MEAN FIELD MODELING OF METASTABLE AUSTENITIC STAINLESS STEEL

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ABSTRACT A physically based, macroscale constitutive model has been developed that can describe the complex mechanical behavior of metastable austenitic stainless steels. In the developed model a generalized model for the mechanically induced martensitic transformation is introduced. Mechanical tests have been carried out to verify the model. To compute the mechanical response based on the phases present in the material, the mean-field homogenization approach is followed.

INTRODUCTION: The complex behavior of metastable austenitic stainless steels stems from the mechanically induced martensitic transformation phenomenon. The material is initially in fully austenitic state but during the course of deformation gradually transforms to the martensitic one. The large constrast between the mechanical properties of the two phases reflects itself in the abrupt hardening behavior of the material. In addition to the usual plastic strain and hardening that are caused by dislocation activity, the transformation strain (TRIP) and the gradual shift to a harder material caused by transformation comes into picture. The stress based theories for transformation claim that transformation is related to the thermodynamics of the process (see Bhadeshia [1981]) as opposed to the strain induced transformation theory where the kinetics plays the important role (see Olson and Cohen [1972]). In this study a generalized version of the stress based theories is used. It is claimed in this theory that without any stress, the thermodynamic forces are not sufficient to cause transformation. The application of stress results in a resolved mechanical driving force (see Patel and Cohen [1953]) which can take a number of grains above the critical barrier causing them to transform. During transformation both the austenite and martensite phases co-exist. The mechanical behavior of the material, which can be considered now as a metal-matrix composite, can be calculated using a mean-field homogenization approach in which the behavior of individual phases and the interaction between them is taken into account in terms of averaged quantities. This method has proven to be robust and efficient by previous studies, see for instance Doghri and Friebel [2005] and the references therein.

PROCEDURES, RESULTS AND DISCUSSION: In a stress-free configuration the only thermodynamic force acting on the system comes from the Gibbs free energy difference of the two phases at the prescribed temperature, which is referred to as the chemical driving force. In this study for simplicity the free energy difference (but not necessarily the free energies of individual phases) will be assumed to vary linearly with

temperature. Under resolved stress on austenite grains, an additional driving force is obtained which is caused by the fact that transformation involves deformation (for more details on the microscale mechanism of transformation refer to *e.g.* Bhadeshia [1987]). Using the conventional derivation for the mechanical work, the following result is obtained for the maximum work that can be attained during the transformation: $U^{\max} = \sum_j \sigma_j^* \lambda_j$ where σ_j^* are the ordered principal stresses and λ_j are the eigenvalues of the deformation tensor: $\mathbf{T} = 0.5(\mathbf{s} \otimes \mathbf{n} + \mathbf{n} \otimes \mathbf{s})$ and $\mathbf{n}$ and $\mathbf{s}$ are the habit plane normal and the shear directions, respectively. It is assumed that the transformation starts when the maximum resolved driving force reaches a critical energy barrier, ΔG^{cr}. The evolution of the martensite volume fraction is described by the following function, which is determined using mesoscale simulations of the presented theory:

$$f^{\alpha'} = 1 - \left[1 + (r-1) \left(\frac{U^{\max}}{\Delta G^{cr} + \Delta G^{off}} \right)^m \right]^{\frac{1}{1-r}}$$

As mentioned, the transformation causes a deformation. The amount of transformation strain can be computed analytically using the following formula:

$$T = \frac{\Delta G^{cr}}{U^{\max}} T^{\max} + \left(\frac{\Delta G^{cr}}{U^{\max}} - 1 \right) \frac{\delta V}{3} \frac{\sigma^h}{\sigma^{eq}}$$

Having computed the martensite fraction and the transformation strain as a function of stress, the next step is to compute the mechanical response of the austenite-martensite composite. To achieve this, the Mean-Field homogenization is utilized since it is both computationally efficient and provides information on the microscopic averages. Apart from the upper (Voigt) and lower (Reuss) bounds most schemes are based on Eshelby's solution of the equivalent inclusion problem (see Eshelby [1957]). Eshelby's analytical solution however is for the idealized case where a single ellipsoidal inclusion resides in an infinitely long matrix. Most homogenization schemes differ in the way Eshelby's solution is adapted to find the resulting average fields in a representative volume element (RVE). Furthermore, the analytical solution exists only when both materials are elastic. To generalize the results to inelastic material response the instantaneous elastoplastic moduli of the phases are used as reference. Using the algorithms it is possible to define a 4th order strain-concentration tensor which relates the strain in the inclusion phase to the strain in the matrix or the total strain on the RVE. The algorithms differ in the way the strain concentration tensor is defined. In the Mori-Tanaka (MT) scheme, Eshelby's solution is assumed to be valid: $\mathbf{D}_1 = \left[\boldsymbol{I} + \boldsymbol{S} : \left(\boldsymbol{C}_0 : \boldsymbol{C}_1 - \boldsymbol{I} \right) \right] : \mathbf{D}_0$. The Eshelby tensor $\boldsymbol{S}$ is a function of the shape of the inclusions and the elastoplastic modulus, $\boldsymbol{C}$, of the matrix. Thus, it is assumed that the volume fraction of the inclusions is small. In the Self-Consistent model, the strain concentration is defined as: $\mathbf{D}_1 = \left[\boldsymbol{I} + \boldsymbol{S} : \left(\boldsymbol{C} : \boldsymbol{C}_1 - \boldsymbol{I} \right) \right] : \mathbf{D}$ where the $\boldsymbol{S}$ tensor is now a function of $\boldsymbol{C}$ which is the instantenous modulus of the RVE. Since this is an unknown yet to be determined, this scheme is implicit. To overcome this problem, the model of Lielens (see Doghri and Friebel [2005]) can be used in which the forward and reverse MT schemes are interpolated based on the idea that MT is accurate

at both the inclusion and the matrix sides. In the current study, the Lielens model is used with an interpolant function that closely fits to the response of the Self-Consistent model. The model is implemented in the implicit in-house FE code DiekA and MSC.Marc as a user supplied material model. Fig. 1 shows the results of the material model where the martensite evolution and the stress-strain response is plotted with changing temperature.

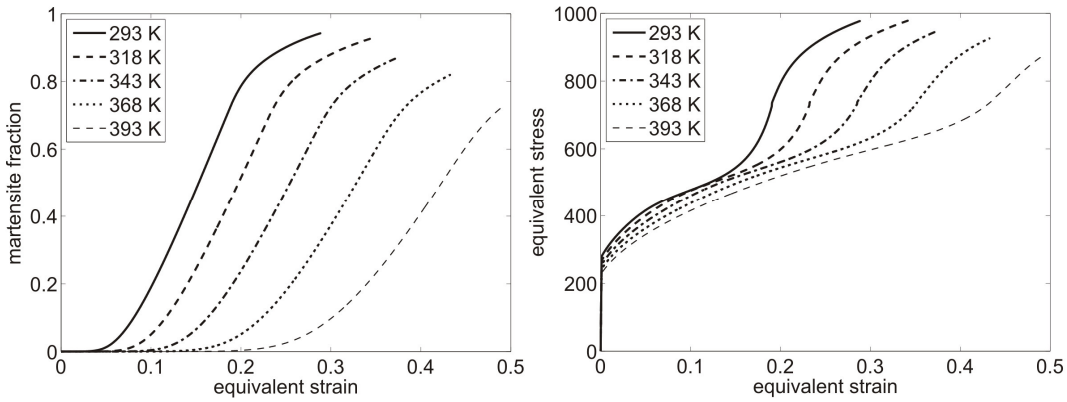

Figure 1: Calculated martensite fraction and stress vs. strain curves.

CONCLUSIONS: A new physically based model is proposed which can predict the kinetics of mechanically induced transformation for different temperature and stress states. Using this model an analytical definition of the transformation strain is obtained. Combining this with a robust and fast homogenization scheme, the constitutive model is built which can be used for simulating the forming of metastable austenitic stainless steel products.

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