Relation between Fatigue Crack Initiation and Structure in Pearlitic Steel

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Abstract. To clarify the relation between fatigue crack initiation and the crystal structure in pearlitic steel used for railroad rails, fatigue tests are performed, focusing on crack initiation. Then, the fracture surfaces are analysed using a scanning electron micro-scope (SEM). To observe the crystal structure, before the fatigue is performed, the specimen surface is etched chemically. The crystal structure of pearlitic steel, is comprised of "pearlite colonies" which have the same lamellar structure direction, and "pearlite blocks" which have the same ferrite crystal direction. A fatigue crack initiation region should be affected by the crystal structure; however, the relation between the crack initiation region and the crystal structure in pearlitic steel has not been clarified. From the fatigue test results, the fatigue crack of the pearlitic steel was initiated at a very early stage of the fatigue test. To determine the unit of fatigue crack initiation in pearlitic steel, the relation between the crack initiation region and crystal structure was clarified by using SEM analysis.

Introduction

To predict the fatigue limit of pearlitic steel, which is used for railroad rails, the relationship between fatigue crack initiation and the crystal structure was clarified. Figure 1 shows the crystal structure in pearlitic steel. Pearlitic steel has a hierarchical crystal structure, for example, prior austenite, pearlite block, and pearlite colony, in descending order of size from the large crystal structure unit [1, 2]. The pearlite colony, which is the minimum unit of a hierarchical crystal structure, is made up of a lamellar structure consisting of cementite and ferrite. The pearlite block is made up of pearlite colonies with the same ferrite crystal orientation. Pearlitic steel has a complicated structure as mentioned above. Urashima et al. [3] performed rotating bending fatigue tests on smooth specimens of pearlitic steel to investigate the initiation and propagation behaviour of fatigue cracks. Based on the result, the fatigue ratio (fatigue limit/tensile strength) of pearlitic steel was found to be lower than that of common steels. Hamada et al. [4] reported the reason for this is that a fatigue crack almost the same size as a pearlite block is initiated during the very first stage of the fatigue life. From that point, it can be considered that pearlitic steel should be treated as a material that has a defect from the first stage of the fatigue life. Based on their result, it is thought that the fatigue limit of pearlitic steel can be predicted using Eq. 1, which was proposed by Murakami: [5]

$$\sigma_w = \frac{1.43(HV+120)}{\sqrt{area}^{1/6}} \quad (R=-1), \tag{1}$$

where σ_w is fatigue limit (MPa), *HV* is the Vickers hardness (kg/mm^2), and $\sqrt{}$area is the initial defect size (μm). It is necessary to provide a reasonable definition of the $\sqrt{}$area for applying this equation to pearlitic steel. To define this factor, the unit of the initial crack must be known. In pearlitic steel, there are domains such as the pearlite block and the pearlite colony, as already described, and it is necessary to clarify the relation between the initial crack and the crystal structure to determine the unit of fatigue crack initiation. If the unit of fatigue crack initiation can be grasped, the fatigue limit of the pearlitic steel can be controlled, and if the size is controlled to be small, the fatigue limit will be improved. To determine the unit of fatigue crack initiation of pearlitic steel, the relation between the crack initiation region and the crystal structure is clarified.

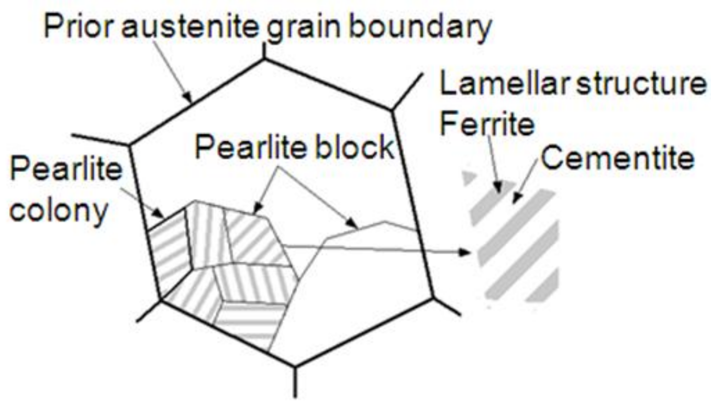

Fig.1. Schematic diagram of pearlitic steel microstructure.

Test Method

Test material. Table 1 shows the chemical composition, and Table 2 shows the mechanical characteristics of the tested material. The material was held for 30 min at 1000 °C, for 10 min at 620 °C, and then cooled in water. The average size of a pearlite block, which was obtained using the electron backscattered diffraction (EBSD) method, was about 78 μm. The fatigue limit of this material, which is obtained using the same specimen using equipment that will be described later, was 400 MPa.

Fatigue test. Figure 2 shows the shape and dimension of the fatigue test specimen. The specimens were mechanically polished finally with #2000 emery paper and then buffed. An Ono-type rotating bending fatigue machine was used for the fatigue test. The stress ratio was −1. The fatigue tests were performed at room temperature. The test frequency was 30 Hz. Using the plastic replica technique, the microscopic deformation behaviour and crack behaviour were successively observed on the specimen surface. After the fatigue tests, scanning electric microscope (SEM) observations were performed on the fractured surfaces.

Table 1 Chemical composition of the tested material.

C	Si	Mn	P	S	Cr	N
0.89	0.40	0.92	0.018	0.013	0.24	0.04

Table 2 Mechanical properties of the tested material.

$\sigma_{0.2}$ [MPa]	σ_B [MPa]	HV [200 gf]
671	1129	327

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

σ_B: ultimate tensile strength

HV: Vickers hardness

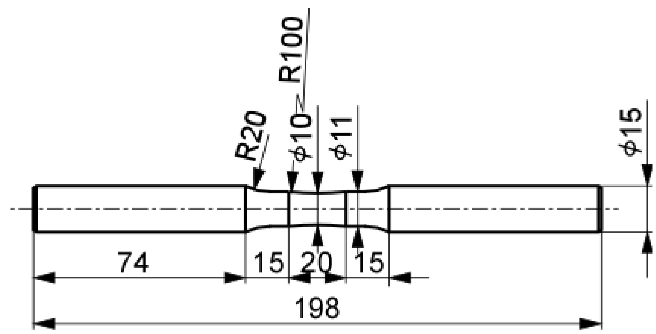

Fig.2. Shape and dimension of the specimen for the fatigue test.

Test results and discussion

Relation between crack initiation and lamella structure. The specimen endured repetitive applied load stress (σ_a = 395 MPa) of $N = 1.0\times10^7$. Because the applied load stress was near the fatigue limit (400 MPa), initiating and non-propagating fatigue cracks were expected. After $N = 1.0 \times 10^7$ repetitions of applied loads stress, a repetitive load stress of σ_a = 470 MPa was applied to the specimen for the fractographic study, and failure was forced. Figure 3 shows fracture surface around a fatigue crack initiation origin. Figure 3(a) shows the morphology of the entire fracture surface. Figure 3(a) shows the fatigue crack initiation origin. Figure 3(b) shows an enlarged view of Fig. 3(a). A facet was observed on the fatigue crack initiation origin. The dashed line in Fig. 3(b) shows the boundary of the facet domain. Figure 4 shows a fatigue crack 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 treat as cracks. Figure 5 shows the detail of the fatigue crack initiation origin on the replica in comparison with the failure specimen. To obtain the resolution, which can show the relation between the crack initiation and the crystal structure of this material, the observation was performed on the domain indicated Fig. 4(a) by a square drawn with a dotted white line. Figure 6(a)-(c) shows the observations from the number of cycles N = 0 to $N = 1.0 \times 10^6$. Figure 6(c) 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 is traced back, successive observation as shown in Fig. 6(a)-(c) is possible. Figure 6(b), shows a fatigue crack initiation of about 1 μm length in a ferrite, which can be confirmed in the early stage ($N = 1.0 \times 10^4$) of the fatigue process; this is shown is shown as lighter grey in the figure. Then, after a number of cycles, a crack appears, (the area that appears white and is becoming thick and long), which has become a fatigue crack. In Fig. 4(a), the crack that was initiated first looks like a 10-μm-length crack. However, a detailed examination of Fig. 6(a)-(c) reveals that short cracks connect and become visible as a crack. Then, it is thought that the crack grew to be a fatigue crack, which can cause a fatigue failure. The above result showed that the initiation of a fatigue crack took place in a ferrite domain located near a cementite domain. It is thought that the reason for the above phenomenon was that the cementite domain restricted plastic deformation of the ferrite domain.

Relation between crack initiation and domain of the pearlite colony. Figure 7 shows the relation between crack initiation and the domain of the pearlite colony. In Fig. 7, the boundary of the pearlite colony is indicated with dashed lines. It turned out that fatigue cracks were initiated in accordance with the lamellar structure, and that the fatigue cracks were initiated in multiple pearlite colonies. Moreover, the pearlite colonies had a lamella structure in almost the same direction. It also turned out that the fatigue cracks formed a line macroscopically. Hamada et al. [6] carried out a detailed analysis regarding fatigue crack initiation in pearlitic steel. They observed a facet on the fatigue crack initiation origin, and a fatigue crack was initiated by slip within a pearlite block. Therefore, the fatigue crack observed in Fig. 7 appears to have been initiated by slip within a pearlite block, and the direction of the slip plane appears to have been in the same direction as the maximum shear stress from the load. Moreover, the direction of the lamella structure in the pearlite colony where the fatigue crack was initiated appears to have been the same as the direction of the slip plane in order for the slip of a ferrite domain acts as a crack. Therefore, by including the observations in the present study, fatigue crack initiation appears to take place at the place under the following three conditions: (a) the direction of the slip plane is the same as the direction of maximum shear stress caused by the load. (b) the direction of the lamella structure in the pearlite colony is the same as the direction of the slip plane, and (c) multiple pearlite colonies that satisfy (b) are located sublinearly. The direction of the line satisfies (a). However, the relative relation of each pearlite colony whose lamella structure corresponds to a pearlite block does not assume a fixed form. Because the above conditions contain many uncertainties, it is presumed that the size of the unit of fatigue crack initiation is a pearlite block. The detailed examination of this is a future task. However, the upper limit of the initial defect size is considered to predict the fatigue limit of pearlite steel for safety. If some pearlite colonies, which satisfy the above condition accidentally, lie linearly next to each other, the initial defect size is the pearlite block size. The boundary of a pearlite block constrains fatigue crack initiation because a fatigue crack is initiated by slip. Therefore, the upper limit of the initial defect size appears to be that of a pearlite block. The initial defect size for the prediction of the fatigue limit of pearlite steel appears to be the pearlite block size.

Fatigue limit estimation and result. The fatigue limit of pearlitic steel was predicted using Eq. 1. The initial defect size was treated as the pearlite block size. The defect shape was treated as a semicircle. The diameter of the semicircle was the dimension of the pearlite block size. The *HV* (hardness) was treated as a Vickers hardness of 200 gf. Table 3 shows the fatigue limit predicted by Eq. 1 and the fatigue limit obtained from the fatigue test. The equation has a margin of error of about 10%. However, the fatigue limit was about 17% higher than predicted. The reason for this is thought to be that estimation of the initial defect size was larger than the actual initial defect size, and that the appropriate Vickers hardness of pearlitic steel, which has a complex texture, has not been clarified for use in the equation. The detailed examination of the appropriate Vickers hardness is a future task.

Conclusion

To clarify the relation between fatigue crack initiation and crystal structure in pearlitic steel, fatigue tests were performed. The results are outlined below.

1. By including the observation in the present study with those of previous studies, it was determined that fatigue crack initiation appears to occur under the following three conditions: (a) the direction of slip plane is the same as the direction of maximum shear stress, which is caused by load, (b) the direction of the lamella structure in the pearlite colony is the same as the direction of the slip plane, (c) multiple pearlite colonies that satisfy (b) are located sublinearly. The direction of the line satisfies (a).
2. The unit of fatigue crack initiation appears to be a pearlite block.
3. The initiation of fatigue crack takes place in a ferrite domain located near a cementite domain. It is thought that the reason for this is that the cementite domain restricts plastic deformation of the ferrite domain.

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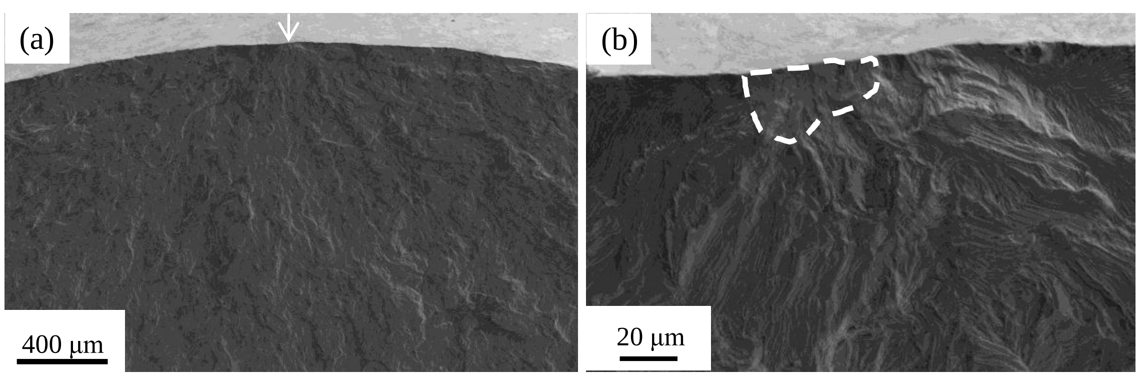

Fig.3. SEM images of the fracture surface and fatigue crack initiation origin. (a) Around the fatigue crack initiation origin. (b) Magnification of (a); dashed line shows the boundary of the fatigue crack initiation origin domain.

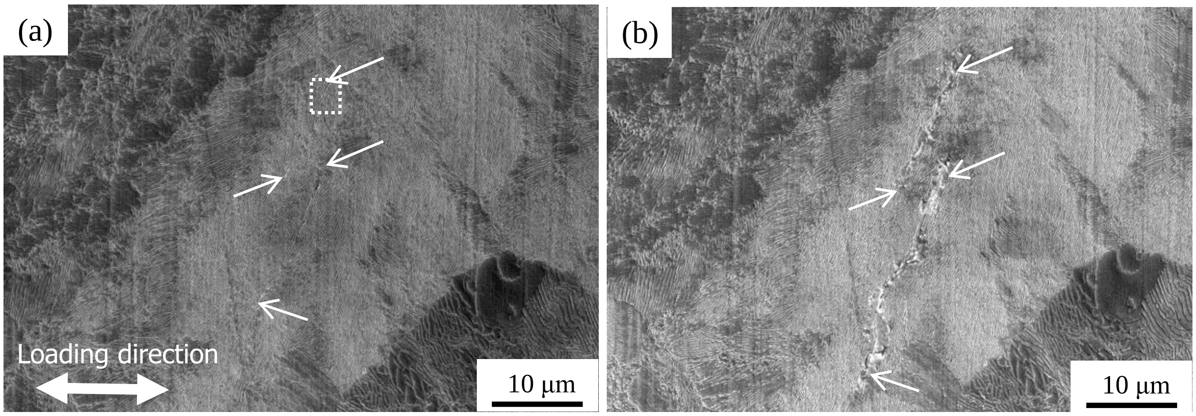

Fig.4. FE-SEM images of the replica around the fatigue crack initiation origin. (Arrows indicate the characteristic points). (a) $N = 1.0 \times 10^6$ (white line indicates the magnified area of Fig. 7 (a)-(c)). (b) $N = 1.0 \times 10^7$.

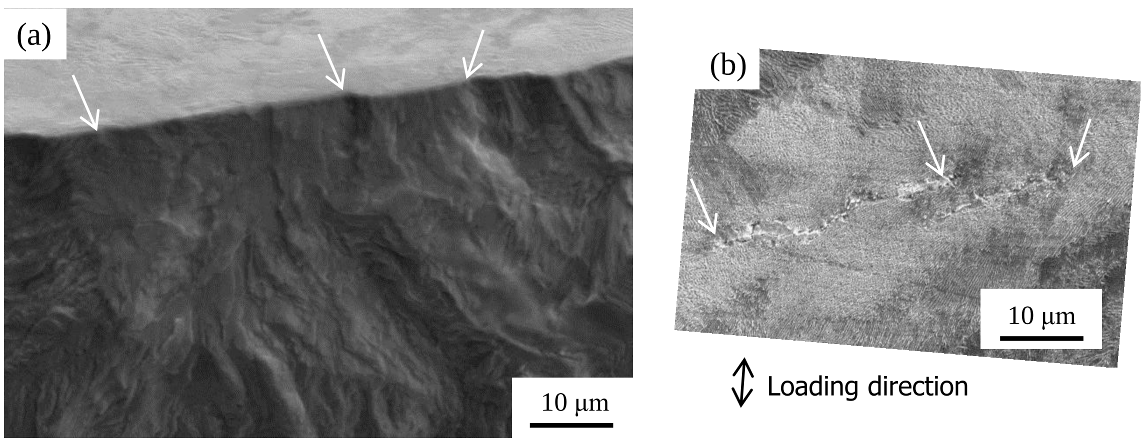

Fig.5. Around the fatigue crack initiation origin (arrows indicate the characteristic points). (a) Fracture surface and surface of the fractured specimen. (b) Replica (mirror-reversed image, $N = 1.0 \times 10^7$)

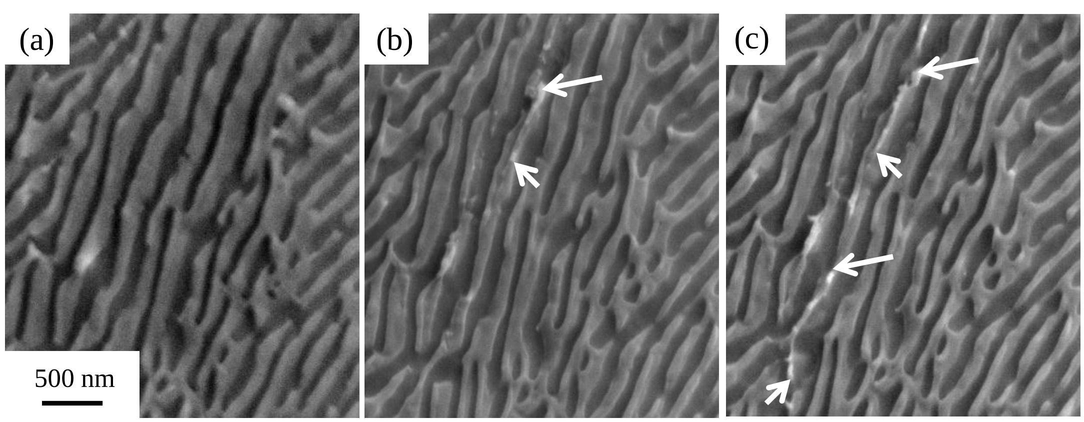

Fig.6. FE-SEM images of the replica around the fatigue crack initiation origin. (Arrows indicate the characteristic points). (a) $N = 0$. (b) $N = 1.0 \times 10^4$. (c) $N = 1.0 \times 10^6$.

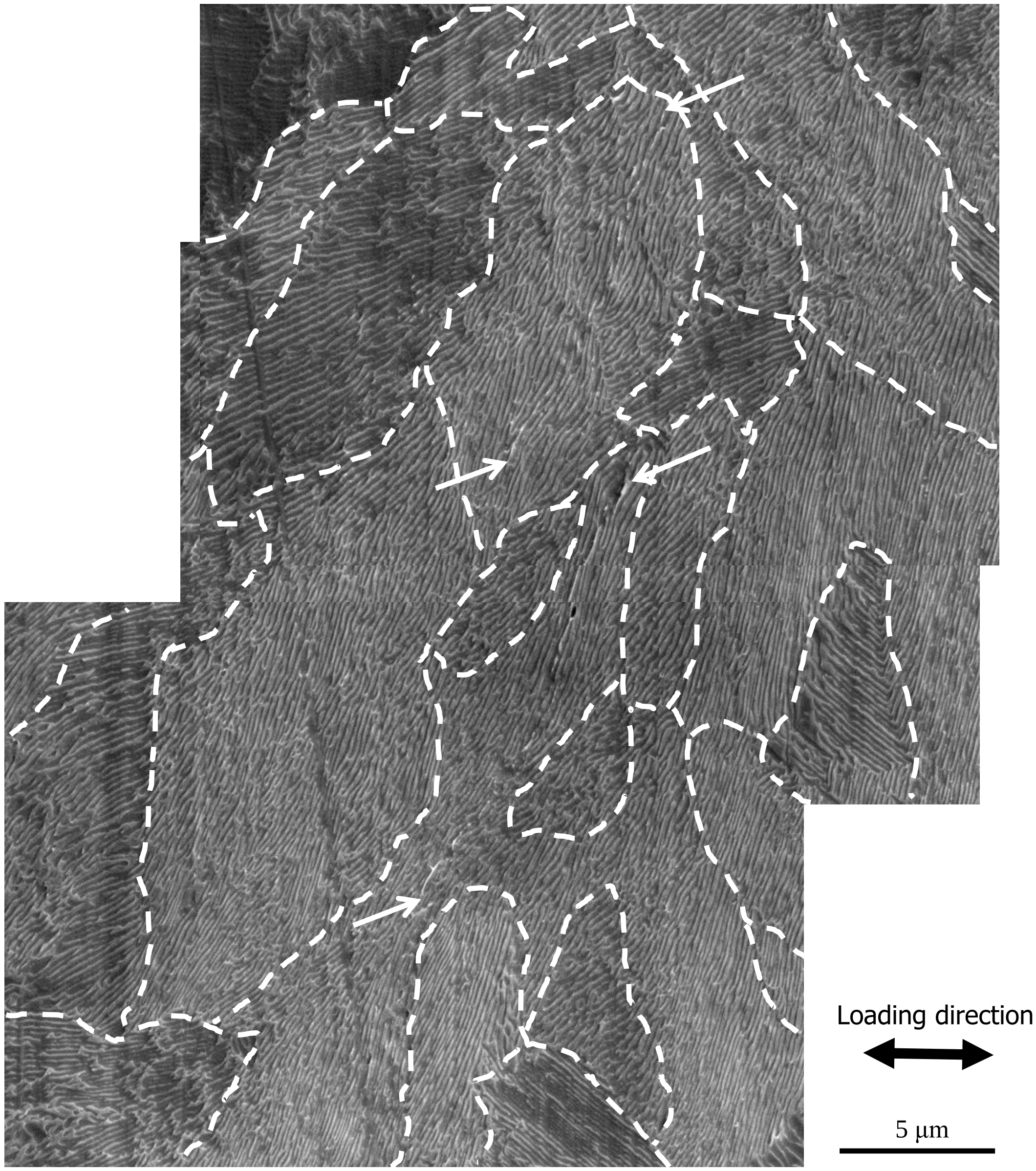

Fig.7. Relation between crack initiation and domain of the pearlite colony (dached white lines indicate the boundaries of the pearlite colonies, arrows indicate the crack tips).

Table 3. Results of fatigue limit prediction

HV [200 gf]	Pearlite block size [μm]	√area	Predicted fatigue limit	The fatigue limit obtained by fatigue test	Error
412	54 μm	33.8 μm	423 MPa	510 MPa	17 %
384	67 μm	42.0 μm	387 MPa	465 MPa	17 %
327	78 μm	48.8 μm	334 MPa	400 MPa	16 %