Effects of an extremely shallow partial notch on fatigue strength of 0.45% C steel
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Abstract

In general machines and structures have a rough surface due to machining. Therefore, it is important to investigate the effect of an extremely shallow notch on fatigue strength. In the present study, rotating bending fatigue tests were carried out on annealed or quenched-and-tempered 0.45% carbon steel specimens with extremely shallow partial notches whose depths are constant and whose notch radii are different. This means that the values of $\sqrt{\text{area}}$ are constant and the radii of notch are different. The fatigue strength of these specimens was investigated by linear notch mechanics and $\sqrt{\text{area}}$ parameter model. Moreover, the limitation for application of the model was discussed.

1 Introduction

Because machines and structures have the roughed surface due to machining, it is important to investigate the fatigue strength of the specimen which simulates the roughed surface. As a method for the fatigue strength of this specimen, the linear notch mechanics\textsuperscript{1} and the $\sqrt{\text{area}}$ parameter model\textsuperscript{2} may be useful.

In the present study, rotating bending fatigue tests were carried out on annealed or quenched-and-tempered 0.45% carbon steel specimens.
with extremely shallow partial notches whose depths are constant and notch radii are different. This means that the values of $\sqrt{\text{area}}$ are constant and the values of notch radii are different. The obtained results were investigated by the linear notch mechanics and the $\sqrt{\text{area}}$ parameter model. Moreover, the limitation for application of the model was discussed.

2 Concept of the linear notch and the $\sqrt{\text{area}}$ parameter model

In this section, the concept of the linear notch mechanics and the $\sqrt{\text{area}}$ parameter model will be given in short.

2.1 Linear notch mechanics

In the specimens with a usual notch (for example, when the notch depth is deeper than 0.1 mm), it is assured by the linear notch mechanics that the same phenomena in the two notched bodies occurs independently of the notch depth or the other geometrical conditions when the values of $\sigma_{\text{max}}$ and notch radius $\rho$ are equal to each other respectively. This is due to the fact that the same elastic-plastic stress fields are determined by $\sigma_{\text{max}}$ and $\rho$ alone (Figure 1). However, because the relative elastic stress distribution of the specimen with an extremely shallow notch is dependent on the notch depth (Figure 2), originally it is not reasonable to apply the linear notch mechanics to the case of extremely shallow notches.

2.2 $\sqrt{\text{area}}$ parameter model

According to the concept of $\sqrt{\text{area}}$ parameter model, it is assumed that the fatigue limit $\sigma_w$ can be predicted by eq (1) where HV is the Vickers hardness number and the $\sqrt{\text{area}}$ is the square root of the projected area of a defect onto the plane normal to the direction of the maximum tensile stress (Figure 3).

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

[ Unit: $\sigma_w$ (MPa), HV (kgf/mm$^2$), $\sqrt{\text{area}}$ (μm) ]

This equation means the following. When the values of $\sqrt{\text{area}}$ are constant, the fatigue limits of specimens are equal to each other.
Figure 1: Condition for causing the same phenomena in two notched bodies.

Figure 2: Relative elastic stress distributions near the root of elliptic holes.
3 Material, specimen and testing method

The materials used in this study are annealed and quenched-and-tempered 0.45% carbon steels. The chemical composition of the materials is shown in Table 1. The heat treatments and mechanical properties are shown in Table 2.

The shape and dimensions of the specimen are shown in Figure 4. The detail of the notch is shown on the upper part in Fig.4. The notch type is a partial notch. The notch depth is 5 μm or 10 μm, and the notch radius is 10 μm, 100 μm or 300 μm. Each shape of cutting tool tip was confirmed from a SEM photograph (X 3000).

After machining, all the specimens were polished by emery papers, and then were electro-polished to eliminate the work hardened layers and to facilitate the observation of the specimen surfaces. The annealed specimens were annealed to eliminate the residual stress at 650 °C for 1 hour in vacuum.

The Ono-type rotating bending fatigue testing machine (the capacity : 15N·m, the rate of stress repetitions : about 40Hz) was used.

Here the stress is defined as the nominal bending stress in the minimum cross section of specimen neglecting the notch depth. The stress concentration factors \( K_t \) of the specimens used were approximated by the \( K_t \) values of a semi-infinite plate with a circular-arc notch under tensile stress. The observation of cracks on the notch roots was made using a metallurgical microscope (X 400).
Table 1: Chemical composition (wt%).

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
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<td>0.45</td>
<td>0.25</td>
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<td>0.09</td>
<td>0.03</td>
<td>0.18</td>
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Table 2: Heat treatments and mechanical properties.

<table>
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<th>Materials</th>
<th>Heat treatments</th>
<th>Mechanical properties</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>HV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annealed steel</td>
<td>Annealing (845°C, 60min, FC)</td>
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<tr>
<td>Quenched and tempered steel</td>
<td>Normalizing (845°C, 30min, AC)</td>
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<tr>
<td></td>
<td>Quenching (845°C, 30min, WQ)</td>
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</tr>
<tr>
<td></td>
<td>Tempering (400°C, 60min, WC)</td>
<td></td>
</tr>
</tbody>
</table>

FC : Furnace cooling, AC : Air cooling, WQ : Water quenching, WC : Water cooling, σ S : Yield stress, σ B : Ultimate tensile strength, * : 0.2% proof stress

\[ \rho = 10, 100, 300 \mu m \]

Longitudinal section

Cross section

Detail of notch

Figure 4: Fatigue specimen.
4 Experimental and discussion

4.1 Estimation by $\sqrt{\text{area}}$ parameter model

The values of notch dimension, stress concentration factor $K_t$, fatigue limit $\sigma_w$ and $\sqrt{\text{area}}$ are shown in Table 3. The values of $\sqrt{\text{area}}$ in these specimens are $\sqrt{\text{area}} = \sqrt{t}$ ($t$: notch depth). Figures 5 and 6 show the relations between $\sigma_w$ and $K_t$ in an annealed steel and a quenched-and-tempered steel, respectively. $\sigma_w$ is the fatigue limit defined as the critical stress for fracture. The open marks in these figure indicate the specimens whose crack initiation site for fracture is the notched part, and the solid marks indicate the specimens whose crack initiation site for fracture is the un-notched part.

As seen from Fig.5, concerning this annealed steel, the fatigue limits of the specimens with an extremely shallow notch can be estimated approximately by the $\sqrt{\text{area}}$ parameter model in most cases. However, the fatigue limits of $\rho = 300 \mu m$ and $\rho = 100 \mu m$ are clearly different, in spite of the same value of $\sqrt{\text{area}}$.

As seen from Fig.6, concerning this quenched-and-tempered steel, the...
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Figure 5: Relations between $\sigma_w - K_t$ in annealed steel (rotating bending).

Figure 6: Relations between $\sigma_w - K_t$ in quenched and tempered steel (rotating bending).
the difference between the experimental fatigue limit and the estimated fatigue limit by the $\sqrt{\text{area}}$ parameter model is about 100MPa in the cases for $\rho < 100 \ \mu m$ and about 150MPa for $\rho = 300 \ \mu m$. The errors are more than 20%.

From these facts obtained from Figs. 5 and 6, it can be concluded that the fatigue limits of specimens with the same value of $\sqrt{\text{area}}$ are dependent on the value of notch root radius $\rho$ when $\rho$ is large. The errors of estimation based on the model are greatly dependent on materials. When $\rho$ is large, the errors are also dependent on the values of $\rho$.

4.2 Estimation by linear notch mechanics

Figure 7 shows the rearranged results for the data in Figs. 5 and 6. The rearrangement is based on the concept of the linear notch mechanics. This figure shows the relation between the maximum stress and $1/\rho$.

The relative stress distribution of the specimen with an extremely shallow partial notch is dependent on the notch depth when $\rho$ is small (Fig.2). Therefore, originally the estimation of the linear notch mechanics on the fatigue strength is not reasonable in this case. However, the errors are less than about 15% and the permissible level in
5 Conclusions

Rotating bending fatigue tests were carried out on annealed or quenched-and-tempered 0.45% carbon steel specimens with extremely shallow partial notches whose depths are constant and notch radii are different. This means that the values of \( \sqrt{\text{area}} \) are constant and the values of notch radii are different. The obtained results was investigated by the linear notch mechanics and the \( \sqrt{\text{area}} \) parameter model. Moreover, the limitation for application of the model was discussed. The main results are summarized as follows:

1. The fatigue limits of specimens with the same value of \( \sqrt{\text{area}} \) are dependent on the value of notch root radius \( \rho \) when \( \rho \) is large.
2. The errors of estimation based on the model are greatly dependent on materials. When \( \rho \) is large, the errors are also dependent on the values of \( \rho \).

References


