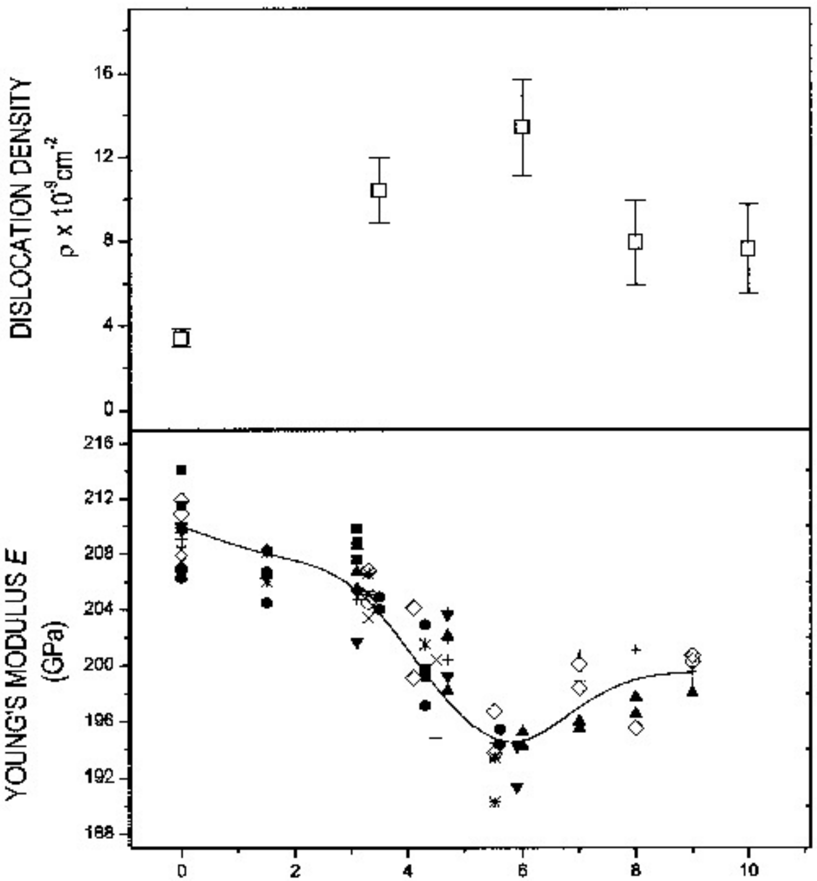
$\rho$: dislocation density

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

$\alpha$: is a function of $l$

# DevTMF

## 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