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# Fatigue Crack Propagation Modes: Plastic Deformation Mode and Damage Accumulation Mode

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## Abstract:

To define the fatigue crack propagation mode for the prediction and classification of the experimental results based on its evolution mechanism, successive mesoscopic observations of a fatigue process under pure cyclic mode II loading are performed. Thus, damage accumulation, which is considered to be a vacancy accumulation, is found to be a mechanism. The phenomena occur not at the crack tip but ahead of it. Thus, “plastic deformation mode” and “damage accumulation mode” are the terms proposed to represent the fatigue crack propagation modes instead of “tensile mode” and “shear mode,” respectively. Moreover, as a method to classify both the fatigue crack propagation modes using the experimental results, it is proposed to identify the plastic strain in the wake of the crack tip.

## Keywords:

Mode II loading; Fatigue crack propagation; Tensile-mode, Damage; Texture; Mechanics

## 1. Introduction

When predicting fatigue crack propagation in ductile metals, it is necessary to consider two mechanical factors: the accelerating factor and arrest factor of the propagation. The former factor is the applied stress range (Laird 1967; Laird and Smith 1962; Neumann 1969; Neumann 1974), and the latter factor is the fatigue crack closure stress intensity factor (Budiansky and Hutchinson 1978; Elber 1970; Ritchie 1988; Tanaka et al. 1981). In various fatigue crack closure phenomena, the change in the fatigue crack propagation is complex (Ritchie 1988; Suresh and Ritchie 1982; Suresh et al. 1981; Suzuki and McEvily 1979). In addition, some conditions cause it to arrest and impose fatigue limits (Nisitani and Takao 1974; Tanaka et al. 1981). Therefore, the accuracy of the prediction of fatigue crack propagation behavior is remarkably improved by understanding the fatigue crack closure phenomena of the used metal and used conditions. Indeed, concepts such as “intrinsic factors” and “extrinsic factors” (Ritchie 1988; Ritchie 1999; Ritchie 2011; Ritchie et al. 2000) are approaches for identifying the deformation factor that determines the fatigue crack propagation behavior. Because the former type is a property of a metal, it is basically measured, whereas because the latter type is a mechanical element, it can be predicted by mechanics. Fatigue crack closure stress intensity factor belongs to the latter category. The above description is of a phenomenon or a concept concerning fatigue crack propagation, which is generally called “tensile mode fatigue crack propagation” caused by cyclic mode I loading. Concurrently, regarding fatigue crack propagation behavior, a phenomenon generally known as “shear mode fatigue crack propagation” caused by cyclic mode II loading, occurs on the precrack extension. However, understanding of the element that arrests the fatigue crack propagation, which can contribute to the prediction of the arrest, has not advanced.

Therefore, the present authors (Hamada et al. 2018) investigated the effect of the roughness-induced stress shielding (RISS) (Ballarini and Plesha 1987; Gates and Fatemi 2016; Rosenfield 1980; Suresh and Ritchie 1982) corresponding to the fatigue crack closure stress intensity factor during shear mode fatigue crack propagation. The material was cold-rolled ferritic

stainless steel, SUS430, and the fatigue crack was a crack that propagates in the rolling direction. In this study, it was quantitatively clarified that the effect of the RISS on the fatigue crack propagation driving force (mode II stress intensity factor range) was sufficiently small to be ignored under pure cyclic mode II loading. Moreover, crack propagation was investigated meso- and macroscopically.

“The RISS is sufficiently small to be ignored,” which is a conclusion derived from the previous study, is an extremely significant feature that affects the fatigue limit controlled by a non-propagating crack and the extrinsic factor in the mechanical analysis of crack propagation. However, it is still not possible to quantitatively define the “shear mode”. Indeed, it is necessary to classify the fatigue crack propagation based on the crack propagation mode to predict its behavior when a mechanical element having a crack is used in an arbitrary mixed fracture mechanics mode. The authors consider that the classification is not for fracture mechanics modes such as “Mode I” and “Mode II”, these are crack deformation mode, but for modes that describe the crack growth or propagation based on these mechanisms. As mentioned before, generally, two modes of fatigue crack propagation are considered: “tensile mode” and “shear mode” (Forsyth 1961; Otsuka et al. 1975). This classification is performed mainly by two methods. One is classification by the crack propagation path (Bold et al. 1992; Doquet and Bertolino 2008b; Murakami and Hamada 1997; Otsuka et al. 1975), which is a result classification, and not suitable for prediction. The other classification is based on the principal stress plane and maximum shear stress plane at the crack tip (Melin 1986; Otsuka et al. 1975; Pinna and Doquet 1999; Tanaka 2003). However, these classifications have the following issues:

- (1) The initial conditions for the propagation are discussed but not the continuity.
- (2) The micro-yielding conditions at the crack tip are discussed in terms of the macroscopic stress conditions.

The purpose of this study is to quantitatively define the fatigue crack propagation mode of the shear mode, whose mechanical feature is that the RISS is negligible, for the prediction and classification of the experimental results based on its evolution mechanism. Therefore, this study is

performed under the following assumptions regarding the shear mode fatigue crack propagation. The fatigue crack propagation in the tensile mode is caused by an irreversible change in the crack shape caused by the blunting and re-sharpening deformation of the crack tip during the present single-cycle loading (Laird 1967; Laird and Smith 1962). Therefore, as an exclusive phenomenon of the tensile mode, damage accumulation, which occurs during certain cycles, can be assumed as a propagation mechanism for the shear mode fatigue crack propagation. The terms “damage accumulation” and “cumulative damage” have been long used in fatigue crack initiation studies (Ghonem and Provan 1980; Miller and Ibrahim 1981; Miner 1945; Tanaka and Mura 1981). Although, specific damage accumulation has been analyzed in detail (Man et al. 2004; Mughrabi 1983; Polák and Man 2016; Sangid 2013; Seidametova et al. 2018; Stanzl-Tschegg 2017), this was mainly in relation to the fatigue crack initiation in smooth metals. The roles of the stress–strain field of a crack have been studied a pioneering research by Doquet and Bertolino (2008a) and recent studies (Gates and Fatemi 2016; Pokluda et al. 2014). However, the roles of the metallic microstructure in crack propagation have not been studied. In the previous study (Hamada et al. 2018), the authors found that the effect of microstructure caused by rolling etc. was large on the shear mode fatigue crack propagation. Therefore, in this study, successive mesoscopic observations of a fatigue process are performed to determine “where and how” the damage occurs. Here, the “where” has two connotations: one is the positional relationship with the crack tip, and the other is the position in the metal microstructure.

As in the previous study, a notch was introduced into a thin-film specimen using the focused ion beam (FIB) process. The specimen was attached to a round bar torsion jig using an instantaneous adhesive, and repeated torsional loading was applied to the latter. Fig. 1 shows the outline of the test method. In this study, to ensure shear mode fatigue crack propagation, a cold-rolled steel, same as the previous study, is used. Before the fatigue test, the microstructure state is confirmed by the electron backscatter diffraction (EBSD) method, and the correspondence with the fatigue crack is investigated. During the fatigue test, the testing machine is stopped after

appropriate cycles, and the fatigue crack and state near the crack tip are observed. In this study, the authors focused on the fatigue crack propagation modes. The behaviors of each mode fatigue crack, such as the relationship between load and propagation ratio, are future tasks.

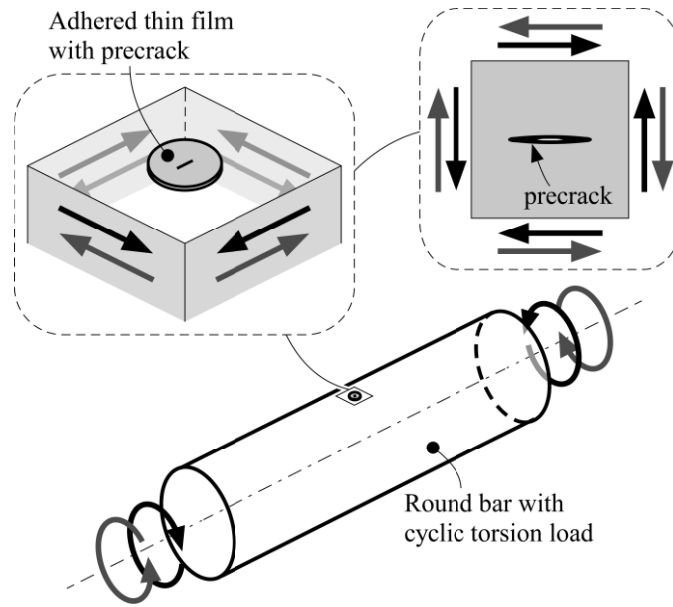


Fig. 1 Schematic of the test method

## 2. Experimental method

### 2.1 Experimental material

To apply a uniform stress to a thin film, the film thickness used in the test must be uniform. Fatigue cracks in mode II loading are expected to propagate along a slip plane, and we considered that fatigue cracks were more likely to propagate when the number of slip planes was larger. Therefore, a BCC metal and not an FCC one was chosen. Thus, a thin-film sheet (film thickness 30  $\mu\text{m}$ ) of commercially available ferritic stainless-steel SUS 430 cold-rolled metal was used for the test. The dimensions of the thin film sheet were  $100 \times 300 \text{ mm}^2$ , and the specimen was cut out from this sheet. Table 1 lists the chemical composition of the film sheet.

### 2.2 Fatigue test specimen

Because the surface of the purchased thin-film sheet was cold rolled, it was cut using scissors

to a size suitable for polishing (about 20 mm in diameter) and pasted on a polishing jig using double-sided tape. Next, one side was polished using alumina of particle diameter 0.3  $\mu\text{m}$  until it transformed into a mirror surface. The polished surface (front) was the observation surface, and the opposite surface (back) was not polished considering its adhesion to the fatigue test jig. After the completion of polishing, the thin-film sheet was peeled off from the polishing jig. A disc-shaped specimen with a diameter of 3 mm was cut from it using a transmission electron microscopy (TEM) disk punch. A notch with a length of 600  $\mu\text{m}$  was introduced in the center of the specimen plate using an FIB device (Quanta 200 3D manufactured by FEI). The direction of the FIB-notch was made parallel to the rolling direction (RD). For the FIB-notch processing by FIB, the specimens were processed from the backside. Considering the specimen thickness penetration, the FIB processing conditions were as follows: an acceleration voltage and a beam current of 30 kV and 65 nA, respectively. Under these conditions, the width of the FIB-notch on the observation surface was approximately 1  $\mu\text{m}$ . Two thin-film specimens, specimen #1 and specimen #2, were tested.

### **2.3 Crystal analysis by EBSD**

To observe the state of the texture before fatigue testing, scanning electron microscopy (SEM) and crystal analysis via EBSD were performed. The device used for the analysis was SU6000 (Hitachi High-Technologies Corporation). Inverse pole figure (IPF) maps of the RD, transverse direction (TD), and normal direction (ND) of the thin-film specimens were obtained. Because the FIB-notch was introduced parallel to the RD, the plane on which the fatigue crack was developed was the TD plane.

### **2.4 Fatigue testing**

Prior to fatigue testing, EBSD analysis was performed ahead of the FIB-notch tip of the thin-film disc specimen, as prepared by the method described in the previous section, and the state of the texture was confirmed. Fig. 2 shows the shape of the round bar torsion jig used for the fatigue testing and the adhered position of the thin-film disc specimen. Because the round bar torsion jig

loads a low-rigidity thin-film specimen by an adhesive, a material having a low elastic modulus and high fatigue strength is suitable for its formation. Therefore, the jig was made using a commercially available Ti-6Al-4V alloy round bar. The specimen was adhered to the round bar torsion jig using an instantaneous adhesive, CC-36 (Kyowa Electronic Instruments Co., Ltd.), which applied a cyclic torsion load to the jig. In this study, the torsion testing machine used was TB-10 (Shimadzu Co.). The load was  $\pm 29.4 \text{ N}\cdot\text{m}$ , and the shear stress acting on the test section of the round bar jig was  $\pm 150 \text{ MPa}$ . This value is the stress acting on the surface of the cylindrical part of the round bar torsion jig when there is no plane for adhering the specimen to the latter. The test frequency was 33.3 Hz. The testing machine was stopped every 300 times of loading, the jig was detached from the testing machine, and the state of the fatigue crack was observed via an optical microscope. Because of the characteristics of the used testing machine, approximately 200 cycles were required (from the start of the test) before the load reached the preset value. The loading and observations were repeated for a preset number of cycles; the fatigue test was then ended. Following this, the thin-film disc specimen was peeled from the jig by applying and washing with acetone, and next, SEM was performed.

Table 1 Chemical composition (wt%)

| C    | Si   | Mn   | P     | S     | Cr    | Fe   |
|------|------|------|-------|-------|-------|------|
| 0.04 | 0.23 | 0.51 | 0.020 | 0.004 | 16.12 | Bal. |

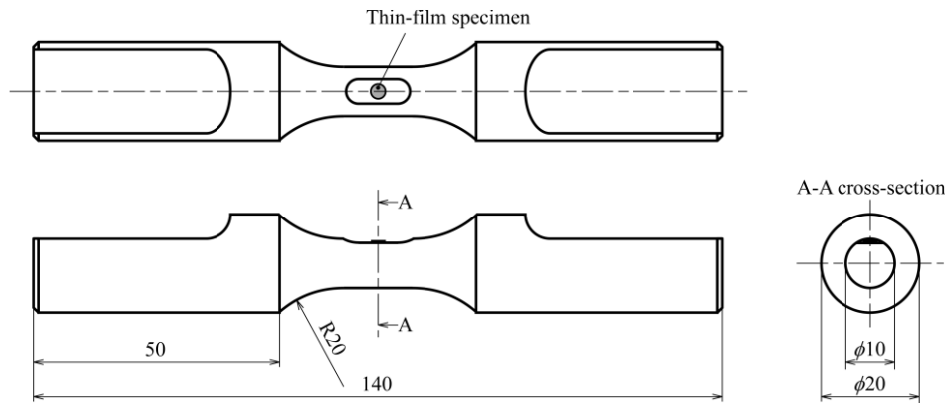


Fig. 2 Shapes and dimensions of the round bar torsion jig and thin-film specimen (unit: mm).

### 3. Test results

#### 3.1 Texture ahead of the FIB-notch tip before fatigue testing

Figure 3 shows the optical microscopy and SEM images of the FIB-notch before the fatigue testing. The black dots of several micrometers observed on the surface are residues of the adhesive used for adhering to the polishing jig during the polishing of the thin-film disc specimen.

Figure 4 shows the EBSD results observed ahead of the FIB-notch tip before the fatigue test. Figures 4(a)–(c) show the results of observing the ND, RD, and TD planes in the same area. The RD plane shows roughly (101) planes, and the texture is developed by the rolling process. The dimensions of the region where the crystal orientations are aligned are roughly a hundred micron in the rolling direction and several to ten micron in the transverse direction. In addition, it can be seen that the texture continuing in the RD is also formed on the TD plane on which (in this study) the fatigue cracks propagate. As shown in Fig. 4(c), for specimen #1, ahead of the FIB-notch tip, a (110) plane, which is slip plane for the BCC metal, exists in the FIB-notch extension plane; therefore, fatigue crack propagation is expected from the FIB-notch tip. As shown in Fig. 4(d), for specimen #1, ahead of the FIB-notch tip, a (110) slip plane also exists in the direction of the FIB-notch extension. However, ahead of the FIB-notch tip of specimen #2, as shown in Fig. 4(e), (110) planes do not exist, and propagation of the fatigue crack cannot be expected. Although (110) planes exist ahead of the FIB-notch tip of specimen #2, as shown in Fig. 4(f), they do not exist in the direction of the FIB-notch extension.

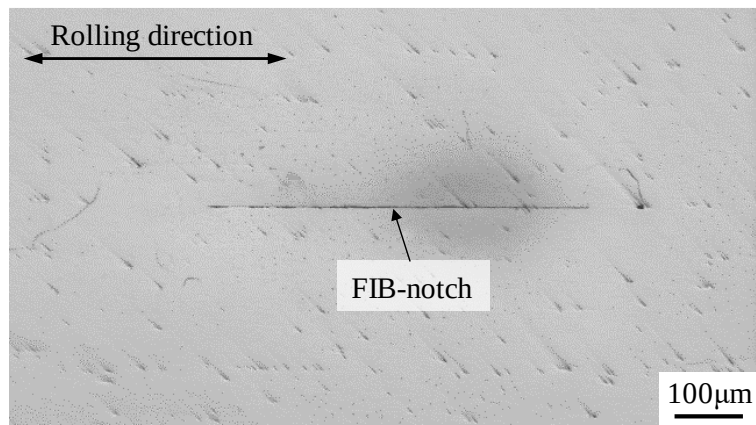
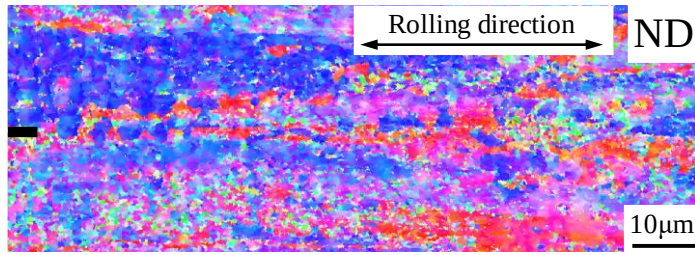
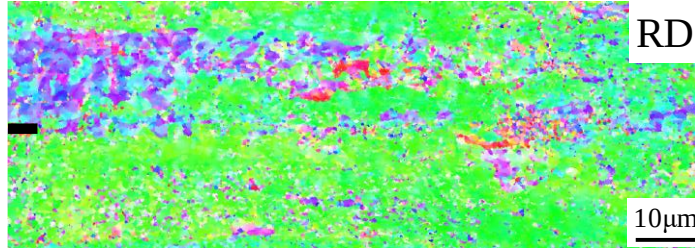


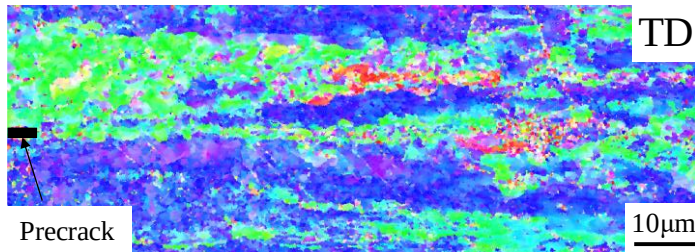
Fig. 3 Optical micrograph of specimen #1.



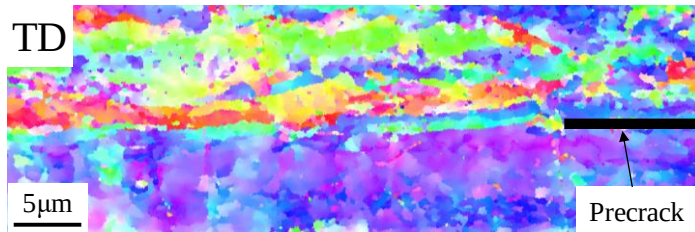
(a) Specimen #1, the right side of the FIB-notch, ND plane



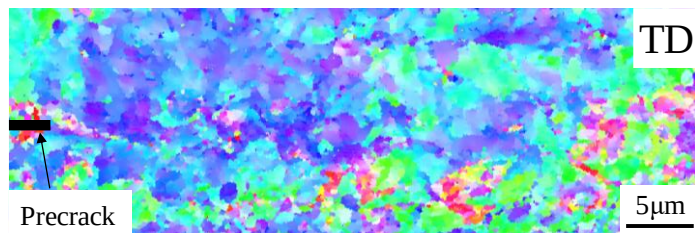
(b) Specimen #1, the right side of the FIB-notch, RD plane



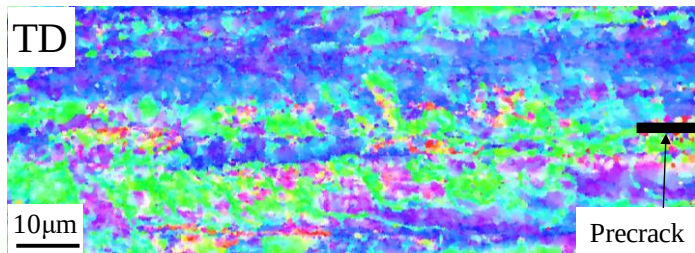
(c) Specimen #1, the right side of the FIB-notch, TD plane



(d) Specimen #1, the left side of the FIB-notch, TD plane



(e) Specimen #2, the right side of the FIB-notch, TD plane



(f) Specimen #2, the left side of the FIB-notch, TD plane

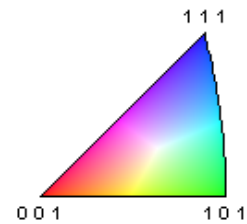


Fig. 4 IPF map for the region around the FIB-notch tip of each specimen.

### 3.2 Fatigue crack propagation behavior

Figure 5 shows the fatigue crack propagation behavior observed via an optical microscope after every 300 cycles of loading. In specimen #1, as shown in Figs. 5(a) and (b), although crack branching occurs, it is confirmed that the shear mode fatigue crack propagates in the same direction as the FIB-notch. The disagreement between the tensile mode and shear mode fatigue crack propagations is confirmed. Here, a crack that propagates in the same direction as the FIB-notch under maximum shear stress is called a shear mode fatigue crack. This classification is based on the propagation form from a macroscopic view. In specimen #2, as shown in Figs. 5(c) and (d), the tensile mode fatigue crack propagates in a direction different from that of the FIB-notch from the FIB-notch tip, and a shear mode fatigue crack propagation in the same direction as the FIB-notch is not confirmed.

Comparing the fatigue cracks that propagate in the same and different directions from the FIB-notch, as shown in Fig. 5, reveals that the tensile mode fatigue crack length elongates with the number of load cycles. Therefore, this fatigue crack propagation occurs under cyclic mode I loading, and the  $da/dN$  concept can be applied to it because it can be considered that the crack propagates once with a single load cycle. Although the length of the shear mode fatigue crack occurring in the same direction as the FIB-notch increases, it is not according to the number of load cycles that is, it can be considered that the crack propagates once with several load cycles. In particular, although the fatigue crack propagation can be observed in Fig. 5(a), the propagation behavior is different from the fatigue crack propagation behavior from that in the fatigue cracks propagating in a direction different from that of the FIB-notch. In addition, while the fatigue cracks propagating in the same direction as the FIB-notch (as shown in Fig. 5(a)) are linearly propagated to some extent (as shown in Fig. 5(c)(d)), those propagating in a different direction from the FIB-notch seem to propagate along straight or macroscopically curved lines. However, when they are observed on the order of micrometers, they appear to propagate in a zigzag manner.

In Fig. 6, we indicate the crystal orientation at each (110) plane on which the fatigue cracks

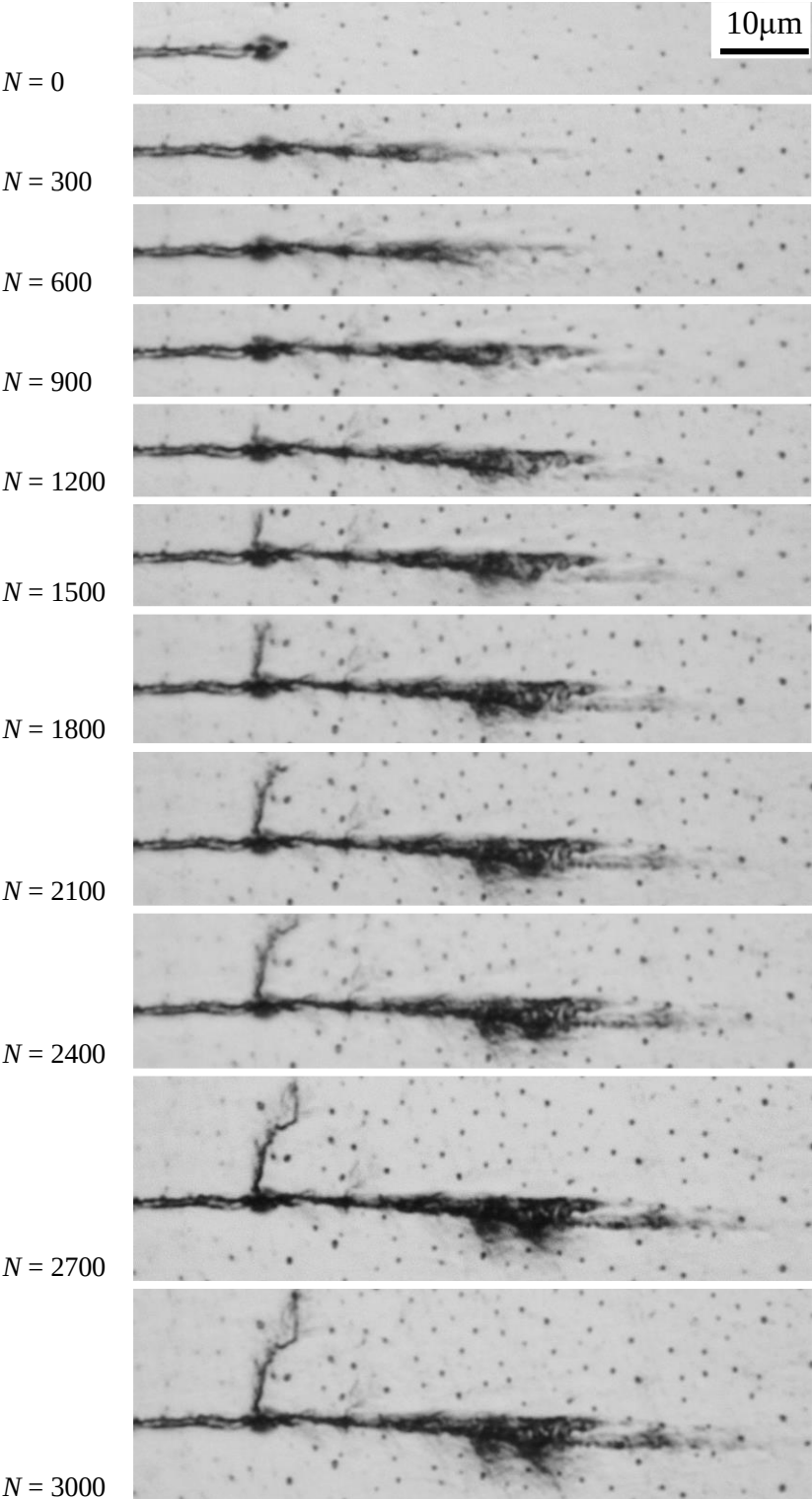
propagate in the same direction as the FIB-notch. Even when all the fatigue crack propagation planes are (110) planes, the slip direction varies depending on the position. In Fig. 6(a), all the observed points lie on approximately the same plane, but the slip directions are different. Specifically, the plane is divided into three parts: (i) and (ii), (iii) and (iv), and (v). Thus, it can be seen that a crystal whose TD plane lies on the extension line of the FIB-notch is the (110) plane, can be divided into three crystals, instead of acting as the same crystal, with respect to the observed point. Similarly, in Fig. 6(b), the crystal is divided into crystal types (i), (ii)–(iv), and (v).

Figure 7 shows the results of the SEM observation of the specimen surface after the test. In the area that appears gray in the optical microscopy images, the asperity of the surface gradually increases, and the area that appears black is the cracked area. In addition, concave shapes like holes are formed in a discrete area.

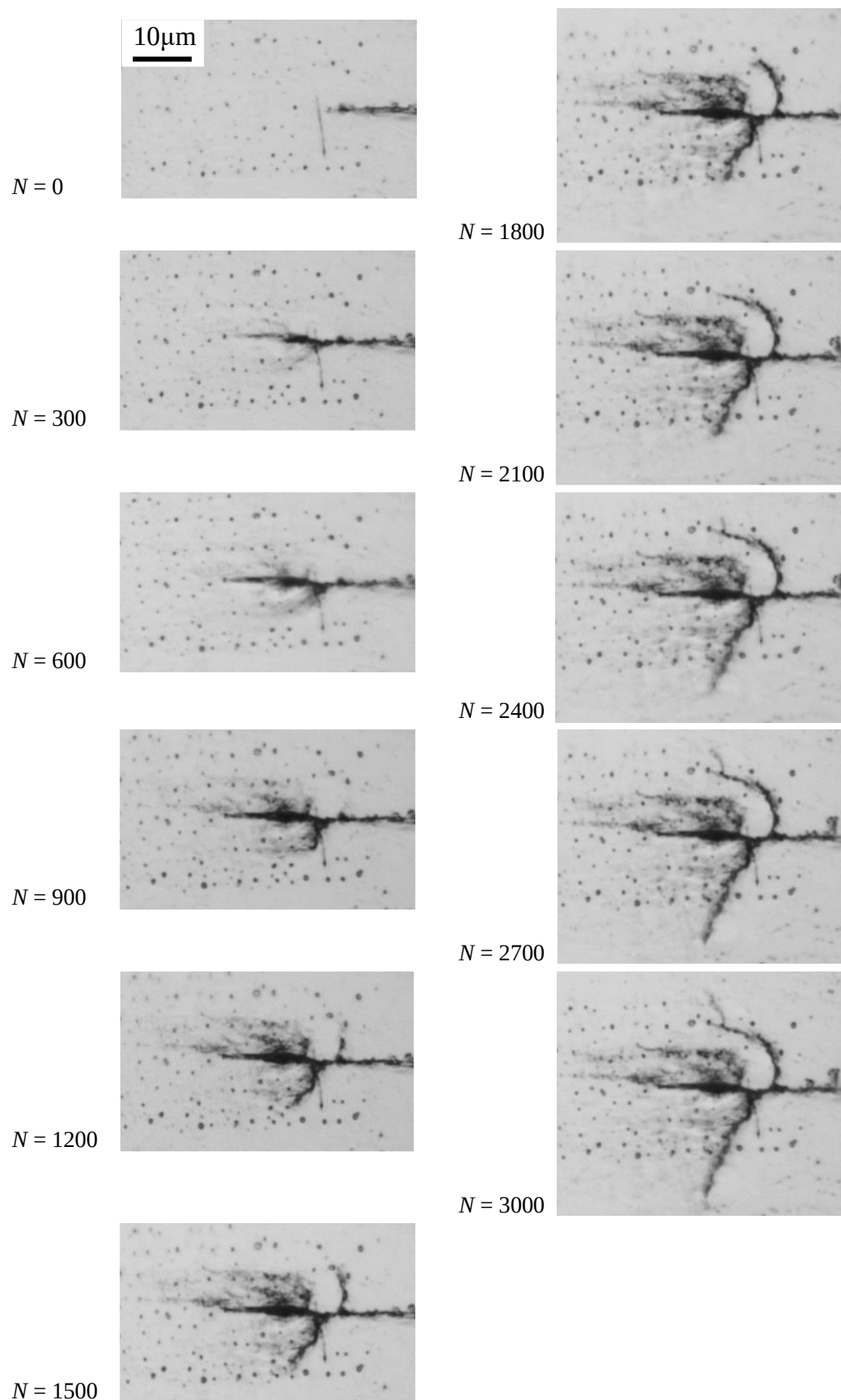
The mechanism of the fatigue crack propagation, as shown in Fig. 5(a), seems to be different from that of a single propagation at the crack tip with a single-load cycle. Thus, an apparently black crack of unit length seems to exist, and the gray area in the unit length ahead of the crack tip gradually becomes darker with the number of cycles. As can be seen from the detailed view in Fig. 5(a), after a one-unit crack is formed, the next unit does not propagate on its extension line. However, according to Fig. 5(a), crack formation appears to be changing from gray to black color as the unit shifts to the right. In addition, this unit corresponds to the unit of the crystal, which is shown in Fig. 6(a).

Figure 8 shows a schematic of the observed results of the fatigue crack propagation behavior displayed in Fig. 5(a). From the direct observation of the fatigue crack propagation behavior, when mode II loading is applied to the rolled texture metal, the following fatigue crack propagation phenomena occur: (1) Voids are formed at intermittent positions on the extended line of the FIB-notch and not at the crack tip. (2) The size and depth of the voids increase with the number of cycles. (3) Intermittent voids coalesce to form a crack of a certain length, and the fatigue crack propagates according to the crack length. (4) An extension unit length is related to the propagation

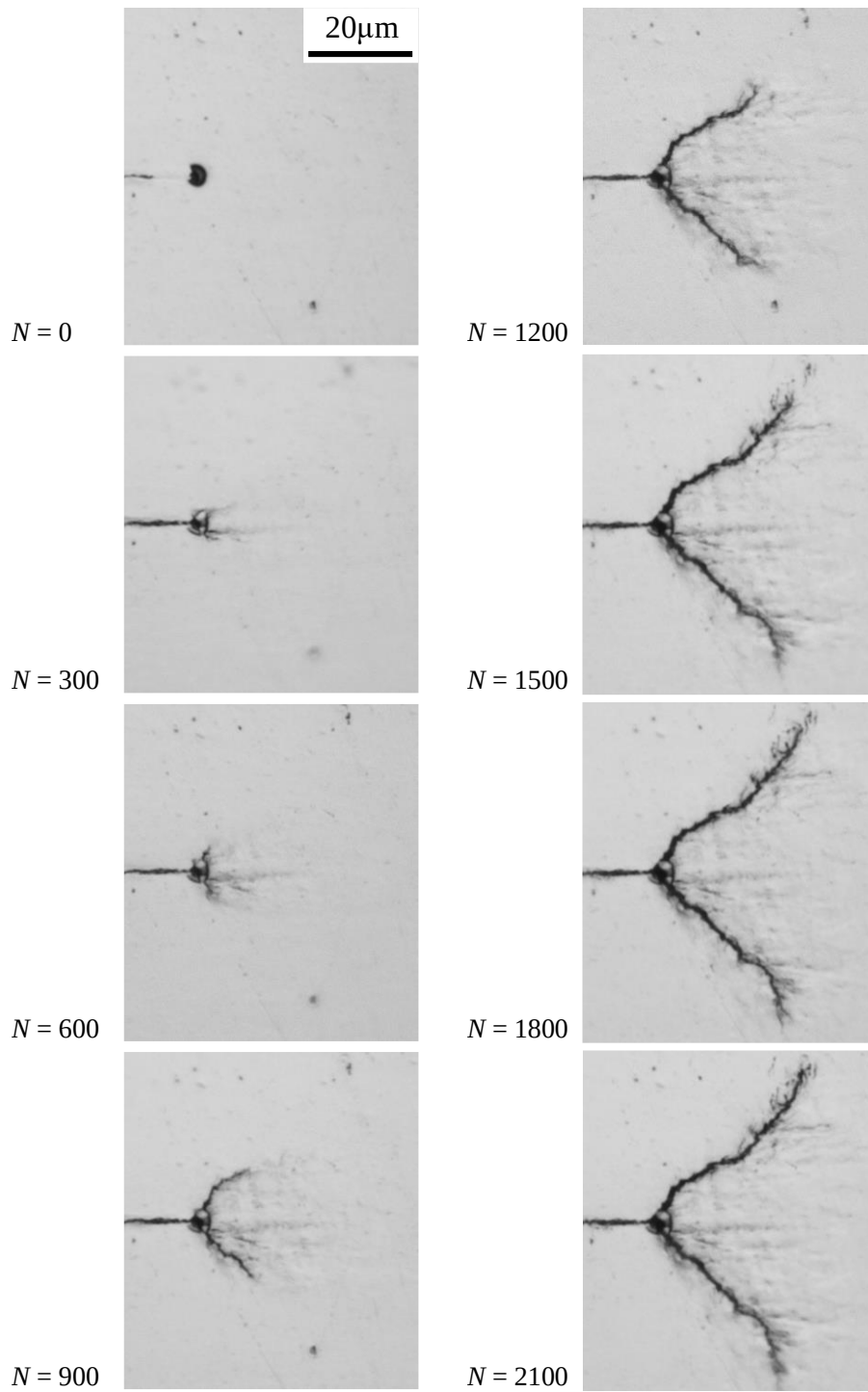
length of the fatigue crack. The failure surface observation in previous study (Hamada et al. 2018) supports the above-mentioned phenomena.



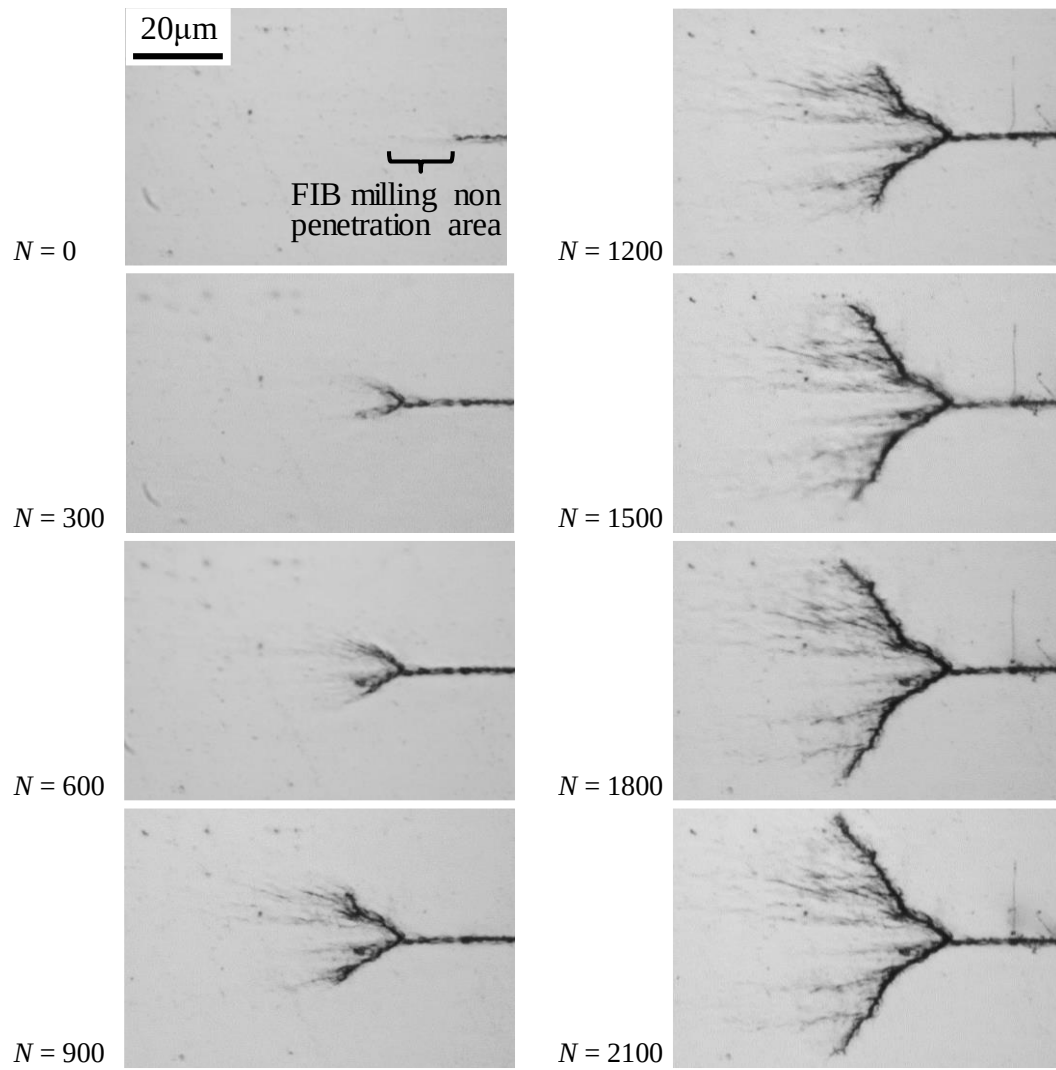
(a) Specimen #1, the right side of the FIB-notch.



(b) Specimen #1, the left side of the FIB-notch.

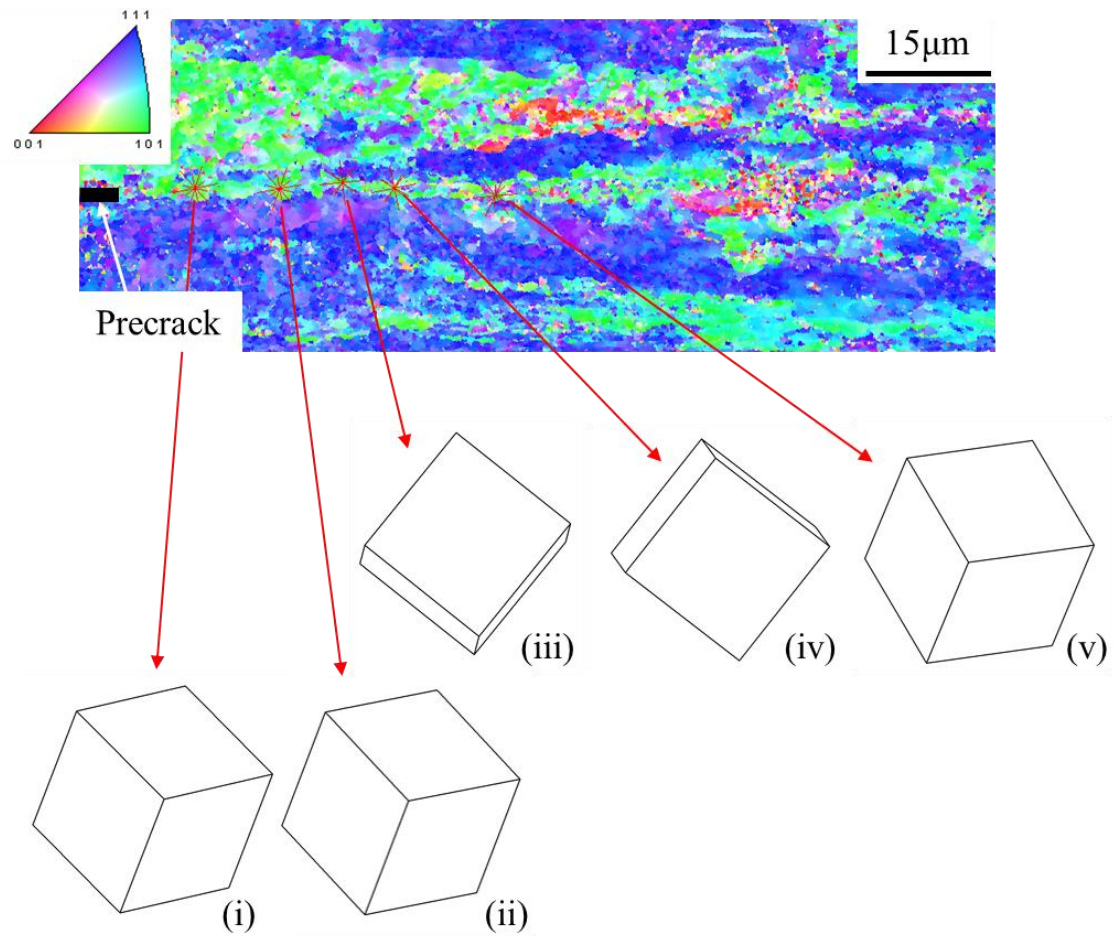


(c) Specimen #2, the right side of the FIB-notch.

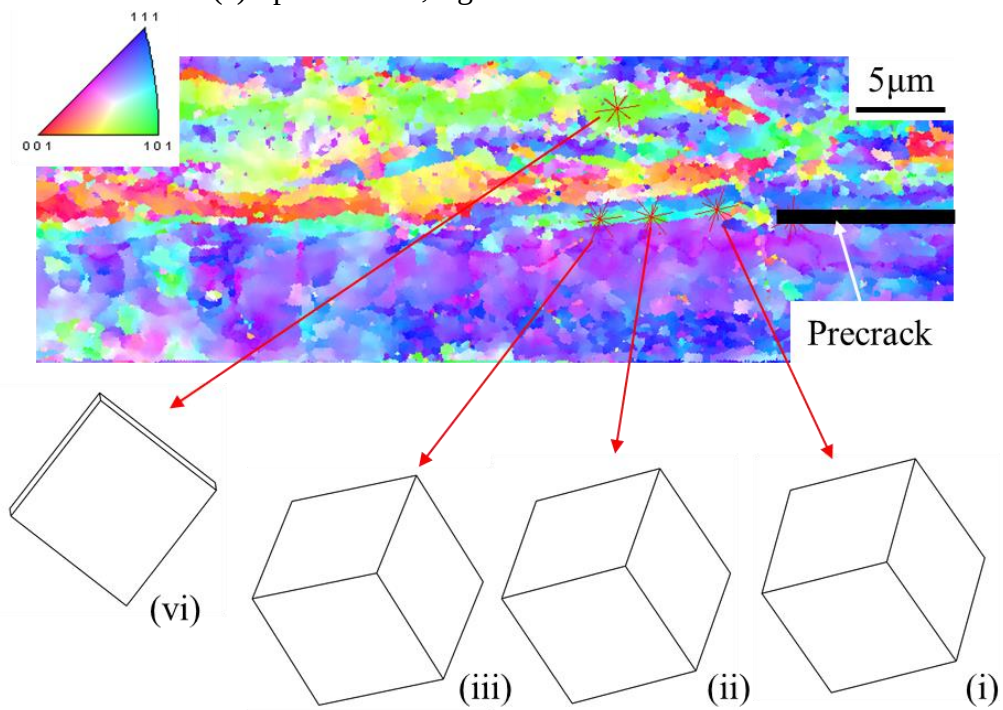


(d) Specimen #2, the left side of the FIB-notch.

Fig. 5 Optical micrographs of the fatigue crack propagation behavior.

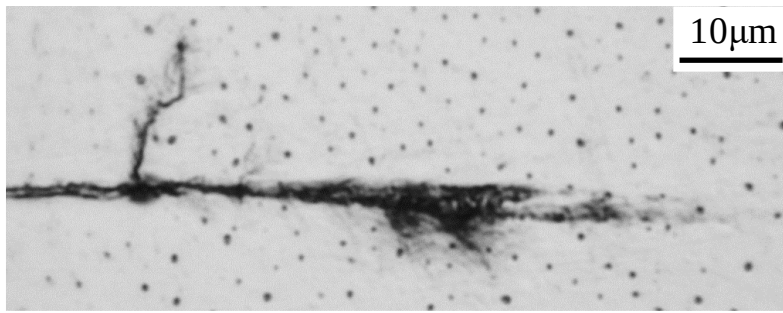


(a) Specimen #1, right side of the FIB-notch.

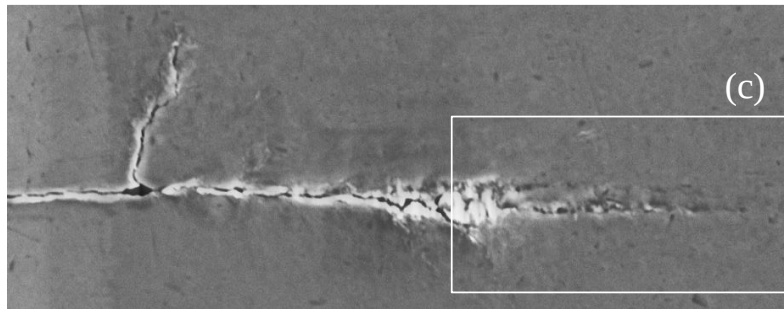


(b) Specimen #1, left side of the FIB-notch.

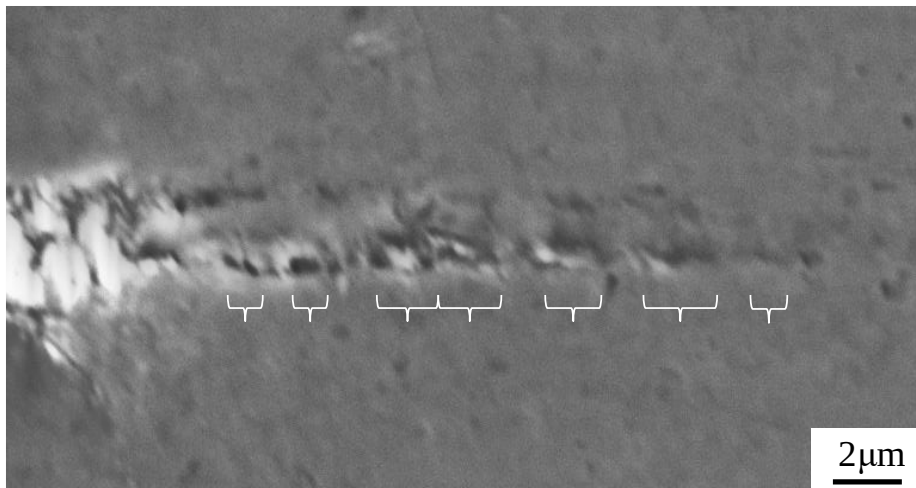
Fig. 6 Orientation of the crystals, TD plane.



(a) Optical micrograph.



(b) SEM image.



(c) Detail of crack tip.

Fig. 7 Fatigue crack morphology of the right side of the FIB-notch, specimen #1.

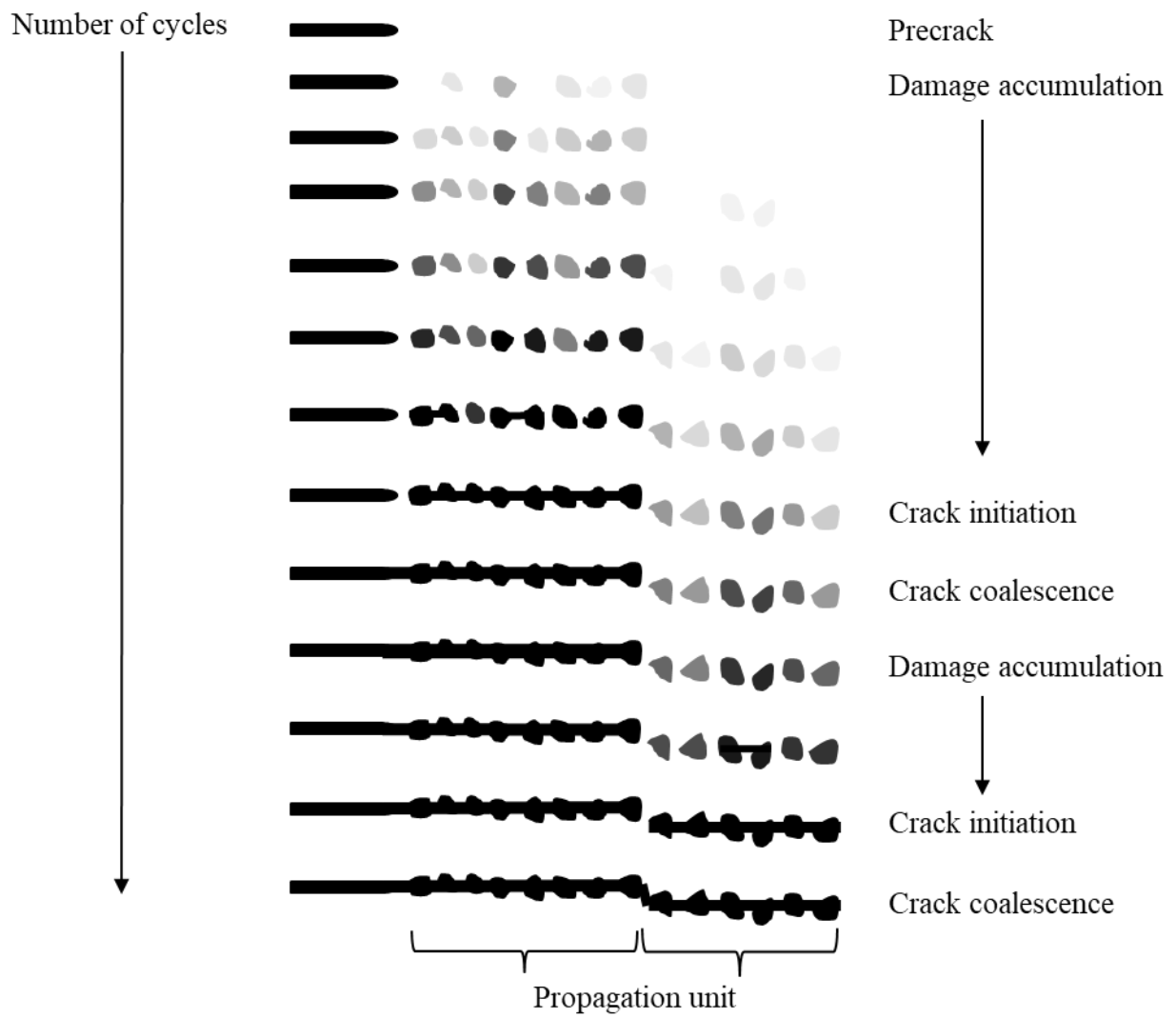


Fig. 8 Schematic of the fatigue crack propagation under mode II loading.

## 4. Discussion

### 4.1 Phenomena occurring ahead of the crack tip and corresponding steel modeling

In this study, the characteristic of the determined shear mode fatigue crack propagation is that the phenomenon occurs not at the crack tip but ahead of the crack. As shown in Fig. 7(c), void generation, which is a process of shear mode fatigue crack propagation, occurs simultaneously over a length of several tens of micrometers in the same direction as the crack. This indicates that within the region of the unit described in the previous section, the magnitudes of the loads that cause the phenomenon are generally similar. Considering the elastic analysis of an isotropic continuum body, it can be predicted that the location where the phenomenon occurs is the crack tip because of the concentration of a high shear stress here under mode II loading. However, it is necessary to consider the effect of the microstructure because the phenomenon that actually occurs is plastic deformation, and dislocation and slip phenomena, which are the basis of plastic deformation, are affected by the microstructure.

In metals, which are processed to form a texture, the slip phenomenon tends to occur in the unit present ahead of the crack tip. This is because of the easiness of the plane to slip. Therefore, the plane with a large shear load is aligned. The discussion on crack initiation by Zhai et al. (Zhai et al. 1990; Zhai et al. 1995) is helpful to understand the phenomenon that occurs in a unit subjected to cyclic shear loading. Based on experiment and observation of a crack initiation, Zhai et al. considered that “a microcrack may be initiated from a dislocation wall in a persistent slip band (PSB) due to the collapse of the wall” (Fig. 9).

The discussion by Zhai et al. (Zhai et al. 1990; Zhai et al. 1995) is applied to the present experimental results. In this experiment, in the unit, dislocation walls, dislocation substructures, and PSBs are assumed to be formed by cyclic shear loading. Therefore, both the dislocation density and cyclic shear plastic strain are averaged in the unit. However, the magnitude of the cyclic shear plastic strain in the unit is larger than those in the surrounding units. Therefore, the phenomenon of a high cyclic shear plastic strain in a given unit can be considered to be a result of the localized

shear plastic strain in it. The three factors of strain localization are as follows: (1) presence of units, (2) increase in the high stress acting on a unit with the stress concentration of the crack, and (3) crystal orientation of a unit. In addition, dislocation accumulates on the dislocation wall, and vacancies, which are the origin of void formation, are generated and accumulated; in comparison, voids or microcracks are only generated. Therefore, here, the fatigue crack propagation phenomenon can be considered to be vacancy accumulation occurring ahead of the crack tip. However, this phenomenon is speculation based on the SEM observation of the specimen surface. It is necessary to observe the dislocations of FIB-cut thin foils using TEM to prove the speculation.

In this study, it is necessary to consider that the metal in which the shear mode fatigue crack propagation phenomenon occurs is not an isotropic continuum body but an aggregate of units, where the region in which the crystal orientation is uniform is one unit. The prediction of the shear mode fatigue crack propagation by numerical analysis seems to be possible only by modeling a similar metal. The damage accumulation mechanism is considered to be not only the formation of a dislocation substructure and the subsequent vacancy accumulation but also other mechanisms.

#### **4.2 Fatigue crack propagation: plastic deformation mode and damage accumulation mode, and engineering classification**

Fatigue crack propagation on the precrack extension line in ductile metals subjected to cyclic mode I loading is caused by the plastic deformation. Thus, “plastic deformation mode” seems to be an appropriate term for representing the fatigue crack propagation of this mode. Contrastingly, as shown in this study, the fatigue crack propagation on the FIB-notch extension line subjected to cyclic mode II loading is caused by damage accumulation occurring ahead of the crack tip and by the subsequent void initiation and coalescence. Thus, “damage accumulation mode” seems to be an appropriate term for denoting the fatigue crack propagation of this mode.

The method that technically classifies the plastic deformation mode and damage accumulation mode is discussed. Figure 10 shows a schematic of the classification method. When the plastic deformation mode fatigue crack propagation, plastic strain remains in the wake of the crack tip. At

the crack tip, the absolute value of the compressive stress is not the same as that of the tensile stress; the latter is increased owing to the crack. And more, in spite of a positive macroscopic  $R$  ratio, the actual  $R$  ratio ahead of the crack tip can be negative, caused by the plastic strain. However, the loadings are not symmetry. This asymmetry of the loading is a factor because of which the plastic strain remains. In contrast, when the damage accumulation mode fatigue crack propagation, it is considered that the plastic strain does not remain, because the absolute values of the positive and negative loads are the same. Moreover, the load is symmetrical at and ahead of the crack tip where the phenomenon occurs. Indeed, dislocations that cause damage remain, but they are in a state of extra half planes, e.g., the dipoles in which the positive and negative dislocations are paired by positive and negative loadings are canceled. Therefore, it is considered that the plastic strain does not remain. However, in spite of the reversed loading, ratcheting can occur locally, then care must be taken in this case. From above discussion, based on the magnitude of the plastic strain remaining on the fracture surface, whether the fatigue crack propagation is a plastic deformation or damage accumulation mode can be classified from an engineering viewpoint.

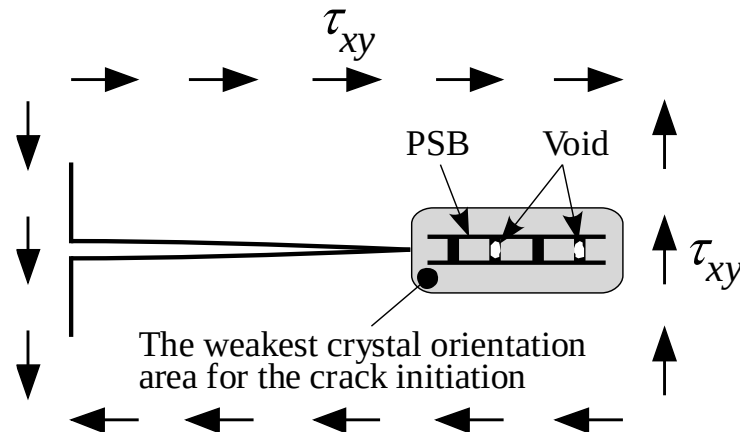


Fig. 9 Schematic of the void formation.

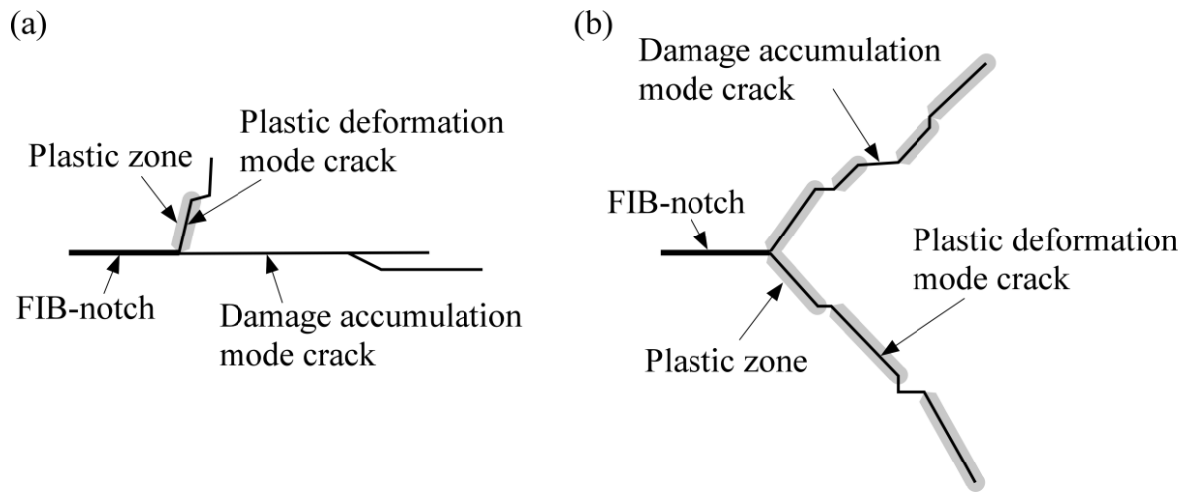


Fig. 10 Schematic of the method for classifying the plastic deformation and damage accumulation mode fatigue cracks. The gray area indicates the plastic zone.

(a) When the damage accumulation mode is dominant; an explanation of Fig. 5(a).

(b) When the plastic deformation mode is dominant; an explanation of Fig. 5(c).

## 5. Conclusions

In this study, by applying cyclic pure mode II loading, the shear-mode fatigue crack propagation phenomenon for a cold-rolled SUS 430 steel thin plate with a FIB-notch was successively observed. Consequently, the following conclusions were drawn:

- (1) A mechanism of the shear mode fatigue crack propagation is damage accumulation, which is considered to be vacancy accumulation due to the formation of a dislocation substructure, followed by the formation and coalescence of voids or microcracks. These phenomena occur not at the crack tip but ahead of the crack tip.
- (2) For crack propagation behavior prediction, “plastic deformation mode” and “damage accumulation mode” are proposed as the terms for representing the fatigue crack propagation modes instead of “tensile mode” and “shear mode”, respectively.
- (3) As a method to classify both the fatigue crack propagation modes using the experimental results, it is proposed to identify the plastic strain in the wake of the crack tip.

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