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Stress–strain response and microstructural evolution of a FeMnCAl TWIP steel during tension–compression tests

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ABSTRACT

The stress–strain response of a Fe–17.5Mn–0.7C–2Al TWIP steel during cyclic loading has been investigated by means of tension–compression tests within the strain limits of ±2%, ±5% and ±10%. In addition, the microstructural evolution during the ±5% cyclic test has also been studied. The difference between the forward and reverse stress for each pre-strain has been analyzed at 0.2% offset strain and at the strains in which forward and reverse curves were parallel in order to study the Bauschinger effect (BE) and permanent softening, respectively. The evolution of the BE with pre-strain for this steel is similar to other FeMnC TWIP steels, that is, increasing values of BE are obtained as the pre-strain increases. However, its absolute values are half those reported in the literature on other FeMnC steels. This diminution of the BE is related to the lower activity of mechanical twinning in FeMnCAl TWIP steels at the pre-strains herein investigated, which promotes less polarized stresses in the matrix due to the lower dislocation storage capacity.

Regarding permanent softening, the evolution is similar to that of the BE and the same analysis can be applied. During reverse compression, a slight increase of twin thickness and twin spacing with respect to the first tensile stage took place. This fact might be linked to the lower flow stress observed in the permanent softening period during reverse straining.

1. Introduction

Twinning-induced plasticity (TWIP) steels are being extensively studied because of their excellent combination of high-tensile strength and large ductility. One of the most promising applications is the manufacture of car components where energy absorption is a determining factor. It is well-known that one of the problems during sheet forming of high strength steels is the large amount of springback.

In the control of springback, numerical methods (such as the finite element method) are used to predict the differences between the final obtainable forms and the designed forms. With this knowledge, die modifications can be carried out and springback can be controlled (and minimized) following an iterative process. In order to obtain accurate forming simulations and therefore diminish the number of iterations, it is necessary to use good plasticity models that can give accurate stress predictions. The hardening law to be introduced in the these models must be able to predict the cyclic stress–strain behavior of the given material, especially when bending–unbending operations are involved, such as the ones taking place in industrial forming processes. It is particularly important to model the reverse loading flow curve, which should include the Bauschinger effect, the transient behavior and the permanent softening [1].

The hardening models that have shown better accuracy in predicting the magnitudes of the forward and reverse stresses are based on mixed isotropic–kinematic hardening laws [2,3]. Kinematic hardening is added to isotropic hardening by the so-called "back stress" that reflects the anisotropy of the yield strength. This back stress causes an increase of stress during forward straining but helps to decrease the flow stress in the opposite direction. This back stress can be determined by different tests: three-point bending tests [1], shear tests [4] and tension–compression tests [5].

Various studies on the cyclic behavior of TWIP steels [6] and on reverse loading [7,8] have been carried out in recent years. In these studies, a Fe–22Mn–0.6C steel was selected, and it was observed a large contribution of the kinematic hardening to the

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overall hardening. This large contribution was related to the combined effect of mechanical twins formed during deformation and the glide of dislocations, which are pinned at twin boundaries [9]. The storage of dislocations in the matrix by the action of twin boundaries is in the basis of the stress–strain response of TWIP steels; some hardening models have been proposed to relate these mechanisms to the pronounced work-hardening observed in these steels [10,11].

Despite the excellent tensile properties of FeMnC TWIP steels, it has to be mentioned that some problems have been reported in the literature. Among these problems we can find low yield strength, delayed fracture and heterogeneous deformation. The addition of Al can solve some of these problems since it suppresses the precipitation of cementite [12], promotes solid solution hardening, reduces H-embrittlement related to the delayed fracture and reduces Dynamic Strain Aging (DSA) [13]. On the other hand, FeMnCAl TWIP steels show less mechanical twinning activity and lower strain hardening rates than FeMnC TWIP steels [13–15]. As already mentioned, the development of back stresses in TWIP steels has been related to the combined mechanism between mechanical twins and dislocations glide, so the lower twinning activity of FeMnCAl steels should reflect in lower values of back stress with pre-strain in cyclic tests.

Although the tensile properties and strain hardening of FeMnCAl TWIP steels have been widely studied [13–16] there is very little information about its response in reverse loading. The present study, therefore, investigates the stress–strain behavior and the microstructural evolution of ~~a~~ FeMnCAl TWIP steels during cyclic tests. The possible differences in the evolution of the back stress with increasing strain and its relationship with mechanical twinning could indirectly help to understand the important contribution of kinematic hardening in TWIP steels.

2. Materials and methods

The studied material was a hot rolled TWIP steel sheet provided by POSCO with a thickness of 2.6 mm. The chemical composition in mass percentage is listed in Table 1 and the initial average grain size was 4 μm, although the grain size varied within from 0.6 to 18 μm. The microstructure and the local texture of the initial and deformed material during the 5% strain cycle were characterized by Electron Back Scattered Diffraction (EBSD) on the longitudinal plane, at approximately half thickness. The samples were mechanically polished with 2500 grit SiC paper until down to 0.02 μm colloidal silica suspension following standard metallographic procedures. EBSD measurements were performed using a JEOL JSM-7001 F Field Emission Scanning Electron Microscope (FE SEM) using the Oxford Instruments HKL channel 5 software package. A step size of 0.1 μm was used and misorentations below 3° were not considered in the post processing data procedure. Additional analysis of the microstructure was performed using the Kikuchi pattern quality (KPQ) maps from EBSD scans and standard FE SEM micrographs. Transmission Electron Microscopy (TEM) was carried out to investigate twin thickness and twin spacing as well as the evolution of the dislocation arrangement in the deformed samples. The specimens were analyzed in a Philips CM30 microscope operating at 300 kV. Samples for TEM observation were thinned by jet-polishing in an electrolyte solution of 94 vol% acetic acid and 6% percloric acid. Finally, X-ray diffraction studies (XRD) were done to verify the absence of ε-martensite in the deformed stages during tensile or cyclic tests (not shown here). The measurements were carried out in a Siemens D-500 equipment using CuKα radiation with wavelength $\lambda = 0.1506$ nm.

Table 1
Chemical composition of the TWIP steel used in this study (in weight percent).

Material	Mn	C	Si	Al	Ti	Mo	Fe
%	17.0	0.73	0.07	1.91	0.10	0.31	Bal.

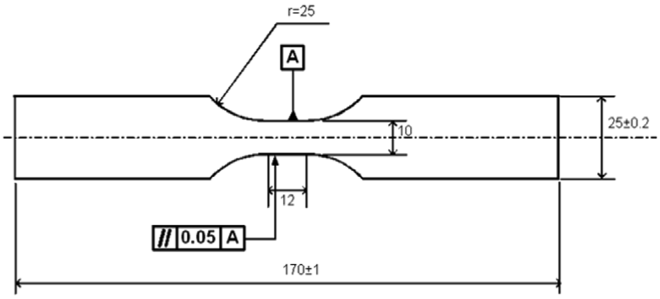

Fig. 1. Dimensions of the samples used for cyclic tests in mm.

The tensile and cyclic tests were carried out at room temperature in a MTS 250 kN testing machine. Tensile samples were machined from the initial sheet according to EN 10002-1 standard, with the tensile axis (TA) parallel to the rolling direction (RD) and a gauge length of 50 mm. For the cyclic tests, the geometry of the samples was designed to minimize buckling during reversal tests. Again, the tensile and compression axis were parallel to the rolling direction. The dimensions of the cyclic samples are illustrated in Fig. 1. In both tests, the strain rate was controlled at $8 \times 10^{-4}\,\mathrm{s}^{-1}$.

In the case of the cyclic tests, an anti-buckling device inspired by the apparatus used by Boger et al. [5] was designed. Flat plates were used for buckling constraint, covering nearly all the free surface of the samples. The clamping system applied a constant force of 10 kN that corresponded to a stress of 5 MPa in both sides of the samples. A Teflon film with a thickness of 0.10 mm was inserted between the clamping system and the sample in order to reduce friction. The displacement was measured in the flank of the specimens using a Real time strain sensor (RTSS) video extensometer from Limess GmbH. The clamping and the measurement systems can be observed in Fig. 2. As described by Lee et al. [17] the constraint in the thickness direction during compression tests requires corrections to eliminate the effect of the friction and the biaxial effects. The friction coefficient was calculated by comparing the values of tensile tests without the clamping system

Fig. 2. Assembly of the anti-buckling device and the video-extensomenter for the cyclic test of sheet samples.