Influence of Microstructure on Crack Paths in a Ferritic-Martensitic Steel

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ABSTRACT. *The effect of microstructural morphology of ferritic martensitic dual phase steel on small crack initiation and propagation under cyclic loading was investigated. Damage accumulation during the experiment was directly observed with a long-distance microscope. Slip bands formed in ferrite grains after several thousands cycles and cracks initiated along some of them due to dislocation pile up. Most of these cracks were oriented at around 45° with respect to the loading direction. Subsurface observation by means of a focused ion beam (FIB) and additional crystallographic analysis with electron backscatter diffraction (EBSD) measurement showed that these cracks initiated as a result of activity of slip system having high Schmid Factor. A few cracks initiated at phase boundaries of ferrite/martensite, which lay in the direction perpendicular to the loading direction, but they propagated in the ferrite grains under the surface. The FIB tomography technique and the EBSD crystallographic technique showed how crack growth in depth direction is affected by the microstructure.*

INTRODUCTION

The crack initiation and the following propagation behavior are strongly affected by microstructure of materials. In ductile materials, cracks initiate along slip bands in a grain, or at grain boundaries on the surface. Crack growth just after the initiation is often blocked at the grain boundaries so that propagation rates of the short cracks are very irregular and intermittent. Because of this complex behavior, linear elastic fracture mechanics is only of limited usefulness for small cracks. Experimental studies on small cracks are usually based on surface observation. Small cracks, however, propagate in depth direction as well as on the surface, so the subsurface observation is also necessary. Focused ion beam (FIB) cross sectioning technique [1, 2] is available to observe a localized area below the surface and allows a 3D analysis of a crack contour.

A ferritic martensitic dual phase steel is used in this study in order to investigate the effect of multiple phase existence on small crack initiation and propagation. Each phase has different mechanical properties i.e., the martensite has high strength but low ductility, whereas the ferrite phase has good ductility but low strength. Some researchers carried out fatigue tests on the martensitic ferritic dual phase steels and studied the effect of microstructure morphology on the small crack behavior [3-6]. From the surface observation, it was shown that cracks initiated in ferrite grains along slip bands and they propagated in the ferrite grains preferably. The martensite grains worked as a barrier and very tortuous crack paths formed because of this behavior.

In this study, we focused on the crack growth behavior in the early stage of fatigue and investigated effects of the microstructure on small crack initiation and propagation in a ferritic martensitic steel. The three dimensional investigation of crack growth behavior was performed by means of the FIB tomography technique. An electron backscatter diffraction (EBSD) system was also used in order to define the crystal orientation of the grains.

EXPERIMENTAL PROCEDURES

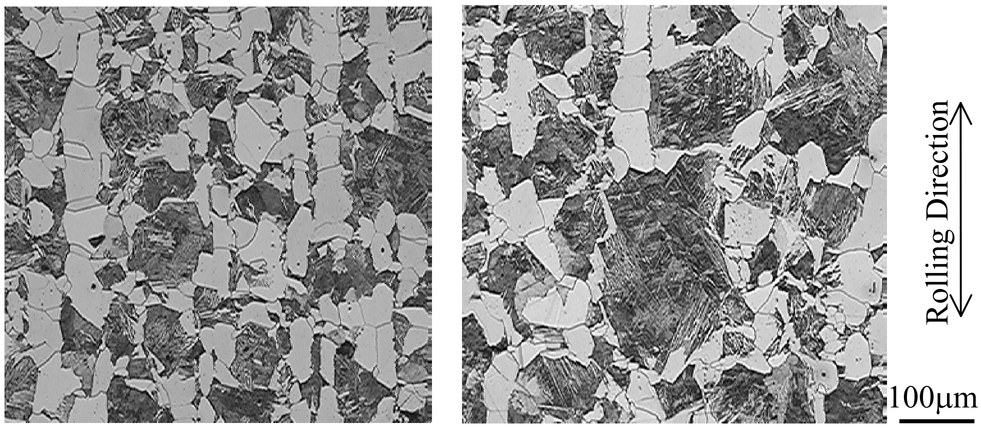
The material was a mild carbon steel (JIS S15C) with the chemical composition of 0.15C, 0.15Si, 0.41Mn, 0.014P, 0.008S (wt. %). A ferrite/martensite dual phase structure was obtained after heat treatment. The microstructure of this material was dispersed martensites and ferrites as presented in Fig. 1 (a). The average grain sizes of martensites and ferrites were 49μm and 32μm respectively, but some martensites were bigger than 100μm, see Fig. 1 (b). Ferrite grains distributed in bands elongated in the rolling direction. The specimen axis was taken along the rolling direction so that most ferrite grains had boundaries with martensites in the direction perpendicular to macroscopic crack growth under axial loading. The mechanical properties, the Vickers microhardness of each phase and the volume fraction of ferrites are shown in Table 1.

Table 1. Mechanical properties of used material

Tensile Stress (MPa)	0.2% Yield Stress (MPa)	Elongation (%)	Average Grain Size (μm)		Vickers Hardness Hv (25g)		Volume Fraction of Ferrite (%)
673	397	13	F	32	F	171	40
			M	49	M	299	

Fatigue tests were carried out with round bar specimens with two axisymmetrical shallow notches. The notch surfaces were finished with 1 μm diamond paste polishing and etched lightly with 2 % nital before each test. The fatigue tests were conducted under fully reversal axial loading (R=-1) with a constant stress amplitude of 380 MPa at the notch root. The estimated fatigue life at this stress level was 190000 cycles. The test was interrupted at every 5000 cycles and the surface at the notch root was observed directly with a long-distance optical microscope.

Subsurface observation can be very useful to understand the small crack behavior because small cracks propagate in the bulk and on the surface at the same time. In this study a focused ion beam (FIB) device (SMI9200, Seiko Instruments Inc.) was employed to create a fine section area along a crack path. Additionally a microscope function called scanning ion microscope (SIM) using ion-induced secondary electrons was used to make an observation at the same location directly after machining. The fatigue test was stopped at 95000 cycles (half of the estimated fatigue life) in order to analyze the crack propagation behavior in the subsurface direction. A small piece of the specimen which contained the cracks of interest was cut out from the specimen and was put in the chamber of the FIB. A small rectangular hole was dug in a target area to make a plane normal to the specimen surface. The created plane was observed with the SIM by tilting the sample by θ= 30 or 45°, as schematically illustrated in Fig. 2.



(a) General distribution of phases (b) Large martensite

Figure 1. Microstructure of ferritic martensitic dual phase steel.

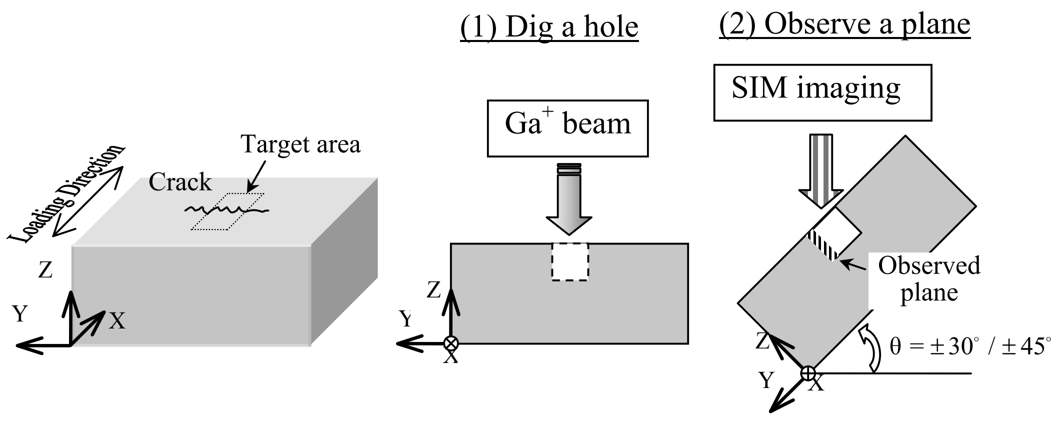
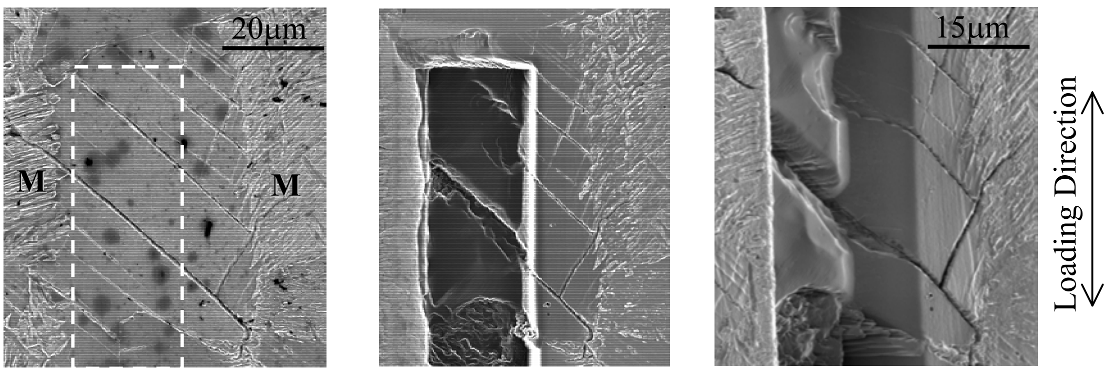


Figure 2. Schematic illustration of FIB milling and SIM observation procedure.

RESULTS AND DISCUSSION

Crack Initiation Behavior in Ferrite Grains

Many cracks were observed on the surface under this loading condition. Most of them initiated along slip bands in ferrite grains. Fig. 3 shows a typical picture of intergranular cracks taken by SIM□where "M" means a martensite phase. The slip bands were inclined at about 47° to the loading direction. This implies that they grew in a shear mode. Their tips were blocked both at the phase boundaries with the martensites and the grain boundaries with the adjacent ferrites. A crack was initiated along one of the slip bands and propagated into the adjacent martensite. In order to see the crack path under the surface, the hole was dug at the location drawn in Fig. 3 (a) with a rectangle whose edge was set to intersect the crack and some slip bands. The top view of the surface after processing was shown in Fig. 3 (b). The depth of the hole was 20 μm, and it took 9 hours for the FIB processing. The right side plane of the hole was observed at the tilt angle of 45° as shown in Fig. 3 (c), where the crack under the surface was observed to be inclined.



(a) Top view before FIB processing (The square with dashed line is a target area to be dug)

(b) Top view after FIB processing

(c) Side view at tilt angle of 45°

Figure 3. SIM observation of transgranular crack along slip bands.

The crystallographic orientation was measured with the EBSD technique and the activated slip system among all 48 possible slip systems of a BCC crystal was examined. The grain was oriented as illustrated in Fig. 4 (a). The specimen surface and the plane created by FIB are the XY- and XZ-planes according to this coordinate system, respectively. Intersection lines of the crack plane were observed both on the XY- and XZ-planes, and on the XY-plane an angle of the intersection line with the respect to the loading axis and on XZ-plane an angle to the normal direction (Z-axis) were measured, which were denoted α and β respectively as presented in Figs 4 (b) and (c). Note that Fig. 4 (c) was originally taken at the tilt angle of 45° and is here expanded in Z direction to measure the angle β. When the angles of α and β of all possible slip planes were calculated, one slip system of $(\bar{2}\,3\,1)[1\,1\,\bar{1}]$ showed very good coincidence with the observed slip bands, as schematically illustrated in Figs 4 (d) and (e). Schmid Factors of all the slip systems in this grain were also calculated and this slip system had the highest value of 0.499. The Schmid Factor indicates the activity of slips in a ductile material. Thus it can be said that this slip system was activated in this grain and the crack initiated as a result of the slip activation. This result shows that the subsurface observation with the help of crystallographic measurement provides a means to identify the active slip system in a grain.

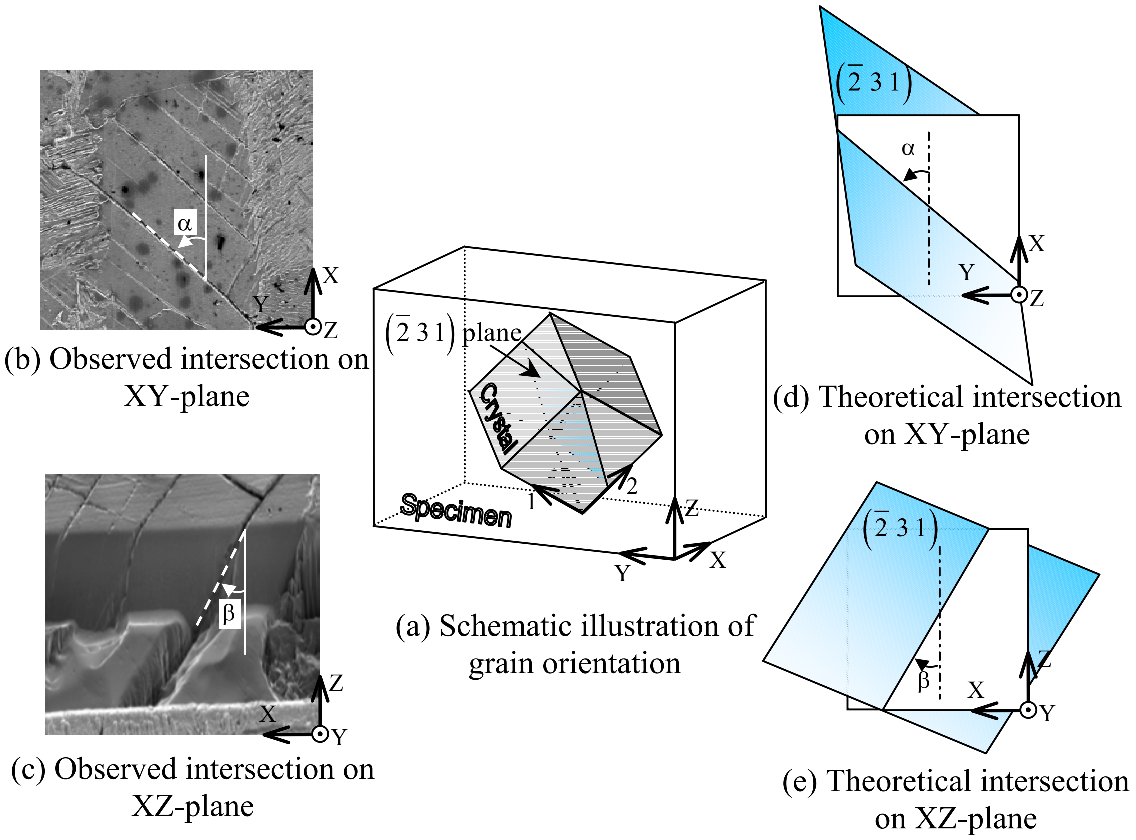
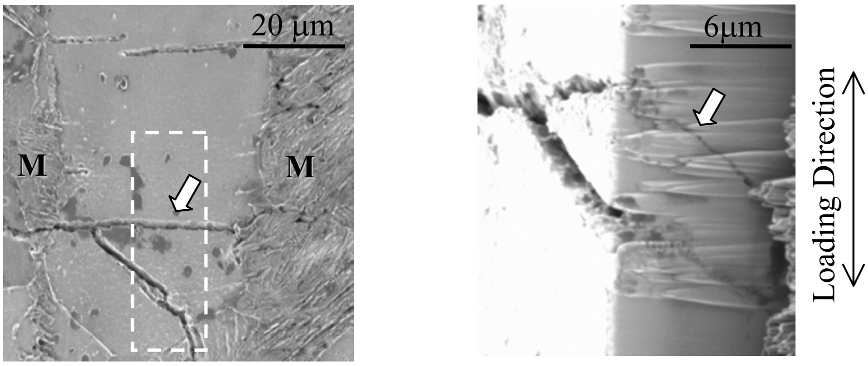


Figure 4. Schematic illustration of grain orientation, and theoretical and observed slip plane appearance on section area.

Another type of transgranular cracks observed in ferrite grains is presented in Fig. 5. The crack oriented nearly perpendicular to the loading direction on the surface was first initiated in this grain. Only a few lines parallel to this were observed in contrast to the grain mentioned above. From the surface observation it could not be decided whether this type of crack was formed by brittle fracture of the grain or along a slip band. The section area across the crack created by FIB showed that the crack was inclined under the surface as presented in Fig. 5 (b). The crystal orientation was measured and all slip systems in the grain were examined, and it was found that the crack generated by slip deformation on $(1\,1\,0)[\bar{1}\,1\,1]$. This slip system had the Schmid Factor of 0.458, which was relatively high among all possible slip systems. Even if a crack appeared perpendicular to the loading direction on the surface, slip occurred with shear stress and formed a crack in the ferrite grain.



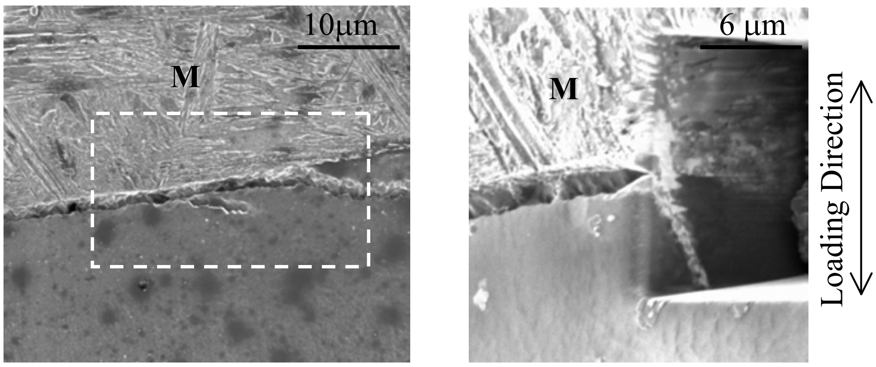
(a) Top view before FIB processing (b) Side view at tilt angle of 45°

Figure 5. SIM observation of transgranuler crack perpendicular to the loading direction.

Crack Behavior around Phase Boundaries and Grain Boundaries

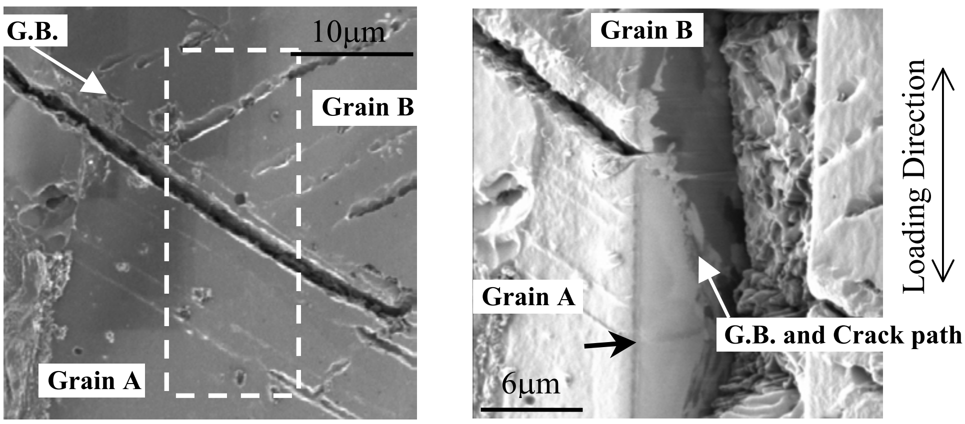
It is observed that boundaries worked as a barriers against crack propagation from the surface observation, for example see Fig. 3 (a), where the slip bands and the cracks were arrested either at the martensite/ferrite or at ferrite/ferrite boundaries. A few martensite/ferrite interphase cracks were also observed as shown in Fig. 6. This type of crack initiation occurred at boundaries which had a large angle with respect to the loading direction. With the SIM observation, the two phases can be distinguished with the difference in contrast even on the smooth surface created by the FIB, see Fig. 6 (b). The crack path did not continue along the boundary below the surface but in the ferrite grain. Based on the assumption that crack initiation happened by slip deformation, the orientation of the ferrite grain was measured, but no corresponding slip system was found. This means that this crack wasn't formed by a single slip operating as in the cases described above. As can be seen in Fig. 6 (b), the interface was inclined at a large angle both to the surface and to the loading axis. Apparently, the crack was initiated along the boundary, but extended into the ferrite grain.

Figure 7 (a) shows a crack in a ferrite grain near a grain boundary. It initiated along slip bands, like the one mentioned in the previous section. A trench hole was dug by FIB and its left side face was observed, as shown in Fig. 7 (b). The grain boundary deviated from the normal to the surface and was inclined towards the grain where the crack was initiated. With the crystal orientation measurement and the trace of slip deformation appeared slightly on the right face of the hole as indicated by arrow in Fig. 7 (b), the active slip system was identified as $(1\,\bar{3}\,2)[1\,1\,1]$. This slip plane was nearly normal to the specimen surface but the crack path in depth direction followed the grain boundary. Since the misorientation angle between these grains was about 45°, the crack propagation behavior can be explained as follows: First slip deformation occurred in the grain and a crack was initiated along the slip band. During propagation in depth direction, the crack tip encountered a high angle grain boundary which acted as a barrier for crack propagation. Apparently, the energy needed for the crack to grow through the high angle grain boundary was higher than the energy needed to separate the grain boundary, and intergranular extension phase followed the transgranuler initiation phase. Thus grain boundaries can be both a crack origin and a crack path depending on a crystal orientation and grain distribution.



(a) Top view before FIB processing (b) Side view at tilt angle of 30°

Figure 6. SIM observation of martensite/ferrite interphase crack.



(a) Top view before FIB processing (b) Side view at tilt angle of 30° (black arrow shows slip trace)

Figure 7. SIM observation of crack which grew at grain boundary in the subsurface.

CONCLUSIONS

Fatigue tests were carried on a ferritic martensitic dual phase steel and the effect of microstructure such as grain orientation, phase or grain boundaries on crack initiation and crack extension behavior in the early stage of fatigue life was investigated. The subsurface crack paths were observed by creating a small cross section along the crack path with the FIB tomography technique. A 3-dimensional analysis of the crack path can be performed by combining the local subsurface observation with the surface observation. With crystallographic characterization by the EBSD measurements in addition to the 3D observation, it can be considered that transgranular cracks in ferrites were initiated as a result of single slip system operation and this was independent of crack direction which appeared on the surface. The activated slip system resulting in a crack had high values of the Schmid Factor. A martensite/ferrite phase boundary can also act as a crack origin but the crack then propagates preferably in a ferrite grain when it lies at a large angle to the loading direction. A high angle grain boundary blocks crack propagation into a neighboring grain and becomes a crack path. Thus the 3 dimensional analysis by means of the combination of FIB tomography and EBSD crystallographic characterization gives additional information to the surface observation. This method is thought to be very effective to elucidate small crack behavior which is strongly affected by microstructure.

REFERENCES

1. Inkson, B.J., Mulvihill, M. and Möbus, G. (2001) *Scripta Mater.* **45**, 753-758.
2. Wu, H.Z., Roberts, S.G., Möbus, G. and Inkson, B.J. (2003) *Acta Mater.* **51**, 149-163.
3. Shang, J.K., Tzou, J.-L.and Richie, R.O. (1987) *Metal. Trans. A* **18A**, 1613-1627.
4. Wang, Z.G. and Al, S.H. (1999) *ISIJ International* **39**, 747-759.
5. Sudhakar, K.V. and Dwarakadasa, E.S. (2000) *Bull. Mater. Sci.* **23**, 193-199.
6. Nakajima, K., Urabe, T., Hosoya, Y., Kamiishi, S., Miyata, T. and Takeda, N. (2001) *ISIJ International* **41**, 298-304.