Fatigue Strength of Carbon-Steel Castings*

By Hisashi Ouchida**, Kenji Chijiwa***, Jirō Hoshino†, and Kunio Nishioka††

This paper summarizes the results of fatigue tests of round specimens of carbon-steel castings 10, 35, 50 and 100 mm in diameter. The specimens were tested under rotating bending, pulsating tension, and completely reversed tension and compression in order to investigate the effects of various defects on the fatigue strength. The various defects were all deliberately made and included artificially drilled holes, blowholes, and shrinkage cracks. The fatigue strength, the fatigue ratio, and the fatigue strength reduction factor were obtained from the fatigue test results of specimens having these various defects, and the fatigue strength of steel castings was compared with that of steel forgings. The following results were obtained.

1. The fatigue strength, the fatigue strength reduction factor, and the size effect on the fatigue strength are smaller in the case of steel castings than in the case of steel forgings.
2. The fatigue strength of specimens having artificially drilled holes is approximately equal to that of specimens having blowholes of the same size.
3. In the case of small blowholes ($d/D<0.2$) the size effect is extremely small.
4. There is a correlation between the defect ratio, obtained from radiographic inspection or fatigue fracture of the specimens, and the fatigue strength.
5. From these fatigue test results, we obtained the endurance limit diagram of carbon-steel castings under direct stress.

1. Introduction

In the past the fatigue strength of carbon-steel castings has not been understood adequately\(^{(1)}\). In fact, one may even say that there has been a complete lack of any materials concerning the fatigue strength of large-size carbon-steel castings and concerning the effects of pinholes, blowholes, and shrinkage cracks, which are the defects peculiar to castings.

Nevertheless, large numbers of carbon-steel castings are used in marine machine parts, in the machine parts of transportation equipment, in industrial machinery, and in other applications requiring a high degree of durability. Information concerning their fatigue strength is absolutely indispensable for the designing of such parts, and urgent demands for research in this field have been voiced by these various industrial circles.

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In an attempt to respond to these demands, the authors conducted measurements of the fatigue strength of specimens of carbon-steel castings, both with and without defects. In addition to standard specimens, large-size specimens ($50\text{ mm}\phi$ and $100\text{ mm}\phi$) were also prepared. Furthermore, an attempt was also made to determine the effects on the fatigue strength of such factors as the sizes of the specimens and the defects such as pinholes, blowholes, and shrinkage cracks.

2. Preparation and inspection of specimens

In this research, the tests enumerated in Table 1 were conducted in order to discover the fatigue strengths of carbon-steel castings under rotating bending, under pulsating tension, and under completely reversed tension and compression. Both sound specimens and defective specimens were tested.

It was quite difficult to prepare specimens having a definite number of defects of a given size. However, great care was taken in preparing large numbers of specimens. These specimens were then inspected, and those having various types of defects were extracted from among them and
classified. The defects were classified by a combination of methods such as naked eye inspection, radiographic inspection, magnetic inspection, and dye penetrant inspection.

3. Fatigue tests of specimens having transverse holes under rotating bending stress

3.1 Testing method

The fatigue strength of specimens having transverse holes was measured in order to investigate the effects of blowhole defects on the fatigue strength.

As is shown in Table 1 and Fig. 1, holes of various sizes were drilled in specimens of 10 mm φ, 50 mm φ, and 100 mm φ, and the effects upon the fatigue strength of the hole diameter \( d \), as well as the effects of \( d/D \), the ratio between the hole diameter \( d \) and the specimen diameter \( D \), were investigated. The larger holes penetrated all the way through the specimen. The smaller holes had a depth of \( h > 5d \), and the holes were drilled on both sides of the specimen.

In order to investigate the effects of the depth of the holes on the fatigue strength, fatigue testing was performed of 50 mm φ specimens with holes of different depths. The following fatigue testing machines were used.

**Table 1 Experimental details**

<table>
<thead>
<tr>
<th>Kind of test</th>
<th>Kind of defect</th>
<th>Dia. of specimen mm</th>
<th>Size of hole or defect</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotating bending</td>
<td>Sound</td>
<td>10 ( \phi )</td>
<td>( d/D = 0.01, 0.02, 0.05, 0.1, 0.5, 1.0, 2.0 ) mm</td>
<td>( d ): dia. of hole ( D ): dia. of specimen ( h ): depth of hole ( h &gt; 5d )</td>
</tr>
<tr>
<td></td>
<td>Drilled hole</td>
<td>50 ( \phi )</td>
<td>( d/D = 0.01, 0.02, 0.05, 0.1 ) ( d = 0.5, 1.0, 2.5, 5.0 ) mm</td>
<td>Number of defects# 5<del>17\ 8</del>19\ 12~28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 ( \phi )</td>
<td>( d/D = 0.02 ) ( d = 0.2 ) mm</td>
<td>ditto</td>
</tr>
<tr>
<td>Blowhole</td>
<td>50 ( \phi )</td>
<td></td>
<td>( d = 0.4<del>1.0 ) mm, small size ( d = 1.5</del>2.5 ) mm, middle size ( d = 3.0~5.0 ) mm, large size</td>
<td>Number of defects# 5<del>17\ 8</del>19\ 12~28</td>
</tr>
<tr>
<td></td>
<td>100 ( \phi )</td>
<td></td>
<td>( d = 0.5<del>1.5 ) mm, small size ( d = 4.0</del>8.0 ) mm, large size</td>
<td>ditto</td>
</tr>
<tr>
<td>Pulsating tension</td>
<td>Sound</td>
<td>35 ( \phi )</td>
<td>( d = 0.2<del>1.0 ) mm, small size ( d = 1.5</del>3.0 ) mm, middle size ( d = 3.5~5.0 ) mm, large size</td>
<td>Number of defects 6<del>57\ 4</del>69\ 23~68</td>
</tr>
<tr>
<td></td>
<td>Blowhole</td>
<td>35 ( \phi )</td>
<td>( \gamma_1 = 3.3 % ), small size ( \gamma_1 = 6.5 % ), middle size ( \gamma_1 = 8.0 % ), large size</td>
<td>( \gamma_1 ): Ratio of defect</td>
</tr>
<tr>
<td></td>
<td>Shrinkage crack</td>
<td>35 ( \phi )</td>
<td>( \gamma_1 = 1.0 % ), ( d = -0.7 ) mm</td>
<td>Number of defects 16~18</td>
</tr>
</tbody>
</table>

* Number of defects was counted on the surface of specimen
10 mmφ specimens: Ono type rotary bending fatigue machine 8 kgm, 2 000 rpm
50 mmφ specimens: Cantilever type rotary bending fatigue machine 400 kgm, 1 200 rpm
100 mmφ specimens: Cantilever type rotary bending fatigue machine 7500 kgm, 1 250 rpm

The nominal stress σ of the specimens with holes was calculated by means of the following equation regardless of whether the holes penetrated all the way through or not:

$$\sigma = \frac{M}{\pi D^3 - \frac{dD}{6}}$$

where

- $M$: Bending moment
- $D$: Diameter of specimen
- $d$: Diameter of hole

All the specimens were subjected to $10^7$ iterated stress cycles. In those cases when failure had not occurred, the upper limit of stress was adopted as the endurance limit. Even in those specimens which were able to withstand $10^7$ cycles of stress without failure, minute fatigue cracks would sometimes occur on the edges of the holes. Therefore, it was decided to adopt the following distinctions in expressing the endurance limit.

- $\sigma_{ew}$: Endurance limit in cases when there are cracks
- $\sigma_{ew}$: Endurance limit in cases when there are no cracks
- $\sigma_{ew}$: Value of $\sigma_{ew}$ modified by the section modulus calculated disregarding the hole

The values of the endurance limit for specimens without holes (plain specimens) were expressed in values divided by these endurance limits, i.e., by the fatigue strength reduction factors of $\beta_p$, $\beta_f$, and $\beta_p$.

3-2 Fatigue test results

The S-N curves for the 10 mmφ, 50 mmφ, and 100 mmφ specimens are shown in Figs. 2, 3 and 4, respectively. Specimens with holes have a lower fatigue strength than sound specimens regardless of the sizes of the specimens, and the extent of the decrease in the fatigue strength is the greater, the larger are the holes.

Typical fatigue fractures of specimens with holes are shown in Fig. 5. The fatigue fractures originate on the hole surfaces at points somewhat inside from the outer surface of the holes.

Table 2 lists summarily the values of the en-
The endurance limit sought from the S-N curves, the fatigue strength reduction factor, and the fatigue ratio.

(1) Effects of $D$, $d$, and $d/D$

Fig. 6 shows the relationship between the endurance limits ($\sigma_{ut}$, $\sigma_{ot}$, and $\sigma_{ut}$) and $d/D$ for different specimen diameters and hole diameters.

The following conclusions can be stated on the basis of the data in Table 2 and in Fig. 6.

(a) The endurance limit of plain specimens is greater in small specimens than in large specimens. That is, in comparison with the endurance limit of a specimen with a diameter of 10 mm, there will be a drop of 2~4% in the endurance limit of a 50 mm specimen, and of 12~21% in the endurance limit of a 100 mm specimen.

(b) When one compares the endurance limits ($\sigma_{ut}$, $\sigma_{ot}$ and $\sigma_{ut}$) of specimens having different diameters when there is the identical $d/D$ ratio, smaller specimens are found to have greater endurance limits. For example, in comparison with the endurance limit of a 10 mm specimen, there is found to be a drop of about 20~25% in the endurance limit of a 50 mm specimen, and a drop of about 45% in the endurance limit of a 100 mm specimen.

(c) In specimens having the same $d$, the size of the specimen is found to affect the values of $\sigma_{ut}$ and $\sigma_{ot}$, but $\sigma_{ut}$ is found to display approximately the same values regardless of the specimen size.

In other words, when the endurance limit is sought on the basis of the section modulus disregarding the hole, it is believed that its value will be determined according to the hole diameter alone within the range of $d/D<0.2$. This is believed to be attributable to the following reason. That is, when one seeks $\alpha$, the theoretical stress concentration factor with respect to the maximum stress occurring in the vicinity of the hole, on the basis of the stress which is sought disregarding the hole, the results will be as shown in the

| Dia. of specimen | Dia. of hole $d$ | $d/D$ | Fatigue strength | Fatigue strength reduction factor | Fatigue ratio | Tensile strength $\sigma_s$ kg/mm$^2$
|------------------|-----------------|------|------------------|---------------------------------|--------------|-----------------
| $D$ mm           | $d$ mm          |      | $\sigma_{ut}$    | $\sigma_{ot}$                  | $\sigma_{ut}$ | $\sigma_{ut}/\sigma_s$ |
| 10               | 0.3             | 0.03 | 2.59             | 17.5                            | 1.21          | 0.46            | 0.044          |
|                  | 0.5             | 0.05 | 2.68             | 15.7                            | 1.37          | 0.34            | 0.31           |
|                  | 1.0             | 0.10 | 2.28             | 13.5                            | 1.55          | 0.29            | 0.33           |
|                  | 2.0             | 0.20 | 2.02             | 10.5                            | 1.90          | 0.23            | 0.35           |
| 50               | 0.5             | 0.01 | 2.83             | 15.2                            | 1.32          | 0.31            | 0.30           |
|                  | 1.0             | 0.02 | 2.69             | 14.5                            | 1.39          | 0.28            | 0.26           |
|                  | 2.5             | 0.05 | 2.46             | 11.7                            | 1.72          | 0.24            | 0.26           |
|                  | 5.0             | 0.10 | 2.26             | 10.5                            | 1.91          | 0.20            | 0.24           |
| 100              | 0.5             | 0.01 | 2.83             | 15.2                            | 1.32          | 0.31            | 0.30           |
|                  | 1.0             | 0.02 | 2.69             | 14.5                            | 1.39          | 0.28            | 0.26           |
|                  | 2.5             | 0.05 | 2.46             | 11.7                            | 1.72          | 0.24            | 0.26           |
|                  | 5.0             | 0.10 | 2.26             | 10.5                            | 1.91          | 0.20            | 0.24           |

![Fig. 5 Typical appearance of fatigue fracture of 50 mm specimens having drilled holes under rotating bending](image)

![Fig. 6 Relationship between endurance limit and $d/D$](image)
upper curve in Fig. 7. However, if the theoretical stress concentration factor is sought on the basis of the stress taking the hole into consideration, the factor will be found to decline uniformly as the value of $d/D$ grows larger, as is shown in the lower curve in Fig. 7. On the other hand, the value of $\alpha$ sought as mentioned above will be between 2.7 and 3.0 within the range of $d/D=0-0.2$. Thus, the results are almost identical. Consequently, it is concluded that the stress distribution around the hole is probably affected chiefly by the hole diameter $d$, and it is thought that if the values of $d$ are identical there will be the same endurance limits regardless of the sizes of the specimens.

(2) Effects of the depths of the holes

Fig. 8 shows the $S-N$ curves for specimens when $h$, the hole depth, and $r$, the radius of the rounded bottom of the hole, were varied. On the basis of these data, it appears that in shallow holes which have equal values of $r$ and $h$, practically no effects of the hole sizes are observed. However, a decrease in the strength is observed when the holes have a depth greater than their diameter ($r=3\text{mm}, h=6\text{mm}$). Nevertheless, when the holes are deeper than this, almost no variations of the strength are observed. In the previously described $50\text{mm}$ specimens, when the holes had a depth five times the diameter, in the case of $2.5\text{mm}$ holes, $\sigma_{w2}/\sigma_y=0.26$, and in the case of $5\text{mm}$ holes, $\sigma_{w2}/\sigma_y=0.26$. The results were thus almost identical, and consequently it is believed that there are no differences in the fatigue strength when the hole depth is greater than $1.5$ times the hole diameter.

3-3 Comparison of carbon-steel castings and steel forgings

When these test results are compared with data on steel forgings\(^{(3)}-^{(5)}\), approximately the following conclusions can be made.

(1) The bending endurance limits of plain sound specimens of carbon-steel castings are lower than those of forged steel specimens with the same tensile strength (SF 45, SF 50, endurance limits 20$\sim$30 kg/mm$^2$). The former is approximately 80% of the latter.

(2) The fatigue strength reduction factor of carbon-steel casting specimens with holes is smaller than that of forged steel specimens. There are little differences in the fatigue strength due to the effects of the specimen sizes.

4. Fatigue tests of specimens having defects under rotating bending

4-1 Fatigue test methods

Fatigue tests under rotating bending were performed of large-size castings having defects in order to elucidate the effects of defects such as blowholes and shrinkage cracks on the fatigue strength. The specimens had diameters of 100 mmφ and 50 mmφ.

In order to investigate the effects of size, fatigue tests were also performed with $10\text{mm}$ specimens taken from the chucking parts of large-size sound specimens with a diameter of $100\text{mm}$.

The various specimens were examined by naked eye inspection, radiographic inspection, and magnetic inspection. As a result, large numbers of large and small blowholes were detected, as shown in Table I.

4-2 Fatigue test results

Fig. 9 shows the fatigue test results of the specimens with a $100\text{mm}$ diameter and of the $10\text{mm}$ specimens taken from them. Fig. 10 shows the results of the tests of specimens with a $50\text{mm}$ diameter. The test results are presented in the form of $S-N$ curve diagrams.

In specimens with pinholes smaller than...
0.2 mm, fatigue cracks did not occur from the defects located on their surfaces. However, when there were defects with a size greater than 0.5 mm on the surface, fatigue cracks occurred with these defects as their points of origin. Typical fatigue fractures of this type are shown in Fig. 11.

Table 3 shows the endurance limits under rotating bending, the tensile strength, and the fatigue ratio as calculated from the S-N curves. The relationship between the sizes of the blowholes and the fatigue ratio is shown in Fig. 12. The decrease of the endurance limits is directly proportional to the logarithmic value of the blowhole diameter.

4.3 Comparison of specimens with drilled holes and specimens with defects

Comparisons were made of the fatigue strength of 50 mm Ø specimens having drilled holes and those with blowhole defects. The relationship between \( \sigma_{es} \), the endurance limit under bending, and the diameter of the blowhole or the drilled hole is shown in Fig. 12. As a result, it is believed that decrease in the endurance limits due to the size of the drilled hole or the blowhole is more or less the same, although there are slight differences depending upon the hole diameters. This is believed to be caused by the following facts. That is, the sections surrounding the blowholes, rather than being smooth, have a certain amount of notches. Besides, there are cases in which there are several blowholes in a fracture, rather than a single blowhole.

Therefore, when one is estimating the fatigue

Table 3  Fatigue strength of specimen having defect under rotating bending stress

<table>
<thead>
<tr>
<th>Dia. of specimen mm</th>
<th>Dia. of blowhole mm</th>
<th>Tensile strength ( \sigma_p ) kg/mm²</th>
<th>Fatigue strength ( \sigma_{es} ) kg/mm²</th>
<th>Fatigue ratio ( \sigma_{es}/\sigma_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0–0.2</td>
<td>46.0</td>
<td>16.5</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>0.5–1.5</td>
<td>47.0</td>
<td>18.0</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>4–8</td>
<td>53.9</td>
<td>12.0</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.17</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
<td>52.5</td>
<td>20.1</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>0.4–1.0</td>
<td>47.7</td>
<td>14.5</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>1.5–2.5</td>
<td>47.7</td>
<td>11.5</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>3.0–5.0</td>
<td>47.7</td>
<td>10.0</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Fig. 9  Fatigue test results of 100 mm Ø specimens having defects under rotating bending

Fig. 10  Fatigue test results of 50 mm Ø specimens having defects under rotating bending

Fatigue crack initiates from 1.0 mm Ø blowhole

Fig. 11  Typical appearance of fatigue fracture of specimens of 100 mm in diameter having blowholes under rotary bending
strength of specimens with blowhole or pinhole defects from fatigue test results of specimens with holes produced by machining, it is believed that one may safely assume the fatigue strengths of both to be more or less identical within the range where the hole sizes are not too large.

5. Fatigue tests under pulsating tension

5-1 Testing method

Fig. 13 shows the shape and dimension of the specimen with a 35 mm diameter which were used in the fatigue tests. The specimens were divided into seven types as shown in Table 4, depending upon the sizes and types of the defects.

As the testing machine, an Amsler type universal fatigue testing machine (load capacity 50 tons, test frequency 300~400 c/min) was used. As the test conditions, a lower limit of stress of 2 kg/mm² was adopted, and the upper limit of stress was varied. The fatigue strength was measured after $2 \times 10^8$ stress cycles. The stress was calculated without considering the reduction of the cross section of the specimens caused by the defects.

5-2 Fatigue test results

Figs. 14 and 15 show the $S-N$ curves of specimens without defects and of specimens with blowholes and shrinkage cracks, respectively.

The photographs in Fig. 16 show the typical appearance of fatigue fractures of specimens with

![Graph showing fatigue test results](image)

![Graph showing fatigue test results for specimens with blowholes](image)

![Graph showing fatigue test results for specimens with shrinkage cracks](image)

**Table 4** Fatigue strength of specimen under pulsating tension ($N=2 \times 10^8$)

<table>
<thead>
<tr>
<th>kind of specimen</th>
<th>Size of defect (mm)</th>
<th>Fatigue strength (kg/mm²)</th>
<th>Fatigue ratio</th>
<th>Fatigue strength reduction factor</th>
<th>Fatigue strength reduction %</th>
<th>Defect ratio**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$T_1$ %</td>
</tr>
<tr>
<td>Sound</td>
<td>—</td>
<td>26.0</td>
<td>0.50</td>
<td>1.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Blowhole</td>
<td>0.2~1.0</td>
<td>22.0</td>
<td>0.43</td>
<td>1.18</td>
<td>15</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>1.5~2.0</td>
<td>19.0</td>
<td>0.37</td>
<td>1.37</td>
<td>27</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>3.5~5.0</td>
<td>12.0</td>
<td>0.23</td>
<td>2.17</td>
<td>54</td>
<td>14.8</td>
</tr>
<tr>
<td>Shrinkage crack</td>
<td>Small</td>
<td>24.0</td>
<td>0.47</td>
<td>1.08</td>
<td>8</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>20.0</td>
<td>0.39</td>
<td>1.30</td>
<td>23</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>18.0</td>
<td>0.35</td>
<td>1.44</td>
<td>31</td>
<td>6.6</td>
</tr>
</tbody>
</table>

* Tensile strength $\sigma_p=51.6$ kg/mm²
** $T_1$, $T_2$: Defect ratios of unbroken specimens at stress cycles $N=2 \times 10^8$
large, medium, or small blowholes. In all of the specimens with blowholes, fracture began from the largest one of the blowholes on the surface.

The photographs in Fig. 17 show fatigue fractures of specimens with large, medium, or small shrinkage cracks. The shrinkage defects are located at approximately the center of the specimens, and in all of the specimens there were fatigue cracks originating at these defects.

5.3 Fatigue cracks

Table 4 shows the fatigue strengths of the specimens under pulsating tension after $2 \times 10^6$ stress cycles. The tensile strength of the specimens without defects was 51.6 kg/mm$^2$, and the fatigue strength was 26 kg/mm$^2$. The fatigue ratio (the ratio of the fatigue strength to the tensile strength) was 0.5. The decrease of the fatigue strength in these specimens was found to be 15% when there were small blowholes, 27% when there were medium-size blowholes, 54% when there were large blowholes, 8% when there were small shrinkage cracks, 23% when there were medium-size shrinkage cracks, and 31% when there were large shrinkage cracks.
5-4 Effects of blowholes and shrinkage cracks

The following defect ratio was established in order to express quantitatively the effects of the blowholes and shrinkage cracks, particularly the latter. It was decided to seek the relationship between the value of this defect ratio and the fatigue strength.

\[ \text{Defect ratio } \gamma_1 = \frac{A_d}{A} \times 100 (\%) \]
\[ \text{Defect ratio } \gamma_2 = \frac{A_{dr}}{A} \times 100 (\%) \]

where:

- \( A_d \): Area when defective part seen on the fatigue fracture surface was projected in axial direction on the specimen
- \( A_{dr} \): Area of defective part obtained photographically when specimen was projected radiographically from two directions at right angles to each other
- \( A \): Total cross section of specimen

The values of \( \gamma_1 \) and \( \gamma_2 \) are relatively close to each other except in cases where there are large blowholes. However, the value of \( \gamma_2 \) was much larger when there were large blowholes because some of the blowholes faced lengthwise in the radial direction of the specimens.

Fig. 18 shows the calculated results for the relationship between \( \gamma_1 \) and \( \gamma_2 \), on the one hand, and the fatigue strength under pulsating tension, \( \sigma_{pu} \), on the other. These results show that when there are blowholes, the fatigue strength decreases proportionally as the defect ratio increases. When there are shrinkage defects, there is almost no decrease in the strength when the defect ratio is small, but decrease of the strength becomes visible when the defect ratio rises above a certain level.

Shrinkage defects are located at the axis centers of the specimens. They are cylindrical defects extending lengthwise in the loading direction.

Therefore, there is relatively little stress concentration, and little decrease of the fatigue strength occurs. However, it is believed that when the defect ratio increases, the fatigue strength decreases because of the reduction of the effective sectional area.

6. Fatigue tests under completely reversed tension and compression

6.1 Testing method

Fatigue tests under completely reversed tension and compression were conducted using two types of specimens: sound specimens, and specimens with small blowholes. The sound specimens had a diameter of 20 mm, and the specimens with small blowholes had a diameter of 35 mm. As the testing machine, a Losenhausen type universal fatigue testing machine (UHS 100, 100/60 ton, 500~600 c/min) was used.

6.2 Fatigue test results

The test results are shown in Fig. 19 as S-N curves. The previously mentioned results of tests under pulsating tension are also entered, converted into terms of half of the pulsating stress amplitude.

The results obtained for the fatigue strength after \( 2 \times 10^6 \) stress cycles are as shown in Table 5.

6.3 Endurance limit diagram under completely reversed tension and compression

The endurance limits under completely reversed tension and compression and under pulsating tension for SC46 round machined specimens were obtained from Fig. 5 and from the previously mentioned test results. Thus, an endurance limit diagram for carbon-steel castings after \( 2 \times 10^6 \) stress

![Fig. 18 Relationship between defect ratio and fatigue strength in specimens having blowholes or shrinkage cracks](image)

![Fig. 19 Fatigue test results for specimens having small blowholes under completely reversed tension and compression](image)
cycles was plotted. This is the diagram in Fig. 20.

In both the case of the sound specimens and that of the specimens with blowholes, the points of intersection between the line connecting the endurance limit under completely reversed tension and compression and the endurance limit under pulsating tension and the abscissa coincide quite well, as is shown by the broken lines in the diagram. In the former case, the stress at the intersecting point was 60 kg/mm², and in the latter case it was 58 kg/mm².

The value of the tensile strength of this material i.e. 51.6 kg/mm² is entered on the mean stress axis. When the points for the fatigue strength under pulsating tension were connected with this point on the mean stress axis together, the solid lines shown in the diagrams were obtained.

In this diagram, the endurance limit lines for medium and large blowholes are also plotted on the basis of analogy from the results for the small blowholes, taking into consideration the fact that these defects have practically no effects on the tensile strength.

7. Conclusion

The following findings were obtained from the results of testing the fatigue strength of carbon-steel castings (SC46). (Refer to Table 6.)

(1) Fatigue strength under rotating bending
   (a) The fatigue ratio \( \sigma_w/\sigma_b \) of sound carbon-steel castings differs depending on the size of the specimens, but it is 0.46—0.36 within the specimen size range of 10—100 mmφ. Smaller specimens have a greater endurance limit. Besides, the fatigue strength of carbon-steel castings is about 80% of that of steel forgings of approximately the same tensile strength.
   (b) The fatigue strength of carbon-steel castings with a minute porosity measuring less than 0.2 mmφ does not differ at all from that of sound castings.
   (c) The fatigue strength of carbon-steel castings having blowholes decreases in direct proportion to the logarithmic value of the hole diameter.
   (d) Within the range where \( d/D<0.2 \), the endurance limit \( \sigma_{e0} \) (the endurance limit found by disregarding the size of the hole) roughly, depends on the size of the hole, regardless of the size of the specimen.

(2) Fatigue strength under pulsating tension
   (a) The fatigue ratio of sound specimens \((N=2\times10^6)\) is 0.50.
   (b) When blowholes are present, the fatigue strength will decline about 15% when the blowholes are small, about 27% when they are of medium size, and about 54% when they are large.
   (c) The fatigue strength will decline about 8% when there are small shrinkage cracks, 23% when there are medium size shrinkage cracks, and 31% when there are large shrinkage cracks.

(3) Fatigue strength under completely reversed tension and compression

---

![Fig. 20 Endurance limit diagram for carbon-steel castings under direct stress](image)

---

**Table 5 Fatigue strength of specimen under completely reversed tension and compression \((N=2\times10^6)\)**

<table>
<thead>
<tr>
<th>Kind of specimen</th>
<th>Dia. of specimen mm</th>
<th>Fatigue limit kg/mm²</th>
<th>Fatigue strength reduction factor</th>
<th>Fatigue strength reduction ratio %</th>
<th>Fatigue ratio %</th>
<th>Defect ratio %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound</td>
<td>20</td>
<td>17</td>
<td>—</td>
<td>—</td>
<td>0.33</td>
<td>0</td>
</tr>
<tr>
<td>Blowhole</td>
<td>35</td>
<td>14</td>
<td>1.21</td>
<td>18</td>
<td>0.27</td>
<td>1.0</td>
</tr>
</tbody>
</table>

\( \sigma_b=51.6 \) kg/mm²

**Table 6 Fatigue ratio of carbon-steel castings having defect**

<table>
<thead>
<tr>
<th>Kind of defect</th>
<th>Size of defect</th>
<th>Rotating bending ((N=10^6))</th>
<th>Pulsating tension ((N=2\times10^6))</th>
<th>Completely reversed tension and compression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>Sound</td>
<td>0—0.2 mmφ</td>
<td>0.36—0.38</td>
<td>0.38—0.41</td>
<td>0.44—0.46</td>
</tr>
<tr>
<td>Blownhole</td>
<td>0.4—1.5 mmφ</td>
<td>0.22</td>
<td>0.31</td>
<td>0.44—0.46</td>
</tr>
<tr>
<td></td>
<td>1.5—3 mmφ</td>
<td>0.22</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3—8 mmφ</td>
<td>0.17</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Shrinkage crack</td>
<td>71=3.3 %</td>
<td>0.47</td>
<td>0.39</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>71=4.5 %</td>
<td>0.47</td>
<td>0.39</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>71=6.6 %</td>
<td>0.47</td>
<td>0.39</td>
<td>0.35</td>
</tr>
</tbody>
</table>
(a) The fatigue ratio of sound specimens \(N=2 \times 10^9\) is approximately 0.33.

(b) When there are small blowholes, the fatigue ratio is approximately 0.27.

(c) Endurance limit diagram. As shown in Fig. 20, success was achieved in obtaining an endurance limit diagram under completely reversed tension and compression for both sound carbon-steel castings and castings with defects.

8. Acknowledgments

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