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Four-point bending test of the Bauschinger effect in prestrained IF steel thin sheet

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ABSTRACT

The Bauschinger effect in a 1 mm thick sheet of interstitial free (IF) steel was examined by tensile testing (prestraining) and subsequent four-point bending. The effect was absent when the prestrain was below 4% and was present when the prestrain was above 4%. The Bauschinger effect parameter determined the elastic back stress which developed after prestraining. The occurrence of back stress coincided with the development of dislocation cell structures, observed with transmission electron microscopy.

1. Introduction

The Bauschinger effect is associated with the decrease in flow stress when the direction of loading is reversed. The effect is observed not only in two-phase alloys and composites [1,2] but also in single phase materials [3]. The purpose of the present study is to observe the effect in an IF steel sheet with a thickness of 1 mm. These rolled sheets of IF steel are usually supplied for press working. A pressed product might suffer a load which causes deformation opposite to that given during press work. Thus, the examination of a Bauschinger effect has a practical application. Also, this effect, if examined with structural changes, helps understand the basic mechanism of strain hardening.

Generally speaking, uniform in-plane compression is difficult to apply to thin sheets, since elastic buckling occurs under a much smaller load than the plastic yielding load. The end effect (the gripping effect or lubricant effect) in compression tests also results in other difficulties, noted by various authors who have reported on the Bauschinger effect in IF steels [4–6]. Teodosiu and his coworkers first reported the results of simple-shear testing [4,5], and Yoshida, Uemori and Fujiwara prepared laminated thin specimens for the push–pull tests in order to suppress buckling [6].

Recently a four-point bending method was proposed for examining the Bauschinger effect [8]. The advantage of this method is that the determined elastic limit is indifferent to the geometry of deformation between uniaxial tension/compression and bending. Some examples of the method used for steels and nonferrous metals are given in reference [7]. The method has been successfully applied to thin sheets of transformation-induced plasticity (TRIP) steel of 1.2 mm thickness [8]. In this work, the method is used to examine the Bauschinger effect in thin plates of IF steels.

Over the past decade, quite a few authors have reported the mechanical properties of IF steel [9–12]. This classical subject again became a point of interest as researchers addressed such basic issues as the Taylor problem of polycrystal plasticity [4], the formation of recrystallization texture [5,9,11,13], and the formulation of the yield criterion in anisotropic hardening materials [6,12]. In this ten year period, the electron backscattering diffraction (EBSD) technique [14] has become increasingly popular. This technique provides new information about the crystallographic microstructures which determine the mechanical properties of IF steel together with the Bauschinger effect studied in this work.

The Bauschinger effect is understood in such a manner that dislocations move under the external stress which is balanced with the friction force and the internal force (the back stress) [2,3,8]. The friction force action is symmetrical with regard to the forward and reverse flow, while the back stress is asymmetrical. The major origin of the back stress in single phase materials is the repulsive force from stored dislocations, particles, if there are, and/or the strain (eigenstrain) misfit between grains (the Taylor hardening) [2]. Some classic literature dealt with Bauschinger

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effect by considering this concept [1–3]. However, none of the previous studies on IF steels have discussed the Bauschinger effect in terms of the mechanical properties of the steel. This is likely because the Bauschinger effect is difficult to detect in thin sheet materials.

2. Experimentals

2.1. Sample preparation

The chemical composition of the IF steel is listed in Table 1. This steel underwent annealing at 1100 °C and hot rolling down to 4 mm thickness. After further cold rolling of 75% and subsequent annealing at 800 °C, a recrystallized sheet of 1.0 mm in thickness was obtained.

Specimens, 3 mm wide, 1 mm thick and 60 mm long, were cut from the sheet by spark erosion. Note that rather than a wide plate, a narrow rectangular bar is preferable for bending the specimen in order to avoid horseback deflection.

The top and bottom surfaces were parallel to the rolling direction (RD). The surface normal is indicated by the ND. The longest dimension was taken parallel to the RD. The width was along the transverse direction, TD. Tensile testing was performed to obtain a prescribed amount of prestrain under the nominal strain rate of 1.6×10^{-4}/s. The elongation of tensile specimen was measured by an extensometer. The dislocations formed by the prestraining was observed with a transmission electron microscope, HF-2000, 200 kV.

2.2. Four-point bending test

Two wire strain gauges for steels, TML FLA-5-11, were glued on the top and bottom surfaces of a prestrained specimen. The principle of four-point bending [7] is illustrated in Fig. 1(a). The outer span was 40 mm and the inner span was 20 mm and thus the lever d, which is the distance between the indenter and the simple support, was 10 mm. When the bending load was applied under a constant speed of 1.6×10^{-3} mm/s, the strain rate on the outermost surfaces was equal to that in tensile prestraining.

The bending load P and the output of the strain gauge of ε_1 in compression and that of ε_2 in tension were measured simultaneously. A uniform moment of $M = Pd/2$ in the central part was applied to the beam.

If the elasticity modulus is the same in tension and compression, the two outermost surfaces are under the identical bending stress, equal to the moment M divided by the section modulus S. This modulus is a constant of $bh^2/6$ for the rectangular cross section of thickness h and width b. In elastic bending the bending strain on the surface is $\varepsilon = M/ES$, where E is Young's modulus, so that the M/S vs. ε relation is a straight line with the slope equal to E [7].

Fig. 1(b) is a pair of bending curves of a hypothetical elastic-perfectly plastic material, having a lower yield stress Y_1 in compression which is lower than the yield stress Y_2 in tension. The method of calculation used for this figure has been described in a previous paper [7]. If plastic yielding occurs on the compression side under the stress Y_1, the bending curve deviates from the linear elastic line under the stress $M/S = Y_1$ and separates into two different curves. The bending curve then changes slope abruptly when the stress reaches Y_2. Thus, the two yield stresses in compression and tension can, in principle, be measured in a single bending test.

Table 1
Chemical composition (weight percent).

C	Si	Mn	P	S	Al	Ti	N
0.0022	< 0.003	< 0.003	0.010	< 0.0003	0.032	0.037	0.0011

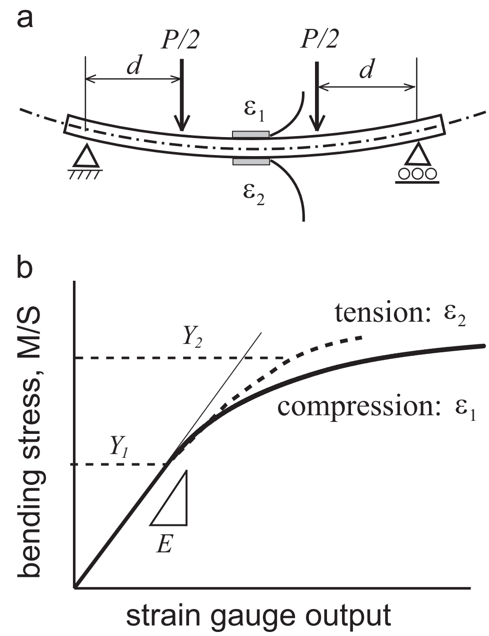

Fig. 1. (a) Illustration of the four-point bending test and (b) schematic bending curves of tension and compression surfaces. Here, P is the load, d, the distance between the loading point and a support,Y_1, the yield stress in compression,Y_2, the stress in tension, S, the section modulus.

3. Results

3.1. Microstructure of specimens

As-received samples were polished mechanically and etched by nital. Fig. 2 shows an optical micrograph of the etched surface. The grains are equiaxed and the grain diameter was 38 μm on average. Precipitates of carbide and nitride were so small that these could not be resolved in this photograph. [10].

The IF steel was textured by the thermo-mechanical processing [4,5,9,11,13]. To identify the texture in the present sample, the EBSD patterns were taken using a scanning electron microscope of JSM 7001. As described in the literature, the γ-fiber, the alignment of the {111} plane in the rolling plane, < 111 > //ND [14], was observed.

The Millar indices of the grains observed by SEM were

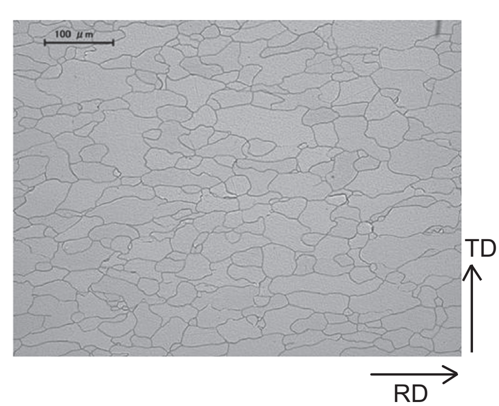

Fig. 2. Optical micrograph of unstrained sample.