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<https://hdl.handle.net/2324/7169347>

出版情報 : International Journal of Fracture. 185, pp.17-29, 2013-10-25. Springer
バージョン :
権利関係 :



Proposal of an engineering definition of a fatigue crack initiation unit for evaluating the fatigue limit on the basis of crystallographic analysis in case of pearlitic steel

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Abstract

In this study, in order to define a fatigue crack initiation unit, the relationship between the fatigue crack initiation process and the crystal structure in the pearlitic steel used for railroad rails was examined and fatigue tests, focusing on crack initiation, were performed. The fracture surfaces were analyzed using a scanning electron microscope (SEM) and electron backscatter diffraction (EBSD). The crystal structure of the pearlitic steel is composed of “pearlitic colonies” that have the same lamellar structure direction and “pearlitic blocks” that have the same ferrite crystal direction. The SEM and EBSD results revealed that the crack initiation depends on the pearlitic colonies. Therefore, we defined the characteristic dimension for fatigue crack initiation as the pearlitic colony size. However, for safety purposes, the pearlitic block size should be considered the engineering definition of the fatigue crack initiation unit, since decreasing the pearlitic block size should cause an improvement in the fatigue limit of pearlitic steel.

keywords: Fatigue, Fatigue Limit, Fatigue Crack Initiation, Pearlitic Steel

1. Introduction

The fatigue limit of a plain specimen is determined by the non-propagation limit condition of an initiated fatigue crack (Wadsworth, 1961; Frost and Dugdale, 1967). If the characteristic size of fatigue crack initiation can be defined, the fatigue limit can be predicted by using the fracture mechanics approach (Murakami, 2002). In a case where the fatigue crack is initiated in a crystal grain while the crystal grain is damaged as a unit (Katagiri et al., 1977), a fatigue crack initiation unit can be determined. However, in an age-hardened aluminum alloy, for example, a fatigue crack is initiated and propagates in Stage I and Stage II; therefore, the boundary between Stage I and fatigue crack initiation has not been identified (Forsyth, 1963). Furthermore, its unit and unit size for fatigue crack initiation have not been clarified. To overcome these shortcomings, in this study, a measurement method for fatigue crack initiation size in an arbitrary metal is discussed by defining the fatigue crack initiation process from engineering and mechanical viewpoints. In doing so, the present authors focus upon the fact that Murakami’s prediction equation (Murakami, 2002) is the non-propagation limit of Mode I type crack propagation caused by plasticity-induced crack closure.

Various studies have focused upon a particular type of texture for pearlitic steel. Pearlitic steel has a hierarchical substructure (Fig. 1) consisting of, for example, prior austenite, pearlitic blocks, and pearlitic colonies, in descending

order of size (Takahashi et al., 1978a and 1978b). Pearlitic colonies, which are the smallest units in the hierarchical substructure, contain a lamellar structure consisting of cementite and ferrite. Pearlitic blocks are made up of pearlitic colonies having the same ferrite crystal orientation. Thus, pearlitic steel has a complicated structure. Various studies have focused on crack initiation in pearlitic steel (Gray et al., 1985; Daeubler et al., 1990; Urashima and Nishida, 1994; Kimura et al., 2004; Hamada et al., 2011). Urashima et al. (1994) performed rotating bending fatigue tests on smooth specimens of pearlitic steel to investigate the fatigue crack initiation and propagation behaviors. Their results indicated that the fatigue crack initiation is affected by the direction of the lamellar pearlitic microstructure in railroad rail steel. Furthermore, the initial cracks have almost the same size as the pearlitic blocks. However, whether the fatigue crack initiation size depends on the pearlitic block size has not been confirmed microscopically and micro-mechanically. To define a unit for fatigue crack initiation in pearlitic steel used for railroad rails, the relationship between fatigue crack initiation and the crystal structure was examined. In pearlitic steel, there are different domains such as pearlitic blocks and pearlitic colonies, and it is necessary to clarify the relation between the initial crack and the crystal structure to determine the unit for fatigue crack initiation. If such a unit can be defined, the fatigue limit of pearlitic steel can be controlled and improved.

2. Experimental procedure

2.1 Test materials

In this study, a pearlitic steel was used because of its hierarchical substructure. Table 1 shows their chemical composition and Table 2 shows their static tensile properties. Materials were held for 30 minutes at 1000 °C, held for 10 minutes at 520 °C (A-2) and at 620 °C (A-3) then water-cooled, Figure 2. And Figure 3 shows the tensile stress-strain curve. The stress-strain curves were obtained by using type A specimen on the basis of Japanese Industrial Standards Z2201. The stroke speed was 0.5mm/s. The pearlitic steel used are hypereutectoid steels (weight % C: 0.89%) with an average pearlitic block size of 67 μm and 78 μm for A-2 and A-3, respectively, as found by EBSD studies.

2.2 Fatigue test

Two kinds of specimens were used in the fatigue test: a plain specimen and a notched specimen. Figure 4 shows the shape and dimensions of the fatigue tests specimens. In order to obtain replicas of the fatigue crack initiation structures at maximum stress during repeated observations, a specimen with a shallow notch was prepared. Finally, the specimens were mechanically polished with #2000 emery paper then buffed. And the specimen of A-3 surface was etched with a 3% nital solution to make the structure easier to observe. For the fatigue testing, an Ono-type rotating bending fatigue machine was used and the tests were run at a stress ratio of -1 . Fatigue tests were performed at room temperature, and the test frequency was 30 Hz.

Pearlitic steels have a hierarchical crystal substructure, so the relationship between the fatigue crack initiation and the crystal structure is complicated. Crystallographic analysis of fatigue crack initiation origin was performed and the fatigue crack behavior was investigated.

2.2.1 Localization of the fatigue crack initiation

In order to localization of the fatigue crack initiation, fatigue tests were performed by using plain specimen of A-2 material. The microscopic deformation behavior and crack behavior were successively observed on the specimen surface using the plastic replica technique. As a replica sheet for the replica technique, acetyl cellulose was used. The sheet was

immersed in methyl acetate, and attached to the specimen surface where it remained. The testing machine was intermittently stopped and surface replicas were obtained. Then, we found the fatigue crack initiation region by observing both the fracture surface and its replica.

2.2.2 Crystallographic analysis of the fracture surface

Scanning electric microscope (SEM) observations were performed on the fractured surface around the fatigue crack initiation region, and EBSD analysis was performed on the side surface of the fracture origin. To measure the crystal orientation at the fatigue crack initiation region, the side of the fatigue crack initiation region was buffed using colloidal silica for EBSD analysis. The crystal orientation of the facet was determined using both the EBSD analysis and laser microscope analysis. Figure 5 shows material coordinate system. The relative angle between the facet and side of the fatigue crack initiation region was measured in the RD direction and the TD direction relative to the ND direction using a laser microscope. Consequently, the crystal orientation of the fracture surface was determined using a laser microscope and EBSD.

2.2.3 Observation of the fatigue crack initiation behavior

A fatigue test was performed so that the fatigue crack initiation behavior could be observed. The A-3 material is more suitable than A-2 for observations of the fatigue crack initiation behavior because the lamellar spacing of A-3 is wider than that of A-2. A facet is observed in the fatigue fracture surface around the origin of the fatigue crack initiation. It is formed during fatigue crack initiation, as discussed below. We performed a rotating bending fatigue test on a plain specimen of A-3 material, and a facet was observed in the fatigue fracture surface around the origin of the fatigue crack, Fig. 14(a). Therefore, we conclude that there is no difference between A-2 and A-3 materials in terms of the fatigue crack initiation behavior, and the fatigue test could be performed using A-3. A plain and a notched specimen were used. A notched specimen was used so that the fatigue crack could be observed directly. To make these observations even easier, a replica was obtained at the maximum stress amplitude in a notched specimen. After the sample had been buffed, etching was performed so that the structure could be observed easily. The replica surface was sputtered with platinum using ion-coating equipment (JFC-1600, JEOL Co., Ltd.) to enable easy observation. After the fatigue test, the fatigue crack initiation region was observed on the replica by using FE-SEM. EBSD analysis and kernel average mis-orientation (KAM) analysis were also performed on the fatigue crack. The mis-orientation between a data point and its next neighbors was calculated by using KAM. The scan step size was 0.04 μm and the maximum mis-orientation angle was 5°. KAM is an appropriate parameter to evaluate the plastic strain for a given point. Thus, the fatigue crack behavior can be evaluated in detail.

3. Results

3.1 Fatigue test results

S-N curves for the A-2 and A-3 materials are shown in Figure 6. Fatigue limit is threshold stress of fatigue crack initiating or on-propagating. A-2 and A-3 materials have a non-propagating crack, so the fatigue limits of these materials are threshold stress of non-propagating crack. A non-propagating crack has a three phases; initiating, propagating and non-propagating. The difference between the fatigue limit and the rough fatigue limit is caused by the non-propagating phase. In this study, fatigue crack initiation behavior is focused. So the rough fatigue limit of plain specimens of A-2 and

A-3 were 470MPa and 400MPa, respectively whereas the rough fatigue limit of the notched A-3 specimen was lower, as expected, 323MPa.

Specimens I, II and III were used for the detail analysis. And the fatigue crack behavior of different specimens in Fig.6 was observed. Then, the fatigue crack initiation behavior of fatigue limit was different from that of high stress. In this study, fatigue crack initiation behavior of fatigue limit was focused. So specimens of only the fatigue limit stress were discussed, and fatigue crack initiation behavior in high stress will be reported in the near future.

3.2 Fatigue crack initiation region

The plain specimen of A-2 material endured $N = 1.0 \times 10^7$ repeated applied stress load ($\sigma_a = 465$ MPa). Because the applied stress was near the fatigue limit (about 470 MPa), both initiating and non-propagating fatigue cracks were expected. After $N = 1.0 \times 10^7$ repeated applications of the stress loads, a stress amplitude of $\sigma_a = 550$ MPa was applied to the specimen for the fractographic study and failure was forced. Figure 7 shows the morphology of the entire fracture surface: Fig. 7(a) shows the fracture surface around the fatigue crack initiation region, and Fig. 7(b) shows an enlarged view of Fig. 7(a). The dashed line in Fig. 7(b) shows the boundary of the facet domain. A facet was observed on the fracture surface around the fatigue crack initiation region. It is proposed that this facet is the fatigue crack initiation site; however, there is no definitive evidence supporting this supposition. To determine that the facet is the origin of fatigue crack initiation, the very early stages of crack initiation, after a certain number of cycles, must be observed. Figure 8 shows the fatigue crack on the replica. The fatigue crack initiation region was found by observing both the fracture surface and the replica. Figs. 7(b) and 8(c) show similar fatigue crack behaviors of the fracture surface and the replica. Therefore, the fatigue crack initiation on the replica corresponds to the facet on the fracture surface.

3.3 Crystallographic analysis of the fatigue crack initiation region

Figure 9 shows the result of EBSD analysis. Figure 10 shows the result of the RD direction analysis, and Fig. 11 shows the result of the TD direction analysis. Then, the relative angle between the edge of the specimen and the TD direction was measured (ND direction). Figure 12 shows the result of the ND direction analysis. In order to clarify the crystal orientation of the facet, the crystal orientation of the side of the fatigue crack initiation region was turned towards the RD, TD, and ND directions. Figure 13 shows the crystal orientation of the facet, namely (110).

3.4 Observation of the fatigue crack initiation behavior at the fatigue limit

A fatigue test was performed so that the fatigue crack initiation behavior could be observed. The plain specimen of A-3 material endured $N = 1.0 \times 10^7$ at $\sigma_a = 395$ MPa. Because the stress was near the fatigue limit (about 400 MPa), both initiating and non-propagating fatigue cracks were expected. After $N = 1.0 \times 10^7$, a repetitive load stress of $\sigma_a = 470$ MPa was applied to the specimen for the fractographic study, and failure was forced. Figure 14(a) shows the fracture surface around the fatigue crack initiation origin. A facet was observed on the fatigue crack initiation origin. The dashed line in Fig. 14(a) shows the boundary of the facet domain. Figure 14(b) shows the detail of the fatigue crack initiation origin on the replica using FE-SEM. The convex area, which appears grey, is ferrite, and the concave area, which appears black, is cementite. The white lines were treated as cracks. Figure 14(b-1)-(b-3) show the observations from the number of cycles $N = 0$ to $N = 1.0 \times 10^6$. Figure 14(b-3) shows the observation at $N = 1.0 \times 10^6$, and a crack is clearly visible as a white line. If the same location of a replica is traced back, successive observation as shown in Fig. 14(b-1)-(b-3) is possible. Figure 14(b-2), shows a fatigue crack initiation of about 1 μm length in a ferrite phase, which can be confirmed in the early stage ($N = 1.0 \times 10^4$) of the fatigue process; this is shown as lighter grey in the figure.

The notched specimen of A-3 material endured $N = 1.0 \times 10^7$ repeated applied stress loads ($\sigma_a = 323$ MPa). Because the applied stress load was near the fatigue limit (about 323 MPa), both initiating and non-propagating fatigue cracks were expected. After $N = 1.0 \times 10^7$ repetitions of the applied stress loads, the fatigue crack was observed directly using FE-SEM (Fig. 15). The microscopic deformation behavior and crack behavior were successively observed on the specimen surface using the plastic replica technique. Figure 16 shows the fatigue crack behavior observed on the replica. The convex area, which appears gray, is ferrite, and the concave area, which appears black, is cementite; the white lines are cracks. Figures 16(a)-(d) show the observations after different numbers of cycles from $N = 0$ to $N = 1.0 \times 10^7$. Figure 16(a) shows the initial condition, and Figure 16(d) shows the observation at $N = 1.0 \times 10^7$, where a crack is clearly visible as a white line. If the same location on the replica is traced back, the crack's progression can be observed successively in Figs. 16(a)-(d). Figures 16(b) and (c) show that a fatigue crack was initiated between $N = 1.0 \times 10^5$ and $N = 1.0 \times 10^6$ cycles and propagated along the lamellar layer. To further evaluate this propagation mode, the fatigue crack was analyzed using EBSD and KAM method. Figure 17 shows the results. Figure 17(a) shows the low-angle boundary, which indicates that each pearlitic colony has a minor mis-orientation in one pearlitic block (Walentek et al., 2006; Zaefferer et al., 2008; Nakada et. al., 2009). Figure 17(c) shows the boundary of the pearlitic colony as determined using SEM and Figure 17(a). The fatigue crack stopped propagating around the colony boundary. Figure 17(d) shows the results of the KAM analysis. Figures 18(a) and (b) show detailed observations of the fatigue crack tip. KAM level is high around the fatigue crack tip. Figures 19(a) and (b) show the marks on form of characteristic cementite. In Fig. 19, the tone is reversed in the replica pictures. The convex portion, which is white, is cementite and the concave portion, which is gray, is ferrite. In Fig. 19, a crack is observed as a black line in the concave section. The behavior of cementite can be characterized by observing the gap between the marks shown in Figs. 19(a) and (b). Figure 19(b) shows the movement of the cementite at the crack tip, which was caused by the crack opening and thus depends on the stress load. This is because the direction of this cementite movement was perpendicular to the direction of crack propagation. Therefore, no slip cutting of cementite was found in these observations.

4. Discussion

4.1 Identification of the fatigue crack initiation behavior

Oxide (Stewart, 1980), fracture surface roughness (Minakawa and McEvily, 1981), and plastic deformation (Elber, 1971) are suspected to be main sources of the fatigue crack closure. In this study, in order to analyze and control the pearlitic steel dynamically, we focus on the fatigue crack closure induced by plastic deformation. Plasticity-induced crack closure is caused by the plastic region which is made by the fatigue crack propagation in Mode I. This plastic region prevents crack opening, so fatigue crack closure does not occur until the fatigue crack begins to propagate in Mode I. Therefore, in this study, for evaluation of fatigue limit, fatigue crack initiation unit is defined as the range from the point of fatigue crack initiation to the point where it begins to propagate in Mode II. The results in section 3.3 show that the crystal orientation of the facet is (110), which is the slip plane of pearlitic steel. This is the slip plane of pearlitic steel. This result and the correspondence between the replica and the facet suggest that at the fatigue limit the fatigue crack appears to be initiated by a slip within the pearlitic steel. Therefore, the reason that the KAM level is low in the center of the fatigue crack (Fig. 17(d)) appears to be caused by that fatigue crack is initiated by a very local slip in one lamellar layer.

This raises the question of what kind of slip happens in domains with high KAM levels. KAM level is high in several lamellar layers around the fatigue crack tip (Figs. 17(d), 18(a) and 18(b)). Two slip patterns are considered: the fatigue crack could propagate in Mode I or in Mode II. If the fatigue crack propagates in Mode II, KAM level increases because of a slip which occurs along the lamellar layer. Therefore, in Mode I, a slip occurring at some angle to the direction of fatigue crack propagation will exist, and a traced cut should be observed in the cementite. However, no gap was observed in the cementite (Fig. 19). Thus, the fatigue crack observed in Figs. 16(c) and 16(d) appears to propagate in Mode II. This process is similar to the conclusion of Forsyth (1963). When the fatigue crack propagates along the lamellar layer, dislocations appear to pile up around the boundary of the pearlitic colony, causing work hardening at the fatigue crack tip. This process is similar to the conclusion of Miller (1993). Dislocations appear to pile up caused by either minor mis-orientation or the direction of cementite plate, or both. This process prevents the fatigue crack from propagating. Therefore, a slip must have occurred in the lamellar layer around the fatigue crack tip as a result of work hardening at the fatigue crack tip. The fatigue crack propagates only because of shear stress, so this process appears to be the fatigue crack initiation process. Therefore, the appropriate unit of fatigue crack initiation appears to be the pearlitic colony. On the basis of these results, a descriptive model of the fatigue crack initiation process is proposed, Figure 20. Figure 20(a) shows that the fatigue crack is initiated in the lamellar layer by a slip occurring in the pearlitic colony. Then, the fatigue crack propagates in Mode II in the lamellar layer (Fig. 20(b)). Work hardening occurs at the fatigue crack tip because of the pileup of dislocations, and then fatigue crack propagation stops. Finally, a slip happens in the lamellar layer around the crack tip because of the work hardening (Fig. 20(c)). In contrast to this fatigue crack initiation process, the fatigue crack propagation process involves the fatigue crack propagating beyond the boundary of the pearlitic colony.

4.2 Engineering definition of fatigue crack initiation unit

The process in which fatigue crack closure does not happen, that is, the fatigue crack propagates in Mode II, is defined as the fatigue crack initiation process. Therefore, the fatigue crack initiation unit is defined as the pearlitic colony on the basis of the results discussed in section 3.3. In this study, it is not clear that any mis-orientation would stop the crack at these boundaries. Quantification of the mis-orientation which stops the crack is required. However, the directions of the lamellar structures in each pearlitic colony have no fixed relationship. In addition, the relationships between pearlitic colonies within a pearlitic block whose lamellar structures are similar do not have a fixed form. And relative relationship around the weakest pearlitic colony is uncontrollable. For safety reasons, the upper limit of the initial crack size is used to predict the fatigue limit of pearlitic steel. If some pearlitic colonies have similar orientation by accident then the initial crack size will be pearlitic block size. The boundary of the pearlitic block constricts the fatigue crack initiation, because a fatigue crack is initiated by a slip. Therefore, it can be presumed that the upper limit of the initial crack size is that of a pearlitic block. Thus, the engineering definition of the fatigue crack initiation unit at the fatigue limit of pearlitic steel should be the pearlitic block size. If the pearlitic block size is decreased, fatigue cracks will rapidly encounter the boundary of a pearlitic colony and a pearlitic block. Dislocations will pileup as a result of the minor differences in crystal orientation occurring at the boundaries of pearlitic colonies, so fatigue cracks cannot propagate. Therefore, decreasing the pearlitic block size would improve the fatigue limit of the pearlitic steel.

5. Conclusions

To define the fatigue crack initiation unit in pearlitic steel, the relationship between fatigue crack initiation and the

crystal structure was investigated. The main findings from this work are listed below.

1. A model of the fatigue crack behavior in a pearlitic colony at the fatigue limit is proposed.
2. Fatigue crack initiation unit is defined as the range from the point of fatigue crack initiation to the point where it begins to propagate in Mode II.
3. The fatigue crack initiation unit is the pearlitic colony. However, the engineering fatigue crack initiation unit is the pearlitic block size.
4. Controlling the pearlitic block size could possibly improve the fatigue limit.

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Table1 Chemical composition (mass%)

Material	C	Si	Mn	P	S	Cr	N
A-2,3	0.89	0.4	0.92	0.018	0.013	0.24	0.041

Table2 Mechanical properties.

Material	$\sigma_{0.2}$ (MPa)	σ_B (MPa)	HV
A-2	764	1215	360
A-3	671	1129	320

$\sigma_{0.2}$: 0.2% proof strength

σ_B : ultimate tensile strength

HV: Vickers hardness

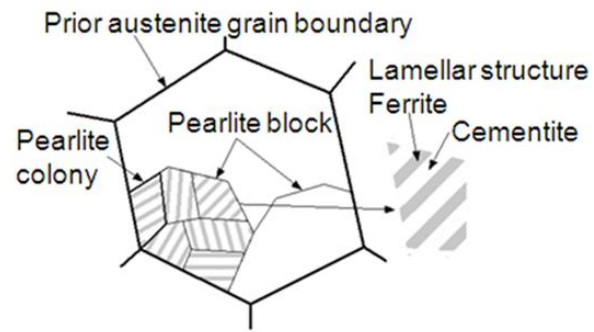


Fig. 1 Schematic diagram of pearlite steel microstructure

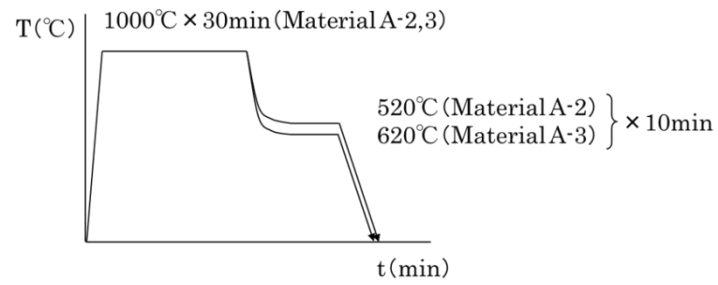


Fig.2 Heat treatment condition

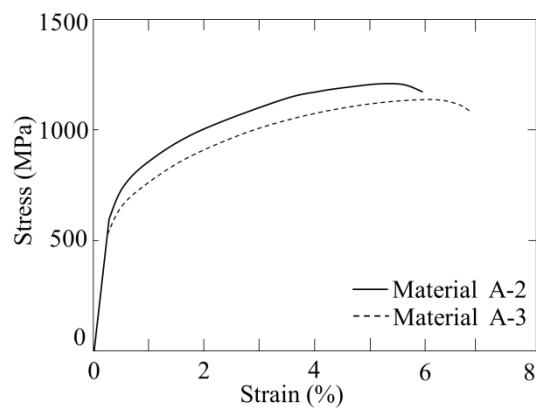
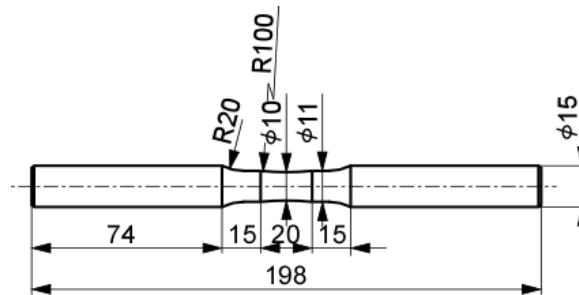
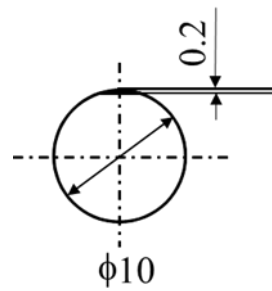


Fig.3 Tensile stress-strain curve



(a) Plain specimen



(b) Notch of the minimum cross-sectional surface

Fig.4 Shapes and dimensions of specimen for fatigue test. (a) Plain specimen, (b) Notch of the minimum cross-sectional surface

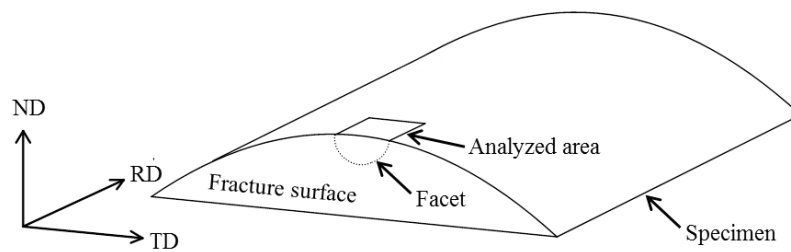


Fig.5 Material coordinate system for EBSD and laser microscope analysis.

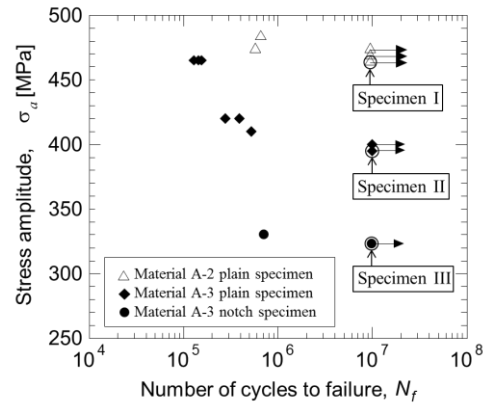
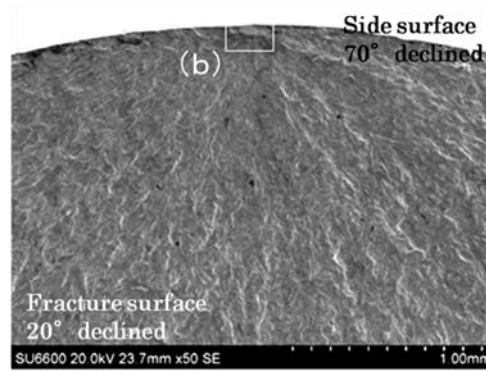
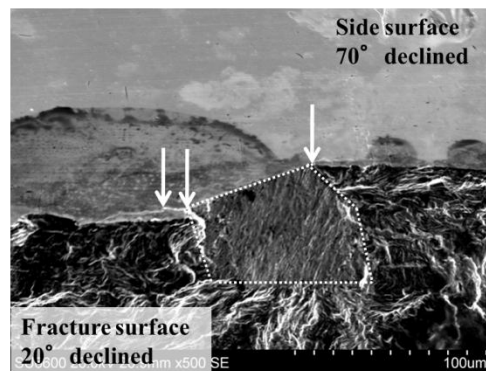


Fig.6 S-N curve



(a)



(b)

Fig.7 Analyzed surface of the Specimen I (Arrows indicate the characteristic points, $\sigma_a = 465\text{MPa}$, $N = 1.0 \times 10^7$ cycles). (a) Analyzed surface 1, (b) Analyzed surface 2

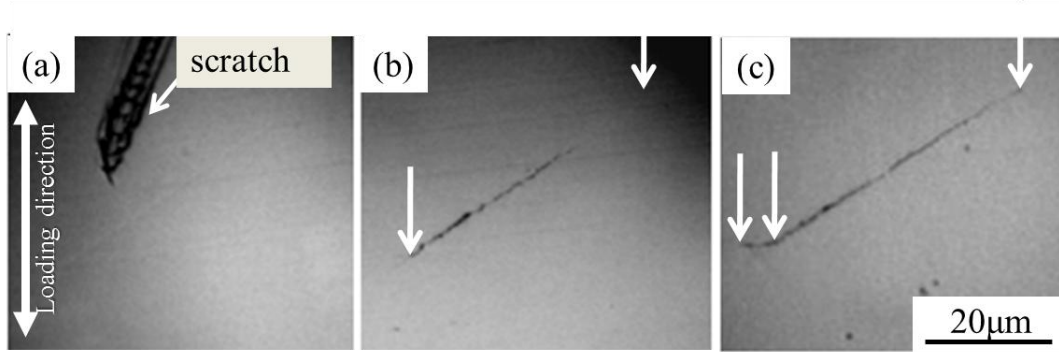
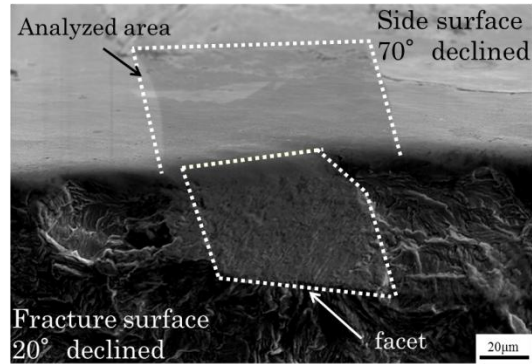
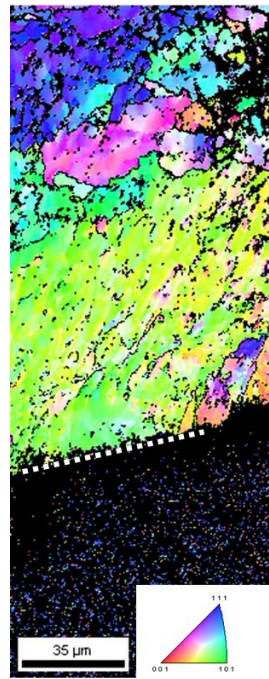


Fig.8 Replica of surface of specimen for fatigue test (Mirror-reversed image, Specimen I, arrows indicate the characteristic points) (a) $N = 6.0 \times 10^3$ (b) $N = 1.0 \times 10^4$ (c) $N = 1.0 \times 10^7$

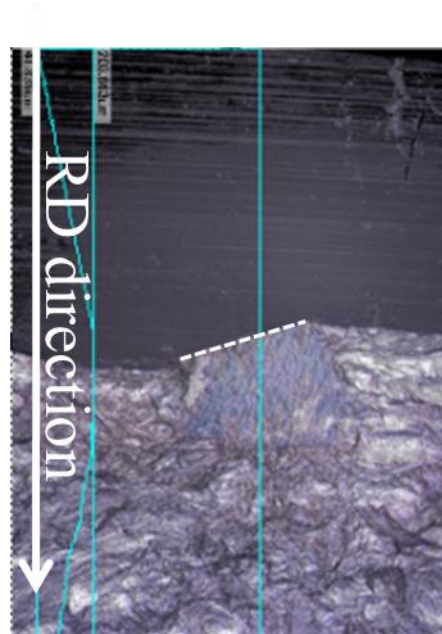


(a)

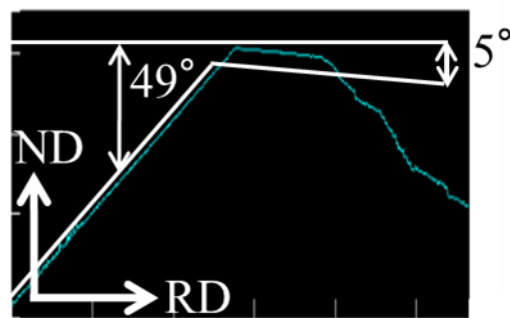


(b)

Fig.9 Results of SEM image and EBSD analysis (Specimen I, $\sigma_a = 465\text{MPa}$, $N = 1.0 \times 10^7$ cycles). (a) SEM image of the fracture surface (b) Inverse pole figure map

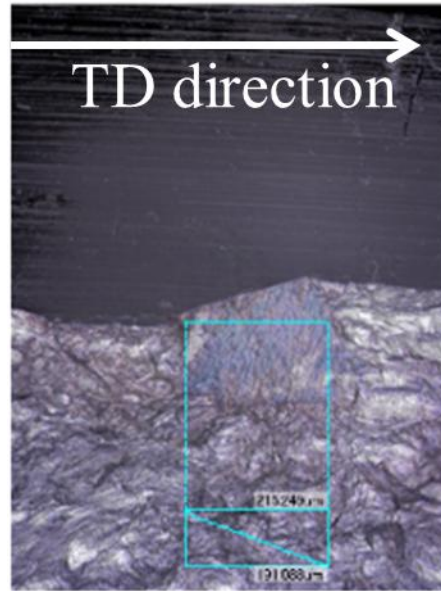


(a)

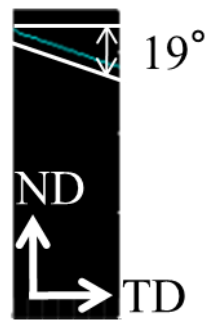


(b)

Fig.10 Laser microscope analysis result (The direction of RD). (a) Laser microscope analysis result (b) Laser microscope analysis result



(a)



(b)

Fig.11 Laser microscope analysis result (The direction of TD). (a) Laser microscope analysis result (b) Laser microscope analysis result

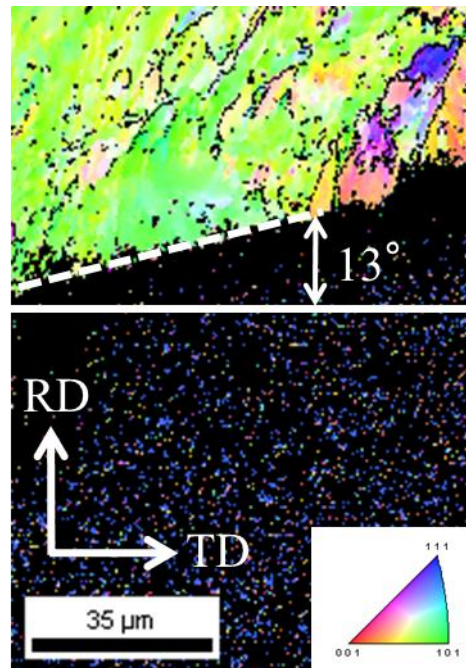


Fig.12 EBSD analysis result (The direction of ND).

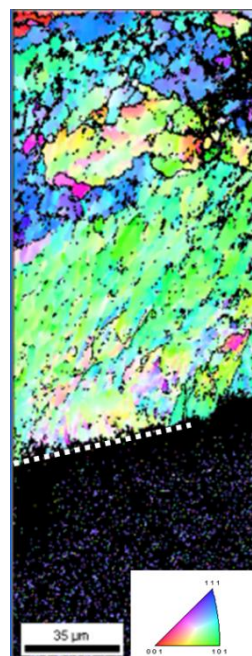


Fig.13 Inverse pole figure map by results of EBSD and laser microscope analysis (Specimen I, $\sigma_a = 465\text{MPa}$, $N = 1.0 \times 10^7$ cycles).

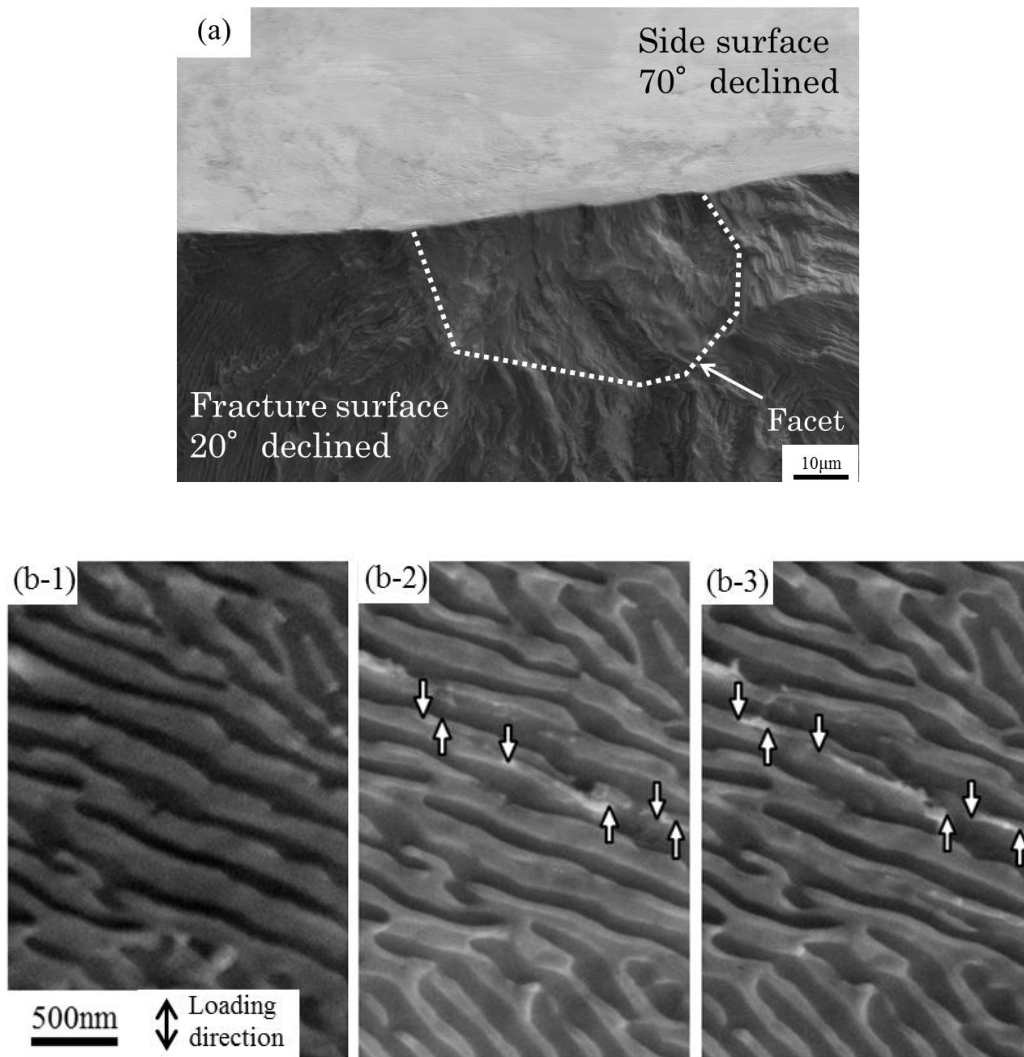


Fig.14 Observation of the fracture surface and the fatigue crack initiation (Arrows indicate the characteristic points, Specimen II, $\sigma_a = 395\text{MPa}$, $N = 1.0 \times 10^7$ cycles). (a) SEM image of fracture surface (b) FE-SEM images of the replica around the fatigue crack initiation origin (b-1) $N = 0$ (b-2) $N = 1.0 \times 10^4$ (b-3) $N = 1.0 \times 10^6$

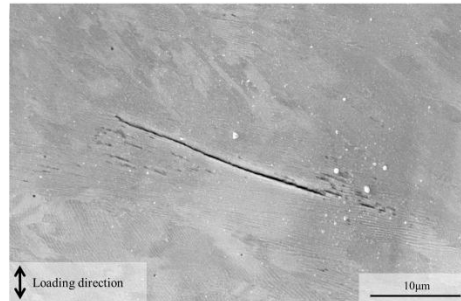


Fig.15 SEM images of the fatigue crack. (Mirror-reversed image, Specimen III, $\sigma_a = 323\text{MPa}$, $N = 1.0 \times 10^7$).

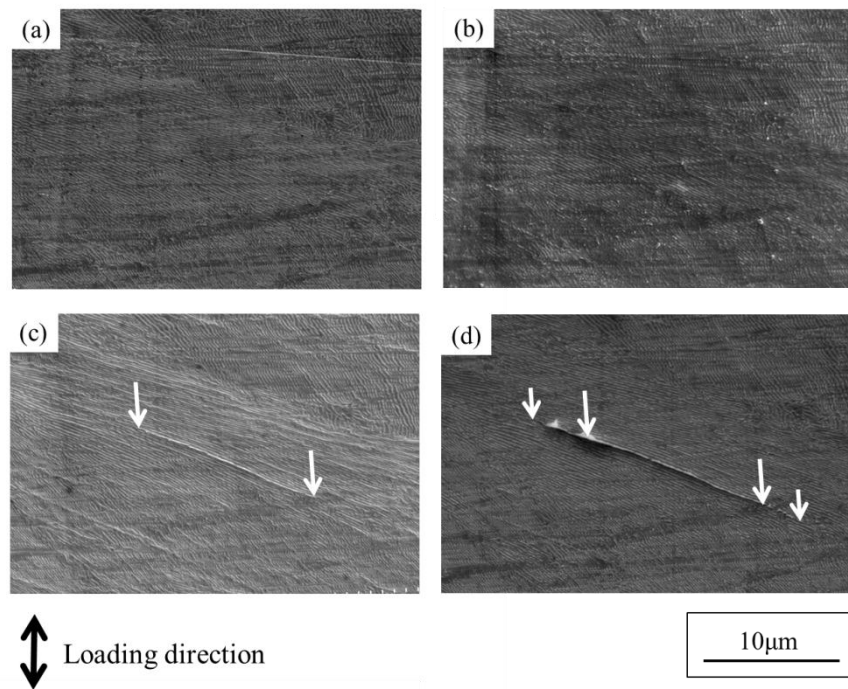


Fig.16 FE-SEM images of the replica around the fatigue crack initiation origin. (Arrows indicate the characteristic points, Specimen III, $\sigma_a = 323\text{MPa}$). (a) $N = 0$ (b) $N = 1.0 \times 10^5$

(c) $N = 1.0 \times 10^6$ (d) $N = 1.0 \times 10^7$

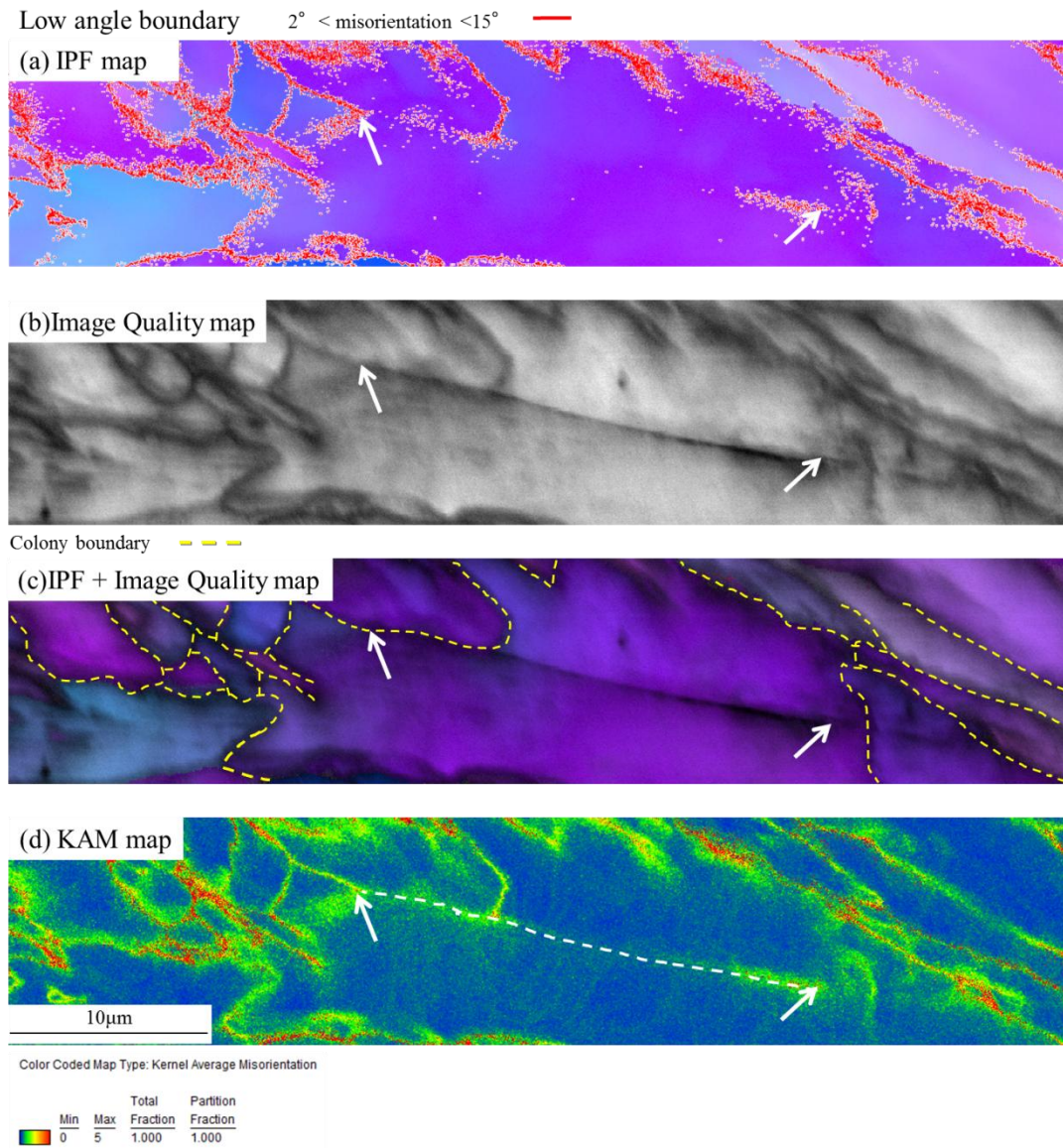


Fig.17 Results of EBSD and KAM analysis (Arrows indicate the characteristic points, Specimen III). (a) Inverse pole figure map (b) Image quality map (c) Pearlite colony boundary (d) KAM map (step size is 0.04 μm)

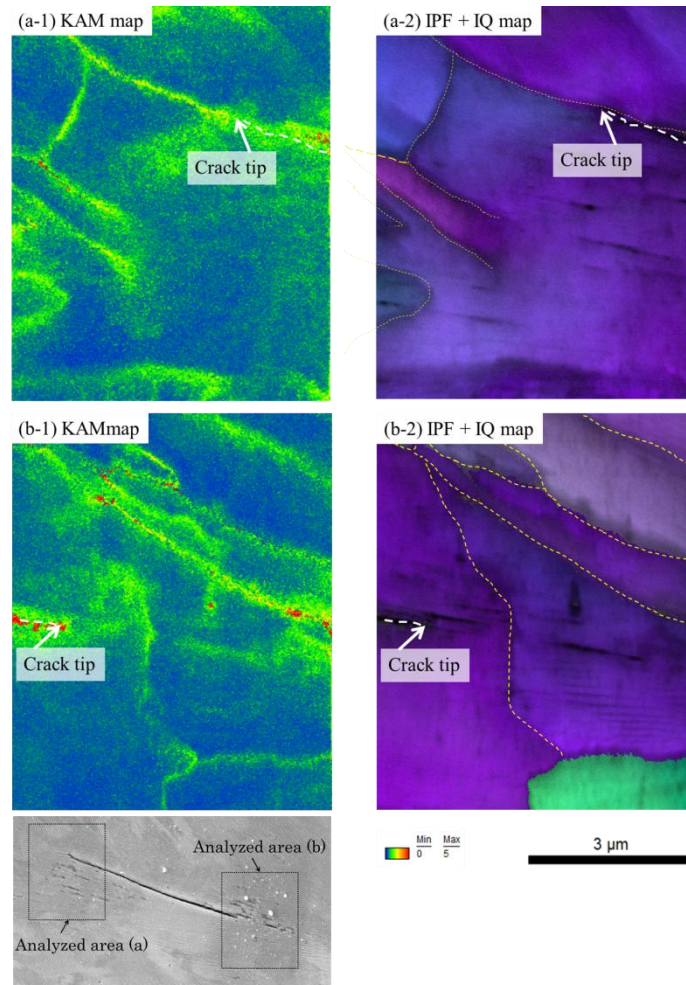


Fig.18 Results of KAM analysis around the fatigue crack tip. (Arrows indicate the characteristic points, Specimen III, step size is $0.02\ \mu\text{m}$). (a) KAM map of left side crack tip. (b) KAM map of right side crack tip.

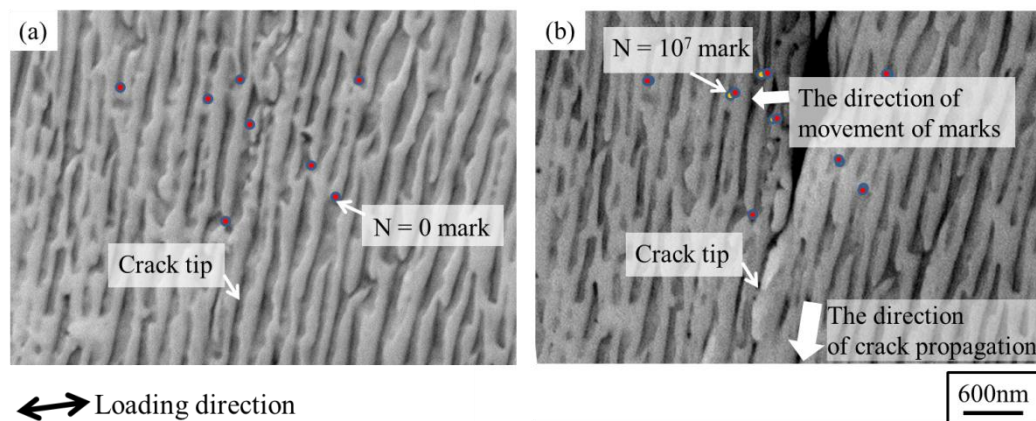


Fig.19 FE-SEM images of the replica around the crack tip (Specimen III). (a) $N = 0$
(b) $N = 1.0 \times 10^7$

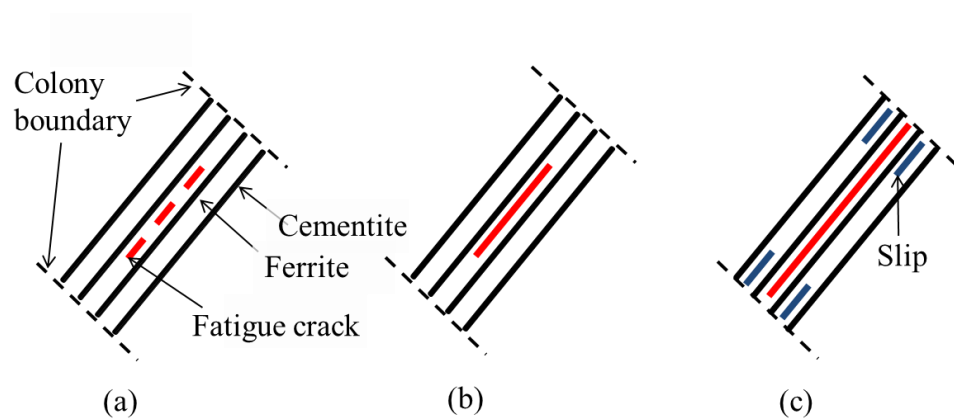


Fig.20 The model for the fatigue crack initiation of the pearlitic steel.