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Fatigue studies on dual-phase low carbon steel

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Low cycle fatigue studies have been carried out on 2 wt% Mn, 2 wt% Si and 0.1 wt% C steels with dual-phase and tempered martensitic structures. Fatigue crack initiation and propagation were investigated using scanning electron microscopy as well as optical microscopy. In addition, taper-section and cross-section techniques were also performed for more detail studies on the correlation of crack initiation with the internal microstructures of the testing samples. Internal microstructures were also investigated on the dual-phase steel sample before and after fatigue fracture by transmission electron microscopy.

1. Introduction

In the past few years, good strength and ductility properties of dual-phase steel (DFM) have been developed by optimizing the alloy composition and formation process [1, 2]. The good ductility and formability properties of these steels has given them a high potential for practical use in the automobile industry.

Most of the previous research work reported on DFM steels has concentrated on the analysis of the correlation between the tensile and impact properties with various two-phase morphologies. Only a few fatigue studies on the dual-phase structure have been carried out [3–6], and most of them concentrated on a discussion of fine grained ferrite and uniformly dispersed patches of martensite. From a different stand point, these results showed some inconsistency and some very interesting contradictions about the correlation of crack initiation and propagation with various duplex microstructures in a different range of strains or stresses. However, a complete, detailed understanding is still far beyond our present knowledge especially on the topic of fatigue crack initiation.

The purpose of the present work is to study the fatigue surface phenomenon of fatigue cracking which is associated with crack initiation in high stress testing of the DFM structure with a chemical composition of about 0.08 wt% C, 2 wt% Si and 2 wt% Mn. The fatigue behaviour of tempered martensitic produced with the same materials are also investigated for comparison.

The high concentration of silicon in the material chosen for the present work can promote the appearance of dislocated martensite as a fine and discontinuous fibrous distribution. In addition, silicon also increases solid solution strengthening in the ferrite and improves the ferrite–martensite interface by inhibiting the formation of coarse carbides during the final quenching from the two-phase region. The high manganese content provides a high hardenability.

2. Experimental procedure

2.1. Material preparation and heat treatment

The chemical compositions of the alloys used are shown in Table I. The testing material was prepared by melting, casting, forging, hot rolling, homogenization and finally shaping into a steel plate 2.5 mm in thickness.

Two kinds of heat treatment procedures were performed and are shown in Fig. 1. Both heat

TABLE I Chemical composition of the testing material in wt%

C	Mn	Si	P	S	Cu	Fe
0.08	1.90	2.50	0.007	0.014	0.02	Balance

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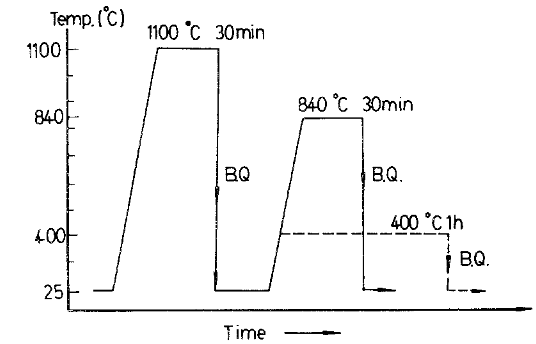

Figure 1 The heat treatment process.

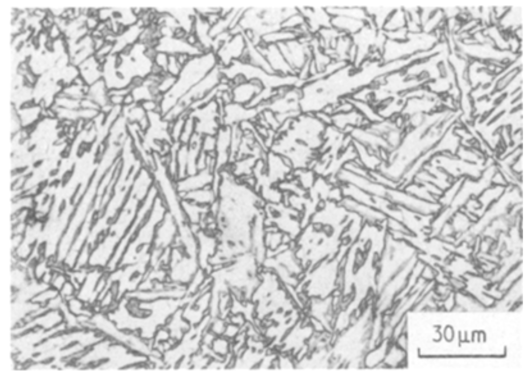

Figure 2 Optical micrograph of the DFM structure.

treatments consist of austenitizing at 1100° C for 30 min and quenching with brine for form a complete martensite phase. Then, in one case the quenched material was annealed in the two-phase region at 840° C for 30 min followed by a final quenching process to produce the DFM structure. Then in the second case the material was tempered at 400° C for 1 h to form tempered martensite. All heat treatment processes were carried out in a salt-bath furnace.

2.2. Mechanical testing

All tensile tests were performed with an Instron Tensile Machine Model 1115 at a cross-head speed of 0.05 cm min^{-1}. A Sonntage Model SF-2-U fatigue testing machine with a cyclic frequency of 1800 cycle min^{-1} with bending stress was used for investigating fatigue. All fatigue tests samples were electrolytically polished before testing to minimize the surface effect.

2.3. Metallography studies

Electroless nickel plating was performed as a protection in examining the correlation between internal microstructure and the fatigue fracture path from an etched surface normal to the fracture surface. In addition, a flat surface electropolishing process was carried out in order to study the relationship between crack initiation and the internal microstructure underneath the surface. Taper-sectioning was also applied to the investigation of crack initiation of samples with tempered martensite. Most fracture surface observations were performed with a JSM-U3 scanning electron microscope (SEM) operated at 25 kV. Internal microstructure was studied by the thin film technique using a JEOL-100B transmission electron microscope (TEM) operated at 100 kV.

TABLE II Mechanical properties at room temperature

Property	As-quenched martensite	The tempered martensite	The DFM structure
YS*(kg mm^{-2})	96.8	88	52.6
UTS(Kg mm^{-2})	105.7	98	77.4
Elong.† (%)	8.2	9.3	20.4

*0.2% proof stress.
†Total elongation in 40 mm.

3. Results

3.1. Microstructures before fatigue testing and their tensile properties

The room temperature tensile properties and the optical microstructure of DFM and tempered martensite steels before fatigue testing are shown in Table II and Figs 2 and 3. A very complete needle-like morphology is adopted for the formation of austenite from the initial martensitic structure. According to the nucleation and growth of needle-like structures which always appear along the martensitic lath boundaries, the influence

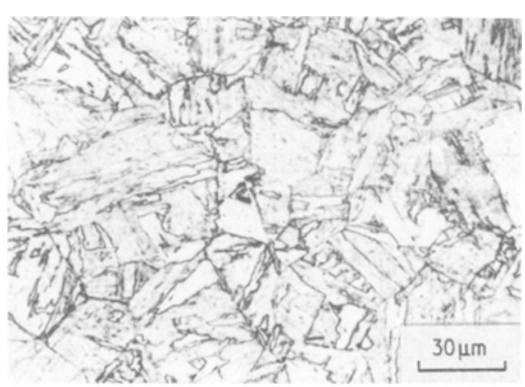

Figure 3 Optical micrograph of the tempered martensitic structure.

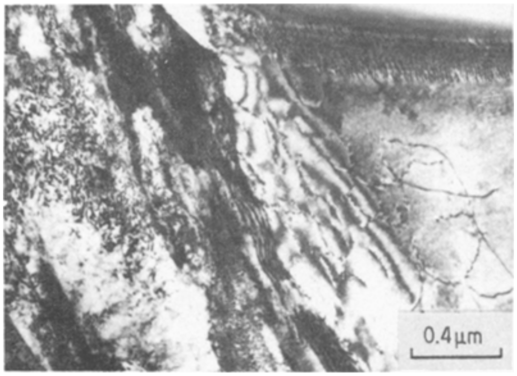

Figure 4 TEM micrograph of the DFM structure with martensitic region on the left side.

of the initial martensitic structure is still clearly reflected in the fine acicular morphology of the martensitic particles. By linear extrapolation the volume fraction of martensite in the DFM steel is about 25%. Figs 4 and 5 indicate the initial TEM microstructure of the DFM and tempered martensite samples.

3.2. Crack initiation studies

Typical surface damage or fatigue crack initiation of DFM steel with a cyclic stress $\sigma_{ap} = 70.4$ kg mm^{-2} and $N_f = 3 \times 10^3$ cycles are shown in Figs 6 and 7. Fig. 6 indicates that each individual crack on the flat free surface of the test samples occurs at about 45° to the stress axis, shown as SA on the figures, but that the mean path of a large crack that is formed by the linking together of many small cracks is about normal to the stress axis. Fig. 7 shows the correlation between crack existence and microstructure underneath the flat free surface by a surface etching process; it indicates that cracks always lie along the boundaries of second-phase particles. In some areas the

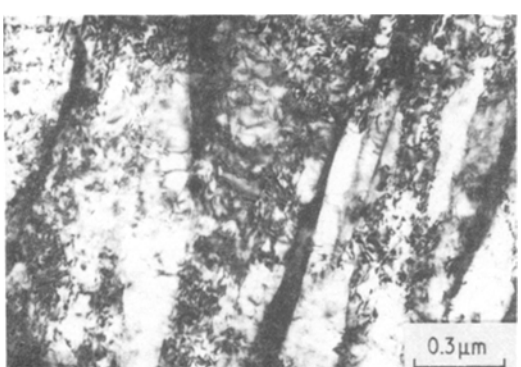

Figure 5 TEM micrograph of tempered martensite.

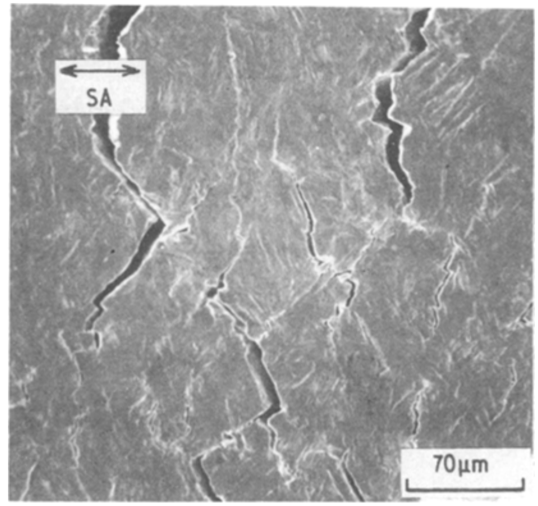

Figure 6 SEM micrograph from the free surface of DFM test sample.

cracks link together by breaking through martensitic particles.

Fatigue crack initiation on tempered martensitic samples is shown in Figs 8 and 9. The slip bands in Fig. 8 are relatively finer and less wavy than those found in Fig. 6 with a duplex structure, with cyclic stress of $\sigma_{ap} = 93$ kg mm^{-2}. These slip bands are either perpendicular or parallel to the crack. Fig. 9 shows an etched flat free surface; it indicates that small cracks are always nucleated along the lath and furthermore that crack growth also tends to follow the lath direction.

3.3. Taper-section and cross-section techniques

The taper-section technique is used to study fatigue fractured tempered martensitic samples. As shown in Fig. 10, it indicates that slip bands

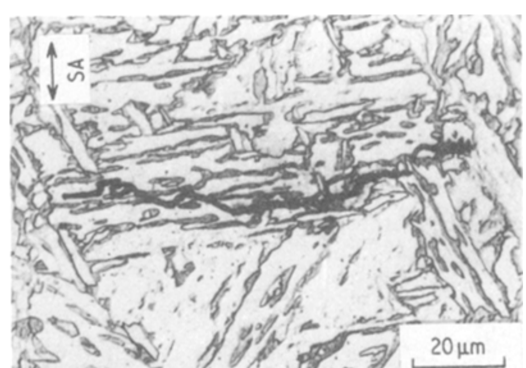

Figure 7 Optical micrograph of the free surface of the DFM test sample after etching.

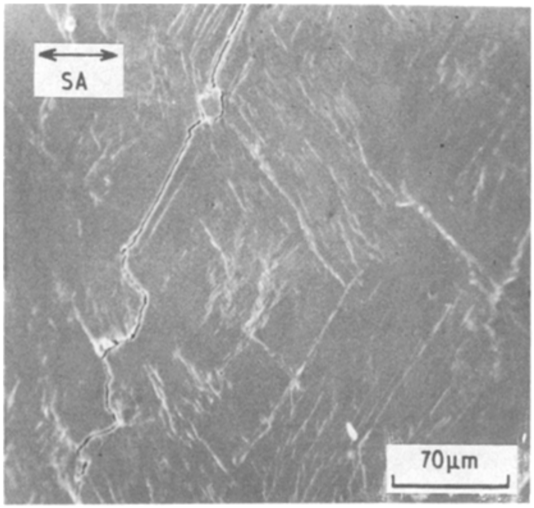

Figure 8 SEM micrograph of the free surface of tempered martensitic test samples.

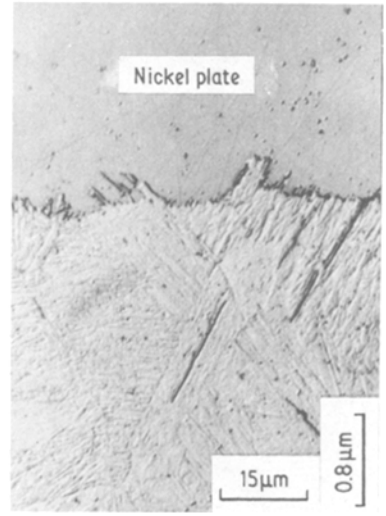

Figure 10 Extrusions examined by taper-sectioning for tempered martensitic test sample.

always exist with an extrusion form with a height of about 0.13 μm.

Cutting at 90° to the fracture surface of a DFM fatigue fractured sample by the cross-section technique plus etching the cutting surface, as shown in Fig. 11, indicates some secondary cracks which exist roughly perpendicular to the fracture surface and grow along the plane boundaries. Using the same technique for DFM fatigue fractured samples, Fig. 12 shows that the appearance of fatigue crack initiation and propagation does not correlate to the microstructure underneath the flat free surface. The early crack growth follows along the phase boundaries, but after the crack has penetrated some depth, it may break down some martensitic particles on the propagation path. For tempered martensitic samples as shown in Fig. 13, the fatigue cracks grow initially along these lath boundaries and packet boundaries, but as it grows further into the bulk of the sample, the crack paths adjust to make approximately a right angle with the principle stress axis.

3.4. Interior microstructure study of DFM steel after fatigue fracture

Fig. 14 shows a high density of tangled dislocation cells in the ferrite region that exist underneath the flat free surface. That indicates that there is a big difference in the internal microstructure of the sample before fatigue testing which is shown in Fig. 4.

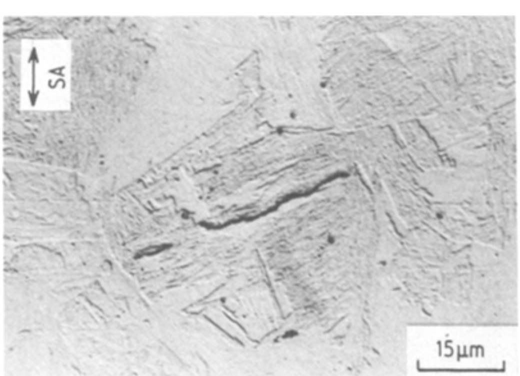

Figure 9 Optical micrograph of the free surface of tempered martensitic test sample after etching.

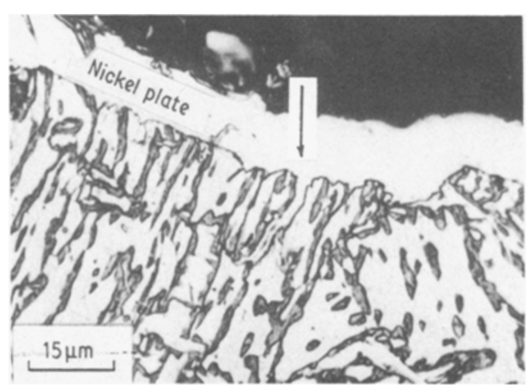

Figure 11 Cross-sectional view of fatigue fractured specimen with DFM structure. A secondary crack is indicated by the arrow.

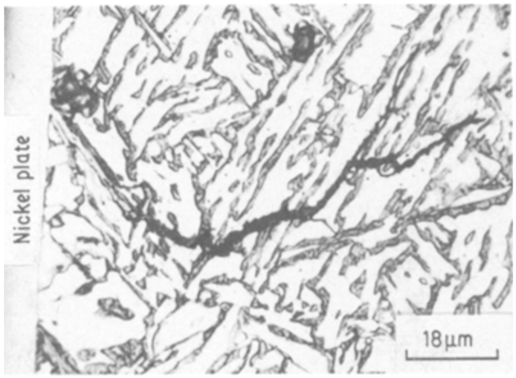

Figure 12 Crack initiation and early stage of crack propagation of test sample with DFM structure.

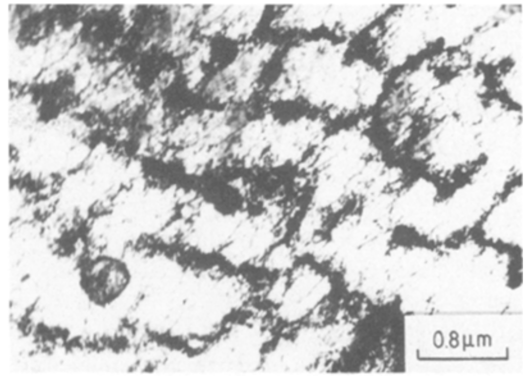

Figure 14 TEM micrograph of the ferrite region in a DFM test sample after fatigue fracture.

4. Discussion

4.1. Crack initiation with the DFM structure

It has been proposed that fatigue crack can start at the interface of a two-phase structure, especially as this interface intersects with the free surface of the test sample. Some previous work which concentrated on fatigue cracking at the inclusion–matrix interface found interfacial crack initiations that were perpendicular to the stress axis. This is due to the existence of martensitic particles in a ferrite matrix which is very similar to a structure with a hard second-phase in a soft matrix. The present study confirms that the martensite–ferrite interface is a favourable site for crack initiation during high stress fatigue testing. In view of the foregoing results, the following physical mechanism can be suggested to describe fatigue crack nucleation in DFM. After a certain number of cycles of repeated stress, the ferritic portion of the fatigue test sample can always be hardened and some dislocation cells are also produced in comparison with the low density of dislocation before fatigue testing. Generally, inhomogeneous plastic strains can always be developed in the form of slip bands after a saturated hardening stage is reached in the ferrite region. In addition, this homogeneous plastic strain will always be restricted by dispersed martensite particles and will accumulate at the martensite–ferrite interface.

During maximum cyclic tension and compression stress applied to the free surface in a fatigue test higher tensile stress is usually produced at the phase boundary as the fibrous martensitic particles lie perpendicular or nearly perpendicular to the stress axis. Naturally, that leads to crack initiation occurring at some points with the interface acting as a crack embryo. If the cycle is repeated continually these crack embryos then begin to grow and link up.

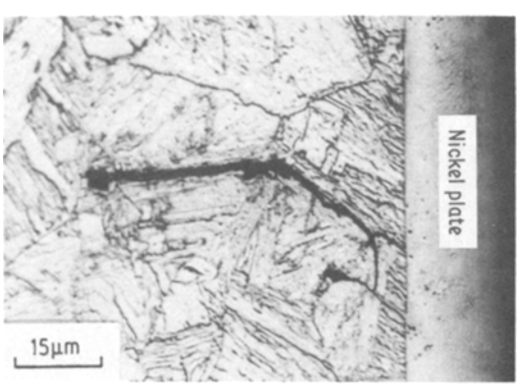

Figure 13 Crack initiation and early stage of crack propagation in test sample with tempered martensitic structure.

4.2. Crack initiation with tempered martensite

Previous workers [9] have suggested that fatigue crack initiation in tempered martensite is a possible mechanism of formation of intrusions and extrusions. In the present study slip bands were observed to play a dominant role in fatigue crack initiation. Fine slip traces generally indicated a slip band topography of extrusion and which existed along the lath boundaries underneath the surface. Usually, intrusion and extrusion formed due to the interactions between cyclic stress and dislocation movement, while further changes in the internal microstructure of the testing samples caused fatigue crack initiation [10, 11]. Theilsen *et al.* [12] studied fatigue hardening/softening of 4140 steel in the quenched and tempered conditions. Through TEM investigations they revealed that the fatigue softening of 400 and 550° C tempered samples resulted in part from the rearrangement of the dislocation substructure and the reduction of dislocation density. There is a close similarity between the results of Thielsen *et al.* [12] and the present work. It is suggested that under repeated cycling stress, tempered martensite will be fatigue softened through a rearrangement of the dislocation substructure within the lath. From SEM flat free surface investigations, slip bands are always observed to exist along the lath direction and that leads to the formation of some creases on the surface. According to the model of plastic instability, cyclic plastic strain will deepen the creases until a micro-crack in formed. In addition, there are some steps which are also observed on the flat free surface after fatigue fracture; this is most likely to be due to late boundary sliding. These surface steps always act as an effective stress raiser on a macroscale. Detailed mechanistic investigations of lath boundary sliding is still required.

4.3. Crack growth in samples with a DFM structure

In the present work it was observed at an early stage of crack growth that the cracks always propagate along the plane boundaries. Since the strain which is induced by the plastic zone at the crack tip will accumulate at the interface between the ferritic matrix and the martensitic particle, it will lead the nucleation of some microcracks ahead of the main crack. Also, in advance some small cracks link together to form a large crack. There are also some microcracks which lie in directions non-parallel to the main crack, which generally lead to the formation of secondary cracks.

4.4. Crack growth in samples with a tempered martensitic structure

From the optical observations in the present study it was seen that cracks initially propagate along the lath boundaries as well as the packet boundaries. After the crack has penetrated to a certain depth all the cracks change their directions roughly perpendicular to the flat free surface.

On the basis of the present studies, the mechanism of crack growth for tempered martensitic fatigue samples is still not yet clearly understood. However, as mentioned before, the presence of undissolved second-phase particles may lead to an acceleration of crack growth due to the nucleation of microcracks which exist ahead of the main crack. It is suggested that the possible existence of a small amount of fine carbides at the lath, the packet or even at the grain boundaries, may act as the nucleation sites for the induced microcracks. Thus, at an early stage of crack growth, the preferred paths always follow these various boundaries. More experimental work is necessary to prove this.

5. Conclusions

(1) For the DFM structure samples, fatigue crack initiation commonly occurs at the martensitic particle–ferrite matrix interface. The mechanisms of crack initiation are suggested to be the accumulation of inhomogeneous strain at the phase boundaries while the ferrite matrix is fatigue hardened to a saturated stage.

(2) Crack initiation in the tempered martensite sample always occurs along the persistent slip band by extrusion. The persistent slip bands are always observed to lie along the lath boundaries and it is suggested this is due to fatigue softening occurring within the lath.

(3) Through phase boundary nucleation and the linking up process of microcracks, early stage crack propagation path occurs which always follows the phase boundary for DFM test samples.

(4) Lath boundaries and packet boundaries are observed as the preferred path for early stage fatigue crack growth for tempered martensitic test samples. Further advanced work is required for a detail explanation of the mechanism of this crack growth.

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