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The Effect of Dynamic Strain Aging on Subsequent Mechanical Properties of Dual-Phase Steels

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Dual-phase (DP) steels with different martensite contents were produced by subjecting a low carbon steel to various heat treatment cycles. In order to investigate the effect of dynamic strain aging (DSA) on mechanical properties, tensile specimens were deformed 3% at 300 °C. Room temperature tensile tests of specimens which deformed at 300 °C showed that both yield and ultimate tensile strengths increased, while total elongation decreased. The fatigue limit increased after pre-strain in the DSA temperature range. The effects of martensite volume fraction on mechanical properties were discussed.

Keywords dual-phase steels, dynamic strain aging, fatigue strength, martensite

1. Introduction

Dual-phase (DP) steels are a group of low carbon steels which have excellent fatigue properties due to the high resistance to crack propagation, especially at low strain rates. High threshold values in DP steels are due to the crack tip shielding effects caused by the crack deflection and constraining of plastic deformation in ferrite. It has been reported that DP steels have the highest threshold values among metallic materials (Ref 1-6). Crack deflections in the ferrite, ferrite grain boundaries, and ferrite/martensite interfaces result in crack closure effects (Ref 7-10). Although fatigue properties of DP steels have been investigated for many years (Ref 11-16), the effects of dynamic strain aging (DSA) on fatigue properties of DP steels with different martensite morphology have not been reported yet.

The high temperature mechanical properties and strain aging of low carbon steels have been studied for many years. Strain aging is caused by the interaction between mobile dislocation and solute atoms. Because of their high diffusivity, these solute atoms are mainly carbon and nitrogen in low carbon steels. When these atoms form atmospheres around mobile dislocation and lock them, strain aging occurs and results in increased strength and decreased ductility (Ref 17-20). When the straining and aging processes take place simultaneously, it is called DSA, which affects work-hardening behavior of the material.

It has been reported (Ref 21) that DSA improves the fatigue strength of A-242 and vanadium-containing HSLA steels. Li and Leslie (Ref 22) reported that the fatigue strengths of 1008- and 1020-renitrogenized steels increases as a result of DSA effects. Previous studies on high temperature deformation of DP steels showed that DSA occurs in the temperature range of 150-450 °C, and deformation at 300 °C has the highest effects on room temperature tensile properties (Ref 20, 23).

This research was undertaken to investigate the effects of deformation at DSA temperature range on fatigue properties of DP steels with different martensite volume fractions and martensite morphologies.

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1.1 Experimental Procedure

A low carbon steel plate in the as-rolled condition, ST52, with chemical composition of 0.1C, 1.40Mn, 0.33Si, 0.026P, 0.011S, was used in this research. Samples were cut from the received plate in the longitudinal direction, with dimension of $10 \times 10 \times 22$ mm. All the samples were homogenized at 1100 °C for 1 h and then normalized at 980 °C and then cooled in air. The DP microstructures with different volume fractions of network martensite are obtained by heating the normalized bars at the intercritical temperatures of 778 and 805 °C for 30 min, and then quenching into cold water.

A few of these samples, with different martensite volume fractions, were strained 3% at 300 °C using a 6027 Instron tensile machine with a cross head speed of 2 mm/min. Tensile and fatigue specimens were prepared according to ASTM A370-B and ASTM E-466, respectively. Room temperature fatigue tests were carried out on a Newman rotating-bending fatigue test machine at a frequency of 2850 rpm. S-N curves for base material and those deformed at high temperature were determined according to ASTM E 739. Microstructures and fatigue fracture surfaces were studied by optical and a Philips XL30 scanning electron microscope (SEM), respectively. The microstructure was analyzed by a Bohler image analyzer.

2. Results and Discussions

2.1 Microstructure

Figure 1 shows typical microstructure of steels with 0.20 volume fraction of network martensite. Martensite volume fractions of steels were 0.20 and 0.28 (Table 1).

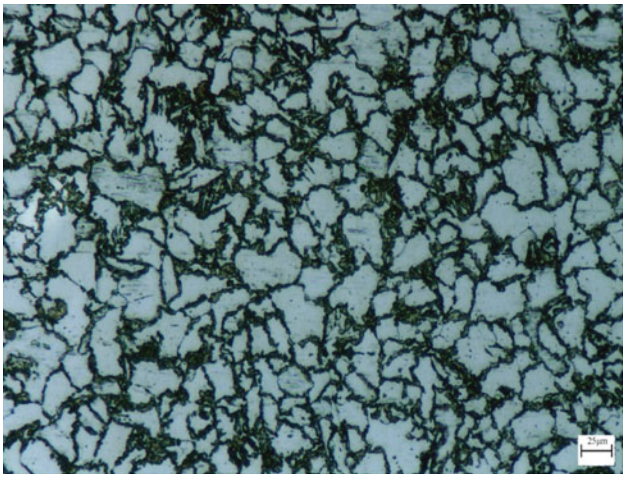

Fig. 1 Microstructure of produced DP steels, 0.20 network martensite

Table 1 Microstructure and martensite content of DP steels

Group	Heat treatment	Intercritical temperature, °C	Martensite morphology	Martensite volume fraction, %
A	Intercritical annealing	778	Network	20
B	Intercritical annealing	805	Network	28

Table 2 Mechanical properties of DP steels

Group	UTS, MPa	YS, MPa	El, %
A	621	330	22.5
B	695	387	27.5

2.2 Tensile Properties

Table 2 shows yield and ultimate tensile strengths of DP steels with different volume fractions of martensite for as-produced samples. As can be seen, both yield stress (YS) and ultimate tensile strength (UTS) increase with increasing volume fraction of martensite at a given martensite morphology. DP steels might be considered as metallic composites (Ref 24) and the increasing strength with increasing martensite content has been related to the increase of volume fraction of the hard phase in the composites. In addition, increasing dislocation densities due to the martensitic transformation cause cold work (Ref 25) in the adjacent ferrite, which makes ferrite stronger. As is obvious from the data in the Table 2, total elongation decreases with increasing martensite volume fraction at a given martensite morphology, which is in agreement with the variations of YS and UTS.

The room temperature tensile properties of steels deformed 3% at 300 °C are given in Table 3. The variations of YS and UTS with martensite volume fraction are similar to the variations of these parameters in the as-produced DP steels. These data also show that both YS and UTS of steels deformed at high temperature are greater than the YS and UTS of as-produced steels. The increase in yield and ultimate tensile strengths may be due to the DSA effects. The effects of high temperature deformation on tensile properties of DP steels are discussed in our previous articles (Ref 20, 23). The previous results showed that at 300 °C the DSA effects are dominant and result in the increase of strength. In iron-based alloys this phenomenon has been related to the interaction of dislocations with the solute atoms of C and N (e.g., Ref 17, 26). Moreover, because of transformation-induced dislocations in DP steels, during high temperature deformation, more dislocation locks are formed, which in turn results in more work hardening in ferrite.

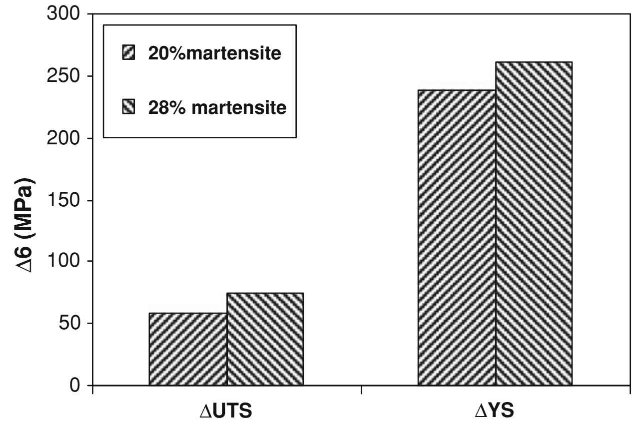

Fig. 2 Increase in YS and UTS after deformation at 300 °C

Table 3 Mechanical properties of DP steels after 3% deformation at 300 °C

Group	UTS, MPa	YS, MPa	El, %
A	680	569	11.8
B	769	648	17.3

The difference between the YS, as well as the UTS, of steels deformed 3% at 300 °C and the YS of as-produced steels, $\Delta\sigma$, are plotted in Fig. 2. As can be seen from this figure, deformation at 300 °C has greater effect on YS than that on UTS. This may be due to the occurrence of DSA during high temperature deformation. DSA increases the flow stress at high temperature, which in turn increases the YS at room temperature. However, some of this increment may be due to the static strain aging which occurs during the cooling of tensile specimens to room temperature.

As can be seen from Fig. 2, as the martensite content increases, YS and UTS after DSA also increase, which is due to the increased work-hardening effects of martensite- and transformation-induced dislocations.

2.3 Fatigue Properties

The Stress-Fatigue life curves of as-produced and high temperature deformed DP steels are shown in Fig. 3. The stress at 10^7 cycles to fracture was taken as fatigue limit. Figure 3 shows that steels deformed 3% at 300 °C have greater fatigue strength than as-produced steels. These results are in agreement with the results of tensile tests.

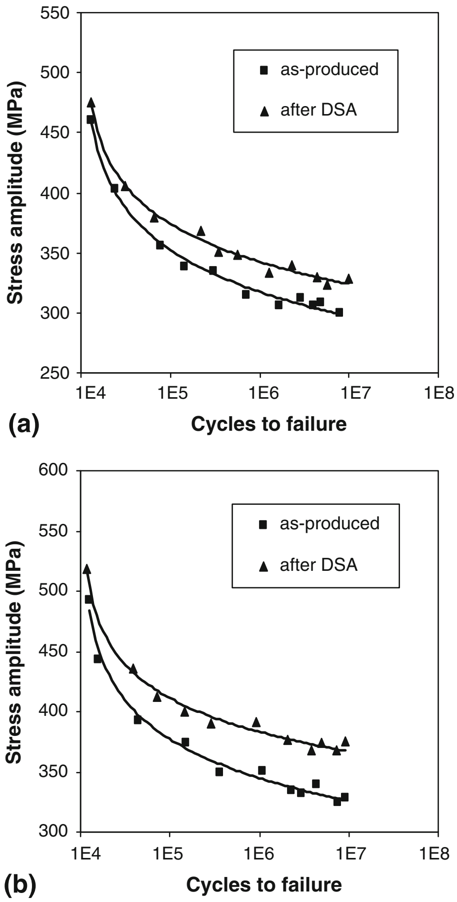

Fig. 3 Effect of 3% deformation at 300 °C on S-N Curves of DP steels with (a) 20% network martensite, (b) 28% network martensite

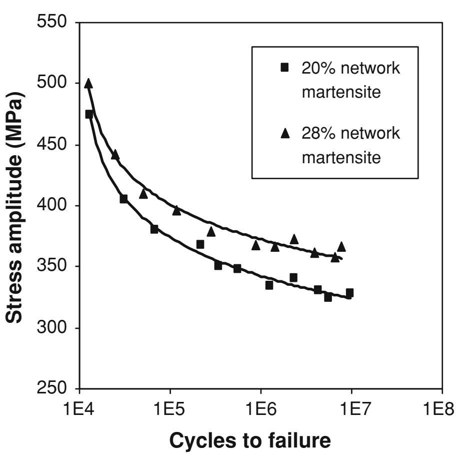

Fig. 4 Stress-Fatigue life curves of DP steels after high temperature deformation

Figure 4 shows Stress-Fatigue life curves of DP steels after high temperature deformation, for the same martensite morphology with different martensite volume fractions. This figure shows that the fatigue limit increases with increasing volume fraction of martensite. This may be due to the greater strength of steels with higher martensite volume fraction as a result of greater volume fraction of hard phase and also greater dislocation density before and after high temperature deformation. It has been reported (Ref 27) that the surface fatigue limit of low and medium strength steels (with UTS up to about 1050 MPa) increases with increasing the tensile strength following a linear relation.

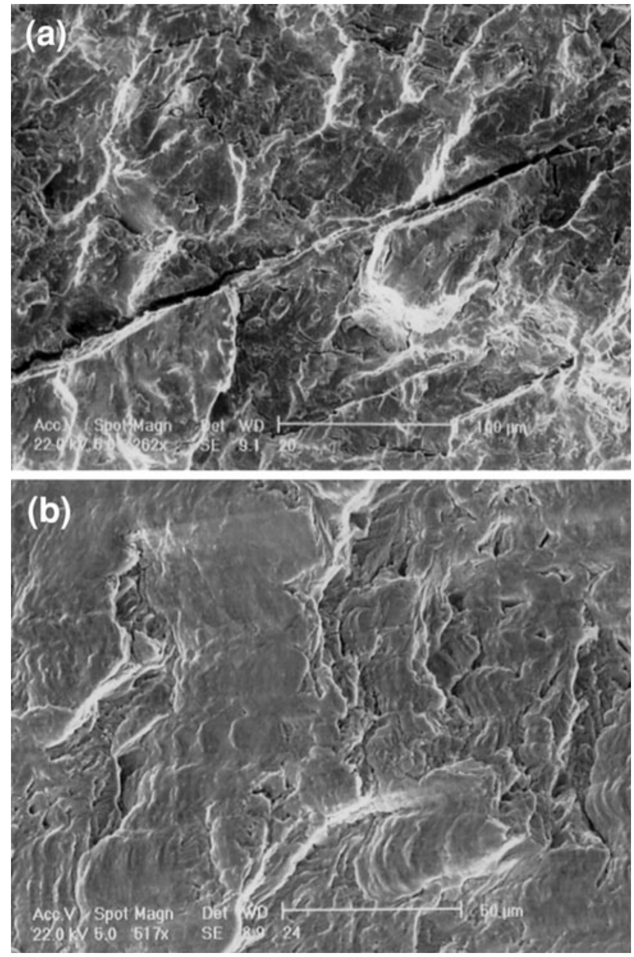

Fig. 5 SEM micrograph of fatigue fracture surfaces of DP steels with network martensite; (a) Cracks in DP steels with network martensite travel in a nearly straight line, (b) Large smooth areas indicate a nearly straight line for crack path in these steels

Fracture studies of fatigue fracture surfaces by SEM showed that in steels with network martensite crack propagates in nearly a straight line (Fig. 5). On the other hand, in steels with network martensite crack has not a preferred path due to the microstructure and passes through both hard phase and soft phase.

3. Conclusions

Steels with different volume fractions of martensite were produced by different heat-treatment cycles. The steel bars were then deformed 3% at 300 °C before mechanical tests. The results of fatigue and tensile tests at room temperature showed that

1. Increasing martensite volume fraction increases both YS and UTS of DP steels.

2. Increasing the martensite volume fraction for a given martensite morphology increases fatigue limit of DP steels both in as-produced samples and samples deformed at DSA temperature.
3. The YS and UTS of DP steels increases with deformation of DP steels at 300 °C, which is related to the DSA effects.
4. Deformation of steels at 300 °C increased the fatigue limit of DP steels due to DSA effects. These increments were greater for DP steels with greater amount of martensite.

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