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Constitutive modelling of the deformation-induced martensite transformation observed in metastable austenitic CrNi steels

Hari Kisan Thammineni[1,*], **Tong Zhu**[2], **Marek Smaga**[2], **Tilmann Beck**[2], and **Ralf Müller**[1]

[1] Institute of Applied Mechanics, University of Kaiserslautern, Gottlieb-Daimler-Straße, 67663 Kaiserslautern, Germany
[2] Institute of Materials Science and Engineering, University of Kaiserslautern, Gottlieb-Daimler-Straße, 67663 Kaiserslautern, Germany

Metastable austenitic CrNi steels undergo phase transformation when loaded or deformed plastically. In the current work a macroscopic and phenomenological constitutive model is presented to model the strain induced transformation of austenite to martensite. The approach is based on the previous works of Olsen and Cohen [1] & Stringfellow et al. [2]. The kinetics of the phase transformation is modelled based on the assumption that the intersections of the shear bands in the austenitic phase, act as potential martensite nucleation locations. Evolution of the shear band density and their intersections are modelled using the plastic strain in the austenitic phase. The probability of the intersection creating martensite is given by a Gaussian cumulative distribution, which in turn depends on the temperature and stress triaxiality. The resulting stress- strain behavior considers the volume fraction, plastic strains and the strain hardening parameters of the individual phases as internal variables. An explicit formulation of the material model is implemented as a user subroutine in a bi-linear element formulation of FEM. Some of the required material parameters are estimated by fitting experimental stress-strain and martensite volume evolution curves. For the purpose of illustrating the model's behavior, boundary value problems of components with structured surfaces are presented.

1 Material model

The model consists of one part which models the kinetics of austinite to martensite phase transformation and an another part which models the flow behavior of the two phase composite.

1.1 Phase transformation

The volume fraction of martensite is represented by f and its evolution based on [2], is given by,

$$\dot{f} = (1-f)\bar{v}_m \dot{N}_m \qquad \text{where,} \qquad \dot{N}_m = \dot{N}^I_{sb} P + N^I_{sb} \dot{P} H(\dot{P}) \tag{1}$$

represents the rate of number of the martensite units in an austenitic unit. The parameter $\bar{v}_m$ is a constant representing the average volume per martensitic unit and $H(\cdot)$ is a Heaviside function. N^I_{sb} represents the number of shear band intersections per unit volume and P is the probability that such an intersection nucleates martensite. It is defined as a Gaussian cumulative probability distribution of the thermodynamic driving force g.

$$P = \frac{1}{\sqrt{2\pi} S_g} \int_{-\infty}^{g} \exp\left[-\frac{1}{2}\left(\frac{g' - \bar{g}}{S_g}\right)^2 \right] dg', \qquad g = g_0 + g_1\Theta + g_2\Sigma \tag{2}$$

The parameters $\bar{g}, S_g$ are the mean and standard deviation of the distribution and g_0, g_1, g_2 are the material constants. The normalized driving force g has a chemical component, modeling the difference in Gibbs free energy of two phases as a function of the normalized temperature Θ and a mechanical component, modeled using the stress triaxility Σ. N^I_{sb} in (1) is dependent on the volume fraction of the shear bands f_{sb}, which in turn is a function of plastic strain in the austentic phase as,

$$f_{sb} = 1 - \exp(-\alpha\gamma_a) \tag{3}$$

Where γ_a represents the equivalent plastic strain in austenitic phase and α is a material parameter representing the rate of shear band formation. Combining the equations above, together with the equations of evolution of the shear band volume fraction f_{sb} given in [2], gives the evolution of martensite volume fraction as,

$$\dot{f} = (1-f)(A_f\dot{\gamma}_a + B_f\dot{\Sigma}) \tag{4}$$

$$A_f = \alpha\beta_0(1-f_{sb})(f_{sb})^{(r-1)}P, \qquad B_f = \beta_0 {f_{sb}}^n \frac{g_2}{\sqrt{2\pi}S_g} \exp\left[-\frac{1}{2}\left(\frac{g' - \bar{g}}{S_g}\right)^2 \right] H(\dot{\Sigma}), \tag{5}$$

Where β_0 is a geometrical constant, as defined in [2].

* Corresponding author: e-mail thammin@rhrk.uni-kl.de, phone +49 631 205 3099

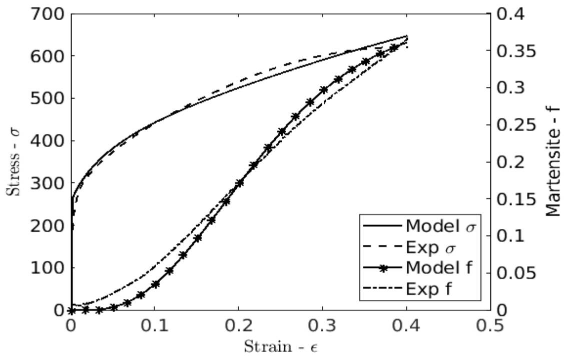

Fig. 1: Curve fitting with uniaxial load data of AISI 347 [3]

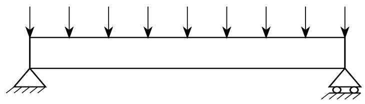

Fig. 2a: Boundary value problem

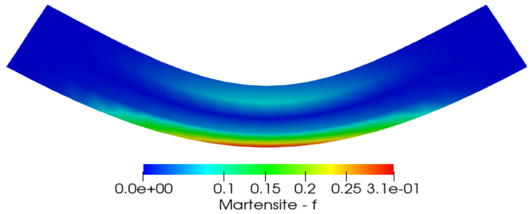

Fig. 2b: Martensite distribution after complete loading

1.2 Constitutive Model

The two phase austenite - martensite composite is modeled using a hypoelastic form of the finite deformation theory. So the stress strain relation is given in rate from as,

$$\overset{\triangle}{\boldsymbol{\sigma}} = \boldsymbol{C} : (\boldsymbol{D} - \boldsymbol{D}^p), \qquad \boldsymbol{D}^p = \boldsymbol{D}^{slip} + \boldsymbol{D}^{tran} \tag{6}$$

Where, $\overset{\triangle}{\boldsymbol{\sigma}}$ is the objective Jaumann derative of stress tensor, $\boldsymbol{C}$ is elasticity tensor, $\boldsymbol{D}$ and $\boldsymbol{D}^p$ are total and plastic strain rate tensors. Further, $\boldsymbol{D}^p$ is decomposed into the plastic strain contributions due to slip and due to the inelastic deformations caused by the phase transformation process. They are correspondingly defined as,

$$\boldsymbol{D}^{tran} = \dot{f}\left(\frac{1}{3}\Delta_v \boldsymbol{I} + \frac{1}{\sqrt{2}} A \boldsymbol{N}\right), \qquad \boldsymbol{D}^{slip} = \frac{1}{\sqrt{2}}\dot{\gamma}^{slip}\boldsymbol{N} = \frac{1}{\sqrt{2}}(\dot{\gamma}_a + \dot{\gamma}_m)\boldsymbol{N} \tag{7}$$

Where Δ_v is the volume change due to the transformation, $\boldsymbol{N}$ is the directional tensor of the deviatoric stress, A is a dimensionless coefficient, γ^{slip} is the total equivalent plastic strain due to slip and γ_a, γ_m are the equivalent plastic strains in the austenitic and martensitic phases.
In contrast to [2], to reduce the computational effect due to the self consistent homogenization method, the stresses in both phases here are assumed to be equal (Sachs assumption). The evolution of equivalent slip, plastic strain rates and the strain hardening rates in the individual phases are defined using flow rules in power-law format.

2 Numerical implementation

The model is implemented in FEAP using 8 - node elements with bi-linear element formulation. An explicit Euler method has been used to integrate the rate variables. The values of some of the material parameters, in the model, are taken directly from the previous works [1, 2] and the remaining parameters are estimated by a preliminary manual fitting (see Fig 1) of the model's stress - strain & martensite volume evolution - strain curves with the corresponding experimental data obtained from an uni-axial loading of a metastable austenitic CrNi steel AISI 347 [3].
Finally, to demonstrate the model's behavior, a boundary value problem of a simply supported beam with an uniformly distributed load, as shown in Fig 2a, is considered. The beam is initially assumed to be of 100 % austenite and the magnitude of load is increased linearly over the analysis time. The applied load deforms the beam, generating the plastic strains in its austenitic phase, thus onsetting the phase transformation to martensite. Further, the current load secnario causes the top and bottom of the beam to experience a compressive and tensile stress state respectively. This difference in stress state affects the amount of transformation, with tensile stress states being more favorable in comparision to the compressive stress state (see [2]). This behavior can be observed in the martensite distribution shown in Fig 2b, where the bottom part of the beam has around 30 % of its austenite transformed to martensite.

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