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A thermomechanically coupled material model for TRIP-steel

S. Prüger, A. Seupel *, M. Kuna

TU Bergakademie Freiberg, Institute of Mechanics and Fluid Dynamics, Lampadiusstrasse 4, 09596 Freiberg, Germany

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ABSTRACT

The transformation behavior of TRIP-steels is strongly dependent on temperature. Especially inelastic deformations lead to a temperature rise, if the heat cannot be dissipated, for instance under high strain rate loadings. Therefore, realistic mechanical models for TRIP-steel need a thermomechanical coupling to take the interaction between strain rate and transformation behavior into account. The objective of this study is the investigation of the thermodynamical consistency of an material model for a high alloyed cast TRIP-steel and the formulation of an appropriate thermomechanical coupling approach. The discussion is given in the framework of thermodynamics of inelastic processes for small deformations. Subsequently, the gained heat equation is adapted to large deformations. A parameter identification procedure is performed to determine the temperature dependent material parameters at low strain rates. Furthermore, a numerical example is given using the identified parameters for a thermomechanical coupling analysis at elevated strain rates. The simulation results at elevated strain rates are in good agreement with experimental data. Therewith, a future support of structure design through simulations is possible.

1. Introduction

Metastable austenitic steels offer favorable mechanical properties due to possible phase transformation effects. Under thermomechanical loading, a diffusionless solid–solid phase transformation from austenite to martensite can be observed which is induced in the present case by plastic deformation. During the martensite formation, inelastic volumetric and deviatoric deformations occur. This is known as the TRansformation Induced Plasticity (TRIP) effect. The combination of the formed martensite and the hardening of the austenite, according to the plastic straining, contributes to the overall hardening. As a result, pronounced properties of TRIP-steels are high strength, excellent work hardening and high ductility.

An important point of interest is the strain rate dependent behavior of TRIP-steels, for example due to possible applications in crash relevant structures. In Krüger et al. (2009, 2011), corresponding compression tests were performed at high strain rates ($10^0 - 10^3\ \mathrm{s}^{-1}$), using high alloyed cast TRIP-steels. The investigated steels show a significant decrease of the martensite volume at same global strains with increasing strain rates. Furthermore, the yield strength increases with higher strain rates. With ongoing straining, the flow curves at higher strain rates drop under the flow curves at lower strain rates. Similar experimental results are presented in Yoo et al. (2011) for a 304L ASS steel under tensile loading and low strain rates ($10^{-4} - 10^{-2}\ \mathrm{s}^{-1}$) and in Krüger et al. (2009). Their investigations show the same influence of the strain rate on the yield strength and the characteristic crossing of the flow curves.

The reason of the discussed strain rate behavior of TRIP-steel is a rise in temperature due to heat generation. The generated heat is a result of irreversible deformations and phase transformation. For increasing strain rates, the generated heat

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* Corresponding author.
E-mail address: Andreas.Seupel@imfd.tu-freiberg.de (A. Seupel).

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cannot be dissipated to the environment which leads to a temperature rise in the material. In conclusion, the strain rate has a high impact on the temperature dependent driving force of phase transformation. In order to describe the explained strain rate dependency, constitutive models have to contain the phase transformation kinetics and an appropriate thermomechanical coupling.

One established approach of modeling the transformation kinetics of the strain induced phase transformation was presented by Olson and Cohen (1975). They made the observation that shear band intersections are preferred martensitic nucleation sites. Finally, a model for the martensitic volume fraction evolution was derived. Following this, Stringfellow et al. (1992) generalized the model of Olson and Cohen (1975) by taking into account the influence of the stress state through the triaxiality.

Tomita and Iwamoto (1995) implemented their constitutive law of TRIP-steel (TI-model) and the heat equation, assuming that heat generation is a result of plastic deformation work and an amount of latent heat caused by phase transformation. Also heat conduction is applied by using Fourier's law. Thermoelasticity and temperature dependent material parameters are considered, too. In addition to the transformation kinetics of Olson/Cohen and Stringfellow, a strain rate influence was added in the terms related to the shear band formation. The developed model applied to a tensile test example can reproduce qualitatively the observed martensite formation behavior, depending on strain rate ($5 \times 10^{-2}\ \mathrm{s}^{-1}, 5 \times 10^{2}\ \mathrm{s}^{-1}$) and different environmental temperatures. In later publications of the authors, thermomechanical coupling was also considered (Iwamoto and Tsuta, 2002; Iwamoto, 2004).

One furthermore important modification is presented in Iwamoto et al. (1998), where the shear band formation is assumed as a function of the triaxiality. This is motivated by the different shear band formation modes which are described for tension and compression tests. The capability of the modified TI-model is also validated for impact loading conditions as shown in Iwamoto et al. (2008).

Furthermore, in Tomita and Iwamoto (2001) the different macroscopic behavior of the TRIP-steel in tension and compression is considered through the introduction of the third stress invariant.

Many approaches of modeling TRIP-steels based on the work of Olson and Cohen (1975), Stringfellow et al. (1992) and Tomita and Iwamoto (1995) were presented in the past. For example Han et al. (2004), Papatriantafillou et al. (2006), Prüger et al. (2011b), Serri et al. (2005) and Sierra and Nemes (2008) could be mentioned. Other recent macroscopic models for steels with phase transformation and thermomechanical coupling are provided by Mahnken et al. (2012) and Hallberg et al. (2010). Both are formulated for large deformations and in a thermodynamically consistent manner. In Mahnken et al. (2012), multi-phase transformations are considered to simulate hybrid forming processes, whereas in Hallberg et al. (2010) restrictions are made to the diffusionless transformation from austenite to martensite.

Also micromechanical models are established (Cherkaoui et al., 1998, 2000; Fischer et al., 2000; Iwamoto and Tsuta, 2004), but in this paper we focus on thermomechanically coupled models which use the proposed transformation kinetics of Olson/Cohen, Stringfellow or the TI-model.

Yoo et al. (2011) performed simulations with a constitutive model, based on the modified transformation kinetics of Tomita and Iwamoto (1995). The heat equation is reduced to an adiabatic form, i.e. heat conduction is neglected, although low strain rates are considered. Furthermore, a damage model has been implemented to take the observed material degradation behavior into account. In contrast to the often used split of the deformation rate into an explicit phase transformation term and a plastic part, they used a hardening term depending on the volume fraction of martensite which is incorporated into a viscoplastic model. Their model was able to reproduce the strain rate effects on yield strength, the influence of different environmental temperatures, damage and the crossing of flow curves, observed in their experiments.

For simulating the impact loading of TRIP-steel structures, Zaera et al. (2012) modified the isothermal model of Papatriantafillou et al. (2006). The Stringfellow based model of Papatriantafillou et al. (2006) uses a homogenization method to determine the effective viscoplastic response of a multiphase TRIP-steel. Furthermore, Zaera et al. (2012) included adiabatic heating and extended the model with material parameters as function of the temperature. Thermal dilatation was also considered. Their simulations of a tensile bar at high strain rates reproduce qualitatively the dependency of martensite evolution on temperature and quantitatively the experimental stress–strain curves. Later, a variable Taylor–Quinney coefficient of the adiabatic heat equation was examined by Zaera et al. (2013). The coefficient determines the fraction of dissipated inelastic work. These investigations were based on the observation that Taylor–Quinney coefficients greater than one are possible for adiabatic considerations. Here, latent heat as additional heat source due to phase transformation becomes important.

In conclusion, the cited literature offers different pragmatic approaches of formulating a thermomechanical coupled model. The current paper is an attempt to examine how a thermomechanical coupling of this often used approach has to be formulated in a thermodynamic consistent manner. The study is based on the preliminary work of Prüger et al. (2011b) for a high alloyed cast CrMnNi-TRIP-steel. Some modifications are proposed in Prüger et al. (2011b) which differ from the models of Stringfellow et al. (1992) and the TI-model. This is discussed within the model review in the next section. One emphasis is on the consistency of the material model, here discussed in the framework of thermodynamics of irreversible processes. The considerations are constrained to small deformations. As important results of the thermodynamic discussion, restrictions of the modeling concept are pointed out.

To validate the material model of TRIP-steel and the thermomechanical coupling, a numerical example is presented. The performed simulations of a tensile test focus on the strain rate dependent behavior of a high alloyed CrMnNi TRIP-steel, also experimentally investigated in Krüger et al. (2009) and Wolf (2012). As special feature, the model is only calibrated at a low strain rate for different temperatures, in order to determine the temperature dependency of the material parameters. The so