Fatigue Strength of Steel Shafts Built-Up by Welding*

By Hisashi Ohuchida**, Akio Nishioka***, Ichiro Kitamura****, and Etsuya Kuboki☆

This paper presents the fatigue test results of steel shafts built-up by welding of 20 and 60 mm in diameter under rotating bending. Using carbon steels for base metal and austenitic stainless steel electrode for build-up welded metal, the influences of build-up welding on the fatigue strength of notched specimens and of build-up welding and shot-peening on the fatigue strength of shrink-fitted shafts were investigated. The following conclusions were drawn.

(1) By the build-up welding using an austenitic stainless steel electrode, the fatigue strength of notched specimens increased.

(2) In the shrink-fitted specimens built-up by welding, the fatigue strength was slightly lower than that of base metal. However, the fatigue strength was remarkably improved by shot-peening.

(3) The fatigue strength of notched specimens built-up by welding can be estimated by calculation.

1. Introduction

Studies on the fatigue strength of steel shafts built-up by welding have been published at the International Institute of Welding and others in the last several years, and the fatigue test results of carbon steel shafts built-up by welding using carbon steel and austenitic stainless steel electrodes have been reported1) - 4). From the results of these studies, it can be concluded that the fatigue strength of carbon steel shafts built-up by welding using carbon steel electrodes greatly decreased on account of weld defects, residual stress, etc. Wolf1) presented a method of determining the maximum stress at the notch root when the specimen is built-up by welding at the notch using materials having a low modulus of elasticity. This paper suggests that the stress concentrated parts of notched specimens and shrink-fitted specimens of carbon steel be built-up by welding using austenitic stainless steel electrodes to diminish the maximum stress at the stress concentrated parts and to improve the rotating bending fatigue strength, and further, proposes a method to estimate the fatigue strength of specimens built-up by welding.

2. Method of testing

2.1 Items of fatigue tests

(1) Influence of build-up welding on the fatigue strength of unnotched specimens.

(2) Influences of layer thickness of weld metal, specimen shape prior to build-up welding and shot-peening after build-up welding on the fatigue strength of notched specimens.

(3) Size effect on the fatigue strength of notched specimens.

(4) Influence of build-up welding and shot-peening on the fatigue strength of shrink-fitted specimens.

2.2 Steels used in tests

There are three kinds of steels used in the tests.

Low Carbon Steel “SS 41” hot rolled
Medium Carbon Steel “S 30 C” hot rolled and normalized
“SF 60” forged and normalized

The steels SS 41 and S 30 C of 32 mm in diameter were used for specimens of 20 mm in diameter, and the steels S 30 C and SF 60 of 90 mm in diameter were used for specimens of 60 mm in diameter. Their chemical compositions and mechanical properties are listed in Tables 1 and 2.
2.3 Fatigue test specimens

Specimen shapes for fatigue tests are illustrated in Fig. 1. The theoretical stress concentration factor of notched specimens obtained from Peterson's diagram is \( \alpha = 2.0 \). The unnotched specimens of 20 mm in diameter are cantilever beam type and their section under test is a conical one tangential to the fillets of 125 mm in radius of curvature. Their theoretical stress concentration factor is \( \alpha = 1.02 \). These specimens are called unnotched specimens. The fitting allowance of shrink-fitted specimens is \( 1.5d/1000 \), where \( d \) is the diameter.

The fatigue strengths of base metal and deposited metal were obtained from the fatigue tests on unnotched specimens of 6 mm in diameter and notched specimens having a theoretical stress concentration factor of 2.0. Their shapes are shown in Fig. 2.

Specimen shapes prior to build-up welding are illustrated in Figs. 3 and 4. From the specimens in Fig. 3 (a), unnotched and notched specimens of S30C (I) steel with a layer of weld metal of 1 mm in thickness were prepared, and from the specimens in Fig. 3 (b), notched specimens of SS41 steel with a layer of weld metal of 1 mm in thickness, and from the specimens in Fig. 3 (c), notched specimens of S30C (I) steel with a layer of weld metal of 3 mm in thickness were prepared.

The specimens in Fig. 4 (a) were used for preparing notched specimens of SF60 (I) steel with a layer of weld metal of 3 mm in thickness, and those in Fig. 4 (b), for notched specimens of S30C (II) steel, and also those in Fig. 4 (c) were used for preparing shrink-fitted specimens of SF60 (II) steel, respectively.

Each specimen was polished with emery paper of \#04 before the fatigue test in the longitudinal direction for unnotched specimens or in the circumferential direction for notched specimens.

![Notched specimen of 20 mm in diameter](image)

![Notched specimen of 60 mm in diameter](image)

![Shrink-fitted specimen](image)

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### Table 1 Chemical analysis of steels used

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Remarks</th>
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<td>SS41</td>
<td>0.20</td>
<td>0.29</td>
<td>0.52</td>
<td>0.008</td>
<td>0.020</td>
<td>—</td>
<td>for 20 mm diameter specimen</td>
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<tr>
<td>S30C</td>
<td>I</td>
<td>0.28</td>
<td>0.32</td>
<td>0.69</td>
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<td>0.021</td>
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<td></td>
<td>II</td>
<td>0.33</td>
<td>0.29</td>
<td>0.68</td>
<td>0.012</td>
<td>0.021</td>
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<tr>
<td>SF60</td>
<td>I</td>
<td>0.42</td>
<td>0.29</td>
<td>0.67</td>
<td>0.009</td>
<td>0.007</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>0.41</td>
<td>0.28</td>
<td>0.73</td>
<td>0.010</td>
<td>0.009</td>
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### Table 2 Mechanical properties of steels used

<table>
<thead>
<tr>
<th>Steel</th>
<th>Mechanical properties</th>
<th>Vickers hardness number ( H_v )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \sigma_s )</td>
<td>( \sigma_b )</td>
</tr>
<tr>
<td>SS41</td>
<td>32.2</td>
<td>47.6</td>
</tr>
<tr>
<td>S30C</td>
<td>I</td>
<td>33.6</td>
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<td></td>
<td>II</td>
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<tr>
<td>SF60</td>
<td>I</td>
<td>34.6</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>41.2</td>
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</tbody>
</table>

\( \sigma_s \): yield stress kg/mm², \( \sigma_b \): ultimate tensile strength kg/mm²
\( \varepsilon \): elongation %, \( \psi \): reduction of area %,
\( E \): modulus of elasticity kg/mm²

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Fig. 1 Details of fatigue test specimens built-up by welding

(a) Unnotched specimen

![Unnotched specimen](image)

(b) Notched specimen

![Notched specimen](image)
2.4 Welding conditions and shot-peening conditions

All specimens were built-up with longitudinal weld beads manually deposited using austenitic stainless steel electrodes (D 309 Mo). The distortion of specimens after welding was not straightened. The chemical compositions and mechanical properties of deposited metal are shown in Table 3, and their welding conditions are given in Table 4.

Shot-peening was carried out by the compressed air method. Shot size was 0.4~0.8 mmφ and arc height in Almen A strip was about 0.3 mm. These conditions are given in Table 5.

2.5 Residual stress

The distributions and magnitudes of residual

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Table 3 Chemical analysis and mechanical properties of deposited metal

<table>
<thead>
<tr>
<th>Steel</th>
<th>Chemical analysis %</th>
<th>Mechanical properties kg/mm² %</th>
<th>Vickers hardness number Hv</th>
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</thead>
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<tr>
<td></td>
<td>C</td>
<td>Si</td>
<td>Mn</td>
</tr>
<tr>
<td>D 309 Mo</td>
<td>0.06</td>
<td>0.65</td>
<td>0.39</td>
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Table 4 Welding conditions

<table>
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<tr>
<th>Electrode</th>
<th>Welding current amp.</th>
<th>Welding speed mm/min</th>
<th>Preheat temperature °C</th>
<th>Postheating</th>
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<tbody>
<tr>
<td>D 309 Mo (3.2 mmφ)</td>
<td>100~120</td>
<td>150~200</td>
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<td>—</td>
</tr>
<tr>
<td>D 309 Mo (3.2 mmφ)</td>
<td>100~120</td>
<td>150~200</td>
<td>—</td>
<td>150</td>
</tr>
<tr>
<td>D 309 Mo (4 mmφ)</td>
<td>130~150</td>
<td>150~220</td>
<td>150</td>
<td>250</td>
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</table>

(a) Unnotched specimen  
(b) Notched specimen  
(c) Notched specimen

Fig. 3 Specimen shapes of 20 mm in diameter prior to build-up welding

(a) Notched specimen  
(b) Notched specimen  
(c) Shrink-fitted specimen

Fig. 4 Specimen shapes of 60 mm in diameter prior to build-up welding

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(a) Built-up  
(b) Built-up and shot-peened

Fig. 5 Residual stress distributions for specimens built up by welding
stresses in round bar specimens built-up by welding under the same conditions as those of fatigue test specimens were determined by Sachs boring-out method with the results shown in Fig. 5. A large tensile residual stress was produced by build-up welding near the surface but most of it disappeared by shot-peening.

2.6 Method of fatigue tests

Fatigue tests were carried out on the specimens of 20 mm in diameter by a cantilever beam type rotating bending fatigue testing machine (capacity of 30 kg m and testing speed of 1500 rpm). However, on the specimens of 60 mm in diameter, they were carried out by a rotating bending fatigue testing machine for large specimens (capacity of 7.8 tm and testing speed of 800 rpm).

3. Results of fatigue tests

3.1 Unnotched specimens

S-N curves for unnotched specimens of 20 mm in diameter obtained from fatigue tests are shown in Fig. 6. The fatigue strength of build-up welded specimens was 26 kg/mm², which decreased by 13% from 30 kg/mm² of that of the base metal.

3.2 Notched specimens

S-N curves for notched specimens obtained from fatigue tests are shown in Figs. 7, 8, and 9. From the results of these tests, the following conclusions were drawn.

(a) Specimens of 20 mm in diameter

(b) In the specimen with a layer of 3 mm in thickness, the fatigue strength decreased by 10% from that of the specimen with a layer of 1 mm in thickness.

(c) In the shot-peened specimen built-up by welding, the fatigue strength increased by 56% from that of the base metal or by 25% from that of an as-welded specimen.

(2) Specimens of 60 mm in diameter

In the build-up welded specimens the fatigue strength increased by 7% for S30C (I) or by 21% for SF 60 (I) from that of the base metal.

3.3 Shrink-fitted specimens

S-N curves for shrink-fitted specimens obtained from fatigue tests are shown in Fig. 10. The fatigue strength of shrink-fitted specimens built-up by welding was 8 kg/mm², which was slightly lower than that of the base metal.
lower than 9 kg/mm² of the strength of the shrink-fitted specimen of base metal presumed from the experimental results hitherto obtained. However, in the shot-peened and shrink-fitted specimens, the fatigue strength of base metal was 18 kg/mm², and that of build-up welded specimens was 21 kg/mm², which was a great improvement. The fatigue strengths of shrink-fitted specimens indicated the stresses at which non-propagating cracks did not occur after $10^7$ stress cycle repetitions.

The results of fatigue strength obtained from the above tests are summarized in Table 6.

### 3.4 Base metal specimens of 6 mm in diameter and deposited metal specimens

$S-N$ curves for base metal specimens of 6 mm in diameter and deposited metal specimens obtained from fatigue tests are shown in Figs. 11 and 12. The fatigue strengths obtained from $S-N$ curves ($10^7$ stress cycles) are shown in Tables 7 and 8.

![Fig. 10 S-N curves for shrink-fitted specimens](image1)

![Fig. 11 S-N curves for base metal specimens of 6 mm in diameter](image2)

<table>
<thead>
<tr>
<th>Diameter of specimen mm</th>
<th>Shape of specimen</th>
<th>Steel</th>
<th>Description of specimen</th>
<th>Layer thickness of weld metal mm</th>
<th>Fatigue strength at $10^7$ cycles kg/mm²</th>
<th>Fatigue strength relative to that of base metal %</th>
<th>Remarks</th>
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<tr>
<td>20</td>
<td>Unnotched</td>
<td>S 30 C (I)</td>
<td>Base metal</td>
<td>—</td>
<td>30</td>
<td>100</td>
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<td></td>
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<td>Built-up</td>
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<td>87</td>
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<td>Base metal</td>
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<td>Shot-peened after build-up welding</td>
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<td>Built-up</td>
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<td></td>
<td></td>
<td></td>
<td>Base metal</td>
<td>—</td>
<td>18</td>
<td>138</td>
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<tr>
<td></td>
<td>Notched</td>
<td>SF 60 (I)</td>
<td>Base metal</td>
<td>—</td>
<td>25*</td>
<td>100</td>
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<td>Built-up</td>
<td>3</td>
<td>14</td>
<td>100</td>
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<td></td>
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<td>Base metal</td>
<td>—</td>
<td>17</td>
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<td></td>
<td></td>
<td></td>
<td>Base metal</td>
<td>—</td>
<td>16</td>
<td>100</td>
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<td>Built-up</td>
<td>3</td>
<td>9**</td>
<td>100</td>
<td>Shot-peened after build-up welding</td>
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<td>Base metal</td>
<td>—</td>
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<td>200</td>
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<td>Built-up</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Shr. fitted</td>
<td>—</td>
<td>21</td>
<td>233</td>
<td>Shot-peened after build-up welding</td>
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</tbody>
</table>

* Presumed value from fatigue strength of 6 mm diameter specimen shown in Table 7

** Presumed value from previous fatigue test results

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3.5 Fatigue fracture surface

The typical fatigue fracture surfaces of shrink-fitted specimens are shown in Fig. 13. In build-up welded specimens, most of the fatigue cracks are initiated from the surface of specimens as shown in Fig. 13 (a). However, in shot-peened and shrink-fitted specimens built-up by welding, fracture occurred away from the shrink-fit end as shown in Fig. 13 (b).

4. Discussion

4.1 Stress distribution of notched specimens built-up by welding

When bending stress acts on notched specimens built-up by welding, the stress at the notch root can be determined by the following method.

As shown in Fig. 14, when nominal bending stress, $\sigma_n$, acts on a notched specimen, maximum strain at notch root, $\varepsilon_{max}$, is expressed as follows:

$$\varepsilon_{max} = \alpha \frac{\sigma_n}{E_b}$$  \hspace{1cm} (1)

where

- $\alpha$: theoretical stress concentration factor due to notch
- $E_b$: modulus of elasticity of base metal, kg/mm$^2$

When a material having a lower modulus of elasticity than that of the base metal is deposited to the notched part shown by the broken line, the total average modulus of elasticity, $E_n$, of a round bar due to bending moment can be determined by the following Eq. (2)

$$E_n = \frac{c^4 E_b + (a^4 - c^4) E_d}{a^4}$$

where

- $a$: radius of specimen mm
- $c$: radius of base metal mm
- $E_d$: modulus of elasticity of deposited metal kg/mm$^2$

Therefore, nominal strain of build-up welded specimen, $\varepsilon_n$, is expressed as follows:

$$\varepsilon_n = \frac{\sigma_n}{E_n}$$  \hspace{1cm} (3)

Assuming that when there is a difference between modulus of elasticity of base metal and that of deposited metal, $\alpha_n$, theoretical stress concentration factor of base metal, and $\alpha_d$ that of build-up welded layer, act respectively and $\varepsilon_n$ becomes $\varepsilon_{max}$, the surface maximum strain of build-up welded specimen, $\varepsilon_{max}$, can be determined by the following

### Table 7 Fatigue test results for base metal specimens of 6 mm in diameter

<table>
<thead>
<tr>
<th>Shape of specimen</th>
<th>Steel</th>
<th>Fatigue strength at $10^6$ cycles kg/mm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unnotched</td>
<td>SF 60 (1)</td>
<td>27.5</td>
</tr>
<tr>
<td>Notched</td>
<td>SF 60 (1)</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>SS 41</td>
<td>14</td>
</tr>
</tbody>
</table>

### Table 8 Fatigue test results for notched specimens of deposited metal

<table>
<thead>
<tr>
<th>Diameter of specimen mm</th>
<th>Deposited metal</th>
<th>Fatigue strength at $10^6$ cycles kg/mm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>D 309 Mo</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>D 309 Mo</td>
<td>23</td>
</tr>
</tbody>
</table>

Fig. 12 S-N curves for notched specimens of deposited metal

Fig. 13 Typical fatigue fracture surfaces for shrink-fitted specimens

$a = 9$ kg/mm$^2$, $N = 3.503 \times 10^6$

(a) Built-up

$b = 24$ kg/mm$^2$, $N = 1.838 \times 10^6$

(b) Built-up, shot-peened
Eq. (4)
\[ \varepsilon_{d_{\text{max}}} = \alpha_s \varepsilon_0 \frac{\sigma_0}{E_0} \]  

Accordingly the ratio of maximum strain at notch root of base metal specimen to that of build-up welded specimen is expressed as follows.
\[ \frac{\varepsilon_{\text{max}}}{\varepsilon_{d_{\text{max}}}} = \alpha_s \alpha_d \frac{E_0}{E_0} \]  

And so the ratio of maximum stresses is as follows.
\[ \frac{\sigma_{d_{\text{max}}}}{\sigma_{\text{max}}} = \frac{\alpha_s \varepsilon_0}{\alpha_s \varepsilon_0} \frac{E_0}{E_0} \]  

The decrease of stress at the notch by build-up welding is expressed by Eq. (6).

4.2 Influence of layer thickness of weld metal

In the specimen of S 30 C (I) steel of 20 mm in diameter, the fatigue strength of the specimen with a layer of 1 mm in thickness was 20 kg/mm², but the strength of the specimen with a layer of 3 mm in thickness decreased to 18 kg/mm². As shown in Fig. 3, the reason for the above difference is that the stress concentration factor of the specimen shape prior to build-up welding is \( \alpha_s = 1.11 \) in the specimen with a layer of 3 mm in thickness and \( \alpha_s = 1.02 \) in the specimen with a layer of 1 mm in thickness, and the value in Eq. (6) is larger when the thickness of weld metal is smaller. Then, the thickness of weld metal would be as small as possible in the range of \( \sigma_{d_{\text{max}}}/\sigma_{\text{max}} > 1 \) (\( \sigma_{\text{max}} \): stress on the side of base metal at the boundary between build-up welded layer and base metal).

4.3 Influence of specimen shape prior to build-up welding

In case of S 30 C (II) steel of 60 mm in diameter, the fatigue strength of notched specimens built-up by welding increased by 7% from that of base metal. However, in case of SF60 (I) steel, the strength increased by 21% from that of base metal. The reason for the above difference is roughly as follows:

The theoretical stress concentration factor of the specimen shape prior to build-up welding is \( \alpha_s = 1.2 \) for S30C(II) steel, while it is 1.0 for SF60(I). Steel. As the theoretical stress concentration factor of the specimen shape prior to build-up welding has an influence on the relation expressed by Eq. (6), the value must desirably be set at \( \alpha_s = 1.0 \).

4.4 Effect of shot-peening

As austenitic stainless steels have high strain hardening, the hardness of surface layer of the shrink-fitted specimen built-up by welding greatly increases due to shot-peening as shown in Fig. 15. Furthermore, as shown in Fig. 5, a large tensile residual stress of surface layer almost disappeared by shot-peening, which would remarkably improve the fatigue strength.

4.5 Size effect of notched specimens

Table 9 Size effect of notched specimen

<table>
<thead>
<tr>
<th>Diameter of specimen mm</th>
<th>Steel</th>
<th>Description of specimen</th>
<th>Fatigue strength kg/mm²</th>
<th>Coefficient of size effect ( \zeta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>S 30 C</td>
<td>Base metal</td>
<td>16</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Built-up</td>
<td>20</td>
<td>—</td>
</tr>
<tr>
<td>60</td>
<td>SF 60</td>
<td>Base metal</td>
<td>14</td>
<td>0.88</td>
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<tr>
<td></td>
<td></td>
<td>Built-up</td>
<td>17</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Fig. 14 Strain distributions for notched specimen

Fig. 15 Hardness distributions for shrink-fitted specimens built-up by welding
than that of the base metal.

4.6 Influence of build-up welding and effect of shot-peening on the fatigue strength of shrink-fitted specimens

The fatigue strength of shrink-fitted specimens built-up by welding slightly decreased from that of the base metal. As the resistance to corrosion of austenitic stainless steels is superior to that of carbon steels, the former would have less fretting corrosion at the end of shrink-fit. However, it is presumed that as the heat conductivity of the former is as small as 1/4~1/5 of the latter, the temperature rise due to fretting is locally violent, and so the pitting due to fretting easily occurs and a large tensile residual stress produced by build-up welding is harmful to the fatigue strength. Then, the fatigue strength of a shrink-fitted specimen built-up by welding would be less than that of the base metal for the reasons mentioned above. It was found that shot-peening after build-up welding remarkably improved the fatigue strength of shrink-fitted specimens by inducing strain hardening and compressive residual stresses in the build-up welded layer.

5. Fatigue strength of notched specimen built-up by welding

The fatigue strength of build-up welded specimens depends upon the decrease of surface stress by build-up welding expressed by Eq. (6), the difference in fatigue strength between weld metal and base metal and the residual stress due to build-up welding. Assuming that the residual stress acts as a mean stress in endurance limit diagram, the fatigue strength of the build-up welded specimens can be determined by the following Eq. (7).

\[ \sigma_{se} = \frac{1}{\xi_2} \sigma_{se} \left( 1 - \frac{\sigma_R}{\sigma_{zd}} \right) \]  \hspace{1cm} (7)

where

- \( \sigma_{se} \): fatigue strength of notched specimen built-up by welding, kg/mm²
- \( \sigma_{zd} \): fatigue strength of base metal speci-

men having the same shape as that of the specimen build-up by welding, kg/mm²

\( \xi_1 \): coefficient of stress decrease due to build-up welding; it is derived from Eq. (6) as follows.

\[ \xi_1 = \frac{\sigma_{max}}{\sigma_{max}} = \frac{E_n}{E_d} \]

\( \xi_2 \): ratio of fatigue strength between deposited metal and base metal

\( \sigma_R \): residual stress, kg/mm²

\( \sigma_{zd} \): tensile strength of deposited metal, kg/mm²

It can be seen from Table 10 that the value of fatigue strength calculated from Eq. (7) is slightly larger than the experimental value; but they considerably well agree. Accordingly, it was found that the fatigue strength of the specimens built-up by welding can be estimated by Eq. (7), even if there are some variations in layer thickness of weld metal, and specimen shape prior to build-up welding.

6. Conclusions

In order to investigate the influence of build-up welding on the fatigue strength, rotating bending fatigue tests were carried out on round bar specimens build-up by welding, and the following conclusions were drawn.

(1) After the build-up welding using an austenitic stainless steel electrode having a lower modulus of elasticity than that of the base metal, the fatigue strength of unnotched specimens decreased by about 13% from that of the base metal, but the fatigue strength of notched specimens having a theoretical stress concentration factor of 2 increased by about 20% from that of the base metal.

(2) The fatigue strength of the specimens built-up by welding depends upon the specimen shape prior to build-up welding. Then, the specimen shape prior to build-up welding must be one not producing a stress concentration.

Table 10 Comparison of calculated values with experimental results for notched specimens build-up by welding

<table>
<thead>
<tr>
<th>Diameter of specimen mm</th>
<th>Steel</th>
<th>Layer thickness of weld metal mm</th>
<th>Fatigue strength kg/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Calculated value</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \sigma_{se} )</td>
</tr>
<tr>
<td>20</td>
<td>S 30 C (I)</td>
<td>1</td>
<td>21.2</td>
</tr>
<tr>
<td></td>
<td>SS 41</td>
<td>3</td>
<td>17.9</td>
</tr>
<tr>
<td></td>
<td>SF 60 (I)</td>
<td>1</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>S 30 C (II)</td>
<td>3</td>
<td>16.6</td>
</tr>
</tbody>
</table>
(3) In the shrink-fitted specimens built-up by welding, the fatigue strength was slightly lower than that of the shrink-fitted specimen of the base metal. However, the strength was remarkably improved by shot-peening.

(4) The fatigue strength of notched specimens built-up by welding can be estimated by Eq. (7).

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**References**


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**Discussion**

H. Nakamura (Kawasaki Heavy Industry Ltd.):

(1) Generally, I agree with you as it seems to fit with the experiments. But can you explain more in detail about Eq. (4), or how it was derived?

(2) The following Eq. (i) is doubtful.

\[ \varepsilon_{\text{max}} = \alpha \varepsilon_m \] .............................. (i)

If \( E_0 = E_\nu \), using \( \delta \) in Appendix-Fig. 1, the following Eq. (ii) will be better.

\[ \varepsilon_{\text{max}} = \delta \varepsilon_m \] .............................. (ii)

If \( E_0 = 0 \), Eq. (i) seems to be right. Perhaps as shown in Appendix-Fig. 3, \( \delta' \) will lie between \( \delta \) and \( \alpha \).

It will be quite understandable if you say that you have set the value of \( \delta' \) at \( \alpha \) for simplicity's sake as it is too complicated to determine between \( \delta \) and \( \alpha \).

By the way, is \( \alpha \) in Eq. (1) \( \alpha_0 \) or \( \alpha_b \)?

Further, what effect will build-up welding have in case of \( \alpha_0 > \alpha_b \) or \( \alpha_0 < \alpha_b \) or in case \( b \) becomes fairly large in comparison with \( a \)?

A. Ono (Industrial Research Institute of Kanagawa Prefecture):

(3) The effect of shot-peening seems to be quite remarkable. Which, do you suppose, is the major cause of this effect, residual stress or strain hardening? As this is a completely reversed bending fatigue test using a soft material, these seems to be a limit to the effect of residual stress. On the other hand, the hardened zone due to peening seems to be fairly thin. It seems to be important to clarify this cause in connection with choice of shot-peening conditions. Do you intend to measure the change of residual stress in fatigue test?

The shot-peening conditions in this report seem to be slight as compared with the specimen size. Generally, I think that arc height in Almen C strip is over 0.25 mm, but these conditions must be used for a centrifugal force type machine and with 1.2 mm dia. shot.

Shrink-fit was carried out in as shot-peened state in this case, but the contact stress locally increases either statically or dynamically on an aventurine lacquer surface due to peening, and, therefore, its effect of fretting is expected to be pretty negative.

In conclusion, it is anticipated that the effect of the hard shot-peening is the greatest when it is followed by surface finishing by grinding or by honing to remove surface roughness. What is your comment on this point?

**Authors' closure**

(1) Equation (4) was derived from Eq. (3)
by the following method.

Nominal strain of build-up welded specimen was $\varepsilon_{n'}$, and nominal strain on the side of base metal at the boundary between build-up welded layer and base metal, $\varepsilon_{a'}$, is as follows.

$$\varepsilon_{a'} = \varepsilon_{m} \frac{c}{a}$$

By assuming that this $\varepsilon_{a'}$ becomes $\varepsilon_{b_{\text{max}}}$, maximum strain on the side of base metal at point B, due to theoretical stress concentration of base metal, and $\varepsilon_{b_{\text{max}}}$ becomes $\varepsilon_{b_{\text{max}}}$, maximum surface strain at point A, due to theoretical stress concentration of build-up welded layer, the following equations are derived.

$$\varepsilon_{b_{\text{max}}} = \alpha_{b} \varepsilon_{m}$$

$$\varepsilon_{b_{\text{max}}} = \alpha_{b} \frac{a}{c} = \alpha_{b} \varepsilon_{a} \frac{c}{E_{m}}$$

(2) When there is a difference in the modulus of elasticity, the precise value of $\alpha_{b}$ is unknown. Probably, the value of $\alpha_{b}$ will lie somewhere between the case of $E_{b}=E_{s}$ and that of $E_{b}=0$.

In this report, however, we have assumed that $\alpha_{b}$ and $\alpha_{d}$ act respectively, and $\varepsilon_{m}$ becomes $\varepsilon_{d_{\text{max}}}$ when there is a difference in the modulus of elasticity. Under these assumptions, the calculated values of fatigue strength agree well with the experimental value even if there are some variations in layer thickness of weld metal and $\alpha_{s}$.

In Eq. (1), $\alpha$ was neither $\alpha_{s}$ nor $\alpha_{d}$. These values in SF60 (1) steel of notched specimen of 60 mm in diameter are as follows. $\alpha$ is 2.0, which is the theoretical stress concentration factor of the form of $d=60 \text{mm}$, $D=66 \text{mm}$ and $\rho=4.3 \text{mmR}$, and $\alpha_{s}$ is 1.0 because of straight part, and $\alpha_{d}$ is 1.7, which is the theoretical stress concentration factor of a cylindrical shaft of notch depth $t=3 \text{mm}$, notch radius $\rho=4.3 \text{mmR}$, thickness $a=3.5 \text{mm}$, and radius $r=30 \text{mm}$.

In case of $\alpha_{s} \geq \alpha_{d}$, fatigue tests were not carried out, but the effect of build-up welding using materials having a lower modulus of elasticity than that of base metal was large since $\alpha$ was larger than $\alpha_{d}$. But in case of $\alpha_{s} \geq \alpha_{d}$, there is no effect of build-up welding, and there may occur a decrease in fatigue strength owing to layer thickness of build-up welded metal. When $b$ was large as compared with $a$, maximum value of $b$ equals to $a$ because $b \leq a$, namely, base metal part was 0, and the strength equals that of deposited metal.

(3) As for the effect of shot-peening on the shrink-fitted shafts built-up by welding, when residual stress becomes nearly zero from 25 kg/mm² as welded due to shot-peening, the fatigue strength will increase only by about 3~5 kg/mm² assuming that the residual stress acts as a mean stress in endurance limit diagram, thus, the effect of the residual stress will be small. Therefore, the effect of shot-peening may depend more largely on strain hardening than on residual stress. In case of measuring the residual stress in fatigue test, the meaning would be small, if the part under fretting were not measured. But with shrink-fitted shafts, this is very difficult; therefore, the authors intend to measure the change of residual stress by some method with which the specimen may be able to be removed and the position under fretting does not change by its removal.

As for the shot-peening conditions, this report is not concerned with the effect of shot-peening conditions, and, hence, only one condition, the suitability of which is not confirmed, is used. The hardened zone due to shot-peening seems to be fairly thin in comparison with the specimen size as you said, but when shot-peening is too hard, micro cracks may occur in surface layer, and residual stress in this layer may also decrease. And since the strength of surface layer of 0.2~0.3 mm is important for shrink-fitted shafts, it is considered that arc height of 0.3 mm in Almen A strip is good enough; thus, there will be no need for deepening the hardened zone too much. Moreover, since unevenness of surface due to peening may develop contact stress locally, the hardened zone needs to be a little deepened in case of removal of surface roughness by grinding.