Fatigue limit evaluation considering crack initiation for lamellar pearlitic steel

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Abstract

In order to evaluate the fatigue limit of lamellar pearlitic steel used for railroad rails, tensile tests and fatigue tests are performed. Although the fatigue ratio of the lamellar pearlitic steel is lower than that of general steels, the reason for this has not been clarified. The fatigue cracks of the pearlitic steel initiate at a very early stage during the fatigue test. It is speculated that the steel should be treated as a steel with initial defects. In order to determine the initial defect size of the ultra-low cycle fatigue test, tensile tests are performed. Based on the test results, it was clarified that the crack initiation size depends on the crystal structure. In order to predict the fatigue limit of the pearlitic steel, Murakami’s prediction method is applied to the steel. The measured defect sizes are applied to the method, and the fatigue tests are performed. The predicted fatigue limits and the test results have good agreement. In addition, from the SEM observations, the initial crack causing the fatigue failure was found to be a pearlite block. We then concluded that the fatigue limit of the pearlitic steel can be predicted by Murakami's method and the defect size is the pearlite block size. If the pearlite block sizes then become small, the fatigue limit of the pearlitic steel will increase.

1. Introduction

The pearlitic steel, which is used for railroad rails, has a microscopic in-layer pearlitic crystalline structure, which is called a lamella structure. In the crystalline structure, there are domains called the...
“pearlite block” which have a constant ferrite crystal direction, and there is another domain called the “pearlite colony” which has a complete set of directions for a lamella crystalline structure [1, 2]. Figure 1 shows a schematic diagram of the pearlite crystalline structure and Fig. 2 shows the microstructure of the pearlitic steel.

Urashima et al. [3] performed rotating bending fatigue tests of railroad rail smooth surface specimens in order to investigate the initiation and propagation behavior of the fatigue crack. Based on their result, the direction of the lamellar microstructure in railroad rail steel, which has a lamellar pearlitic microstructure, is affected by the fatigue crack initiation. The fatigue ratio (fatigue limit / tensile strength) of the lamellar pearlitic steel is lower than that of general steels, but the reason for this has not been clarified. A crack that is almost the same size as the “pearlite block” initiates at 1 to 4 % number of cycles to failure. From the results that the fatigue crack initiates during the very first stage of the fatigue life, it can be considered that the fatigue life of the pearlitic steel is a crack propagation-life-like material which has a crack equivalent “defect” from the first stage of the fatigue life. A new problem now emerges as to what is the “defect” on smooth surface material. Since it is thought that the defect is the weakest part of the smooth surface pearlitic steel, if some load is applied to the material, it can be expected that the weakest part appears as a “defect”, i.e., a crack. In the pearlitic steel, there are domains such as the “pearlite block” and the “pearlite colony” as already described, and if the relation for the weakest part of each domain is clarified, knowledge of the fatigue characteristics of the pearlitic steel can be expected.

Fig. 1 Schematic diagram of the pearlite steel microstructure

Fig. 2 Microstructure of the pearlite steel (SEM picture)
2. Test Method

2.1. Test materials

The test materials included pearlitic steels that are used for railroad rails. Table 1 shows the chemical composition. In order to compare the fatigue characteristics, which have different pearlite block sizes, colony sizes and hardness, three materials (Material A, B and C) that have different heat treatment conditions were used for the tests. Table 2 shows the mechanical characteristics of each material.

2.2. Tensile test

In order to investigate the weakest area of the smooth surface specimen, tensile tests were performed. Figure 3 (a) shows the shapes and dimensions of the static tensile specimens. The specimens were mechanically-polished with #2000 emery paper, then buffed. The specimens were next etched for observing the crystal structure. The static tensile tests were performed at room temperature. The stroke speed of the test machine was 0.5mm/s. The stress-strain curves were obtained by carrying out the static tensile test using specimen type A which was formed on the basis of JIS (Japanese Industrial Standards) Z 2201. The total strain was measured by an extensometer. Specimen type B has a shorter length than specimen type A in order to observe the entire test area during the static tensile test. Using the plastic replica technique, the microscopic deformation behavior was continuously observed on the specimen surface.

Table 1. Chemical composition (mass%)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.89</td>
<td>0.4</td>
<td>0.92</td>
<td>0.018</td>
<td>0.013</td>
<td>0.24</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties

<table>
<thead>
<tr>
<th>Material</th>
<th>(\sigma_{0.2} ) [MPa]</th>
<th>(\sigma_B ) [MPa]</th>
<th>HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>873</td>
<td>1268</td>
<td>413</td>
</tr>
<tr>
<td>B</td>
<td>671</td>
<td>1129</td>
<td>327</td>
</tr>
<tr>
<td>C</td>
<td>765</td>
<td>1224</td>
<td>384</td>
</tr>
</tbody>
</table>

Fig. 3 Shapes and dimensions of the specimen for the tensile test; (a) For tensile test; (b) For fatigue test
2.3. Fatigue test

Figure 3 (b) shows the shapes and dimensions of the fatigue test specimen. The tested surface is treated as the tensile test specimen. In order to evaluate effect of a defect, a small hole was introduced. The hole was introduced after the buff-polishing. For the fatigue test, an Ono-type rotating bending fatigue machine were used. The fatigue tests were performed at room temperature. The test frequency was 30Hz. After the fatigue tests, scanning electric microscopic (SEM) observations were performed on the fractured surfaces.

3. Test results and discussion

3.1. Tensile test

Figure 4 shows the stress – strain curve of the pearlitic steels. From the figure, we found that the pearlitic steel had undergone a strong work hardening. Figure 5 shows an example of the crack on the specimen surface during the tensile test. The size of the crack has some relation to the crystal structure. The crack sizes of the tested materials are as follows: materials A and B are about 30μm and material C is about 20μm. Based on the optical microscopic observations, the crystal directions cannot be determined, thus we cannot determine the relationship between the crack size and pearlite block or colony size from the optical microscopic observations.

![Stress-Strain Curve](image)

Fig. 4 Stress-Strain Curve

![Static tensile crack](image)

Fig. 5 Static tensile crack (material A, arrow shows crack tip); (a) ε = 0.0 %; (b) ε = 4.0 %
3.2. Fatigue limit estimation and discussions

The fatigue limits of the pearlitic steel are predicted using the idea that the weakest area would appear as a crack when a static load is applied to the specimen as described in the introduction and by using the equation (1) proposed by Murakami. The defect shape for Murakami’s equation is treated as a semicircle.

\[
\sigma_w = \frac{1.43(HV+120)}{(\sqrt{\text{area}})^{1/6}}
\]  

(1)

The \(\sqrt{\text{area}}\) obtained from the tensile test of materials A, B and C are 30, 30 and 20\(\mu\)m, respectively. The predicted fatigue limits (\(\sigma_w\)) of the smooth surface specimen by equation (1) for materials A, B and C are 432MPa, 362MPa and 437MPa, respectively. Figure 6 shows the fatigue test results. The fatigue limits (\(\sigma_w\)) of materials A, B and C are 510MPa, 400MPa and 480MPa, respectively. Figure 7 shows the relationship between the predicted fatigue limit and defect size. The tested fatigue limits are 9 to 15% higher than that of the predicted, but when compared with Murakami’s results for various materials [4], the results show good agreements. As already mentioned, it is thought necessary to treat the pearlitic steel as a material which has a defect when repeated loads are applied to the material, because the crack initiated during the early stage of the fatigue life. The sizes of the defects correspond to the crystal structure.

3.3. Fracture surface analysis

Although the initial defect size measured by the tensile test treated the shape of the crack as a semicircle, validity confirmations are needed. Figure 8 shows the observed SEM pictures for material B. The shape of the crack initiation point is semicircular in shape and the defect size is almost the same as the size measured by the tensile test. In addition, unlike the surrounding fatigue fracture surface, the fracture surface looks like a brittle fracture surface. Figure 8 (b) shows the SEM photograph for the 60-degree inclined fracture surface. The brittle fracture surface at the crack initiation point consists of three steps. The boundaries of the steps correspond to the boundary of the pearlite colony. The initial crack is then presumed not to be the pearlite colony, but the pearlite block.

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![Fig. 6 S-N Curve](image)
Fig. 7 Relationship between $\sigma_w / (HV+120)$ and $\sqrt{\text{area}}$

Fig. 8 Fatigue fracture surface of material B ($\sigma_w = 410\text{MPa}$, $N_f = 5.26 \times 10^5$ cycles, Dashed line shows fatigue crack initiation); (a) Fracture surface; (b) 60-degree inclined fracture surface

4. Conclusion

It is presumed that the method of substituting the pearlite block size as the defect size is appropriate using equation (1) as the prediction method for the fatigue limit of the pearlitic steel.

References