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A model for the strain rate dependent plasticity of a metastable austenitic stainless steel

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ABSTRACT

A continuum material model is developed for the dynamic plastic deformation behavior of metastable austenitic stainless steel EN 1.4318-2B. An incremental approach in both experimental testing and in the model is used to distinguish between the direct effects of strain rate and the macroscopic adiabatic heating effects. In the model a set of evolution equations is integrated over the deformation path, which makes the model flexible in terms of changes in the strain rate and material temperature. The strain-induced phase transformation from austenite to α′-martensite is accounted for with evolution equations based on the Olson-Cohen transformation model. In order to describe the phase transformation accurately during dynamic loading, the original model is modified by adding instantaneous strain rate sensitivity to the α′-transformation rate. Comparison with experimental results shows that the model can be used to describe the strain rate and temperature dependent behavior of a metastable austenitic alloy with a reasonable number of material parameters. Finally, the model gives realistic results in a set of validation experiments.

1. Introduction

Modern industrial applications often pose very demanding and conflicting requirements for structural materials. For example, in the automotive industry one needs materials that can be deformed into complex shapes but are then able to carry high loads during use. In addition, in the event of an accident the structure should be able to withstand dynamic loading without uncontrolled catastrophic failure. That is, an optimal structural material should possess a combination of good ductility and high strength as well as high energy absorption capability during high strain rate deformation. Furthermore, in order to fully exploit the capabilities of a given material, one needs accurate and representative material models that are also computationally feasible.

In response to the above mentioned demands the steel community is using and developing alloys that contain metastable austenite as one of the microstructural constituents. These alloys benefit from the inherent tendency of the austenite phase to transform into α′-martensite upon plastic deformation, which in suitable conditions leads to notable strain hardening capability without sacrificing ductility [1–3]. However, the presence of metastable phases in the microstructure can lead to a considerably more complex mechanical behavior than observed in stable alloys. This is due to the fact that the transformation of austenite into α′-martensite has notable influence on the plasticity of the steel, but at the same time the transformation itself is strongly affected by the loading conditions, such as strain rate and temperature [1–8]. Due to these characteristics, the traditional material models that were developed for stable single phase materials are often inadequate to fully represent the mechanical behavior of metastable austenite containing steels.

In this paper, the strain rate dependent plasticity of metastable austenitic stainless steel EN 1.4318-2B is experimentally studied and numerically modeled. This alloy was selected since it is fully austenitic in the annealed state but transforms readily into α′-martensite during plastic deformation at room temperature. This feature allows one to concentrate on the effects of the metastability of the austenite without the complications introduced by other non-transforming phases. It is, however, believed that the results of this study are useful also in the analysis of other multi-phase alloys.

The strain rate dependent mechanical behavior of metastable austenitic stainless steels has been widely studied in the literature [4–9]. There are also many works on the numerical modeling of the rate dependent behavior of these materials [10–20]. However, one aspect appears to have been previously somewhat overlooked. Most of the experimental and numerical works cited above concentrate on comparing material behavior measured at constant strain rates, i.e., using tests that are done at different strain rates but keeping the strain rate constant in an individual test. As noted by Ghosh [21], these tests inherently include simultaneous strain rate and temperature effects due to adiabatic heating. Moreover, a complete description of strain rate

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dependency should include a distinction between *instantaneous* and *evolutionary* effects [22]. The former effects are dependent on the deformation behavior of the current microstructure, while the latter effects are related to the strain rate dependency of the evolution of the microstructure, leading to so-called *strain rate history effects*. As a practical and measurable example, the flow stress of the material can be affected by strain rate in two different ways; directly through the *instantaneous strain rate sensitivity of the flow stress*, i.e., a sudden change in strain rate leads to an immediate change in flow stress, and through *the strain rate sensitivity of the strain hardening rate*, i.e., the previous history of strain rate values affects the current level of flow stress through its influence on material hardening (slope of the stress-strain curve). It is not well established that the results from constant strain rate tests facilitate this distinction to be made in the case of metastable austenitic stainless steels, in which considerable microstructural evolution takes place during plastic deformation. In fact, in a recent experimental work [23] carried out by the authors of this work it was verified that high strain rate loading of metastable austenite involves additional phenomena that are not revealed by the comparison of constant strain rate tests only. The knowledge on the subject thus appears to be incomplete.

The above discussed challenge has direct implications in the development and use of material models; material loading in practical applications does not necessarily take place at a constant strain rate. An obvious example is the in-service loading of a component that has been plastically deformed at a different strain rate during its manufacturing process. On the other hand, even if the global strain rate is fixed in a given case (for example by the boundary conditions), locally the strain rate can be subjected to sudden variations. An accurate prediction of for example strain localization phenomena requires that the material model is able to realistically predict the effects of these variations.

The aim of this work is to develop a continuum level material model that is able to describe the strain rate dependent plasticity of alloy EN 1.4318-2B. A special emphasis is put on accounting for the above described instantaneous and evolutionary strain rate sensitivities. The model is calibrated with data from experimental work that involves tests designed to facilitate distinguishing between direct strain rate and adiabatic heating effects on material behavior. The model is then validated with a set of experiments in deformation conditions where the amount of adiabatic heating is a strong function of the strain rate.

2. Model theory

2.1. Motivation

In the following a continuum model for the strain rate dependent plasticity of metastable austenitic stainless steels is presented. The model will concentrate on describing the strain rate and temperature effects under uniaxial tensile loading. Therefore, the material is assumed to be isotropic and multi-axial effects such as kinematic hardening [24–27] and stress state dependence of the martensitic transformation [27–32] are neglected. Following previous studies [10–20], the model will involve thermomechanical coupling, i.e., during numerical simulations the simultaneous solution of both the mechanical and the thermal (heat transfer) problem is required. As a general note considering the scope of this work, material behavior is considered only up to the start of tensile necking. That is, flow localization behavior, material damage and failure are excluded from the analysis.

As noted in the Introduction, the main motivation for this work was a recent experimental finding [23], according to which the strain rate dependency of a metastable austenitic stainless steel is not fully described by comparing constant strain rate tests. Fig. 1 illustrates the main results from the above mentioned study [23]. Fig. 1a) presents flow stress data from three different tensile tests, i.e., two tests involving different but constant strain rates and a third test, in which the strain rate is suddenly increased during the test. Fig. 1b) depicts the corresponding evolution of the α'-martensite volume fraction. The following conclusions can be drawn from the data shown in Fig. 1; firstly, the low strain rate ($2 \cdot 10^{-4}\,\mathrm{s}^{-1}$) test clearly illustrates the notable increase in the strain hardening capability of the material, when the conditions are beneficial for the α'-martensite transformation [1–3,7]. Secondly, the often reported [5–9] negative (reducing) effect of strain rate in both the α'-martensite transformation tendency and in the strain hardening capability is visible in Fig. 1. A general conclusion reached in the literature [5–10,12,14,18,19] seems to be that the observed reduction is caused by adiabatic heating. However, in the third test shown in Fig. 1, in which the strain rate was suddenly increased from the lower to the higher value at 0.1 plastic strain, both the α'-martensite transformation rate and the strain hardening rate decrease immediately after the strain rate increase. Similar tendency can be seen in the experiments reported by Larour et al. [8], who studied the effect of quasi-static pre-straining on the dynamic behavior of alloy EN 1.4318 up to ~0.1 pre-strain. This evidence casts doubt on the explanation based on adiabatic heating, since shortly after the strain rate jump the material temperature should still be close to room temperature. This topic will be the first focus point of the model development. The second focus point will be on the selection of the state variables of the model. It is noted that the quite common approach of using the plastic strain as a state variable for the mechanical properties is too limited for the description of material behavior in this case. Instead, the flow equations will be based on a set of internal variables, whose evolution equations are integrated over the entire deformation path.

2.2. Mechanical model

In the literature there are two main approaches to model the mechanical response of metastable austenitic steels. In the first approach,

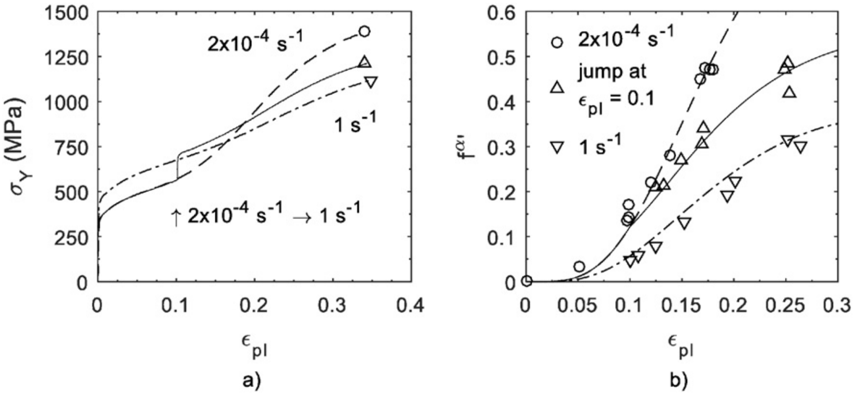

Fig. 1. Tensile test data for EN 1.4318-2B measured at the laboratory temperature of 297 K. a) stress-strain behavior in constant strain rate and strain rate jump tests and b) corresponding evolution of the α'-martensite volume fraction. Data adopted from [23].