THE EFFECT OF MICROSTRUCTURE AND PRESTRAIN ON FATIGUE CRACK PROPAGATION OF DUAL-PHASE STEELS

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ABSTRACT

The effects of microstructure and prestrain on the propagation behavior of small fatigue cracks in dual-phase (DP) steels were investigated by in-situ observation with fatigue testing in scanning electron microscope. The material with a continuous martensite phase around ferrite grains exhibited a higher fatigue strength and longer fatigue life than those of the material with martensite phase dispersed in ferrite matrix. Cold rolling prior to fatigue testing resulted in a decrease of fatigue life in both materials, especially an extreme decrease in the martensite-dispersed material. It was found that fatigue crack propagation was sensitive to microstructure and prestrain only in the small crack within a range of approximately 250 μm and the propagation life of this region governed the total fatigue life. Furthermore the effects of microstructure and prestrain on macroscopic large fatigue crack propagation were studied. The microstructure and cold reduction exerted a great influence on crack path and that caused a large difference in crack closure. A quantitative correlation existed between crack closure level and surface roughness of fatigue fracture.

KEYWORDS

small crack, large crack, crack propagation, crack closure, microstructure, prestrain, dual phase steel

INTRODUCTION

It is known that the ferrite-martensite DP steels offer a better combination of strength and ductility than do the other steels with equivalent static strength. The DP steels are in general use in the automobile industry where higher strengthening for fatigue is required. Several investigators have shown that the fatigue strength of DP steels which usually consist of a martensite phase dispersed in a ferrite matrix exhibits an improvement by controlling the heat treatment process. Continuity of martensite phase seems to have an important role on fatigue strength with particular

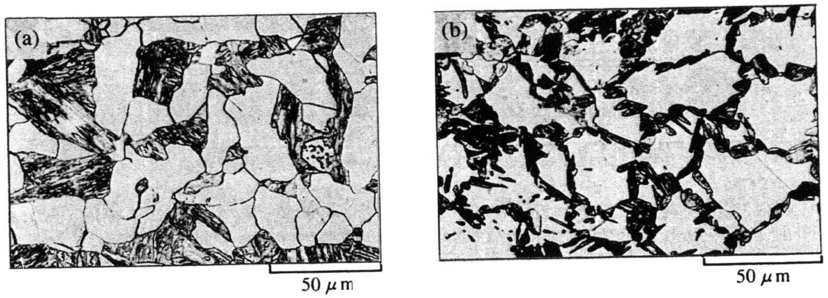


Fig. 1. Microstructure of investigated steels without prestrain.
(a) Martensite-dispersed structure (M-D steel),
(b) Martensite-continuous structure (M-C steel).

reference to small and large fatigue crack growth. Additionally it is very important from a practical point of view to know how the service properties of the material are influenced by prestrain or cold working. The influence of prestrain on large fatigue crack growth in low carbon steels has been studied earlier. The general tendency is that cold deformation results in a decrease in the fatigue threshold stress intensity range. The effects of cold rolling on the fatigue strength and the crack propagation for the martensite-dispersed and the martensite-continuous DP steels were investigated.

EXPERIMENTAL PROCEDURES

The material tested was a commercial low carbon steel with a main composition of Fe/0.2C/0.5Si/1.5Mn, received as 2 mm thick hot-rolled sheet. Two microstructures, one consisting of martensite dispersed in ferrite matrix and the other continuous martensite phase, were examined, which are shown in Fig.1 . The martensite-continuous material was obtained by reheating normalized steel into α - γ region, partially transforming the microstructure to austenite and then quenching. Prestrain was given by a cold rolling reduction of approximately 20%. The material properties are in Table 1. The in-situ observation of small crack propagation was carried out for 1 mmR notched specimens with an Instron closed-loop servo-hydraulic testing machine in scanning electron microscope. The specimen configuration for the experiment is shown in Fig.2 . The fatigue test for the large fatigue crack propagation was conducted at room temperature on a Shimadzu closed loop servo-hydraulic machine using half-inch size compact tensile specimens with a thickness of 1.6 mm. Crack closure measurements were made by means of a strain gauge placed on the back face of the specimen. Both fatigue experiments were carried out at a load ratio of 0.1 with a frequency of 20 Hz.

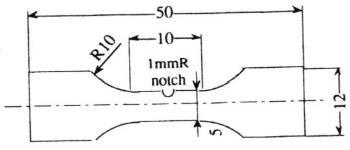


Fig. 2. Specimen for in-situ observation of small fatigue crack growth (in mm).

Table 1. Mechanical properties and martensite fraction of materials tested.

specimen	Cold Reduction (%)	0.2%P.S. (MPa)	T.S. (MPa)	El. (%)	Vol. fraction of Martensite (%)	Hv (1kg)	Hv (10g) in Ferrite	Hv (10g) in Martensite
Martensite-Dispersed structure (M-D)	—	395	690	18.8	36	239	147	427
	20.0	880	920	3.0	36	339	277	699
Martensite-Continuous structure (M-C)	—	403	688	18.9	35	228	144	400
	18.5	745	755	4.1	35	307	241	565

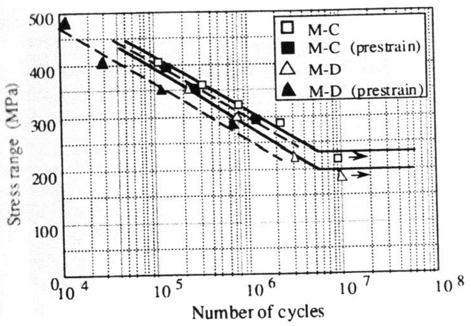


Fig. 3. S-N curve for all materials.

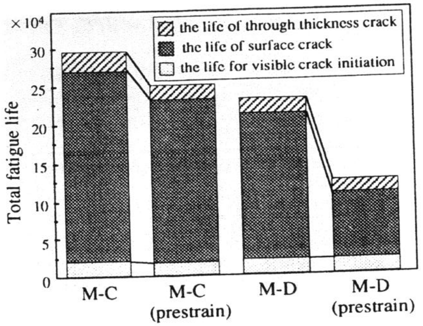


Fig. 4. Propagation life of each stage in the total fatigue life.

IN-SITU OBSERVATION OF SMALL CRACK PROPAGATION

Propagation life of small crack

Figure 3 shows S-N curves for all the materials. The fatigue strength of the martensite-continuous (M-C) material is superior to that of the martensite-dispersed (M-D) material, which is consistent with the earlier results (Kawagoishi *et al.*, 1991). Cold reduction prior to fatigue testing causes the larger difference between the two materials for the fatigue life.

Figure 4 indicates the life of each stage in the total fatigue life in the case of a maximum applied stress of 350 MPa. The total fatigue life is divided into three parts, namely, the life for visible crack initiation, the propagation life of surface crack and the propagation life of through thickness crack. The fatigue crack initiates at the notch root at mid-thickness with a size of a

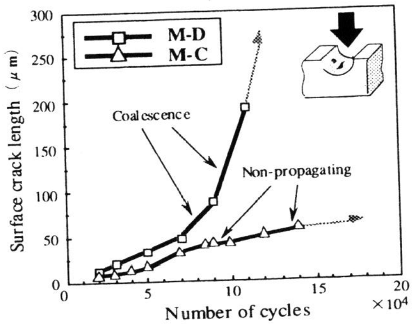


Fig. 5. Increase of small crack length with number of cycles for materials without prestrain.

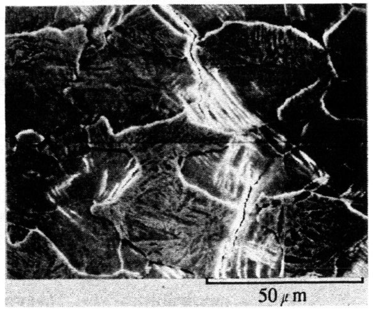


Fig. 6. Coalescence of small cracks for M-D steel.

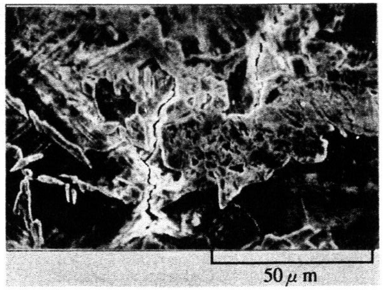


Fig. 7. Non-propagation of small cracks for M-C steel.

ferrite grain, and propagates as a surface crack with coalescence of small individual cracks in the direction of plate thickness, then finally propagates as a through thickness crack in the direction of specimen width. The propagation life of surface crack accounts for a very large part of total fatigue life and is subject to the effects of microstructure and prestrain. On the other hand, the life for crack initiation and the propagation life of through thickness crack show little difference in all the materials as shown in Fig.4 .

Microstructure effect on small crack

Figure 5 shows the growth of the surface crack with the number of cycles on the notch root surface. In the case of the martensite-dispersed material, some cracks initiate in ferrite grain and coalescence of these cracks happens frequently as seen in Fig.6 . The coalescence of cracks accelerates the small crack propagation for the martensite-dispersed material. On the other hand, the small crack of the martensite-continuous material is prevented from extending at ferrite-martensite boundary as seen in Fig.7 and this type of material shows the longer propagation life in this stage.

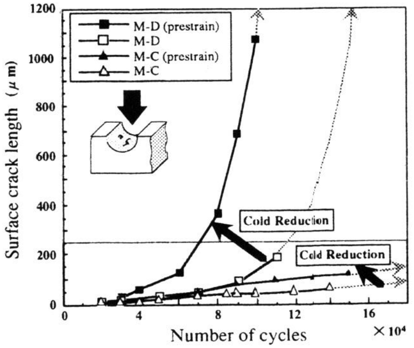


Fig. 8. Propagation behavior of small crack for the prestrained materials.

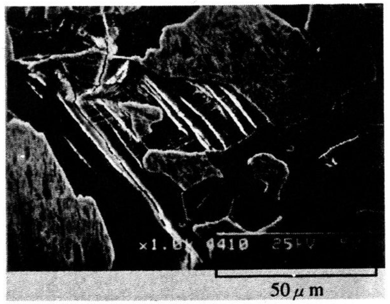
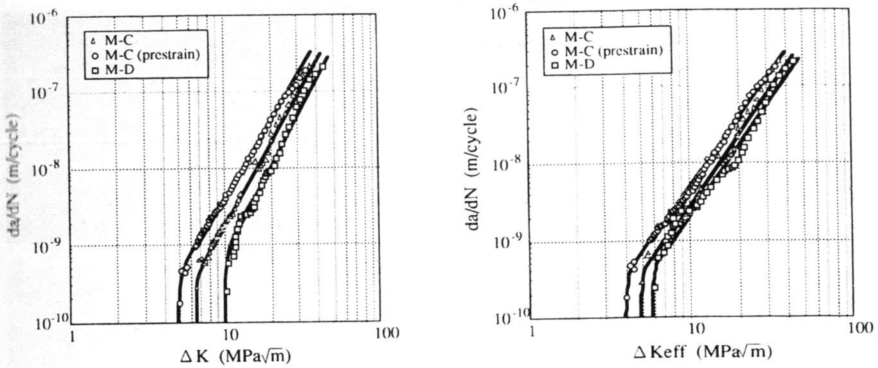


Fig. 9. Propagation behavior in the prestrained ferrite of M-D steel.



(a) da/dN vs. ΔK

(b) da/dN vs. ΔKeff

Fig. 10. Relation between crack propagation rate and stress intensity ranges.

Prestrain effect on small crack

In Fig.8, the growth of a small crack in the prestrained and non-prestrained materials is plotted with the number of cycles. While the crack length of the prestrained materials develops rapidly for the martensite-dispersed material, only a slight increase due to the prestrain is found in the crack growth of the martensite-continuous material. In the prestrained ferrite, a small crack has a tendency to propagate straight along a single slip band as seen in Fig.9 . Consequently the propagation rate of the martensite-dispersed material increases in the prestrained ferrite grains. The crack propagation rate in the prestrained ferrite of the martensite-continuous material also increases, but the martensite phase around ferrite grain prevents the crack extension. The crack growth on the surface beyond the length of 250 μm is similar among all the materials and is followed by the growth of the through thickness crack, and shows little influence of the microstructure. Microstructure and prestrain seem to have a significant effect on the part of small crack propagation within a range of approximately 250 μm and the propagation life of that region governs the total fatigue life.

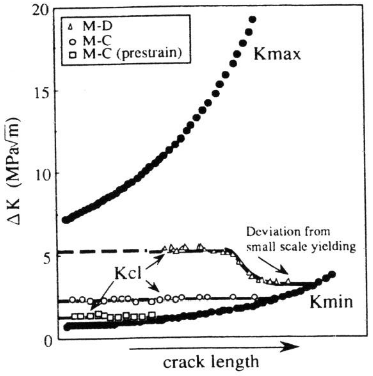


Fig. 11. Variance of Kcl with crack length in increasing ΔK testing.

LARGE CRACK PROPAGATION BEHAVIOR

Crack propagation rate

It is well known that in the threshold stage, the fatigue crack propagation behavior of DP steels is sensitive to the microstructure of material and prestrain (Suzuki *et al.*, 1979, Minakawa *et al.*, 1982, Ramage *et al.*, 1987) . This sensitivity arises as a result of microstructure induced crack closure which effectively shields the crack tip from the far field stress intensity range. Figures 10 (a) , (b) show the crack growth rate plotted against Δ Kth, Δ Keffth for three materials of the martensite-continuous material, the martensite-dispersed material and the prestrained martensite-dispersed material. While there is a remarkable difference among the three materials in terms of Δ Kth, a little difference exists near threshold region for Δ Keffth. The martensite-continuous material shows the lowest threshold and the highest crack propagation rate.

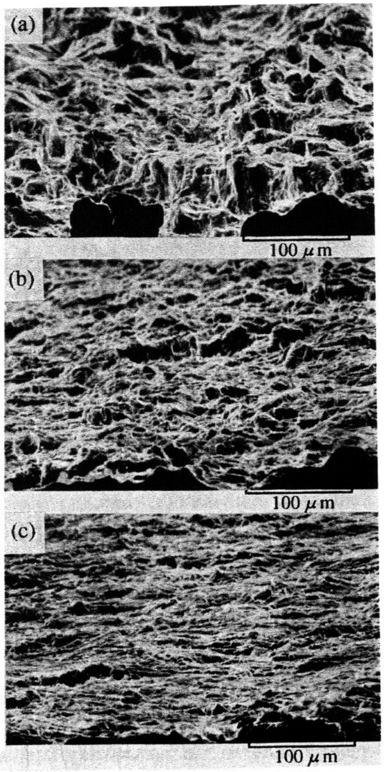
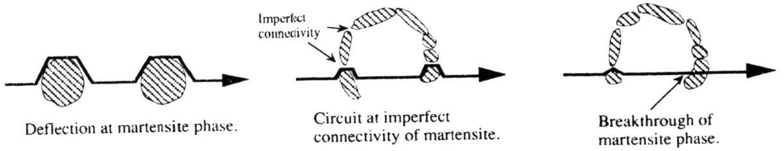


Fig. 12. Scanning electron micrographs of fatigue fracture surfaces from the parallel direction to the surface for (a) M-D steel, (b) M-C steel and (c) M-C steel with prestrain.

Microstructure and prestrain effect on crack closure

Figure 11 indicates the variance of the crack closure K (Kcl) level against crack length during the increasing Δ K test. Kcl level has a tendency to be independent of crack length for all the materials. Microstructure and prestrain have a great influence on Kcl level. Scanning electron micrographs of fatigue fracture surface at near-threshold level are shown in Fig.12 . The fatigue fracture surface is roughest in appearance for the martensite-dispersed material and this roughness corresponds to crack path deflection at the dispersed martensite phase. In the case of the martensite-continuous material, the crack passes selectively through the imperfect connecting part of the apparent continuous martensite phase and therefore an extreme deflection can not be seen. The crack of the prestrained martensite-continuous material breaks through the martensite phase because of a decrease in the resistance to crack growth due to cold reduction. In the prestrained material, the crack path is almost straight, but there is little brittle appearance in the fatigue fracture surface. The surface roughness suggests crack path profile for each material as shown in Fig.13 and therefore causes a large difference in Kcl level.



Deflection at martensite phase. Circuit at imperfect connectivity of martensite. Breakthrough of martensite phase.

(a) M-D steel (b) M-C steel (c) M-C steel with prestrain

Fig. 13. Schematic crack path predicted from fractography.

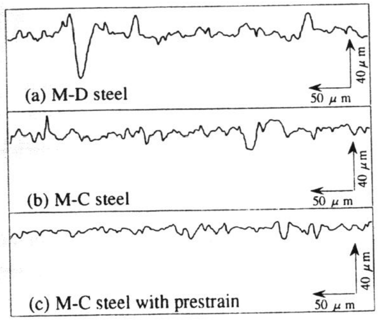


Fig. 14. Typical roughness profile of fatigue fracture surface.

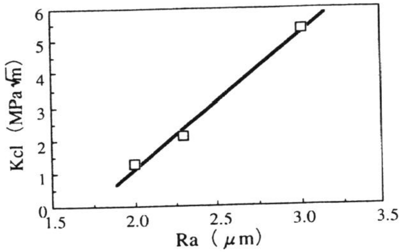


Fig. 15. Relation between Kcl and surface roughness of fatigue fracture.

Relation between crack surface roughness and Kcl

Figure 14 shows the typical profile line from the vertical section in the perpendicular direction to the fracture surface at near-threshold level. The feature of each profile line agrees with the scanning electron micrograph as shown in Fig.12 . The surface roughness of the fatigue fracture was quantified with an arithmetical mean deviation of profile from the center line (Ra) . Figure 15 reveals the quantitative relation between crack closure level and Ra , which supports the earlier report (Wasen *et al.*, 1989) . This result suggests that Kcl in these materials including the prestrained material can be explained mainly in terms of roughness-induced crack closure. It was found that not only microstructure, but also prestrain had a large influence on crack closure level through crack path deflection.

As shown in Fig.10, in spite of removing the crack closure effect, Δ Keffth for the martensite-dispersed material and the martensite-continuous material were larger than those of the steels with the equivalent static strength (Ogura *et al.*, 1988) . This might be caused by the other effects of crack deflection, because crack deflection gives an influence on apparent measured crack length and apparent stress intensity factor as well as crack closure level (Dutta *et al.*, 1984) . Some models have been proposed to explain the effect of prestrain on the effective crack growth threshold value (Lin *et al.*, 1982, Tanaka *et al.*, 1984) . In this work it was not clear enough whether prestrain decreased the effective threshold value. The second phase of hard martensite has an extreme effect on the deflection of large crack path, but as shown in Fig.4, that makes little contribution to total fatigue life.

CONCLUSIONS

1. Prestrain as well as microstructure has an extreme effect on the propagation behavior of a small fatigue crack within a range of approximately 250 μ m. The martensite-continuous material shows little decrease in fatigue life even after cold reduction because of the resistance of martensite phase to small crack growth.
2. The propagation rate of a macroscopic large crack is also affected by microstructure and prestrain because of crack closure level. The dispersed martensite phase with large size in the martensite-dispersed material causes large crack closure due to crack deflection, however that contributes little to any increase in total fatigue life.

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