CONSTITUTIVE MODELING OF MULTIPHASE MATERIALS INCLUDING PHASE TRANSFORMATIONS

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ABSTRACT- A constitutive model is developed for materials involving two or more different phases in their microstructure such as DP (Dual Phase) or TRIP (TRansformation Induced Plasticity) steels. Homogenization of the response of the phases is achieved by the Mean-Field method. One of the phases in TRIP steels is metastable austenite (Retained Austenite) which transforms to martensite upon deformation. A stress-based mechanically induced martensitic transformation model is incorporated in the algorithm in order to capture this behavior.

INTRODUCTION: The existence of different phases in the microstructure of TRIP steels is a consequence of its chemical composition and the performed heat treatment during production. Two main constituent phases are ferrite and austenite and depending on the heat treatment bainite and martensite may also form. The austenite phase is in a metastable state hence can transform into stable martensite during deformation. One of the attractive features of these steels is the fact that with slight changes in the heat treatment and/or chemical composition, a material with significantly different mechanical properties can be obtained. The aim of this study therefore is to build a model that can be used to predict the final mechanical properties based on the knowledge of the constituent phases.

The model is based on the Mean Field homogenization technique for computing the stress-strain distribution into different phases (see for instance Doghri and Friebel [2005] and the references therein). In this method the fields for the mechanical variables such as strain and stress are represented by their average values over the sub-domains. This method is well established to be used for binary mixtures of phases. In this research application of this method for more than two phases is investigated. One of the possibilities is to use the Self-Consistent scheme that implicitly takes into account existence of any number of phases. The drawback however with this method is that it is computationally inefficient. Here therefore we propose another scheme that is much more efficient and comparable in accuracy to the Self-Consistent method for special cases. The martensitic transformation is modeled as a stress-driven process (Geijselaers and Perdahcioglu [2009]). This model depends on the stress resolved in the austenite phase and transformation is determined as a function of the additional mechanical driving force supplied to the material.

PROCEDURES, RESULTS AND DISCUSSION: The Mean-Field method is based on the interaction and evolution of the average values of the field variables in sub-domains that divide the overall structure. It is assumed that the macroscopic stress-strain relation that is determined for an individual phase is also valid within the imaginary RVE. This allows to compute the average stress in a phase once the average strain is known and vice versa. In the following we will consider only strain driven problems so that the main concern will be to determine the partitioning of strains in each phase. This computation is the most important ingredient of the Mean-Field method because this is basically the core of the homogenization problem. Different schemes exist to solve this problem most of which rely on Eshelby's solution of the inclusion problem (Eshelby [1957]). The most common schemes that also can be used for more than two phases are Voigt (iso-strain), Reuss (iso-stress) and Self-Consistent. Among these only the Self-Consistent scheme uses Eshelby's solution and is believed to be the most accurate one. The strain concentration in all schemes is determined using a fourth order strain concentration tensor which supplies the relation between the concentrated average strain in a sub-domain and the total strain over the RVE as $\mathbf{D}_i = \boldsymbol{A}_i : \mathbf{D}$ where $\mathbf{D}$ is the deformation rate, $\boldsymbol{A}$ is the strain concentration tensor and i is the phase indicator. In the Voigt scheme therefore $\boldsymbol{A}_i = \boldsymbol{I}$ and the homogenized response is $\boldsymbol{C} = \sum_i f_i \boldsymbol{C}_i$. In the Reuss scheme $\boldsymbol{A}_i = \boldsymbol{C}^{-1} : \boldsymbol{C}_i$ where $\boldsymbol{C}^{-1} = \sum_i f_i \boldsymbol{C}_i^{-1}$. It is clearly seen that these schemes are explicit. The Self-Consistent scheme on the other hand defines $\boldsymbol{A}$ as: $\boldsymbol{A}_i = \left[\boldsymbol{I} + \boldsymbol{S} : \left(\boldsymbol{C}^{-1} : \boldsymbol{C}_i - \boldsymbol{I}\right)\right]^{-1}$ where $\boldsymbol{S}$ is the Eshelby tensor which is a function of the homogenized response of the composite: $\boldsymbol{C} = \sum_i f_i \boldsymbol{C}_i : \boldsymbol{A}_i$. This scheme is implicit and requires an iterative solution procedure which makes it less attractive to be used in full scale simulation. Here we propose another algorithm which interpolates between the Voigt and Reuss schemes. For the proposed strain concentration tensor first the interpolation is defined as: $\boldsymbol{H}_i = \left[\phi \boldsymbol{I} + (1-\phi)\left(\boldsymbol{C}^{re}\right)^{-1} : \boldsymbol{C}_i\right]^{-1}$ where $\boldsymbol{C}^{re}$ is the homogenized response of the Reuss scheme and ϕ is the interpolation function. So far $\boldsymbol{H}_i$ is the tensor defining the strain concentration for all the phases. However, the sum of these does not yield unity as in the Mori-Tanaka scheme for two phases. Therefore the strain concentration for each phase is defined by ensuring consistency as: $\boldsymbol{A}_i = \boldsymbol{H}_i : \left(\sum_i f_i \boldsymbol{H}_i\right)^{-1}$.

The transformation of the retained austenite is modeled using a previously developed algorithm for metastable austenitic stainless steels in which the main driving factor is proposed to be the stress resolved in the austenite phase (Perdahcioglu [2008]): $f = \mathrm{F}\left(U^{\max} / \Delta G^{cr}\right)$ where $U^{\max}$ is the supplied driving force and is a function of austenite stress and lattice parameters only, ΔG^{cr} is the critical energy barrier which is experimentally determined. The transformation strain is calculated as: $\mathbf{D}^{tr} = \dot{f}\left(T\mathbf{n} + \Delta v \mathbf{I}\right)$ where T is the amount of shape change which can be analytically

computed, Δv is the volume difference between austenite and martensite phases, $\dot{f}$ is the rate of transformation and **n** is the austenite deviatoric stress direction. Fig. 1 shows the computed response of a TRIP steel loaded under uniaxial tension. The experimental data are from Jacques et.al [2007].

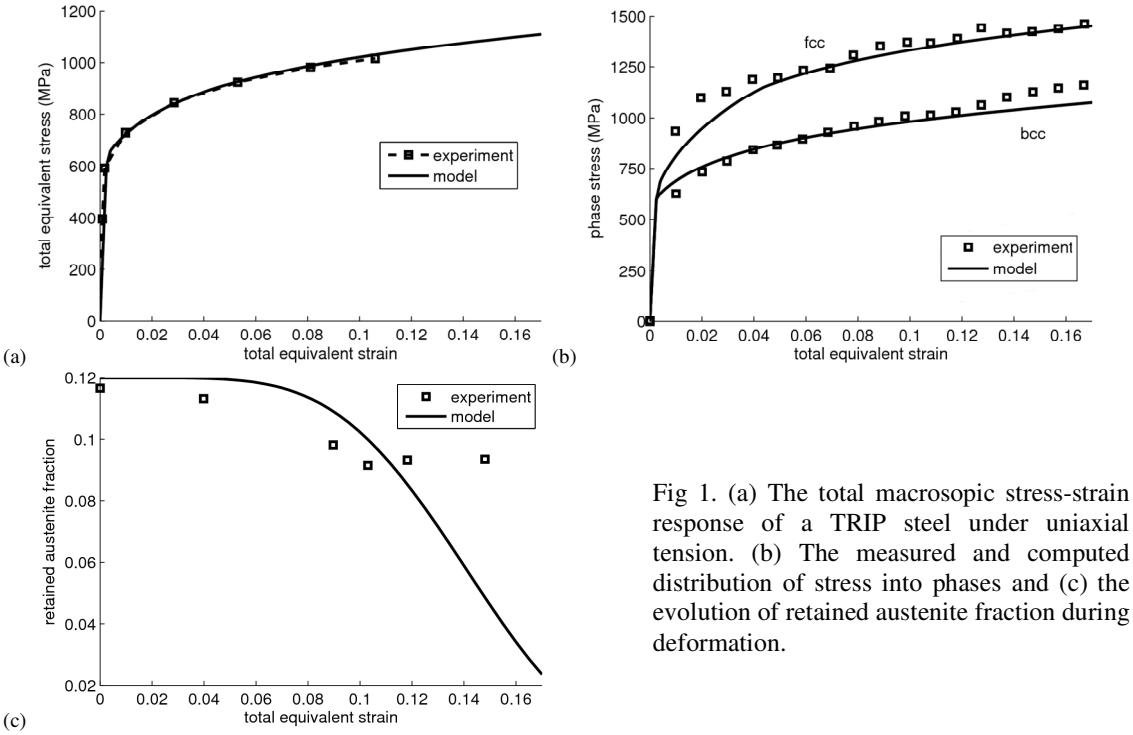

Fig 1. (a) The total macrosopic stress-strain response of a TRIP steel under uniaxial tension. (b) The measured and computed distribution of stress into phases and (c) the evolution of retained austenite fraction during deformation.

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