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# The effect of carbon content on fatigue strength of dual-phase steels

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**Abstract**

Steels which contain 0.085 C, 0.36 C, and 0.38 C were intercritically annealed at 745, 760, 775, and 790 °C for 30 min followed by water quenching to obtain dual-phase (martensite-plus-ferrite) structure. It was found that the volume fraction of martensite increased with increasing annealing temperature. Rotating bending tests (10 million cycles) were conducted on the as-received materials and the dual-phase steels specimens selecting completely reversed cycle of stress. It was seen that the fatigue strength of dual-phase steels increased when compared with as-received materials. The highest fatigue strength was observed in the intercritically annealed steels at 760 °C. The fatigue strength of these steels increased at the annealing temperature up to 760 °C and decreased at the annealing temperatures higher than 760 °C.


*Keywords:* Ferrous metals and alloys-A; Heat treatment-C; Fatigue-E; Microstructure-F

## 1. Introduction

The microstructure of conventional steels often makes it impossible to obtain concurrently good ductility and high strength. However, some applications, especially in the transportation industries, require economical high strength steel with good formability. To achieve weight reductions and fuel saving in the vehicles and to fulfill the energy and resource requirements, materials designers have concentrated on the low-alloy steels. Consequently, dual-phase steels (DPS), mostly containing ferrite and martensite phases that can be obtained by relatively simple heat treatments, have been developed [1].

Dual-phase steels derive their characteristic properties from the presence of martensite and austenite islands dispersed in a ferrite matrix. These steels are produced by annealing plain and low-alloy steels in the ferrite–austenite ($\alpha$–$\gamma$) region and cooling below the martensite start temperature at suitable rate [2].

Many researchers have been working on the DPS to determine relationship between microstructure and mechanical properties, and to develop new materials for specific application. Bayram et al. [1] studied the relationship between the microstructure and notch geometry of DPSs. They obtained optimum results for intermediate quenching. Chen and Cheng [3] investigated the effect of martensite strength on the tensile strength of dual-phase steels. However, they developed a formulation to evaluate the effect of martensite strength on the tensile strength of these materials. Chang and Preban [4] studied the effect of ferrite grain size on tensile strength. Sarwar and Priestner [5] found that an increase in tensile strength could be obtained through an increase in the martensite volume fraction, as well as by an increase in the aspect ratio of martensite.

Tomita [6] investigated the effect of martensite volume fraction and the morphology of the phases. Bag et al. [7] examined tensile and impact properties of high-martensite

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dual-phase steels. They observed that equal amounts of finely dispersed martensite phases exhibit the optimum combination of high strength and ductility with high impact toughness. Battacharyya et al. [8] developed a model to examine the effect of martensite morphology on the initial plastic state of the ferrite matrix and on the stress-strain behavior of DPS during loading.

Sherman and Davies [9] investigated the influence on cyclic properties of martensite content or carbon content at DPSs. They determined that increasing martensite or carbon content of the phases of DPSs generally favorable effect on the fatigue properties. Besides, Sherman and Davies [10] determined the effect of martensite content on the fatigue of a DPS. It was found that monotonic strength increases continuously with increasing martensite contents. Sperle [11] examine the fatigue strength of lean-alloyed dual-phase steels. It was found that the fatigue strengths of lean-alloyed dual-phase steels was similar to those of other steels of equal tensile strength. Hashimoto and Pereira [12] determined the morphological influence on fatigue life of low carbon with dual-phase microstructure. The results of this study demonstrated that ferrite and martensite microstructures had superior symmetrical bending fatigue strength when compared with ferrit-pearlite steel. Mediratta et al. [13] examined the effect of microstructural morphology on the low cycle fatigue of a DPS. All three conditions (type: 1, 2, 3) have been found to exhibit cyclic hardening.

Wang and Al [14] investigated crack initiation and near-threshold fatigue growth at low-alloy DPSs. Sarwar and Priestner [15] also studied fatigue crack propagation in DPSs. Sudhakar and Dwarakadasa [16] made a study on fatigue growth in dual-phase martensitic steel in air environment. Cai et al. [17] examined the dependence of tensile and fatigue properties on microstructure of DPSs. Gustavsson and Melander [18] concerned variable-amplitude strain-controlled fatigue of a cold-rolled dual-phase sheet steel. The aim of this work is to determine the effect of morphology of second phase martensite on the fatigue properties of dual-phase steels containing 0.085, 0.36, and 0.38%C.

## 2. Experimental techniques and methods

The steels used in the present study were Fe–0.085C, Fe–0.36C, and Fe–0.38C, respectively, S1 (3996), S2 (SAE 5035), and S3 (SAE 5040). Chemical compositions of these steels are given in Table 1. The as-received material came in the form of hot-rolled bars, approximately 5.1 mm in diameter. For two-phase annealing, these steels which contain different carbon were hold in furnace at 745, 760, 775, and 790 °C for 30 min, the specimens were quenched directly into water (intercritically annealing). These procedures are represented schematically in Fig. 1.

Table 1
Chemical compositions of steels (wt%)

| | C | Mn | Si | Al | P | S |
|---|---|---|---|---|---|---|
| S1 (3936) | 0.085 | 0.33 | 0.06 | 0.062 | 0.011 | 0.009 |
| S2 (SAE 1035) | 0.36 | 0.71 | 0.23 | 0.041 | 0.012 | 0.006 |
| S3 (SAE 1040) | 0.38 | 0.75 | 0.212 | 0.058 | 0.010 | 0.016 |

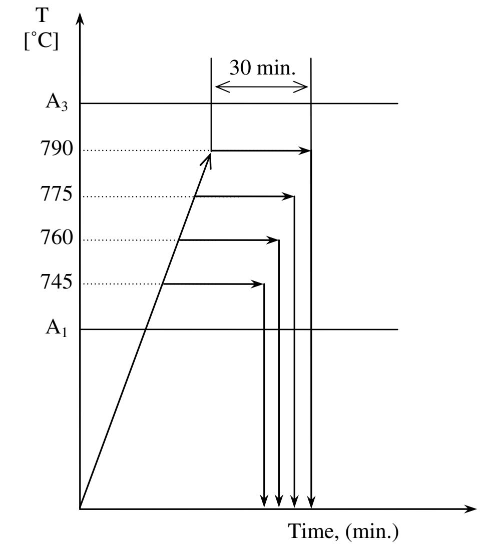


Fig. 1. Schematic heat treatment diagrams of intercritically annealed S1, S2, and S3 steels.

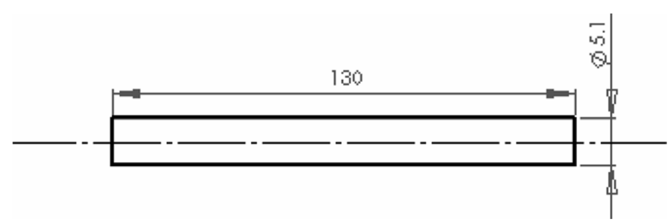


Fig. 2. Dimensions of Fatigue test specimen.

After heat treatment, cross-sections of samples were polished, etched with 5% nital, and observed under light microscope to reveal the morphology of the phases. Fracture surfaces of the specimens were examined under scanning electron microscope (SEM). The volume fraction of martensite at these steels was determined by point counting method.

Fatigue test specimens were prepared as round bars of approximately 20.4 $mm^2$ cross-sections area with a length of 100 mm. Fatigue tests were accomplished with a rotating beam machine. Rotating bending tests were performed at a frequency of 50 Hz (2950 rpm) for each specimen. It was selected completely reversed cycle of stress ($R$ = minimum stress/maximum stress = −1) in fatigue tests. The fatigue test specimens used in the present work are depicted in Fig. 2. Nine samples were tested at each stress level and a sufficient number of stress levels were chosen to obtain *S–N* curves of each heat treatment condition. The highest stress at which the samples endured $10^7$ cycles was taken as the fatigue strength.

The bending stress was calculated using the following equation:

$$\sigma_g = \frac{M_{e\,max}}{W} = \frac{P \cdot I}{\pi \cdot d^3/32} = \frac{P \cdot I \cdot 32}{\pi \cdot d^3} \quad (1)$$

where $\sigma_g$ is the stress amplitude, $M_{e\,max}$ is the maximum bending moment (N m), $W$ is the section modulus ($mm^3$), $P$ is the applied load (N), $I$ is the moment of length (100 mm) and $d$ is the radius of test sample ($d$ = 5.1 mm).

## 3. Results and discussions

### 3.1. Metallography

As-received materials (S1, S2) show ferrite-plus-pearlite microstructure (Fig. 3). The pearlite is distributed uniformly

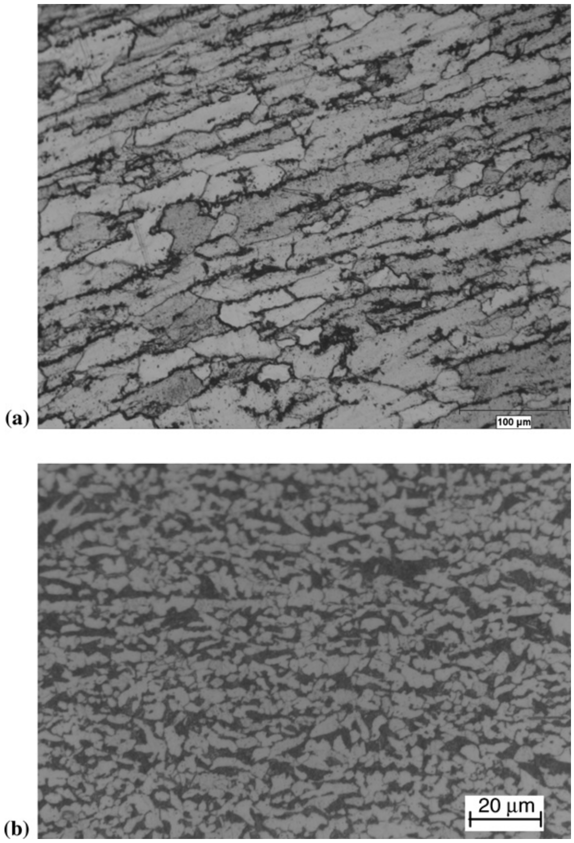


Fig. 3. Light micrographs of the microstructures of as-received materials: (a) S1, and (b) S2.

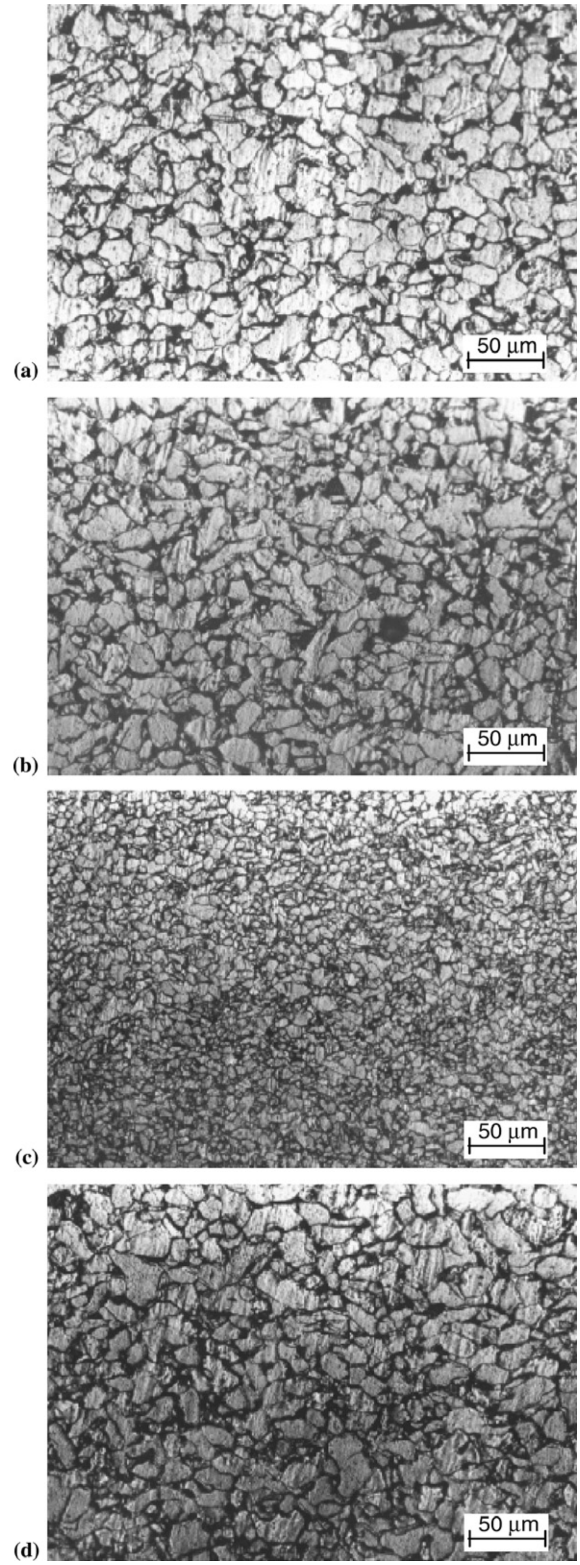


Fig. 4. Light micrographs of the microstructures of intercritically annealed S1 steel at different temperatures: (a) 745 °C, (b) 760 °C, (c) 775 °C, and (d) 790 °C.

but as irregularly shaped volumes embedded in the ferrite matrix (i.e., typical of a fine normalized structure). Figs. 4–6 reveals the microstructure of S1, S2, and S3 steels which was intercritically annealed. These micrographs show equiaxed martensite phase surrounding ferrite grains. The ferrite grains appear unchanged from these observed in the as-received material. The ferrite phase did not experience any structural change after quenching from the austenite-plus-ferrite region. On the other hand, it is observed on these micrographs that the volume fraction of martensite phase increases as carbon content and austenitising temperature increase. The volume fraction of the martensite estimated in DPSs depending on annealing temperature is seen in Table 2.

### 3.2. Fatigue behavior

The *S–N* results of the rotary bending fatigue are depicted in Figs. 7–10. A smooth curve drawn through the data points rather than a straight line, as it fitted the data points better. In each figure, data points with arrows indicate samples and did not fail after an excess of $10^7$ cycles or more stress cycle.

Fig. 11 reveals that the fatigue strength increases as carbon content increases at both as-received materials and intercritically annealed DPSs having different volume fraction of martensite. Sherman and Davies [9] observed that the fatigue properties of DPSs with low carbon improved as carbon content of these steels increase. The volume

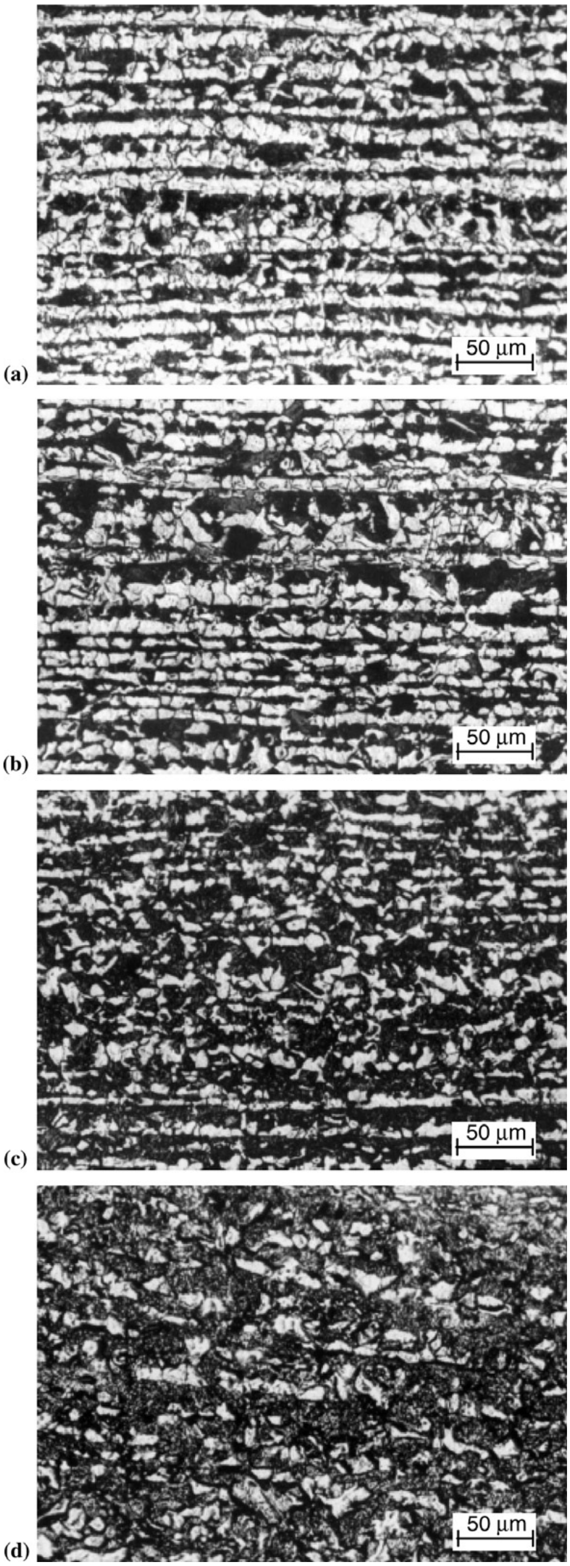


Fig. 5. Light micrographs of the microstructures of intercritically annealed S2 steel at different temperatures: (a) 745 °C, (b) 760 °C, (c) 775 °C, and (d) 790 °C.

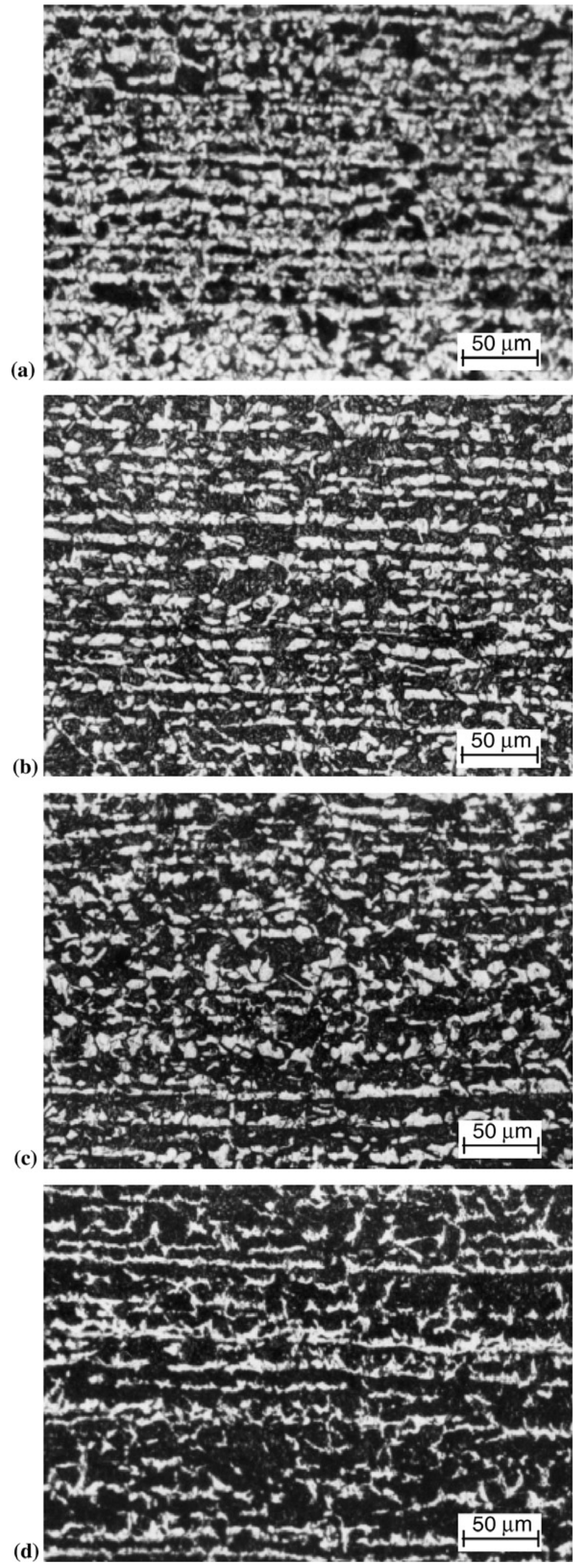


Fig. 6. Light micrographs of the microstructures of intercritically annealed S3 steel at different temperatures: (a) 745 °C, (b) 760 °C, (c) 775 °C, and (d) 790 °C.

raction of martensite also increase with the increase in carbon content of S1, S2, and S3 (Table 2). The reason why the fatigue strengths of intercritically annealed DPSs with carbon content show an increasing might be explained the volume fraction of martensite or fatigue crack growth (FCG). Sudhakar and Dwarakadasa [16] observed that

Table 2
The volume fraction of martensite

| Annealing temperature (°C) | S1 | S2 | S3 |
|---|---|---|---|
| 745 | 16 | 44 | 55 |
| 760 | 26 | 60 | 66 |
| 775 | 32 | 75 | 78 |
| 790 | 45 | 83 | 89 |

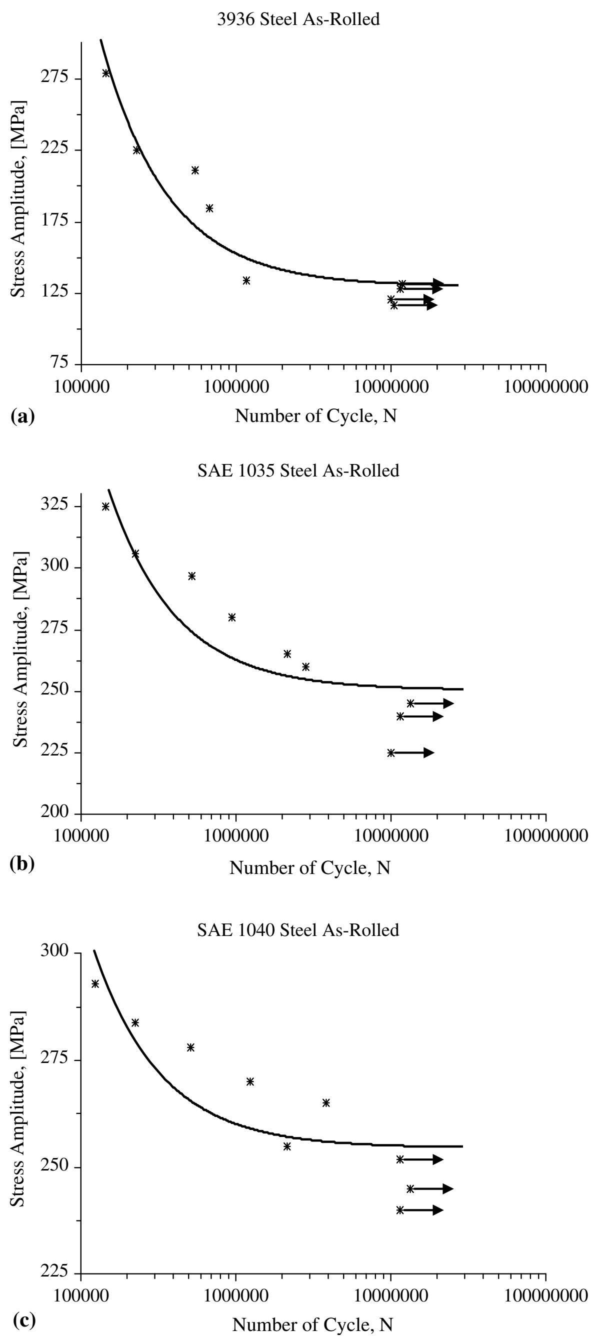


Fig. 7. *S–N* curve of as-received materials: (a) S1, (b) S2, and (c) S3. Arrows shows that the samples did not fail in excess of $10^7$ cycles.

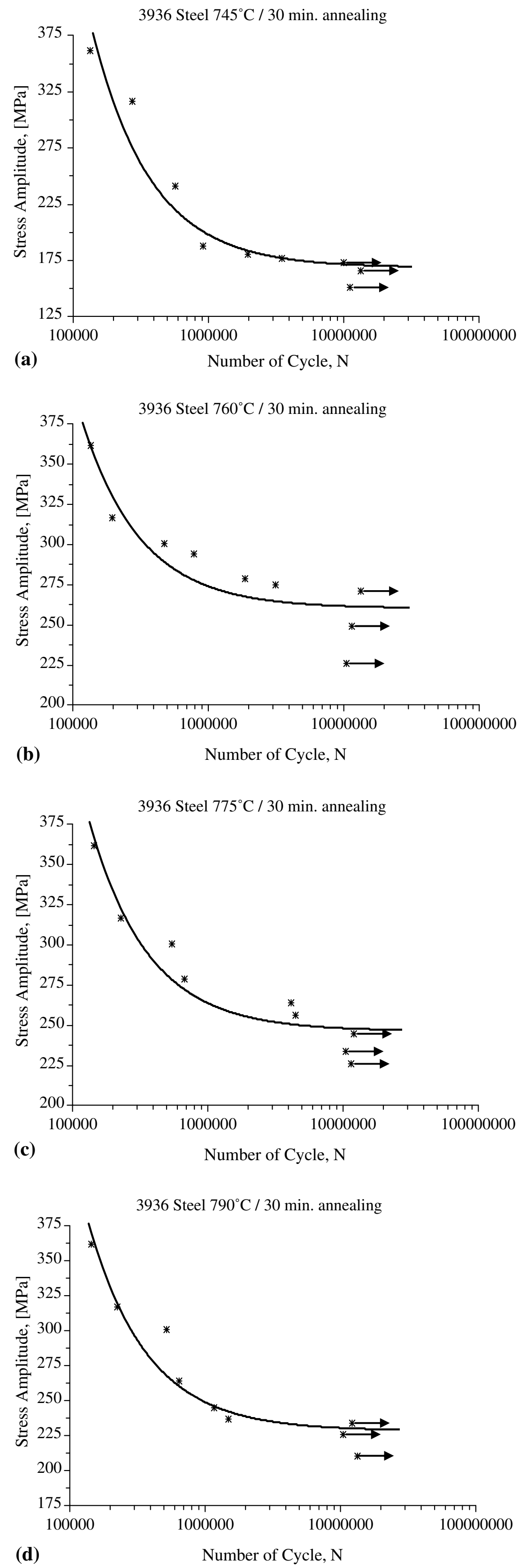


Fig. 8. *S–N* curve of intercritically annealed S1 steel: (a) 745 °C, (b) 760 °C, (c) 775 °C, and (d) 790 °C. Arrows shows that the samples did not fail in excess of $10^7$ cycles.

fatigue crack growth rate decreased with an increase in martensite content. The decrease in FCG rate with an increase in martensite content of DPS is attributed primar-

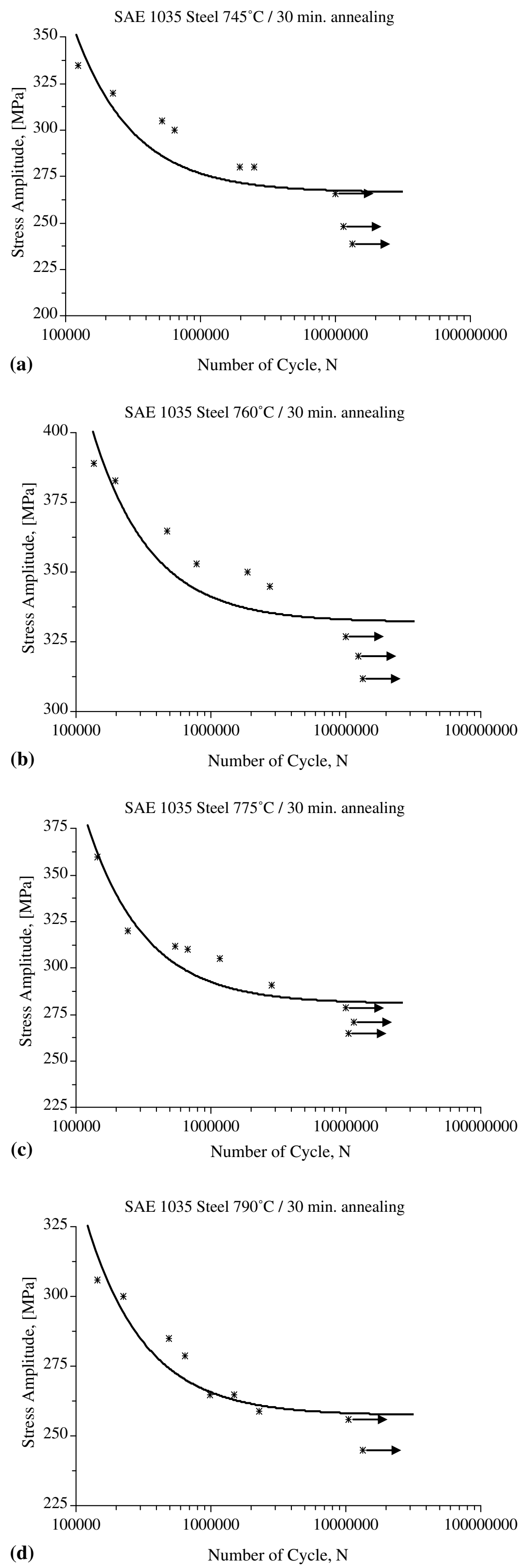


Fig. 9. *S–N* curve of intercritically annealed S2 steel: (a) 745 °C, (b) 760 °C, (c) 775 °C, and (d) 790 °C. Arrows shows that the samples did not fail in excess of $10^7$ cycles.

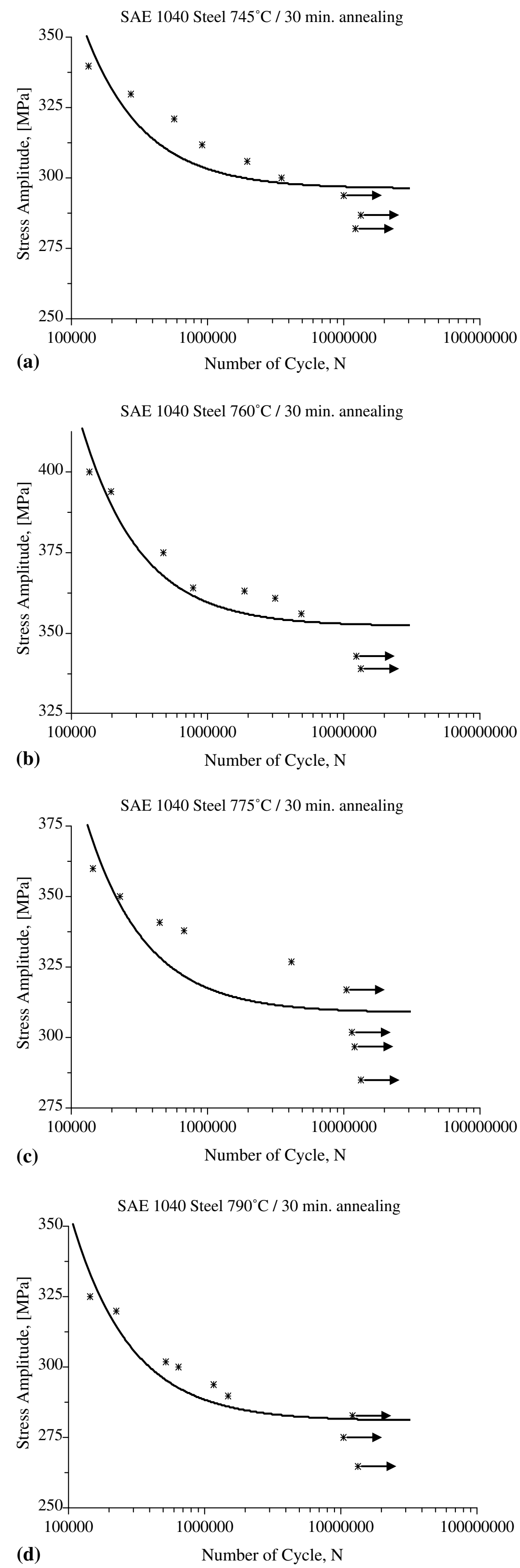


Fig. 10. *S–N* curve of intercritically annealed S3 steel: (a) 745 °C, (b) 760 °C, (c) 775 °C, and (d) 790 °C. Arrows shows that the samples did not fail in excess of $10^7$ cycles.

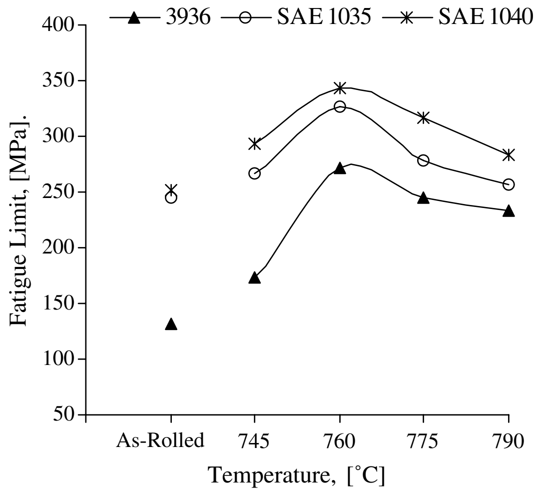


Fig. 11. The fatigue strength of as-received materials, intercritically annealed S1, S2, and S3 steels.

ily to the two mechanisms: (i) lower carbon content in martensite formed at higher intercritically annealing temperatures, and (ii) roughness induced crack closure.

As can be seen in Fig. 11, DPSs have the higher fatigue strength values when compared with as-received. The highest fatigue strengths in S1, S2, and S3 were found at 760 °C annealing temperature. However, it was observed that the fatigue strength of these steels increased from 745 to 760 °C but decreased from 760 to 790 °C. On the other word, the fatigue strength of these steels varies depending on the volume fraction of martensite. Sherman and Davies [10] found similar behavior depending on the volume fraction of martensite. They determined fatigue behavior of dual-phase steels varies with martensite content and overall fatigue performance improves as martensite content is increased, up to 30% but varied only slightly for martensite contents between 30% and 60%. Sherman and Davies [10] explained that a smaller

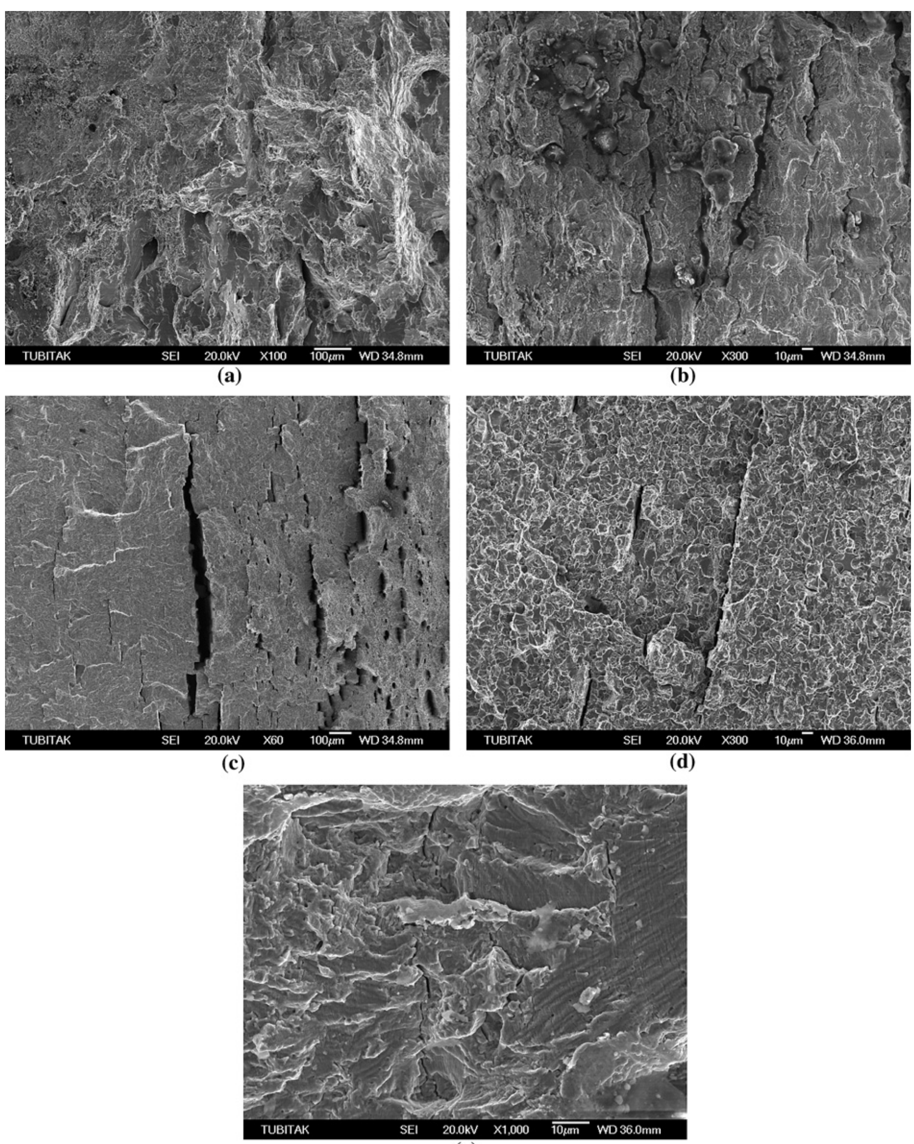


Fig. 12. SEM fractographs of intercritically annealed fatigue specimen: (a) S1 fatigue specimen at 745 °C, (b) S2 fatigue specimen at 745 °C, (c) S3 fatigue specimen at 745 °C, (d) S1 fatigue specimen at 760 °C, and (e) S1 fatigue specimen at 775 °C.

fraction of the total will be plastic strain as the percentage of martensite increases and this leads to the improvement of fatigue properties. When the volume fraction of martensite is higher, the lower ductility of such a structure and this leads to a decrease in fatigue life. The fatigue behavior of a dual-phase steel is a function of the strain distribution between the ferrite and martensite components and of crack initiation and growth (see Fig. 12).

As mentioned above, crack initiation and growth characteristics of both phases also should play a role in fatigue strength of intercritically annealed S1, S2, and S3 steels. However, these observations reflect not only the relationship between martensite content and fatigue properties but also the influence of the carbon content of the phases [9].

The high dislocation density of ferrite phase can be attributed to the improvement of the fatigue strength of intercritically annealed steels at 760 °C when compared with 740 °C. Ferrite dislocation density in as quenched dual-phase steels has been observed to increase with martensite content [19]. The higher density dislocation array is similar to that produced by cold work. Thus ferrite is stronger as the martensite content is high. However, strength increases due to cold work are largely nullified by cyclic loading [20].

### *3.3. Fractography*

SEM micrographs of fatigue specimens are shown in Figs. 12a–e. It can be seen that the intercritically annealed S1 and S2 steel specimens at 745 °C reveals generally cleavage fracture together with some ductile fracture dimple formation (Figs. 12a and b). However, as shown in Figs. 12c, fracture surface of intercritically annealed S3 steel specimen at 745 °C exhibited entirely brittle cleavage type. It can be seen from Fig. 12e that when the volume fraction of martensite is lower, the soft ferrite deforms heavily by forming uniformly spaced slip bands.

There is no much work on fatigue crack initiation and growth in dual-phase steels and reported results do not agree with each other. The factors which control the behavior of fatigue cracking in dual-phase steels are not yet understood [14]. Figs. 12d and e show the role of the volume fraction of martensite. When the volume fraction of martensite is lower, most of the fatigue cracks initiated at the martensite–ferrite interfaces and ferrite grain boundaries (Fig. 12d). An increase volume fraction of martensite promoted most of microcracks to form along slip bands adjacent to martensite–ferrite interfaces at the side (Fig. 12e).

Fracture observations support the experimental results. The fatigue strength of intercritically annealed steels at 760 °C is higher when compared with 775 and 790 °C. It is known that the difference in yield strength and ductility of the two-phases becomes less significant with increasing martensite content. Therefore, the deformation ability of both the ferrite and martensite becomes more compatible. As a result, it is not surprising to find that fatigue cracks prefer to initiate in slip bands rather than at interfaces when the volume fraction of martensite is high as discussed by Wang and Al [14].

As can be seen from Fig. 1, SEM micrographs of fatigue specimens reveal secondary cracks (indicated arrow). Formation of secondary cracks is responsible for the deceleration of crack growth. It may be seen from the fractographs that the degree of secondary cracking increases with an increase in the volume faction of martensite.

## 4. Conclusions

On the basis of the experimental study that has been carried out and presented in this paper, the following conclusions can be drawn.

1. As a result of intercritical annealing, dual-phase steels revealed equiaxed martensite phase surrounding ferrite grains. The volume fraction of martensite increased with increasing annealing temperature.
2. It was found that the fatigue strength of dual-phase steels was higher than the as-received materials.
3. The fatigue strength of intercritically annealed steels did not show a linear increase with the increase in volume fraction of martensite. Annealed steels at 760 °C revealed the highest fatigue strength.

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