Characterization and Simulation of Deformation-Induced Martensitic Transformations in Medium-Manganese Steels

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Résumé :

Le développement des aciers austéno-ferritiques à moyenne teneur en manganèse présente un très bon compromis entre les propriétés mécaniques des aciers TRIP (transformation-induced plasticity) et des aciers TWIP (twinning-induced plasticity) en utilisant la stabilité de l'austénite pour contrôler les mécanismes de déformation actifs. Deux températures de recuit, une haute et une basse, conduisent respectivement à une phase austénitique stable (pas de transformation martensitique) et métastable (transformation martensitique induite) au cours de la déformation. Cette différence de comportement permet d'identifier la contribution de la transformation de phase au durcissement, le travaux en cours visant à déterminer la cinétique de transformation martenistique. Des mesures de l'évolution de la fraction volumique d'austénite en fonction de la déformation totale sont réalisées par diffraction des rayons X et par mesures magnétiques. L'utilisation d'une loi des mélanges basée sur l'hypothèse d'iso-travail permet de prévoir le comportement mécanique à partir de la connaissance des évolutions microstructurales.

Abstract :

The development of medium-manganese austeno-ferritic steels offers a compromise between the mechanical properties of TRIP (transformation-induced plasticity) and TWIP (twinning-induced plasticity) steels by using the austenite stability to control the active deformation mechanism. Low and high annealing temperatures provide austenite phases that are respectively stable (no transformation) and metastable (easily transformed) under deformation. This behavioral contrast allows for the isolation of the contribution to work hardening from the TRIP effect, which the current works seeks to quantify via the kinetics of the martensitic transformation. Measurements of the austenite volume fraction as a function of total strain were made via x-ray diffraction and magnetic measurements and were used to develop an iso-work mixture rule to predict the macroscopic behavior of the sample using microstructural information.

Mots clefs : martensitic transformation, TRIP, XRD, magnetic measurements, iso-work

1 Introduction

In response to increasingly stringent efficiency and emissions standards in the automotive industry, improvements in the mechanical strength of high strength steel alloys have permitted manufacturers to reduce the mass of their vehicles via a reduction in component thickness. Alloys based on the TRIP (transformation-induced plasticity) and TWIP (twinning-induced plasticity) mechanisms have shown great promise in such applications. This study will examine the mechanical behavior of newly-developed "medium manganese" steels, which offer an improvement upon the properties of TRIP steel while avoiding the prohibitive production costs of the more resistant TWIP steel. These new alloys capitalize on both the TWIP and TRIP plasticity mechanisms and thus offer mechanical properties between those of pure TRIP and pure TWIP steels while being able to be fabricated at an affordable cost. This paper presents a microstructural characterization of a medium manganese steel for two different annealing temperatures and proposes a means of numerically modeling the stress-strain behavior in unidirectional tension.

2 Material to be Studied

The alloys studied here contain 0.2wt% carbon and 5-8wt% manganese with an addition of 1-2wt% aluminum. Cast ingots were austenitized, quenched, and cold-rolled to 1.25mm in thickness to provide an entirely martensitic microstructure. Two sets of cold-rolled sheets were annealed at low and high temperatures to provide an ultra-fine grained austeno-ferritic microstructure with austenite volume fractions of 0.29 and 0.2 respectively.

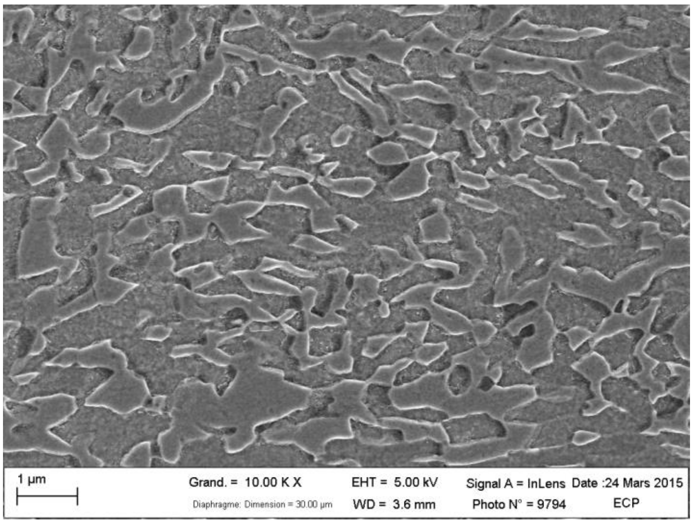

Figure 1 - Microstructure of medium manganese steel annealed at low temperature after a 1% Nital etch. The phase in relief is austenite. The average grain size is roughly 0.45µm.

As seen in Figure 1, the microstructure contains austenite in a ferrite matrix. The exact morphology of the microstructure is unknown; it must be confirmed whether it consists of austenite "islands" completely surrounded by ferrite or if the two phases are intertwined. This will be accomplished by progressive focused ion beam (FIB) erosions and electron backscatter (EBSD) analyses of phase distributions and crystallographic orientations.

The goal of annealing sheets at different temperatures is to achieve different austenite stabilities, thus controlling the initial proportion of austenite and the readiness at which it transforms under strain. For the low temperature anneal, the austenite is very stable and should not transform to martensite during tensile testing. The only work hardening observed in this case should be from the hardening of the ferrite phase and some hardening of the austenite via twinning. Contrarily, the samples annealed at high temperature have less stable austenite that will readily transform to martensite under deformation. This results in a very high work hardening rate, but reduced uniform elongation overall. Figure 2 illustrates this behavioral contrast in unidirectional tension.

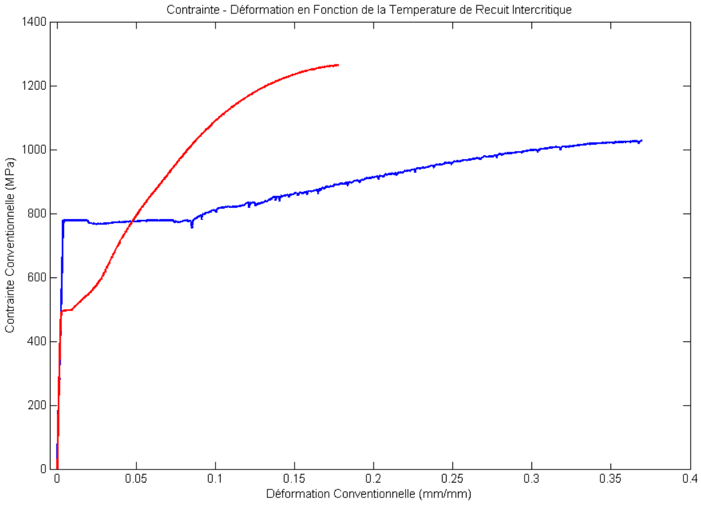

Figure 2 - Results of unidirectional tensile tests on samples annealed at low (blue) and high (red). The change in austenite stability resulting from the different annealing temperatures drastically affects the work hardening rate and provides very different mechanical responses.

It is critical to understand the TRIP phenomena that occurs in these steels and its relation to austenite stability. The kinetics of the martensitic transformation will determine the hardening rate of the alloy and as such, the coupling of transformation rate and work hardening rate must be quantified in order to optimize the annealing temperature and achieve the desired mechanical properties.

3 Microstructural Characterization

Two methods are proposed for the characterization of the martensitic transformation: X-ray diffraction (XRD) of tensile samples loaded to several levels of total strain and magnetic measurements of tensile samples during tensile testing. The data obtained could then be used to identify parameters of the numerical models of macroscopic behavior that are to be developed.

3.1 Phase Fractions via XRD

In order to dose the austenite volume fraction by XRD, samples are rotated from $\chi = 0°$ to $\chi = 45°$ with a step size of 0.1° and for an incident angle of 26°. The spectra for each angle are then summed to remove texture effects. The integrated intensities of the first two peaks---the (111) peak for austenite and the (110) peak for ferrite, respectively---can be used to calculate the volume fraction of austenite using (1) as given in [1].

$$C_\gamma = 1/(1 + 0.75(\frac{I_{110}}{I_{111}})) \qquad (1)$$

If measurements are taken at several values of total strain for each annealing temperature, the amount of retained austenite (and thus transformed martensite) can be plotted as a function of strain. It is expected that both the transformation rate and the critical strain for the onset of transformation will change for different annealing temperatures.

3.2 Magnetic Measurements

A continuous evolution of the martensitic transformation can be obtained by measurements of the magnetic properties of the sample with precision of ±1% [2]. By measuring the change in the saturation induction of the sample, it is possible to calculate the instantaneous austenite fraction as a function of plastic strain. As a point of reference for the saturation induction when no austenite is present, the saturation induction of a sample that has been quenched such that all austenite has been thermodynamically transformed to martensite is used.

By placing a measurement coil around the sample and inducing a saturating magnetic field, the variation in magnetic flux can be measured and integrated in order to obtain the contribution of martensitic transformations to the flux variation [2]. This does, however, require calibration using samples for which the austenite volume fraction is already known.

4 Numerical Simulation of Mechanical Behavior

One of the primary goals of this project is to develop a multi-scale model to predict macroscopic mechanical behavior using information about the microstructure and the behavior of individual phases. To this end, an initial model will be constructed that uses an iso-work mixture rule to construct the macroscopic response from the responses of each constituent phase, as demonstrated by Arlazarov et al. [3]. The hypothesis given in (2) enables us to decompose the increment in total strain by use of a mixture law as shown in (3).

$$\sigma_F d\epsilon_F = \sigma_A d\epsilon_A = \sigma_M d\epsilon_M \tag{2}$$

where F, A, and M represent ferrite, austenite, and martensite, respectively and

$$d\epsilon = C_F d\epsilon_F + C_A d\epsilon_A + C_M d\epsilon_M \tag{3}$$

gives the macroscopic strain increment where C_x gives the volume fraction of phase x. The strain hardening can then be written as

$$\frac{d\sigma}{d\epsilon} = C_F \frac{d\sigma_F}{d\epsilon} + C_M \frac{d\sigma_M}{d\epsilon} + C_A \frac{d\sigma_A}{d\epsilon} + \frac{dC_A}{d\epsilon}(\sigma_M - \sigma_A) \tag{4}$$

Here, the last term accounts for the decreasing volume fraction of austenite as a function of macroscopic strain and as such this term will be defined using the results from aforementioned mechanical measurements.

The stresses in each of the phases present will be calculated from measured microstructural data. For the ferrite, the classic law for deformation by dislocation slip given in (5) will be used [4].

$$\sigma = \sigma_0 + 0.4M\mu b\sqrt{\rho} \tag{5}$$

where σ_0 is the lattice friction stress, M is the Taylor factor, b the Burgers vector, μ the shear modulus, and ρ the dislocation density.

The martensite will be assumed to be elastic, perfectly-plastic with a yield stress proportional to the carbon content.

A law will need to be developed for the austenite and must account for the transition from dislocation slip to TWIP or TRIP deformation modes. As an initial estimation, the austenite behavior will be identified by subtraction of the ferrite behavior from the curve for a low-temperature anneal.

5 Conclusions

It is expected that by combining both XRD and magnetic measurement based data on the kinetics of martensitic transformations of austenite in medium manganese steels, it will be possible to accurately reproduce the macroscopic tensile behavior of the material using constitutive laws for each of its constituent phases.

Acknowledgments

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