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The influence of dynamic strain aging on resistance to strain reversal as assessed through the Bauschinger effect

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ABSTRACT

The Bauschinger effect of three commercially produced medium carbon bar steels representing different microstructural classes with similar tensile strengths and substantially different yielding and work-hardening behaviors at low-strain was evaluated at room temperature and *in situ* at temperatures up to 361 °C. The influence of deformation at dynamic strain aging temperatures as a means to produce a more stable dislocation structure was evaluated by measuring the resistance to strain reversal during *in situ* Bauschinger effect tests. It was shown that the three medium carbon steels exhibited substantial increases in strength at dynamic strain aging temperatures with the peak in flow stress occurring at a test temperature of 260 °C for an engineering strain rate of $10^{-4}\ \mathrm{s}^{-1}$. Compressive flow stress data following tensile plastic prestrain levels of 0.01, 0.02 and 0.03 increased with an increase in temperature to a range between 260 °C and 309 °C, the temperature range where dynamic strain aging was shown to be most effective. The increased resistance to flow on strain reversal at elevated temperature was attributed to the generation of more stable dislocation structures during prestrain. It is suggested that Bauschinger effect measurements can be used to assess the potential performance of materials in fatigue loading conditions and to identify temperature ranges for processing in applications that utilize non-uniform plastic deformation (e.g. shot peening, deep rolling, etc.) to induce controlled residual stress fields stabilized by the processing at temperatures where dynamic strain aging is active.

1. Introduction

The Bauschinger effect, which is a measure of the resistance of a material to strain reversal, is a manifestation of non-isotropic hardening during plastic deformation in an isotropic material [1]. An understanding of the Bauschinger effect is important in applications involving cold-formed or plastically pre-stressed structural components [2] when strain reversals occur during fabrication, during sample preparation for property measurements, or during service [3]. The ability to accurately model material flow behavior often is limited by an understanding of changes in material properties with strain direction, i.e. the Bauschinger effect. Fig. 1 shows a schematic of the Bauschinger effect for an annealed low carbon steel initially strained in tension and then subsequently unloaded and strained in compression. By convention the stress–strain data measured in the compression loading cycle are plotted in the tensile domain. The Bauschinger effect is typified by a loss of the distinct transition between elastic to plastic deformation during strain reversal in addition to a substantial decrease of the resistance to flow in the reversed direction as compared to the strength at the point of strain reversal, and can be accompanied by an apparent difference between the uni-direction and reversed flow behaviors at large accumulated strains. This increment of strength difference is illustrated in Fig. 1 and is termed permanent softening.

The substantial decrease in flow strength during a reversal in strain direction was first noted by Bauschinger [4] in 1881, for whom the phenomenon is named. Methods to characterize the Bauschinger effect [5–9] are based upon flow stress measurements, the strain required to achieve a flow stress level after strain reversal, and energy parameters. As an example, the Bauschinger effect factor (BEF) [10,11] shown in Fig. 1 is the ratio of the reversed yield stress, σ_R, to the flow stress at the point of strain reversal during prestraining, σ_F. A material which hardens isotropically would exhibit a BEF of 1.0, and the magnitude of the BEF decreases with an increase in the susceptibility to the Bauschinger effect [2,11]. The Bauschinger effect has been attributed to large numbers of dislocations moving in a reverse direction during a strain reversal [12], a process attributed to short [6,9,13,14] and long [6,9,13–15] range effects. Variations in the directionality of short range dislocation motion have been attributed to reductions in dislocation energy associated with the recovery of “dislocation debris” such as jogs and kinks [6] with reversed dislocation motion.

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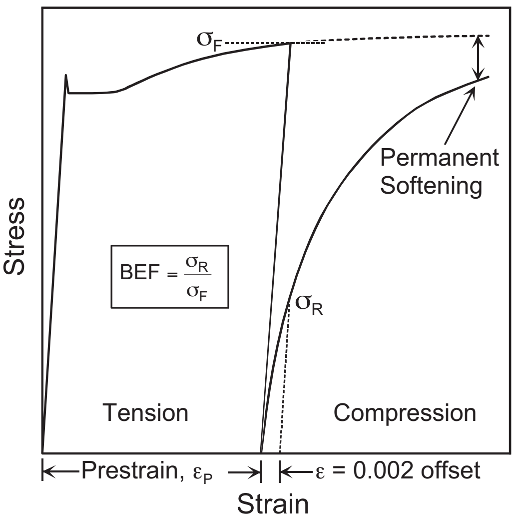

Fig. 1. Schematic of the Bauschinger effect phenomenon in a typical low carbon steel showing the deformation behavior of a sample prestrained in tension to ε_P and subsequently strained in compression with the compression cycle plotted in the tensile domain.

Long range effects are attributed to microstructural scale internal stresses that assist dislocation motion in the reverse direction. Development of internal stresses has been attributed to dislocation pile-ups at impermeable barriers such as grain boundaries, the walls of cellular dislocation structures, and Orowan loops around strong second phase particles [6,9,13,14,16–21]. Internal back stress levels have been estimated from mean residual lattice strain measurements through X-ray diffraction analysis [22] and *in situ* by neutron diffraction [23], and have been shown to increase rapidly with prestrain at small prestrain levels. Upon reversal of strain, the back-stresses quickly diminish and reform in the opposite direction [23]. Accompanying the effects of the back stress, the decay of dislocation cell walls and the reversal of lightly bound dislocations from the structure, which can move appreciable distances at low shear stress due to the differences in barrier spacing and density between the forward and reverse directions [24], are thought to contribute to the Bauschinger effect [16,21,25]. Wilson [18] suggested that the reorganization of internal stresses gives rise to the significant disparity in flow stress upon strain reversal, and that there is a required plastic strain associated with the relaxation of these internal stresses as well as a required strain to reform the internal stresses in the opposite sense. Permanent softening can be considered to be an effect of reversible work hardening which occurs during the decay and reformation of the internal stresses following a strain reversal [18]. The Bauschinger effect increases with an increase in prestrain [3,6,26–28] and saturates above a certain limit [2,3,22]. Additional microstructural features, which give rise to a substantial Bauschinger effect, are twin boundaries [29] and stacking faults [30]. Materials with low stacking fault energies are particularly susceptible to the Bauschinger effect [30] due to the impermeability of stacking fault intersections to dislocation motion, thus generating back stresses.

Efforts to improve the resistance of a material to strain reversal have used a basic understanding of both static [13,25,31–36] and dynamic strain aging [11]. Dynamic strain aging is a process where the combined effects of dislocation–solute interactions and the increased solute mobility in a specific temperature range induce a deformation mechanism change characterized by rapid and repeated pinning and generation of dislocations [16,37]. Li et al. [11] showed that the reversed flow behavior at room temperature of low carbon steel specimens prestrained at dynamic strain aging temperatures exhibited a significant increase in yield strength and return of a sharp yield point in comparison with specimens prestrained at room temperature. During dynamic strain aging, several modifications to dislocation motion and structure occur. These changes include a decrease in mobile dislocations through solute pinning, an increase in dislocation density [37–39], and a change from cellular dislocation structures to diffuse dislocation tangles [16,39–41] developed during deformation. The changes in dislocation structure also lead to reductions in the long range back stresses formed during deformation consistent with the property modifications observed by Li et al. [11].

Table 1
Alloy content of the steels (wt pct).

Steel	C	Mn	S	Si	Ni	Cr	Mo	V	Nb	Al	Ti	N
4140	0.41	0.82	0.039	0.09	0.08	0.89	0.18	0.001	0.001	0.030	0.010	0.008
NTB	0.34	1.21	0.008	0.66	0.10	0.10	0.19	0.090	0.001	0.010	0.020	0.010
C38M	0.36	1.37	0.069	0.56	0.07	0.13	0.02	0.100	0.010	0.030	0.010	0.016

This paper evaluates the interrelationships between resistance to strain reversal and deformation mechanism from room temperature up to dynamic strain aging temperature for three medium carbon bar steels of similar strength level and different microstructure.

2. Experimental materials and procedures

Three commercially produced medium carbon forging steels were selected for the present study. Table 1 lists the chemical compositions. The three steels represent various microstructural classes resulting from differences in alloying and thermomechanical processing and have been used in a recent study on deep rolling [10,42,43]. The three steels have distinct differences in strain hardening behavior.

The 4140 alloy is a quenched and tempered forging steel that was air cooled after hot rolling, induction heated to an austenitizing temperature of 849 °C, quenched, induction tempered at 760 °C for less than 1 min, and subsequently air-cooled. The NTB is a non-traditional bainitic steel in which the traditional bainitic carbide morphology is replaced with aggregates of a martensite plus retained austenite (MA) constituent [44]. Based on X-ray diffraction analysis [45], the NTB steel contained 14.5% retained austenite with 1.63 wt pct C in the austenite. The NTB alloy was direct cooled from hot rolling temperatures to room temperature. The presence of 0.66 wt pct Si retarded cementite formation on cooling below the eutectoid temperature due the insolubility of silicon in the cementite matrix. The C38M is a hot rolled and air cooled ferrite–pearlite microalloyed 1038 steel grade with sulfur additions to promote chip formation during machining. The as-received hardness levels of the 4140, NTB and C38M alloys are 30 HRC, 25 HRC, and 25 HRC respectively.

Uniaxial tension and compression test data were obtained at room temperature at a constant engineering strain rate of $1.6 \times 10^{-3}\,\text{s}^{-1}$ using standard testing techniques on cylindrical samples [10]. The Bauschinger effect was evaluated through single reversal tension to compression tests at temperatures between 21 °C and 361 °C, at a constant engineering strain rate of $10^{-4}\,\text{s}^{-1}$, and at true tensile plastic prestrains of 0.01, 0.02, and 0.03. The Bauschinger effect specimen had a 10.16 mm diameter and a 15.24 mm gage length with a 30.5 mm fillet radius. Strain was measured using a standard extensometer. A 1:1 extension scissors device was used in the elevated temperature tests to offset