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On the Bauschinger effect in dual phase steel at high levels of strain

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ABSTRACT

The effect of volume fraction and hardness of martensite on the Bauschinger effect in Dual Phase (DP) steel was investigated for strain levels close to those observed in automotive stamping. Five different grades of DP steel were produced by controlled heat treatment allowing the examination of the Bauschinger effect for three different volume fractions of martensite and three levels of martensite hardness. Compression–tension and shear reversal tests were performed to examine the Bauschinger effect at high levels of forming strain. Good correlation between the shear reversal and the compression–tension test was observed suggesting that for DP steel, shear stress strain data, converted to equivalent stress–strain, may be applied directly to characterize kinematic hardening behavior for numerical simulations. Permanent softening was observed following strain reversal and increased with martensite volume fraction and pre-strain level. While the Bauschinger ratio saturates at 3% pre-strain, the Bauschinger strain increases linearly with forming strain without showing saturation. This suggests that to model material behavior accurately in forming processes involving complex loading paths and high levels of strain, test data generated at high strain is required.

1. Introduction

Dual Phase (DP) steels consist of a ferritic matrix containing a hard martensitic second phase, which results in high initial work hardening combined with moderate elongation during deformation. These steels generally show significantly higher ultimate tensile strength levels than conventional steels of similar yield strength. This has led to an increased use of DP steels in automotive applications for structural and crash components in the body [1,2]. The material properties of DP steels can be adjusted and optimized by means of their composition and the modification of their microstructure, such as altering the size and morphology of the ferrite grains [3] and the martensite islands [4]. Their overall strength, however, mainly depends on the volume fraction and the hardness of the martensite phase [5].

Due to their high strength, DP steels show a high tendency for spring back and their microstructure containing a soft ferrite and a hard martensite phase leads to a significantly larger Bauschinger effect during strain path reversal compared with conventional steels [6]. Given that automotive components are generally manufactured in draw die operations where the sheet is both bent and unbent, the modeling of the cyclic behavior of DP steel is important to accurately predict spring back [7]. In recent years this has led to the development of numerous advanced material models for the prediction of the material behavior of DP steels during forming strain reversal [8]. Additionally, the manufacture of automotive components generally involves complex material deformation to high levels of forming strain. To study experimentally the material behavior at large strain under reverse loading, the in-plane cyclic shear test has been developed and has received increasing interest for the identification of material parameters for advanced material modeling [9]. In the shear test, a rectangular gauge area is deformed to a parallelogram along the length direction while the width remains constant [10]. Previous studies have shown that the measured shear stress is influenced by planar anisotropy [11]. This generally requires time-consuming numerical modeling of the test itself combined with inverse analysis to identify material model parameters [12]. A more straightforward test is the tension–compression or compression–tension test which measures the hardening behavior of metallic sheet under reversed uniaxial loading [8]. Some commercial Finite Element Analysis (FEA) software packages already allow the direct incorporation of tension–compression test data for advanced model development, making this test the obvious choice for industrial application, but problems with buckling and frictional effects limit the test to reverse strain levels that are significantly lower than those normally observed in automotive stamping [10]. Recent studies showed that the material behavior of DP steel in complex

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stamping operations can be successfully predicted by applying reversed uniaxial loading data generated at strain levels significantly lower than those observed in the actual forming operation [13,14]. In addition, a numerical sensitivity study [15] indicated that the main Bauschinger parameters that represent accurately the material behavior of DP steel following load reversal are the transient hardening and the reverse yield stress; permanent softening only had a minor effect, possibly due to the low level of permanent softening stress experimentally observed for the particular steel analyzed. Previous experimental studies showed that the Bauschinger ratio, which represents the reduction in reverse yield stress, and the Bauschinger strain, a measure for the transient hardening behavior, show a saturation at higher levels of strain [16,17]. This would suggest that for DP steel, reverse stress–strain information gathered at strains lower than those observed in the actual forming process may be sufficient to achieve high model accuracy. Up to now, experimental studies were usually limited to pre-strain levels below 5% [16,17] and information with regard to the Bauschinger effect of DP steels at forming strains comparable to those observed in industrial stamping is limited. Previous studies have shown that the Bauschinger behavior of DP steel is influenced by microstructural features [18,19] and further investigation is required to analyze the Bauschinger behavior of DP steel and the effect of microstructure at forming strain levels that are comparable to those observed in industrial manufacturing. To summarize, it is suggested that previously there has been insufficient information to determine the extent to which the Bauschinger effect following low levels of prestraining can be extrapolated to indicate material behavior in reversed deformation after pre-straining to high levels of strain in the range of 2–15%.

In this study, five different grades of DP steel were produced by controlled heat treatment allowing the analysis of the Bauschinger effect for three different volume fractions of martensite and three levels of martensite hardness. Compression–tension and shear reversal tests were performed, and applying the von Mises criterion, the shear stress–strain data was directly transformed into equivalent stress–strain. A direct comparison between the compression–tension and the shear reversal test is made and the effect of martensite volume fraction and hardness on the Bauschinger behavior at forming strain levels close to those generally observed in automotive manufacturing is established.

2. Experimental method

2.1. Material and heat treatment procedure

The material used in this study was a DP780 steel; the chemical composition is given in Table 1 and the thickness is 2 mm.

The as-received material was machined into 200 mm × 150 mm coupons and heat treated using a muffle furnace to generate microstructures with three different martensite volume fractions and three different levels of martensite hardness. The as-received material was held at 710 °C (M1), 770 °C (M2a) and 800 °C (M3) for 15 min followed by the quenching in water. Material grade M2a was additionally tempered in a fluid bed furnace at 300 °C (M2b) and 500 °C (M2c) for 10 min followed by the cooling in air. Thus there were in total five material conditions tested, and these are shown schematically in Fig. 1.

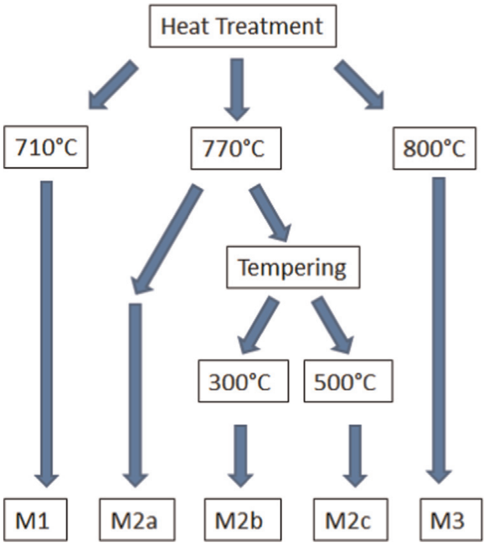

Fig.1. Schematic of the heat treatment procedures used in the current investigation.

2.2. Microscopy

Microstructure samples were hot-mounted in Polyfast and ground with 240 μm, 600 μm and 1200 μm grinding paper followed by polishing with 6 μm, 3 μm and 1 μm and etching with 5% nitric acid. The microstructures of all material grades were analyzed using an Olympus microscope BX51M. To determine the volume fraction of martensite, a 200 point grid was printed onto three microstructure regions of each material grade and the grid-dots placed in the grey martensitic areas were counted. Scanning electron microscopy (SEM) images were additionally produced on a FEI Quanta 3D FEG FIB-SEM using the Secondary Electron (SE) Everhart–Thornley detector.

2.3. Tensile testing

Tensile tests were carried out on an Instron tensile test frame equipped with a 30 kN load cell and longitudinal strain measured using a non-contact extensometer. All samples were deformed at an initial strain rate of 0.001 s^{-1}, at room temperature. The samples had an initial gauge section of 25 mm × 5 mm and for the heat treated samples the tensile direction was aligned to the rolling direction.

In order to determine the plastic anisotropy a second set of tensile tests was performed applying the same conditions as used above. Assuming volume constancy in Eq. (1) during plastic deformation, the *r*-values for samples oriented in 0, 45 and 90 degrees to the rolling direction were calculated using Eq. (2)

$$\varepsilon_l + \varepsilon_w + \varepsilon_t = 0 \tag{1}$$

$$r = \varepsilon_w/\varepsilon_t = -\varepsilon_w/(\varepsilon_l + \varepsilon_w) \tag{2}$$

where ε_l, ε_w and ε_t are the longitudinal, transverse and thickness engineering strains respectively. The specimens were loaded to

Table 1
Composition (wt%) of the DP780 steel measured by atomic emission spectroscopy.

Fe	C	Mn	Ni	Al	V	Sn	Cu	Cr	Si	As
96.9	0.107	1.93	0.0023	0.0312	0.0037	0.0072	0.0084	0.0201	0.901	0.009