Fatigue properties of double-notched specimen

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Abstract

Fatigue properties of double notched specimen have been investigated using Ono-type rotating bending fatigue testing machine. Fatigue crack initiation and crack propagation behavior were observed by the successive-taken replica method in the circumferential direction at the specimen’s surface. From the experimental results, the fatigue micro-cracks of all specimens initiate by about 10% of the total fatigue life. In addition, the fatigue crack is initiated at the high stress distribution place. Moreover, the results were discussed by fatigue notch factor on double notched specimen.

1 Introduction

More than 90% of failures of steel-structural components have eventually occurred from stress concentrated part such as notches. In real design, double notch is often inevitable. For examples, the cases such as the key groove exists on the step and the notch with working flaws under machining around the field where the maximum stress is occurred are a typical ones. As the break stress of double notch is by far lower than the evaluated value, double notched part can play an important part for failure. One of the authors has investigated about the fatigue strength of double notched part of an axis.\(^{(1)}\) Therefore, stress concentrated level at the notched part is esti-
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mated by means of stress concentration factor $K_t$ or fatigue notch factor $K_f$. Few studies have been carried out on the double notch problems until now.

The purpose of this study is to investigate the fatigue properties of the specimen with double notch.

2 Experimental procedure

The material used in these tests is a round bar ($\phi 20$ mm in diameter) of a plain carbon steel (S15C). Table 1 lists the chemical composition. All of specimens were cut down from the round bar and normalized for an hour at the temperature of 890°C. Figure 1 shows the shapes and dimensions of specimens. Those were annealed in a vacuum furnace for half an hour at the temperature of 600°C after polishing with fine emery paper, and thereafter electro-polished to

<table>
<thead>
<tr>
<th>Table 1. Chemical composition</th>
<th>mass%</th>
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<tbody>
<tr>
<td>C</td>
<td>Si</td>
</tr>
<tr>
<td>S15C</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Figure 1: Shape and dimensions of specimens.

Type A: plain specimen, Type B: with a small hole, Type C: with a step, Type D: with a small hole on the step, i.e. double notch specimen by superposed type B and C.
the depth of about 40μm. The fatigue tests have been performed by the Ono-type rotating bending fatigue testing machine of 98 N-m capacity. Fatigue crack initiation and crack propagation rate were observed by the successive-taken replica method in the circumferential direction at the specimen’s surface.

3 Results and discussion

3.1 Fatigue Strength

Figure 2 shows the S-N curves of all kinds of specimens. From this figure, the distinct knee point about the each specimen with notch is not necessarily clarified. The fatigue limit by $1 \times 10^7$ cycles of plain specimen was 190MPa. In addition, these of type B, C, and D were 80MPa, 150MPa and 80MPa, respectively. It is considered the reason why the fatigue limit of type B is much lower than the evaluated value would be caused by the flaws around the small hole edge. According to the above reason, as the maximum stress points of the small hole do not necessarily coincide with those of the step about the double notched part, the fatigue strength of the double notched specimen, i.e., type D becomes nearly the same fatigue strength of the small hole specimen, i.e., type B.

![S-N curves](image)

Figure 2: S-N curves.
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Figure 3: Successive surface observation of crack initiation at the stress amplitude $\sigma_a = 1.24\sigma_w$. 

(a) Type B ($\sigma_a = 100\text{MPa}, \quad N_f = 2.17 \times 10^6 \text{cycles}$)

(b) Type C ($\sigma_a = 150\text{MPa}, \quad N_f = 6.4 \times 10^5 \text{cycles}$)

(c) Type D ($\sigma_a = 100\text{MPa}, \quad N_f = 1.93 \times 10^6 \text{cycles}$)
3.2 Fatigue Crack Initiation

Figure 3 shows the representative successive observation result of fatigue crack initiation of notched specimens under the stress amplitude of 1.24\(\sigma_w\), where \(\sigma_w\) is the stress amplitude of fatigue limit for each specimen. In this figure, fatigue cracks of type B and D initiate in hole edge, the cracks propagate and become catastrophic fracture, while fatigue cracks of type C initiate in any circumferential point at the root of step, and join finally to a single fatigue crack. In the case of type B and D, crack initiation point is absolutely restricted by effect of stress concentration. In contrast, that of type C is not so restricted as to those of type B and D.

3.3 Non-propagating micro-crack

Figure 4 shows the surface states under the stress amplitude of fatigue limit by \(1 \times 10^7\) cycles about notched specimen. The non-propagating micro-cracks in type B and D are not observed. That of type C is not yet confirmed. Therefore, it is probable that fatigue limit of notched specimen with the small hole is based on the limit of crack initiation.

![Surface states under the fatigue limit by \(1 \times 10^7\) cycles](image)

Figure 4: Surface states under the fatigue limit by \(1 \times 10^7\) cycles

3.4 Fatigue Crack Propagation

Figure 5 shows relation between crack length and number of cycles. In case of type B, the crack propagates with increasing the number of cycles after its initia-
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In case of type C, the crack initiates and non-propagates for a while, and then it propagates rapidly. In case of type D, the crack initiates and propagates in proportion to number of cycles. It seems that crack propagation rate of type C is the fastest among those of all notched specimen, but actual rate is different due to combination of plural cracks. Fatigue cracks of type B, C and D initiate by about 5 – 20% of total fatigue life, and the detail for crack initiation is under the investigation.

![Graph showing relation between crack length and number of cycles.](image)

Figure 5: Relation between crack length and number of cycles.

3.5 Fatigue Notch Factor

Table 2 lists the comparison between fatigue notch factor by this experiment and that by the equation. The one is given by

\[ K_f = \frac{\sigma_{wo}}{\sigma_w} \]

(1)

Where \( \sigma_{wo} \) is fatigue limit of plain specimen, \( \sigma_w \) is fatigue limit of notched specimen. The latter is calculated by the experimental equation. Fatigue notch factor \( K_f \) (Equation) of type D in this table should be the product of those of type B and C. In case of type C, fatigue notch factor by eqn.(1) is nearly equal to that by the equation, while in case of type B, there is rather difference between those of experimental value and equation one. Fatigue
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notch factor of double notched part is often estimated by the product of fatigue notch factors of each single notched part.\(^{(3)(4)}\) That of type D calculated by the above method should be 2.03. In case of this study, that method does not provide fatigue notch factor of double notched specimen but those of type B and D are nearly the same value, \(K_f = 2.38\). It is considered that the reason why the fatigue notch factor of type B is much higher than the evaluated value and agrees with that of type D would be caused by the flaws around the small hole edge. As the maximum stress points of the small hole do not necessarily coincide with those of the step about the double notched part, the fatigue notch factor of type D becomes nearly the same fatigue notch factor of type B. It is necessary the relation of position between the step and the small hole should be investigated changing the small hole position of double notched specimen from now on.

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_w) (MPa)</td>
<td>190</td>
<td>80</td>
<td>150</td>
<td>80</td>
</tr>
<tr>
<td>(K_f) (Experiment)</td>
<td>1</td>
<td>2.38</td>
<td>1.27</td>
<td>2.38</td>
</tr>
<tr>
<td>(K_f) (Equation)</td>
<td>1</td>
<td>1.61</td>
<td>1.26</td>
<td>2.03</td>
</tr>
<tr>
<td>(\sigma_{wo} / K_f) (MPa)</td>
<td>190</td>
<td>118</td>
<td>151</td>
<td>93.6</td>
</tr>
</tbody>
</table>

**Conclusions**

The fatigue tests have been performed to investigate fatigue properties of double notched specimen. The main results obtained in this study are as follows:
1. The fatigue limits by \(1 \times 10^7\) cycles of type B, C and D were 80MPa, 150Mpa and 80MPa, respectively.
2. Fatigue cracks are always initiated from the stress concentrated point.
3. The fatigue limit of notched specimen with the small hole is based on the limit of micro-crack initiation.
4. In the case of type B and D, a single fatigue crack respectively initiates in the small hole edge, propagates and become catastrophic fracture. On the other hand, in case of type C, plural cracks initiates at the rounded
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part of the step, join finally to a single fatigue crack and become cata-
strophic fracture.

5. The method by the product of fatigue notch factors of each single
notched part dose not necessarily provide fatigue notch factor of double
notched specimen.

References

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2. JSME, Design Handbook of Fatigue Strength of Metals, Vol.1, p.125
1982.