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Handle ID: .http://hdl.handle.net/10985/11096

To cite this version :

Ramon ZAERA, Alvaro CASADO, José Antonio RODRIGUEZ-MARTINEZ, Alexis RUSINEK, Raphaël PESCI, José FERNANDEZ-SAEZ - Numerical simulation of the effect of adiabatic temperature increase in martensitic transformation of austenitic steels - 2011

Numerical simulation of the effect of adiabatic temperature increase in martensitic transformation of austenitic steels

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Abstract

This work presents a constitutive model for metastable austenitic steels exhibiting **S**train **I**nduced **M**artensitic **T**ransformation (**SIMT**). Based on the description of the kinetics of phase transformation proposed by Olson and Cohen [3], and later generalized to 3D by Stringfellow et al. [7] and Papatriantafillou et al. [4], this model includes the effect of temperature increase on the kinetics of **SIMT** and on the thermal softening of the phases. This allows capturing relevant phenomena exhibited by metastable austenitic steels when subjected to plastic deformation at high strain rates. A systematic procedure for the identification of the constitutive parameters has been proposed. The predictions of the constitutive description are compared with experiments for the austenitic steel **AISI 304** provided by Rodríguez-Martínez et al. [6]. Good correlation between experiments and modelling are achieved in terms of macroscopic strain-stress curves and volume fraction of martensite formed during straining.

Keywords: austenitic steel, strain induced martensitic transformation, constitutive equation, thermo-viscoplasticity, thermography, X-ray diffraction

1. Introduction

Austenitic grades are the most commonly used stainless steels in industry. The high nickel content shifts the martensite start temperature to very low temperatures during cooling, keeping the material fully austenitic after quenching at room temperature. This gives excellent work hardening, high strength, ductility and formability, as well as good weldability. Some of the less highly alloyed austenitic -and yet largely used- grades are referred to as metastable because of their ability to transform from the initial austenite phase to martensite. This transformation may occur in different ways and one of them, namely Strain Induced Martensitic Transformation **SIMT,** takes place when the steel yields at a range of temperatures M_s^{σ} - M_d that covers many of the in-service conditions reached by metastable austenitic steels in industrial applications. The analysis of such a process therefore presents great interest. Due to their ductility and work hardening ability, metastable austenitic steels are used for energy absorption in crash or blast protection. The abovementioned processes, involving high strain rates, are often accompanied by a rise in temperature due to the dissipation of plastic work. This means that the martensitic transformation approaches adiabaticity. Also, forming and machining processes, used to shape components made of metastable austenitic steels, take place in non-isothermal conditions. This work presents a constitutive model for steels exhibiting **SIMT**, based on the previous works of Olson and Cohen [3], Stringfellow et al. [7] and Papatriantafillou et al. [4]. The model includes the effect of temperature increase on the kinetics of **SIMT** and on the thermal softening of the phases. A systematic procedure for the identification of the constitutive parameters is proposed. The predictions of the constitutive description are compared with dynamic experiments for the austenitic steel **AISI 304** provided by Rodríguez-Martínez et al. [6]. Good correlation between experiments and modelling are achieved in terms of macroscopic strain-stress curves and volume fraction of martensite formed during straining.

2. The constitutive description

Since the variation of temperature is intended to be considered in the proposed model, the equations of kinetics of **SIMT** due to Stringfellow et al. [7] have been modified with a new exponential law to account for the influence of temperature change in the thermodynamic driving force. Thermal strains are taken into account, contributing to the instantaneous volume expansion that accompanies the martensitic transformation. The homogenization process proposed by Ponte Castañeda [5] and Suquet [8], and used by Papatriantafillou et al. [4] for Transformation Induced Plasticity (**TRIP**) steels, is considered to obtain equivalent properties from the constitutive equations of austenite and martensite. A potential law is used to determine strain hardening, strain-rate hardening and thermal softening of the phases. The temperature increase during straining is obtained through equivalent properties. Within a corotational frame, the classical return mapping algorithm is proposed to solve the set of nonlinear rate equations in a finite deformation frame. An implicit scheme is used to correct the trial stress and to discretize every constitutive equation, and is implemented in

ABAQUS/Explicit to reproduce the experimental results for the considered austenitic steel.

3. Identification of the constitutive model parameters

The identification procedure is split into two parts:

Identification of the material parameters involved into the strain hardening/softening definition of the single phases *(i. e. determination of the strai, rate and temperature sensitivities of the phases)*. This is supported by the experimental data reported in [1, 6].

Identification of the material parameters involved in the kinetics of the **SIMT** process. This is conducted following Iwamoto and Tsuta's work [2] and based on the experimental observations reported by Rodriguez-Martinez et al. [6].

4. Validation of the constitutive model

In this work, results from dynamic tensile tests performed by the authors within the range of strain rates $10\ s^{-1} \le \dot{\varepsilon} \le 500^{-1}\ s^{-1}$ [6] have been considered to conduct the validation. The X-ray diffraction technique has been used to determine the volume fraction of martensite in the post mortem specimens, leading to a good validation of the transformation kinetics [6]. Moreover, let us mention that the range of loading rates covered during the experiments agrees with that expected in engineering applications like crashworthiness, in which **TRIP** steels are frequently used. Numerical simulations of the dynamic tensile tests have been conducted. It has to be highlighted that considering a viscoplastic material model acts as a regularization method for solving mesh-dependent strain softening problems of plasticity. Rate dependent plasticity introduces implicitly a length-scale parameter into the boundary value problem, diffusing the localization region. It guarantees a good definition of the problem, avoiding pathological mesh dependency and ensuring the uniqueness of the numerical solution. Good correlation between experiments and modelling are achieved in terms of macroscopic strain-stress curves and volume fraction of martensite formed during straining, Fig. 1.

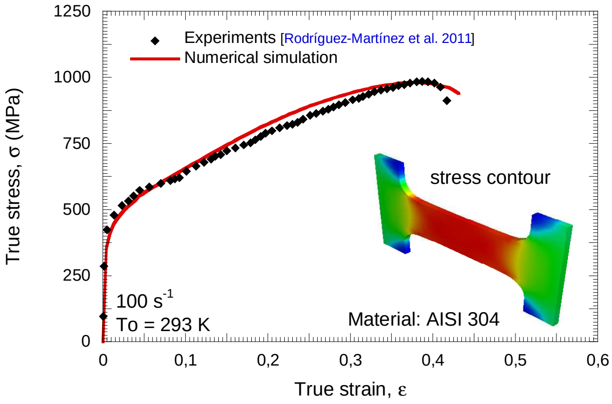

Figure 1. Comparison between numerical predictions of the ***FE*** *model and experiments at 100* s^{-1} *and* T_0*=293 K [6].*

5. Conclusions

This contribution presents a constitutive model for describing the martensitic transformation occurring in metastable austenitic steels at high strain rates. The model extends formulations of Olson and Cohen [3], Stringfellow et al. [7] and Papatriantafillou et al. [4], including both the temperature sensitivity of the single phases and the temperature sensitivity of the transformation. A straightforward method for the model calibration has been developed. The predictions of the constitutive model agree with experimental results in terms of macroscopic stress-strain curves and volume fraction of martensite formed during loading.

Acknowledgements

The researchers of the University Carlos III of Madrid are indebted to the Comunidad Autónoma de Madrid (Project CCG08-UC3M/MAT-4464) and to the Ministerio de Ciencia e Innovación de España (Project DPI/2008-06408) for the financial support received which allowed conducting part of this work.

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