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Mechanical behavior of a metastable austenitic stainless steel under simple and complex loading paths

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Abstract

This paper deals with the characterization and the modeling of the mechanical behavior of an unstable austenitic stainless steel that is commonly used in deep drawing processes. This steel exhibits a martensitic transformation at room temperature induced by plastic deformation during cold forming, which sometimes has an unfavorable influence on the final shape of the part. In order to improve the knowledge of this material, an extensive characterization of its mechanical behavior is performed using tensile and shear tests combined with eddy current measurements. The available material information enables the identification of a two-phase model of elastoviscoplastic type which integrates the knowledge of the initial microstructure and its evolution as a function of the inelastic strain. The model prediction is found to be accurate with respect to the experimental test results.

Keywords: Stainless steel; Martensitic transformation; Two-phase model; Shear tests; Sequential tests; Eddy current measurements

1. Introduction

Stainless steels are widely used engineering materials for applications in hostile environments and as sheet materials, are commonly deep-drawn at room temperature. The numerical prediction of the forming process is now common practice in the industry. Nowadays the simulation of global quantities such as forces and shape leads to results which correspond well to reality. However, predictions and measurements often start to diverge when analyzing local quantities on the formed structure. Evidence based on experimental observations and on literature review is given that shows that plastic deformation of such materials yields a martensitic phase transformation. The amount of formed martensite is strongly coupled to the hardening of the material and is therefore mainly responsible for its drawing characteristics [1,2].

It is now clearly established that the austenite of steels AISI 304 undergoes a martensitic transformation induced by the plastic deformation at room temperature [3–7]. In such materials, the mechanical behavior greatly depends on the temperature since the martensitic phase transformation kinetics is related to temperature through the chemical energy. Furthermore, since martensitic phase transformation occurs without diffusion through a cooperative shear movement of atoms, it is recognized that the applied force as well as internal stresses assist the transformation. Martensitic phase transformation occurs on cooling without any applied stress at M_s temperature. Above M_s, the critical stress to undergo martensitic phase transformation increases linearly with temperature up to M_s^σ which is the temperature defined as the maximum temperature at which martensitic transformation is stress-assisted. At temperatures above M_s^σ, significant plastic flow in the austenite precedes the transformation, and an additional contribution to transformation arises from the production of new nucleation sites by plastic deformation. In this temperature regime where the critical transformation stress decreases significantly, the phase change is defined as the plastic strain-induced transformation.

This strain-induced martensitic transformation strongly manifests dependence not only on the temperature and strain rate but also on the strain path. To obtain the expected mechanical properties of metastable stainless steels through the forming process where the material undergoes complex deformation, the prediction and control of the change in material characteristics due to the deformation are necessary [8]. To this end, the deformation mode-dependent mechanism of martensitic transformation has to be clarified.

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Martensitic transformations in austenitic stainless steels have been studied extensively in uniaxial tension at low strain rates (static loading) [9]. The influence of the stress (strain) state on the phase transformation has received lower attention [9]. Powell et al. [10] experimentally investigated the effect of temperature (10–293 K), strain rate and deformation modes such as tension, torsion and compression on the strain-hardening characteristics of type 301 and 304 austenitic stainless steel and correlated them with quantitative measurements of volume fraction of martensite. They clarified that the deformation mode substantially affects the transformation of martensite in the plastic range, and that uniaxial tension was found to enhance martensite formation more than either compression or torsion. Furthermore, Okutani et al. [11] carried out tests of uniaxial tension and compression, equi-biaxial compression and deep drawing of type 304 austenitic stainless steel at room temperature and reported that the volume fraction of martensite under uniaxial compression is higher than that under tension and that it increases with hydrostatic stress under uniaxial stress. Thus, the results differ and the deformation mode-dependent mechanism is not yet clear. Finally, Iwamoto et al. [8] show that the magnitude of the average volume fraction of martensite for compression is higher than for tension in the initial stage of the deformation, and then the relation is reversed in the high strain region. The same tendency is observed in the deformation mode dependence of the stress–strain relation.

Many studies performed on these steels have led to several macroscopic constitutive laws [12–16]. In parallel, several authors have proposed micromechanical constitutive laws on other types of steel, [17] on dual phase steels or [18,19] on TRIP steels for example. Concerning stainless steels, main achievements in transformation-induced plasticity are analyzed in a paper by Fischer et al. [20]. Continuum thermomechanical theory of martensitic phase transformations in elastoplastic materials is presented by Levitas [21]. Interaction between phase transformation and plasticity at the micro level was studied in [9,22,23]. Considering all these studies, it is clear that the complexity of the involved phenomena and their coupling, in combination with the impossibility to isolate the mechanical behavior of the individual phases implies a limitation on the material model.

The following study presents the identification of a two-phase model of the mechanical behavior of materials that undergo this specific phase transformation [24,25]. Most macroscopic two-phase models are limited to monotonic loading and microscopic material models are too complex and numerically too expensive to be used for the simulation of an industrial forming process. Depending on the loading condition there is a requirement for the use of a different macroscopic material model that is valid for complex loading and that incorporates information on the microstructure of the material after deformation. The identification of this kind of model requires extensive material testing. In a first part, the experimental characterization of an AISI 304 stainless steel is described. This experimental study consists in tensile, shear and sequential tests combined for some of them with eddy current measurements. In a second part, the two-phase model is recalled and then the identification results of this model are discussed in the last part.

Table 1
Ponderal chemical composition of the studied AISI 304 stainless steel and supplier measured mechanical properties

Cr (%)	18.3
Ni (%)	9.2
C (%)	0.04
Mn (%)	1.5
Si (%)	0.5
Mo (%)	0.18
M_{d30} (°C)	40
R_m (MPa)	610
$R_{p0.2}$ (MPa)	270
A (%)	55

2. Experimental characterization

A general approach to characterize the behavior of a material consists of carrying out tensile tests. However in order to carry out a complete identification of the material behavior, it is interesting to obtain more information on the response of materials under different strain states, strain rates and temperatures. In this work, simple shear and uniaxial tensile tests were carried out on a testing machine of maximum capacity 100 kN. Strain measurements are carried out both in tension and simple shear by using a high resolution video camera. The accuracy of the strain measurement reached with the video camera is 5×10^{-3}; it allows the investigation of a wide strain range, as well as the measurement of transverse strains. The anisotropy of the mechanical behavior is investigated by performing both tensile and shear tests at 0°, 45° and 90° to the rolling direction (RD).

The tests that were carried out include monotonic loadings in tension and in simple shear, as well as cyclic and sequential loadings in shear. Each type of test is performed at least three times to ensure good reproducibility of the experiments. The tests were carried out at a low strain rate, thus limiting the rise in temperature caused by the deformation (typically lower than a few °C).

2.1. Material

The studied material is an austenitic stainless steel provided by the Arcelor company of AISI 304 type (X4CrNi18-9). The ponderal chemical composition is provided in Table 1 as well as the mechanical characteristics measured by the supplier. The material is supplied as cold rolled sheets, of dimension 500 mm × 500 mm and thickness 0.78 mm in a shining annealed final state.

2.2. Tensile tests

Tensile tests were carried out on rectangular samples of dimension 20 mm × 180 mm × 0.78 mm. The free edges were machined in order to eliminate the hardened area induced by the cutting and thus to increase the range of homogeneous deformation. Monotonous tensile tests are carried out at 0°, 45°, and