Crystal Viscoplasticity Creep-Fatigue Interaction Model for CMSX-8

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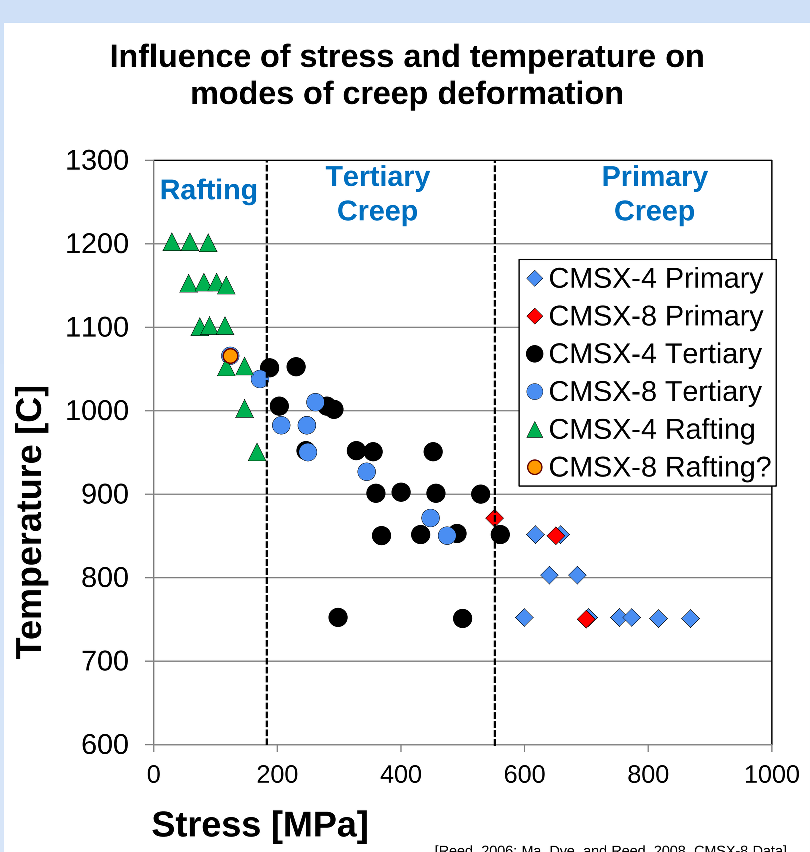
Motivation

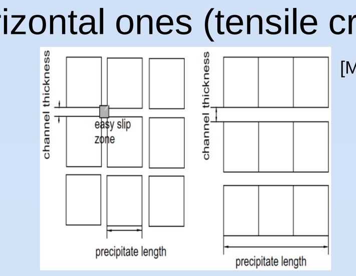
Components in the hot section of Industrial Gas Turbines (IGTs) are subject to a very hostile environments, and creep and fatigue loads. The push for increased efficiency leads to even higher operating temperatures which also affect the microstructure. Commercial software is limited to non-interaction creep and plasticity and cannot account for microstructure evolution. An enhanced crystal viscoplasticity (CVP) model is needed to enhance the design and maintenance of hot section materials and components.

Introduction

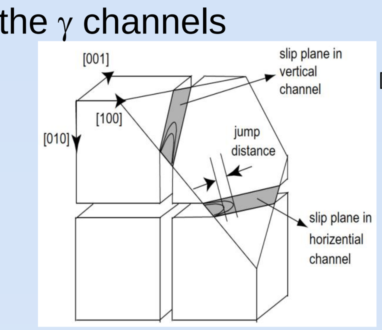
CMSX-8 has primarily two phases, an ordered intermetallic $L1_2$ phase known as γ' and a disordered phase known as γ. Under creep, the deformation mechanisms that take place on each phase are unique to each phase:



Rafting – transport of matter constituting the γ phase out of the vertical channels and into the horizontal ones (tensile creep case)



Tertiary – dislocation activity restricted to a/2<110> form operating on {111} slip planes in the γ channels



Primary – γ' particles are sheared by dislocation ribbons of overall Burgers vector a<112> dissociated into superlattice partial dislocations separated by a stacking fault; shear stress must be above threshold stress (about 550 MPa)

Deformation can be best represented by assuming an additive effect in the deformation:

$$\mathbf{L}^{in} = \dot{\mathbf{F}}^{in}\mathbf{F}^{in^{-1}} = f_\gamma\left(\sum_{\alpha=1}^{12}\dot{\gamma}_\gamma^{in(\alpha)}\left(\hat{\mathbf{d}}^{(\alpha)}\otimes\hat{\mathbf{n}}^{(\alpha)}\right)\right) + f_{\gamma'}\left(\sum_{\alpha=13}^{24}\dot{\gamma}_{L1_2}^{in(\alpha)}\left(\hat{\mathbf{d}}^{(\alpha)}\otimes\hat{\mathbf{n}}^{(\alpha)}\right)\right)$$

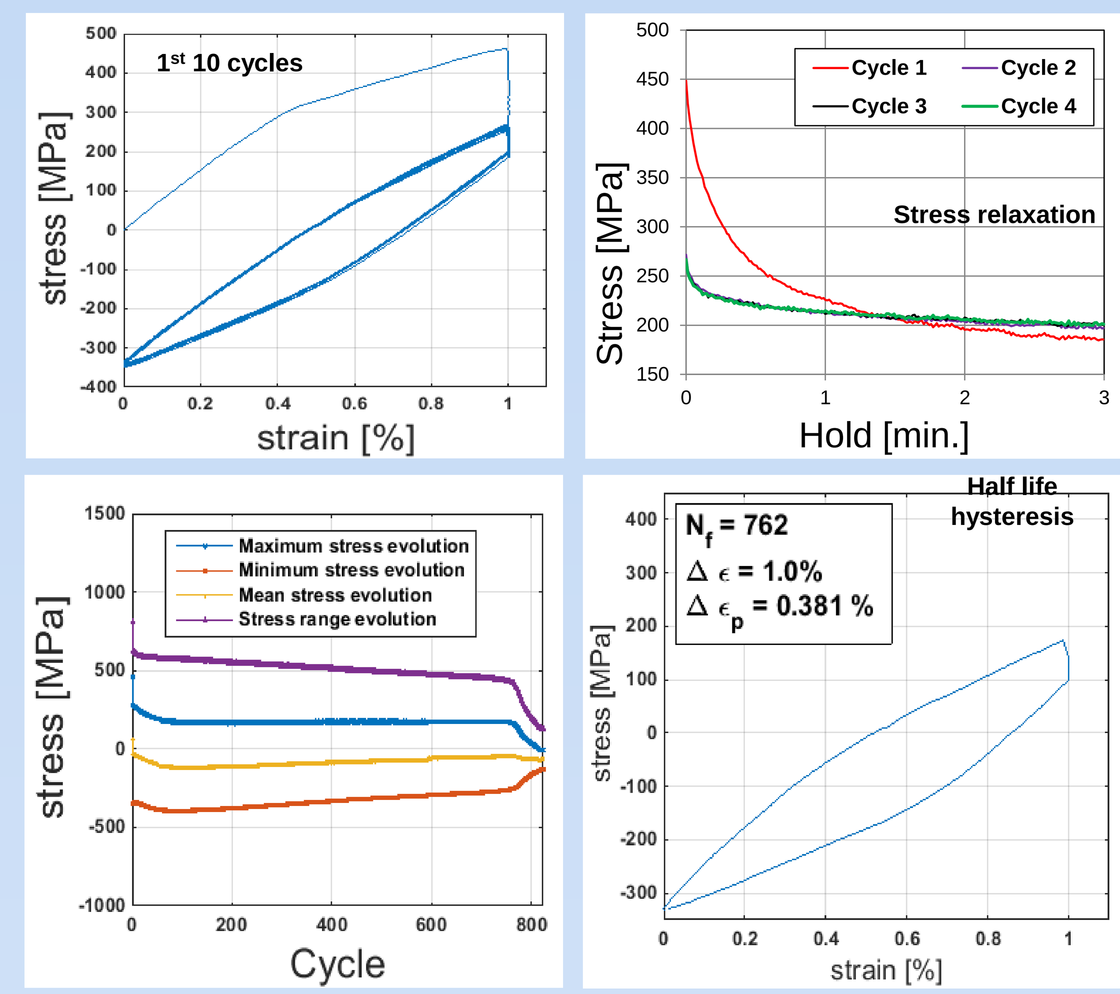
The inelastic strain rates include creep mechanisms and the backstress to model creep-fatigue, dislocation densities and inelastic strain are used as ISV:

$$\dot\gamma_\gamma^{in(\alpha)} = \rho^{(\alpha)}_\gamma b\lambda^{(\alpha)}_\gamma F_{attack}\exp\left\{\frac{-Q^{110}_{slip}+\left(\left|\tau^{(\alpha)}+\tau^{(\alpha)}_{mis}-\chi^{(\alpha)}\right|-\tau^{(\alpha)}_{\gamma pass}-\tau^{(\alpha)}_{oro}\right)V^{(\alpha)}_{c1}}{kT}\right\} sign\left(\tau^{(\alpha)}+\tau^{(\alpha)}_{mis}-\chi^{(\alpha)}\right)$$

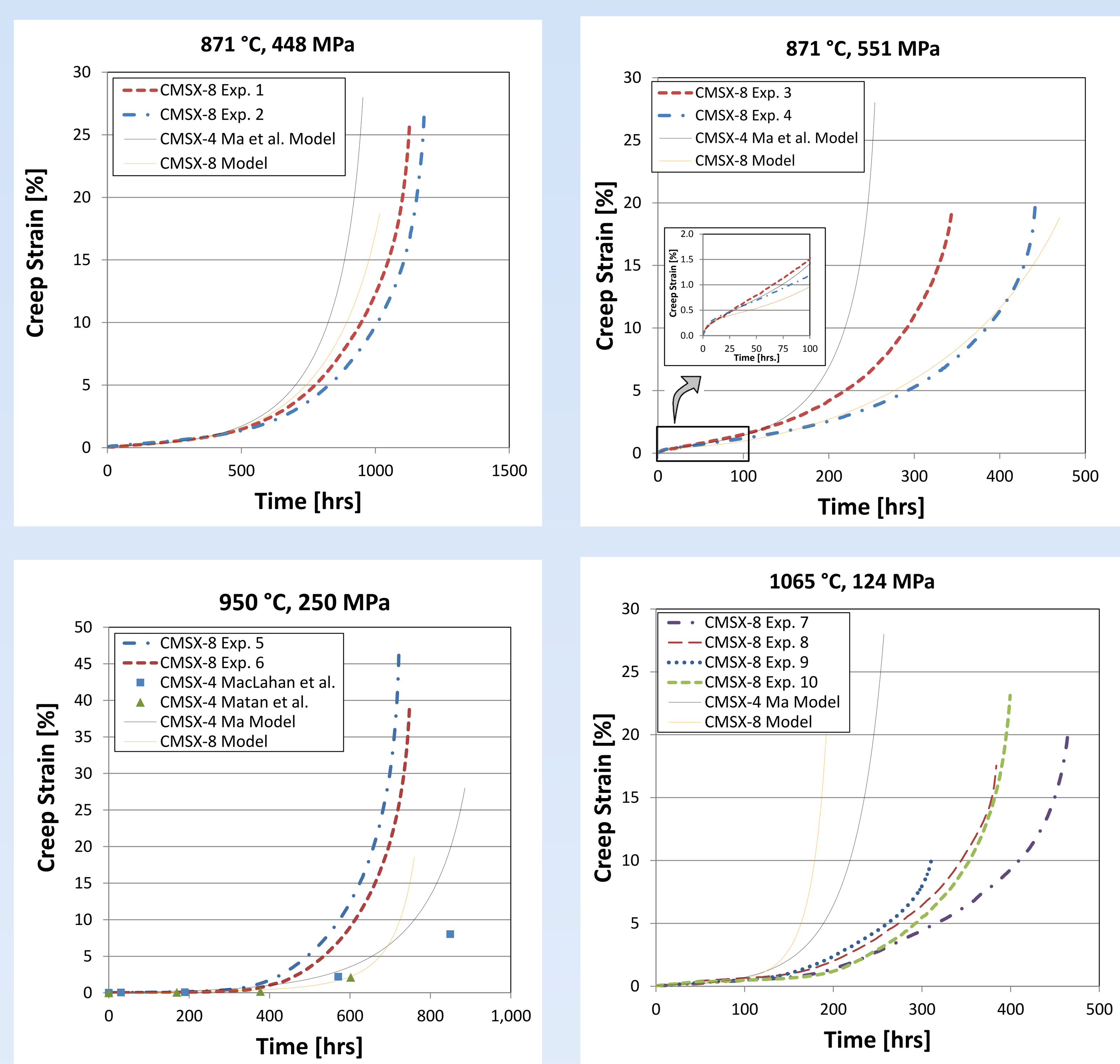
$$\dot\gamma_{L1_2}^{in(\alpha)} = \rho^{(\alpha)}_{L1_2} b\lambda^{(\alpha)}_{L1_2}F_{attack}\exp\left\{\frac{-Q^{112}_{slip}+\left(\left|\tau^{(\alpha)}-\chi^{(\alpha)}\right|-\tau^{(\alpha)}_{L1_2 pass}-\tau_{APB}\right)V^{(\alpha)}_{c2}}{kT}\right\} sign\left(\tau^{(\alpha)}-\chi^{(\alpha)}\right)$$

Creep-fatigue interaction studies and preliminary model calibration

Low cycle creep-fatigue tests provide with very useful data for calibration of the model:

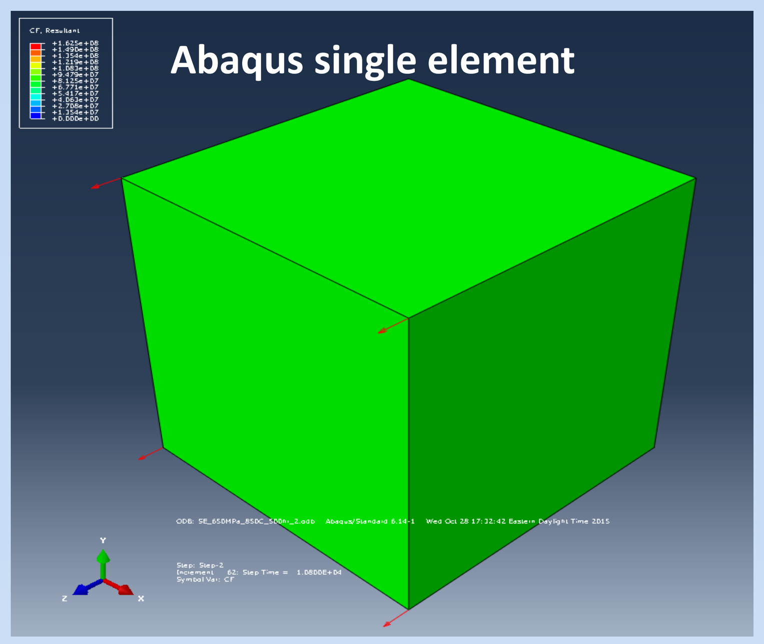


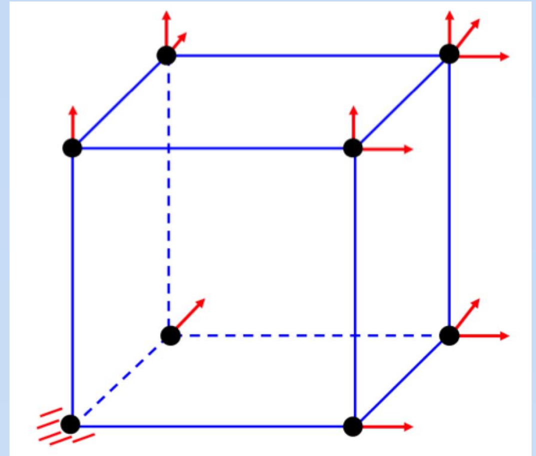
Creep, fatigue and creep-fatigue experimental data will be used to calibrate the CVP model parameters, preliminary it has been calibrated for pure creep:



Implementation as an Abaqus User Material Subroutine (UMAT)

A single finite element representative volume element is used to simulate deformation of dogbone specimens:

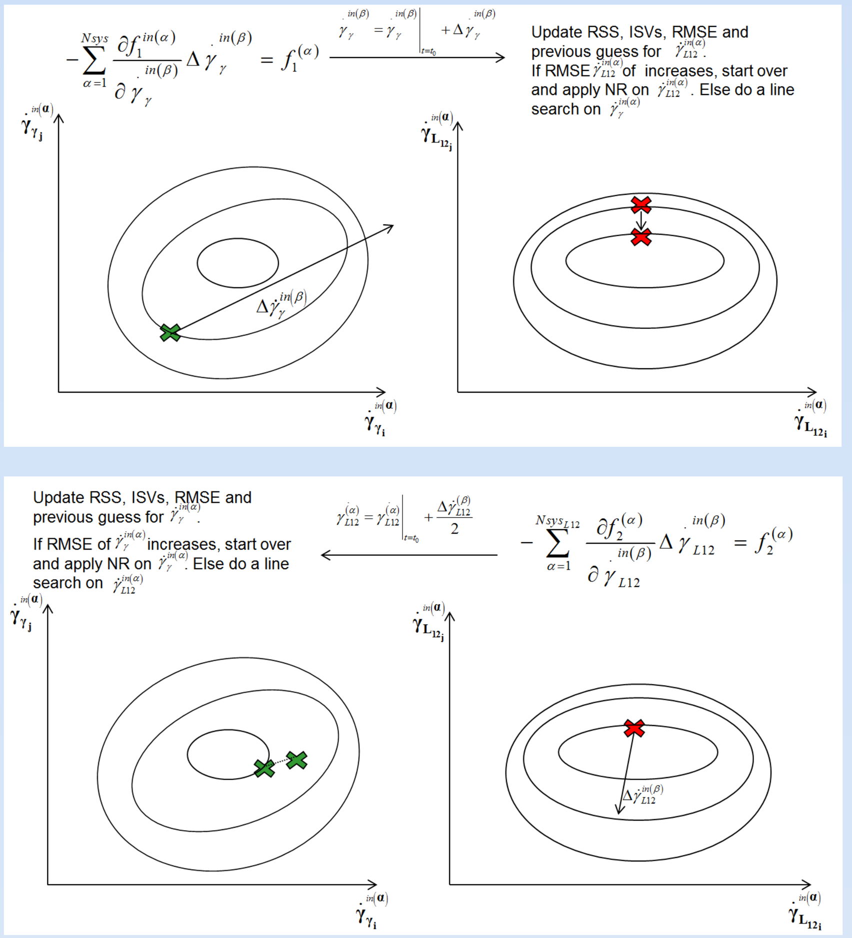




Degrees of freedom used to model a single element under uniaxial tension

The CVP is embedded in a UMAT which defines the material model at each integration point. A modified Newton-Rhapson algorithm is used to solve for the inelastic strains on each slip system at each time step:

- A Newton-Rhapson step is always performed on the level function with greatest RMSE.
- A Newton-Rhapson step on level function *"A"* is flopped to a Newton-Rhapson step on level *"B"* every time a Newton-Rhapson step or line search step applied on level function *"A"* increases the error on level function *"B"*.
- If a Newton-Rhapson step or line search increases the error in both flow rules, then the process is restarted with a decreased time increment



Future work

- Finalize calibration of the model using creep-fatigue data
- Include the effect of alloying composition and microstructure evolution:
  - Include effect of Re% on diffusivity
  - Use data from aged microstructures in the CVP and incorporate a microstructure evolution model
- Prepare a reduced order model to ease implementation of the CVP on industry applications
- Study environmental effects and propose relations to account for their effect on life