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Material behavior of steel – Modeling of complex phenomena and thermodynamic consistency

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Abstract

Steel has a complex material behavior. Stress- and strain-dependent phase transformations, transformation-induced plasticity (TRIP), and its interactions with plasticity are important phenomena of both theoretical and practical interest, as they may cause distortion of work-pieces. These phenomena continue to be intensively studied both experimentally and theoretically. In order to simulate real processes like heat treatment of work-pieces, one has to include the relevant phenomena in a suitable bulk model. It is the aim of the current paper to contribute to the formulation of such a model in the context of macroscopic continuum mechanics and to discuss the capabilities. Due to the possible interaction (coupling) of TRIP and plasticity, the usual approach in plasticity without phase transformations has to be modified substantially. We apply a general approach for non-linear hardening, allowing to model observable effects of interaction of plasticity and TRIP. Besides this, we prove the thermodynamic consistency under sufficient conditions.

Keywords: Steel; Material behavior; Phase transformations; TRIP; Coupling of TRIP and plasticity; Thermodynamic consistency

1. Introduction

In this paper we develop a complex model of the material behavior of *steel* including specific phenomena like transformation-induced plasticity (TRIP), stress-dependent phase

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transformations and the possible interaction of plasticity and TRIP. Generally, the two phenomena (plasticity and TRIP) are present at the same time, and they are coupled. Our modeling approach leads to a so-called *two-mechanism model* (cf. Cailletaud and Sai, 1995; Taleb et al., 2006). We show that this complex model is *thermodynamically consistent* under suitable conditions. In order to focus, we only deal in short with viscous effects in Section 3.5, via some remarks concerning possible extension of the presented model to viscoplasticity. We restrict ourselves to small deformations, as important applications like heat-treatment of work pieces lead (also) to modeling in small deformations. The present paper continues our investigations of general material behavior of steel (cf. Wolff et al., 2005b, 2006a). Among other things, the progress consists in applying the concept of internal variables to a more general situation with non-linear hardening, modeling *experimentally observable effects* of interaction of plasticity and TRIP, and proving thermodynamic consistency of this more general model under suitable assumptions.

The modeling of the material behavior of steel is a large field of current research. Because of the high complexity of some material phenomena of steel (e.g., TRIP, its interaction with plasticity, phase transformations), it is common practice to study these phenomena by experiments in more or less isolated situations in order to find the basic relations: cf. Ahrens (2003), Azzouz et al. (2001), Antretter et al. (2004), Böhm et al. (2004), Denis (1997), Dalgic and Löwisch (2004, 2006), Hunkel et al. (1999), Leblond and Devaux (1984), Nagayama et al. (2000, 2001, 2002), Taleb and Petit-Grostabussiat (2002), Petit-Grostabussiat et al. (2004), Taleb and Petit (2006), Tanaka et al. (2003), Videau et al. (1996), Wolff et al. (2005a, 2007, 2007a). After finding these relations, one has to include them in a bulk model of material behavior. Last, numerical simulations require a further development of this model, including reasonable simplifications. An essential part of modeling of the bulk model consists in finding proposals for the free energy and for the evolution equations governing the internal variables. The proposals are motivated by experiments and/or theoretical considerations on the micro, meso, and macro levels.

In this paper we focus on macroscopic modeling. We note, that transformation-induced plasticity (TRIP) is a macroscopic phenomenon coming from plasticity on the meso (micro) level, if a phase transformation occurs under non-vanishing deviatoric (macro) stress (cf. Leblond et al. (1986a) for a detailed discussion). In order to distinguish the usual metal plastic behavior from TRIP, sometimes, the former one is called "classical plasticity" (e.g., by Leblond et al.). In this paper, we only use the term "plasticity".

For approaches of dealing with steel phenomena in the vicinity of our setting at the meso scale we refer to Fischer (1997), Leblond et al. (1986a,b, 1989), Leblond (1989), Levitas (1998, 2000a,b), Meftah et al. (2007), Patoor and Berveiller (1997), Schmidt et al. (2006), Taleb and Sidoroff (2003), e.g.

Investigations on thermodynamic consistency of complex models of material behavior are widely dealt with. For instance, we refer to Müller (1972), Haupt (2000), Lion (2000), Helm and Haupt (2003) and Helm (2001, 2006). Considering phase transformations in steel, a first general approach of the interaction of plasticity and TRIP is developed in Videau et al. (1994). There are many papers dealing with the material behavior of steel (in connection with phase transformations), its modeling and its simulation. We refer to Ahrens (2003), Böhm et al. (2003), Denis et al. (2002), Fischer et al. (1996, 2000), Hallberg et al. (2007), Hömberg and Weiss (2006), Hömberg (2004), Inoue and Tanaka (submitted for publication), Kim et al. (2005), Lemaitre (2001), Videau et al. (1994), Idesman et al.