Fatigue Properties of Pre-strained Eutectoid Steel

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Abstract: Eutectoid steel is one of the most important industrial materials. In addition, these materials are usually pre-strained before use during production or machining process. In this study, fatigue test has been performed to research the effect of pre-strain on fatigue properties of eutectoid steel with different plastic pre-strain ratio at \( \varepsilon_p = 0 \), 2%, 4% and 6%, respectively. At the same time, microscopic behavior of the crack initiation and propagation are also investigated by the successively taken replica method during the pre-strain and fatigue test. The results of the research indicate pre-strain directly affect the fatigue strength and crack initiation and propagation behavior. All fatigue limits of specimens with different pre-strain ratio are lower than that of specimens without pre-strain (\( \varepsilon_p = 0 \)) and the fatigue limits of pre-strained specimens have no obvious change from \( \varepsilon_p = 2\% \) to 6%. Fatigue cracks initiate from slip lines or micro-cracks that are generated in the process of plastic pre-strain. However, for non-pre-strained one, fatigue cracks initiate from boundary or inter-lamellar of the pearlite. The mechanism for this difference is discussed in this paper.

Key words: Eutectoid steel, Fatigue property, Fatigue crack, Pre-strain, Initiation, Propagation, Rail, Fractography

1. INTRODUCTION

As one of the most important industrial materials, eutectoid steel is used in many industrial fields. For example, rails, wheels, wires, and other machine parts. In practical structural component, many of the components are pre-strained before use or machining process. Although there have been extensive researches concerning eutectoid steel in different aspects (1-8), it is fairly difficult to find out the report about the effect of pre-strain on its fatigue strength and detailed microscopic behavior. The purpose of this study is: to clarify the effect of pre-strain on fatigue strength of eutectoid steel; to investigate its microscopic behavior during plastic pre-strain and fatigue experiment; to study fatigue crack initiation and propagation behavior.

2. EXPERIMENTAL PROCEDURE

The material used in this test is new head hardened rail (NHH). Tables 1 and 2 list the chemical composition and mechanical properties of the specimens, respectively. A conventional carbon rail and NHH rail differ in grain size and surface hardness. NHH rail has finer pearlitic grain size and higher surface hardness than the conventional one. The Vickers hardness of the NHH rail can be Hv. 350-380. These differences will improve the fatigue strength and anti-wear property. The specimens of this test were taken from the upper part of the railhead in longitudinal direction.

Figure 1 shows the shape and dimensions of the specimen for pre-strain and fatigue test. In this figure, solid lines describe the pre-strained specimen and dotted lines describe the fatigue specimen. A shallow notch was made to ensure the fatigue crack would be initiated in this part and it is certified this kind of notch does not affect the fatigue limit of the test material. All of the specimens were annealed in vacuum at 520°C for 30 minute and then electro-polished to the depth of 50\( \mu \)m in diameter to relief the residual stress and remove the work hardened layer. The pre-strain was given by universal testing machine and the microstructure of the specimen was observed by successively taken replica method. The fatigue test was performed with Ono-type rotating bending fatigue testing machine and the hardness were tested with Vickers hardness tester.

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>T-Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.78</td>
<td>0.21</td>
<td>0.89</td>
<td>0.023</td>
<td>0.08</td>
<td>0.03</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties.

<table>
<thead>
<tr>
<th>( \sigma_{0.2} ), MPa</th>
<th>( \sigma_b ), MPa</th>
<th>RA, %</th>
<th>El, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>823</td>
<td>1260</td>
<td>34.0</td>
<td>15.7</td>
</tr>
</tbody>
</table>

Fig.1. Shape and dimensions of the specimen for pre-strain and fatigue test.
Fatigue Properties of Pre-strained Eutectoid Steel

3. RESULTS AND DISCUSSION

3.1. Pre-strain Test

Figure 2 shows the stress-strain curve of eutectoid steel. The yield point, tensile strength, reductions of area and elongation ratio are 823MPa, 1260MPa, 34% and 15.7% respectively, as listed in Table2.

A SEM (Scanning Electron Micrograph) and an optical microscope were used to research the fatigue cracks initiation, propagation behavior and fracture surface.

### Table 3. Relationship of $\varepsilon_p$, Hv and $\sigma_w0$

<table>
<thead>
<tr>
<th>$\varepsilon_p$, %</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hv</td>
<td>350</td>
<td>353</td>
<td>357</td>
<td>357</td>
</tr>
<tr>
<td>$\sigma_w0$, MPa</td>
<td>425</td>
<td>385</td>
<td>390</td>
<td>385</td>
</tr>
</tbody>
</table>

Figure 6. Relationship of fatigue limit and pre-strain ratio.
Tensile force was given along the axial direction. Successive observation of surface under plastic pre-strain is shown in Fig. 3. From the photos, slip line or microscopic crack occurred in the surface of the tensile specimen. Fig. 4 shows the detail observation result of pre-strain ratio at $\varepsilon_p=2\%$, it is clear that the slip lines and micro cracks were initiated in the pearlite block by crossing the lamellar\(^{(9)}\).

Almost all of the slip lines and microscopic cracks that generated in the pre-strain process were inclined about 20° to 45° to the tensile direction, which indicates that the above direction is nearly coincident with the maximum shear stress direction.

### 3.2. Fatigue Strength

Table 3 shows the relationship of pre-strain ratio, Vickers hardness after pre-strain and the fatigue limit. Figure 5 shows the S-N curves of eutectoid steel. The fatigue limits of specimens at $\varepsilon_p=0\%$, 2\%, 4\% and 6\% are 425MPa, 385MPa, 390MPa and 385MPa, respectively.

All of the fatigue limits of the pre-strained specimens are lower than that of the specimen without pre-strain ($\varepsilon_p=0\%$). The fatigue limit of eutectoid steel becomes a little decrease by 2\% and has no obvious change until $\varepsilon_p=6\%$. The increase in the plastic pre-strain ratio did not cause apparent changes in the fatigue limits. This phenomenon is in contrast to other structural steels from low carbon steel S15C to medium carbon one S45C\(^{(10)}\), as shown in Fig. 6. As far as S15C to S45C, the fatigue limits increase with the increase of the pre-strain ratio, even though the fatigue strength of the pre-strained specimen decreased at small pre-strain ratio ($\varepsilon_p=2\%$).

For all of the tested materials (from low carbon steel S15C to eutectoid steel), the fatigue limits at $\varepsilon_p=2\%$ become lower than those without pre-strain, the above phenomenon may be due to the slip lines generated in the process of pre-strain. It is the slip lines that make microscopic plastic deformation during fatigue easier than that of the non-pre-strained one. For the low and medium carbon steels, with the increase of the pre-strain, the density of the dislocation was also increased. At the same time, the material was strengthened due to work harden-
Fatigue Properties of Pre-strained Eutectoid Steel

Both of them may improve the fatigue limit of the material. Therefore the fatigue strength was improved with the increase of the stress ratio and the fatigue limits of pre-strained specimen could be higher than their virgin one. On the other hand, for the eutectoid steel, all the microstructure is fine pearlite, and the effect of strain hardening is not obvious (the increase in hardness is only Hv 7, as listed in Table 3), the effect of work hardening would just compensate that of the slip line or micro-crack, it may be the reason why the fatigue limits of eutectoid steel have no obvious difference at different plastic pre-strain ratios.

According to Fig.6, the fatigue limit ratios decrease with the increase of carbon content at the same pre-strain ratio. The reason for this phenomenon may be explained by the main effect factor of the tensile strength and fatigue limit. The tensile strength is decided by the average strength of the grains; on the other hand, the fatigue limit depends on the microscopic strength of the weakest grains. Table 4 lists the mechanical properties and fatigue limit from low carbon steel S15C to high carbon eutectoid steel. With the increase of the carbon content, the average strength increased significantly, that is, the tensile strength increase from 442MPa to 1260 MPa; however, the microscopic strength in the weakest point (ferrite grains in this case) has no obvious increase from S15C to S45C, the result shows the fatigue limit just increase from 205MPa to 250MPa. For eutectoid steel, although the microscopic strength becomes remarkably increased because of its pure pearlitic structure, the increase value on fatigue limit is smaller than that in the increase of tensile strength; it is the reason why the fatigue limit ratio at the same pre-strain ratio decreases with the increase in carbon content.

Figure 6 also shows different tendency. That is: for low and medium carbon steel S15C to S45C, fatigue limit ratios increase with the increase in plastic pre-strain ratios, and the fatigue limit ratios could be higher than their original fatigue limit ratios (S15C, S25C and S35C) or get to almost the same fatigue limit ratio of the original one (S45C). On the other hand, for eutectoid
Fig. 10. An example of fatigue crack initiation site 
\( \varepsilon_p=4\%, \sigma_a=440\text{MPa}, N_f=19\times10^4\text{cycles}. \)

Fig. 11 Micro-crack generated in the pre-strain 
\( \varepsilon_p=4\%, N=0\text{ cycle}. \)

Fig. 12. Crack propagation behavior of specimen in Fig. 11.

steel, fatigue limit ratios under different pre-strain ratios deteriorate and hardly change between \( \varepsilon_p=2\% \) to \( 6\%. \) The reason for this may be explained by the microscopic structure and work hardening.

With the increase of carbon content, the volume ratio of pearlite becomes increase and that of ferrite becomes decrease at the same time. The main factor for the improvement of the fatigue limit ratio is due to work
Fatigue Properties of Pre-strained Eutectoid Steel

hardening, and it depends on the weak ferrite structure that can be easily work-hardened. The higher ferrite volume ratio becomes, the easier this material can be work hardened. In other word, S15C that has the highest volume ratio of ferrite structure is the most remarkable one that can be work-hardened. For eutectoid steel, all of the microscopic structure is consisted by fine pearlite. Since pearlite is very hard and has much high strength, the effect of work hardening is not expected to improve the fatigue strength (The increase in hardness is only Hv.7). The influence of work hardening just could compensate the minus effect of the slip line or micro-crack that generated in the process of plastic strain, it may be the reason why all of the fatigue limits of eutectoid steel are lower than that of the original one, and why all of the fatigue limit ratios at different plastic pre-strain ratio have no obvious difference.

3.3. Fatigue Crack Initiations and Propagation

The result of the test shows the fatigue cracks were initiated in the surface of the specimen. In this study, for non-pre-strained specimen, crack initiated at the boundary of the pearlite blocks, as shown in Fig.7. The fatigue cracks could also occur at the inter-lamellar of the pearlite (11).

From Fig.7(c), it is clear that the fatigue micro crack was initiated along the boundary of pearlite block at point A, and the crack propagated along the inter-lamellar at B and crossed the inter-lamellar at point C. The other specimens showed almost the same result. That is: the fatigue cracks initiated in the boundary or inter-lamellar of the pearlite due to slip and the direction of the crack occurred was about 20° to 45° from the loading axis, as it grew, the cracks turned their direction to perpendicularly to loading axis.

For pre-strained specimens, the fatigue cracks occurred in the slip lines and micro cracks that were generated in the process of the plastic strain. The slip lines or micro cracks were about 20° to 45° from the tensile axis and the cracks will propagate along this slip lines or cracks. Fig.8 shows the successive observation of pre-strained specimens (εp=2%). The magnification of the crack initiation is shown in Fig.9. It is clear that micro crack generated in the pearlite block by crossing the inter-lamellar. Figs.10 and 11 show the micro cracks in the surface of specimen under pre-strain εp=4% and 6%, respectively. The slip lines and fatigue cracks preferentially initiated in crossing the lamellar (Figs.9 and 11) or along the inter-lamellar in the pearlite (Fig.10). The micro cracks are about 20° to 45° from the tensile stress; this direction is nearly coincident with the maximum shear stress direction. It is also clear that the slip lines and micro cracks were generated in the process of the pre-strain. Fig.12 shows the propagation behavior of the cracks in Fig.11. As the crack grew, it propagated perpendicularly to the loading axis by crossing the inter-lamellar at A, along the inter-lamellar at B or along the boundary at C.

Figure13 shows the fatigue crack propagating behavior of four kinds of specimens with different pre-strain ratios. The stress amplitude applied is 15MPa higher than its own fatigue limit, respectively. It seems there is no obvious different among the propagating rates of fatigue cracks with different plastic strain ratios. In other word, the effect of pre-strain rate on the fatigue crack propagation properties is very small.

4. CONCLUSIONS

The main results obtained in this test are as follows:

(1) Plastic pre-strain decreases the fatigue limit of eutectoid steel. All fatigue limits of specimens with different pre-strain ratio are lower than that of specimens without pre-strain (εp=0%).

(2) The fatigue limits of pre-strained eutectoid steel become deteriorated and have no obvious change in the range of εp=2% to εp=6%.

(3) For non-pre-strained specimen, fatigue cracks preferentially initiate from boundary of the pearlite blocks or inter-lamellar of the pearlite; but for pre-strained specimens, fatigue cracks occur in slip lines, or microscopic cracks that were generated in the process of plastic pre-straining. The fatigue cracks initiate by crossing or along the inter-lamellar of the pearlite and their direction are about 20° to 45° with the loading axis in the early stage. As it grows, however, the cracks change their direction and propagate perpendicularly to the stress axis by crossing the lamellar or along the boundary or the inter-lamellar.

REFERENCE


