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<tr>
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<tr>
<td><strong>Author(s)</strong></td>
<td>KIHARA, Hiroshi; SUHARA, Jiro; KUROKAWA, Tsuneo; KATAOKA, Shigeo; YAJIMA, Hiroshi; FUKAE, Tatsuro</td>
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<tr>
<td><strong>Citation</strong></td>
<td>Transactions of JWRI. 4(1) P.47-P.60</td>
</tr>
<tr>
<td><strong>Issue Date</strong></td>
<td>1975-02</td>
</tr>
<tr>
<td><strong>Text Version</strong></td>
<td>publisher</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/11094/12444">http://hdl.handle.net/11094/12444</a></td>
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<td><strong>DOI</strong></td>
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Effect of Fabricating Process on Notch Toughness of Shipbuilding Steel Plates (Report II)†
—Superposition of Welding on Cold Work and Its Effect on Brittle Fracture Strength—

Hiroshi KIHARA*, Jiro SUHARA**, Tsuneo KUROKAWA***, Shigeo KATAOKA****, Hiroshi YAJIMA***** and Tatsuro FUKAE******

Abstract

Welded sections of grade E high-tensile and mild steel plates are used at the ship rounded gunwales to serve as brittle crack arresters. It is said that welding lifting eyes, etc., to the gunwale should be avoided because the gunwale plating, being initially cold-bent, will be adversely affected by the welding, to the detriment of its brittle fracture strength. The authors carried out brittle fracture initiation and propagation arrest tests on cold-worked-and-bead-welded grade E high-tensile and mild steel test specimens to determine how the cold-working and welding would combine together to affect the brittle fracture strength of the grade E gunwale plating. The tests indicated that: (1) welding on 3—5% cold-worked grade E high-tensile and mild steel plates would exert no adverse effects on the brittle fracture strengths of the plates; (2) welding lifting eyes to the rounded gunwales of grade E steels would suggest nothing alarming from a practical standpoint.

1. Introduction

With the recent increase in size of ship hulls, the riveted joints have largely been replaced as crack arrestors by welded sections of grade E steel in such locations as the rounded deck gunwale. Welding lifting eyes, etc., to the rounded gunwale is generally considered undesirable because the gunwale plating, being initially cold-bent, will be adversely affected by the welding, to the detriment of its brittle fracture strength.

To obtain factual strength data for practical solution of various problems associated with fabrication of the ship gunwale, the authors carried out brittle fracture initiation and propagation arrest tests on cold-worked-and-bead-welded grade E high-tensile and mild steel plate specimens and studied how the cold-working and welding would combine together to affect the brittle fracture strength of the grade E steel gunwale plating.

2. Test Specimens and Test Methods

Test specimens were prepared from K5E 50 kg/mm² high-tensile and KEN mild steel plates, both 30 mm in thickness, manufactured to the rules and regulations of Nippon Kaiji Kyokai (the ship classification society of Japan). Table 1 shows chemical compositions and mechanical properties of these steel plates.

The tests were designed to determine how the brittle fracture strengths of the cold-bent K5E high-tensile and KEN mild steel gunwale plating would be affected by welding thereto of lifting eyes, with an emphasis on evaluating their strengths to resist the initiation and propagation of brittle fracture in the ship transverse direction which might occur after removal of the lifting eyes. Accordingly, three types of test specimen, the bending-prestrained type B and tensile-prestrained types T and T', were prepared from each of K5E high-tensile and KEN mild steel plates as shown in Fig. 1.

The type B specimens were cold-bent (first cold-working), normalized to remove the effect of the first cold-working, cold-bent flat backwards (second cold-working) to induce the same amount of plastic deformation as in the first cold-working, bead-welded from

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****** Research Engineer, Nagasaki Technical Institute, Mitsubishi Heavy Industries, Ltd.
Table 1. Chemical compositions and mechanical properties of steels used.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Heat Treatment</th>
<th>Plate Thickness (mm)</th>
<th>Chemical Compositions (%)</th>
<th>Tensile Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>Si</td>
</tr>
<tr>
<td>KEN</td>
<td>Normalized</td>
<td>30</td>
<td>0.13</td>
<td>0.28</td>
</tr>
<tr>
<td>K5 E</td>
<td>Normalized</td>
<td>30</td>
<td>0.13</td>
<td>0.35</td>
</tr>
</tbody>
</table>

![Diagram of procedure](image)

Fig. 1. Procedure of fabricating test specimens.

Both sides to simulate the welding of the lifting eye, strain-aged, and ground flush at the bead-welded part, all as illustrated. The bending-prestrained type B specimens, however, were considered to fail to faithfully reflect the effect of cold work when tested for brittle fracture initiation and propagation arrest. The tensile-prestrained types T and T' specimens were therefore prepared as illustrated to supplement the type B specimens though these two types of tensile-prestrained specimens did not directly correspond to the actual ship gunwale. In addition, as-received "virgin" plate specimens and renormalized plate specimens were also submitted for test. Thus, V-notch Charpy impact test, brittle fracture initiation test, and brittle fracture propagation arrest test were conducted on all these test specimens.

**Cold-Working**

In most instances, actual ship gunwales are cold-worked up to 2—2.5% in terms of bending plastic deformation. Accordingly the type B specimens were cold-worked up to 3% or 5%, all on the power press. The type T specimens were tensile-cold-worked transverse to the rolling direction while the type T' specimens were tensile-cold-worked parallel to the rolling direction, as illustrated in Fig. 1. Both types T and T' specimens were given 3% tensile cold-working for comparison with the type B specimens. Also, 0% tensile-cold-worked specimens were prepared to evaluate only the effect of welding.

**Normalizing**

For normalizing after the first cold work, the type B specimens were held at 930°C in a heating furnace for 0.5—1.0 hour and removed out of the furnace for cooling in still air. For comparison with the bending-prestrained type B specimens, renormalized specimens were prepared by renormalizing as-received steel plates which had already been normalized in the steel mill before shipment.
Bead-Welding

To simulate the welding of the lifting eye to the rounded gunwale in the ship transverse direction, weld beads were laid by manual welding on the bending-prestrained type B specimens and tensile-prestrained types T and T' specimens at right angles to the rolling direction. The JIS D 5016 electrode was used. The welding conditions used are shown in Table 2 and the welding sequences in Fig. 2. As can be seen from Fig. 2, the brittle fracture initiation test specimens were each provided with one linear bead weld from each side to prevent the angular distortion, and the brittle fracture propagation arrest test specimens were each provided with three parallel-running linear bead welds from each side to balance the residual stresses and to confine the crack propagation to within the center bead-welded path. To simulate the welding of a 30 mm-thick lifting eye to the gunwale plating, the parallel-running bead welds were spaced 45 mm on centers. Also, all the weld beads were ground flush to simulate the grinding-off of the fillet-weld metal following the removal of the lifting eye from the gunwale.

Table 2. Welding conditions.

<table>
<thead>
<tr>
<th>Welding Rod</th>
<th>Welding Current (A)</th>
<th>Welding Speed (mm/min)</th>
<th>Interpass Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JIS D5016 (5.0 mm²)</td>
<td>200~210</td>
<td>150~160</td>
<td>&lt;100</td>
</tr>
</tbody>
</table>

Fig. 2. Welding sequences.

Brittle Fracture Initiation Test Specimens

The purpose of the brittle fracture initiation test was primarily to determine how the brittle fracture would be initiated from surface hair cracks which might be left in the gunwale plating as a result of removal of the lifting eye.

The K5E steel test specimens were each surface-notched at the center and through-notched to the ends of the surface notch from both plate edges as shown in Fig. 3 (a). However, since the center surface notch was provided in each side of the specimen so that its root would coincide with the heat-affected zone of the plate beneath the weld bead (approximately 2.8 mm from the surface as actually measured), the surface notch was not deep enough in relation to the length of the through notch and, consequently, the brittle fracture did not necessarily start at the root of the surface notch, i.e., at the heat-affected zone of the plate. Therefore, the KEN steel test specimens were each surface-notched 6.0 mm deep across the full plate width by cutting a “U” groove of about 4.0 mm in depth in the first place, filling the groove with weld beads, and then milling a 6.0 mm-deep surface notch with a root radius of less than 0.1 mm in it, all as illustrated in Figs. 2 and 3 (b).

Brittle Fracture Propagation Arrest Test Specimens

The purpose of the brittle fracture propagation arrest being to quantitatively evaluate the ability of the gunwale plating to arrest the propagation of brittle fracture (1) through the part which is directly affected by the welding and removal of the lifting eye and (2) through the part other than (1), the bead-welded-and-flushed types B, T, and T' specimens were prepared to the form of the standard double-tension type or standard ESSO type and submitted for test along with the as-received and the renormalized plate test specimens having no weld beads. Figures 4 (a) and (b) show the details of the standard double-tension type specimen and standard ESSO type specimen, respectively.

The brittle fracture was propagated through the bead-welded-and-flushed part (the center bead weld of the three parallel-running bead welds, for test on the types B, T, and T' specimens and just through the plate width for test on the as-received, and the renormalized plate specimens, to determine which specimen would offer the best crack arresting capability.

3. Test Results

The Vickers hardness numbers measured at the cross section of each test specimen are shown in Table 3, from which it will be seen that the maximum hardness numbers registered for the KEN and K5E steel specimens at the part subject to combined effects of cold-work and welding are 258 Hv and 325 Hv, respectively. The hardness distribution determined for a 5% bending-prestrained K5E steel type B specimen
is shown in Fig. 5 by way of typical example. Also, a round 6 mm-diam. × 24 mm-gauge length tension test specimen was cut from the middle thickness of each plate specimen as illustrated in Fig. 6. From the results of the round-bar tension test, the following empirical equation correlating the yield stress and temperature in the 0°–196°C temperature range were obtained.

\[
\sigma_y = 26.5 \times 10^3 \frac{\text{kg}}{\text{mm}^2} \quad \text{(1)}
\]

\[
\sigma_y = 31.8 \times 10^3 \frac{\text{kg}}{\text{mm}^2} \quad \text{(2)}
\]

\[
\sigma_y = 25.6 \times 10^3 \frac{\text{kg}}{\text{mm}^2} \quad \text{(3)}
\]

\[
\text{As-received plate test specimen}
\]

\[
\text{3% tensile-prestrained type T specimen}
\]

\[
\text{3% tensile-prestrained type T specimen}
\]

\[
\text{3% bending-prestrained type B specimen}
\]

\[
\text{5% bending-prestrained type B specimen}
\]

\[
\text{As-received plate test specimen}
\]

\[
\text{3% tensile-prestrained type T specimen}
\]

\[
\text{3% tensile-prestrained type T' specimen}
\]

\[
\text{Renormalized plate test specimen}
\]

\[
\text{3% bending-prestrained type B specimen}
\]

\[
\text{5% bending-prestrained type B specimen}
\]

\[
\text{where} \quad \sigma_y = \text{yield stress, kg/mm}^2
\]

\[
T_k = \text{absolute temperature, °K}
\]

Also, V-notch Charpy specimens were taken from each specimen as illustrated in Fig. 6. From the results of the V-notch Charpy test, energy-temperature
and crystallinity-temperature curves were drawn as shown in Figs. 7 and 8. The results of the V-notch Charpy test may be summarized as follows.

KEN Steel

(1) Both the as-received plate specimen and the renormalized plate specimen satisfied the NK-specified impact value ($E_u \geq 6.2$ kg-m).

(2) Transition temperatures for the as-received and the renormalized plate specimens were almost identical.

(3) The 0% tensile-prestrained type T specimen and 0% bending-prestrained type B specimen, when compared with the as-received plate specimen and renormalized plate specimen, respectively, show signs of some surface embrittlement.

(4) Neither the bending-prestrained type B specimens nor the tensile-prestrained type T and T' specimens exhibited the effect of cold-work.

K5E Steel

(1) The bending-prestrained type B specimens, as normalized after cold-working, did not exhibit microstructures similar to the microstructure of the as-received plate specimen but satisfied the NK-specified impact value ($E_u \geq 6.2$ kg-m).

(2) All the K5E steel test specimens exhibited almost no effect of welding.

(3) The bending-prestrained type B specimens and tensile-prestrained types T and T' specimens commonly indicated signs of embrittlement at the center of plate thickness affected by combined effects of cold-work and welding.

Figure 9 shows the results of brittle fracture initiation test on the surface-notched KEN steel test specimens. $K_{IC}$ was determined by the following equation.
Table 3. Results of Vickers hardness measurements (KEN, K5E).

<table>
<thead>
<tr>
<th>Steel Used</th>
<th>Mother Metal</th>
<th>Weld Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1/2 part</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Part of 1 mm Depth from Surface</td>
<td>(Max. Hardness)</td>
</tr>
<tr>
<td></td>
<td>Compression Side</td>
<td>Tension Side</td>
</tr>
<tr>
<td>As Received</td>
<td>131~133</td>
<td>132~134</td>
</tr>
<tr>
<td>Renormalized</td>
<td>131~132</td>
<td>123~122</td>
</tr>
<tr>
<td>B</td>
<td>0% Bending Pre-Strain</td>
<td>&lt;134</td>
</tr>
<tr>
<td></td>
<td>3% Bending Pre-Strain</td>
<td>&lt;145</td>
</tr>
<tr>
<td></td>
<td>5% Bending Pre-Strain</td>
<td>&lt;151</td>
</tr>
<tr>
<td>T</td>
<td>0% Tensile Pre-Strain</td>
<td>&lt;140</td>
</tr>
<tr>
<td></td>
<td>3% Tensile Pre-Strain</td>
<td>140~160</td>
</tr>
<tr>
<td></td>
<td>3% Tensile Pre-Strain</td>
<td>158~166</td>
</tr>
<tr>
<td>As Received</td>
<td>149~153</td>
<td>147~152</td>
</tr>
<tr>
<td>Renormalized</td>
<td>139~146</td>
<td>142~147</td>
</tr>
<tr>
<td>K5E</td>
<td>B</td>
<td>0% Bending Pre-Strain</td>
</tr>
<tr>
<td></td>
<td>3% Bending Pre-Strain</td>
<td>&lt;156</td>
</tr>
<tr>
<td></td>
<td>5% Bending Pre-Strain</td>
<td>&lt;160</td>
</tr>
<tr>
<td>T</td>
<td>0% Tensile Pre-Strain</td>
<td>&lt;171</td>
</tr>
<tr>
<td></td>
<td>3% Tensile Pre-Strain</td>
<td>&lt;170</td>
</tr>
<tr>
<td>T'</td>
<td>3% Tensile Pre-Strain</td>
<td>&lt;176</td>
</tr>
</tbody>
</table>

(Test Load: 10 kg)

Fig. 5. Results of Vicker hardness measurements (K5E bending-prestrained type B).
Fig. 6. Specimens for tensile test and Charpy V-notch test.

Fig. 7. Charpy V-notch transition curves.

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Fig. 8. Charpy V-notch transition curves.

Fig. 9. Results of brittle crack initiation test (KEN).

\[ K_{ic} = \frac{\pi f(\gamma) \cdot \sigma_t^2 h}{1 - 0.177 \left( \frac{\sigma_a}{\sigma_t} \right)^2} \]  

(4)

where \( f(\gamma) = \sqrt{\frac{1}{\pi h} \left( \tan \frac{\pi h}{t} + 0.1 \sin \frac{2\pi h}{t} \right)} \)  

(5)

\[ \sigma_e = \text{fracture stress (gross stress), kg/mm}^2 \]

\[ \sigma_a = \text{fracture stress (net stress), kg/mm}^2 \]

\[ \sigma_y = \text{yield stress at the test temperature, kg/mm}^2 \]

Also, Fig. 10 shows the results of brittle fracture initiation test on the surface- and through-notched KSE steel test specimens. The critical value of plastic surface energy \( S_i \) was obtained by the following equation.

\[ S_i = \frac{\pi F(\gamma) \cdot \sigma_t^2 C}{2E} \]

(6)

where \( F(\gamma) = f_1(\gamma) \cdot f_2(\gamma) \)

\( f_1(\gamma) = \text{stress correction factor for the outside through notches} \)

\[ = \sqrt{\frac{2}{\pi \gamma} \left( \tan \frac{\pi \gamma}{2} + 0.1 \sin \pi \gamma \right)} \]

(7)

\[ \gamma = \frac{C}{B} \]

(8)
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\[ f_1(\gamma) = \text{stress correction factor for the center surface notch (refer to Eq. (5))} \]

The results of brittle fracture initiation test may be summarized as follows.

<table>
<thead>
<tr>
<th>Spec. No.</th>
<th>Symbol</th>
<th>Steel Type</th>
<th>Test Conditions</th>
<th>Spec. No.</th>
<th>Symbol</th>
<th>Steel Type</th>
<th>Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>As Received</td>
<td>Si=36800 Ω</td>
<td>2</td>
<td>A</td>
<td>Renormalized</td>
<td>Si=335.8 Ω</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>3% Tensile Pre-strain</td>
<td></td>
<td>4</td>
<td>B</td>
<td>0% Bending Pre-strain</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>B</td>
<td>3% Tensile Pre-strain</td>
<td>Si=1680 Ω</td>
<td>6</td>
<td>B</td>
<td>0% Bending Pre-strain</td>
<td>Si=1160 Ω</td>
</tr>
</tbody>
</table>

Fig. 10. Results of brittle crack initiation test (KSE).

KEN Steel

1. Both the as-received plate specimen and the renormalized plate specimen exhibited nearly the same brittle fracture initiation characteristics.
2. The 0% bending-prestrained type B specimen and 0% tensile-prestrained type T specimen were fabricated by laying the weld beads on the renormalized plate specimen and as-received plate specimen, respectively, and appeared to exhibit the same brittle fracture initiation characteristics. Neither did these 0% prestrained types B and T specimens indicate any significant difference in their test results.
3. The bending-prestrained type B specimens and tensile-prestrained types T and T' specimens exhibited no significant difference in their test results, so that the cold-work of the order of 3% provided in the test was not considered to affect the brittle fracture initiation characteristics.
4. Various factors may be considered when evaluating the effect of welding on the brittle fracture initiation characteristics, but laying the weld beads improved the brittle fracture initiation characteristics.

K5E Steel

1. The center surface notch was provided so that its root would coincide with the heat-affected zone produced by the first run of weld, in an effort to start the crack at the transition corner between the outside through notch and center surface notch. However, because the center surface notch was not deep enough in relation to the length of the outside through notch, the brittle fracture started in most instances not at the transition corner but at the middle of plate thickness in way of the tip of the outside through notch, thereby contributing to the scatter of test data.
2. The heat of welding was found to have some deleterious effect on the brittle fracture initiation characteristics.
3. The cold-work of the order of 3~5% provided in the test was not considered to affect the brittle fracture initiation characteristics whether the specimens were of bending-prestrained B type or of tensile-prestrained T and T' types.

Figures 11 and 12 show the results of brittle fracture propagation arrest test on the standard double-tension type and standard ESSO type specimens. \( K_c \) was determined by the following equations.

\[ K_c = f(\gamma) \cdot \sigma_s \cdot \sqrt{\pi C} \]  
\[ \sqrt{2} = \frac{\cos \frac{\pi \gamma}{2}}{\pi \gamma} \]  
\[ C = \frac{C}{B} \]

where \( f(\gamma) = \frac{2}{\tan \frac{\pi \gamma}{2}} \)

\( C = \text{arrested crack length, mm} \)
\( B = \text{width of test specimen (in the direction of crack propagation path), mm} \) 
\( \sigma_s = \text{gross stress, kg/mm}^2 \)

The results of brittle fracture propagation arrest test may be summarized as follows.

KEN Steel

1. Both the as-received plate specimen and the renormalized plate specimen exhibited no significant differences in their brittle fracture propagation arrest capabilities, as in the brittle fracture initiation characteristics test.
2. Whether the specimens were of bending-prestrained
the deposited weld metal possessed greater toughness than the base metal.

**K5E Steel**

1. The as-received plate specimen and renormalized plate specimen showed a considerable difference in their brittle fracture propagation arrest capabilities.

2. Neither the bending-prestrained type B specimens nor the tensile-prestrained types T and T' specimens showed the telltale effect of the cold-work or welding or both.

**Figures 13 and 14** show, for reference, distributions of surface residual stresses measured on the K5E steel 0% tensile-prestrained type T double-tension test specimen. A great amount of tensile residual stresses were measured on the face and back of the specimen, both along and transverse to the direction of welded-and-flushed crack-propagation path as illustrated.

**4. Considerations**

**4.1 Examination of Test Results**

The relation between the allowable surface-crack depth and the critical temperature for brittle fracture initiation and the relation between the allowable crack length and the critical temperature for brittle fracture initiation were established for the KEN and K5E test specimens as shown in **Tables 4 and 5**, respectively.
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Table 4. Critical temperature for brittle crack initiation vs. applied condition (KEN).

<table>
<thead>
<tr>
<th>Applied Stress</th>
<th>12.5 kg/mm²</th>
<th>1/2 σₙ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowable Crack Depth</td>
<td>5 mm</td>
<td>3 mm</td>
</tr>
<tr>
<td>As Received Renormalized</td>
<td>-207°C</td>
<td>-215°C</td>
</tr>
<tr>
<td>0% Tensile Pre-Strain T</td>
<td>-214°C</td>
<td>-220°C</td>
</tr>
<tr>
<td>3% Tensile Pre-Strain T</td>
<td>-136</td>
<td>-150</td>
</tr>
<tr>
<td>3% Tensile Pre-Strain T’</td>
<td>-129</td>
<td>-145</td>
</tr>
<tr>
<td>0% Bending Pre-Strain B</td>
<td>-122</td>
<td>-139</td>
</tr>
<tr>
<td>3% Bending Pre-Strain B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5% Bending Pre-Strain B</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Critical temperature for brittle crack initiation vs. applied condition (KSE).

<table>
<thead>
<tr>
<th>Applied Stress</th>
<th>16.0 kg/mm²</th>
<th>8.0 kg/mm²</th>
<th>1/2 σₙ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowable Crack Depth</td>
<td>200 mm</td>
<td>120 mm</td>
<td>60 mm</td>
</tr>
<tr>
<td>As Received</td>
<td>-149°C</td>
<td>-161°C</td>
<td>-174°C</td>
</tr>
<tr>
<td>0% Tensile Pre-Strain T</td>
<td>-136</td>
<td>-150</td>
<td>-165</td>
</tr>
<tr>
<td>3% Tensile Pre-Strain T</td>
<td>-129</td>
<td>-145</td>
<td>-161</td>
</tr>
<tr>
<td>3% Tensile Pre-Strain T’</td>
<td>-122</td>
<td>-139</td>
<td>-156</td>
</tr>
<tr>
<td>Renormalized</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

using Eqs. (1), (2), and (3) obtained from the round-bar tension test and Eqs. (4) and (6) mentioned in connection with the analyses of brittle fracture initiation characteristics and also the empirical equations given in Figs. 9 and 10. The calculations, however, did not take into account the effect of residual stresses which might have been developed by bead welding. It is generally known that the critical temperature for brittle fracture initiation without the welding residual stress will be higher by about 90°C than with the welding residual stress³. It, therefore, follows that the bending-prestrained type B specimen, and tensile-prestrained types T and T’ specimens would be quite safe for practical use even if the temperatures given in Tables 4 and 5 were about 90°C higher than they are.

Also, Tables 6 and 7 show the relation between the allowable critical crack length for propagation arrest and the critical temperature, for each of the KEN and KSE steel test specimens. The calculations were performed using Eq. (9), empirical equations given in Figs. 11 and 12, and also the following equation which, by applying the calculated Kₑ values, predicts the brittle fracture propagation arrest capabilities for actual structures³.

\[
C_{eff} = 0.1C + 190
\]

where \( C_{eff} \) = effective crack length determined from the results of double-tension test or ESSO test, mm

\( C \) = length of crack fracture propagated in actual structure, mm

Also, Tables 6 and 7 show the temperatures which satisfy the NK-specified \( Kₑ \) values³ which were calculated from the results of brittle fracture propagation arrest test in the following manner.

KEN Steel (30 mm thick): \( Kₑ = 343 \, \text{kg} \sqrt{\text{mm}}/\text{mm}³ \)  
(\( \sigma = 12.5 \, \text{kg}/\text{mm}² \), \( C = 240 \, \text{mm} \))

KSE Steel (30 mm thick): \( Kₑ = 439 \, \text{kg} \sqrt{\text{mm}}/\text{mm}³ \)  
(\( \sigma = 16.0 \, \text{kg}/\text{mm}² \), \( C = 240 \, \text{mm} \))

It can be said from the tables that all the bending-prestrained type B specimens and tensile-prestrained types T and T’ specimens are not adversely affected by cold-work-and welding and show nothing alarming for practical use though the calculation does not take into account the effect of residual welding stresses as mentioned earlier. Dropping the effect of residual welding stresses out of consideration may be justified.
Table 6. Critical applied temperature vs. applied condition (KEN).

<table>
<thead>
<tr>
<th>Applied Stress</th>
<th>12.5 kg/mm²</th>
<th>8.0 kg/mm²</th>
<th>Temperature at $K_c = 343$ kg√mm/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowable Crack Length</td>
<td>3 m</td>
<td>1 m</td>
<td>3 m</td>
</tr>
<tr>
<td>$K_c$ Value</td>
<td>489</td>
<td>377</td>
<td>314</td>
</tr>
<tr>
<td>As Received</td>
<td>9°C</td>
<td>3°C</td>
<td>2°C</td>
</tr>
<tr>
<td>Renormalized</td>
<td>2°C</td>
<td>8°C</td>
<td>241</td>
</tr>
<tr>
<td>0% Bending Pre-Strain T</td>
<td>-7°C</td>
<td>-12°C</td>
<td>-16°C</td>
</tr>
<tr>
<td>3% Bending Pre-Strain T</td>
<td>-2°C</td>
<td>-12°C</td>
<td>-22°C</td>
</tr>
<tr>
<td>0% Tensile Pre-Strain T</td>
<td>-7°C</td>
<td>-12°C</td>
<td>-16°C</td>
</tr>
<tr>
<td>3% Tensile Pre-Strain T</td>
<td>-8°C</td>
<td>-12°C</td>
<td>-22°C</td>
</tr>
</tbody>
</table>

Table 7. Critical applied temperature vs. applied condition (K5E).

<table>
<thead>
<tr>
<th>Applied Stress</th>
<th>16.0 kg/mm²</th>
<th>8.0 kg/mm²</th>
<th>Temperature at $K_c = 439$ kg√mm/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowable Crack Length</td>
<td>3 m</td>
<td>1 m</td>
<td>3 m</td>
</tr>
<tr>
<td>$K_c$ Value</td>
<td>628</td>
<td>483</td>
<td>314</td>
</tr>
<tr>
<td>As Received</td>
<td>5°C</td>
<td>-12°C</td>
<td>-23°C</td>
</tr>
<tr>
<td>Renormalized</td>
<td>5°C</td>
<td>-12°C</td>
<td>-23°C</td>
</tr>
<tr>
<td>0% Bending Pre-Strain T</td>
<td>15°C</td>
<td>7°C</td>
<td>-6°C</td>
</tr>
<tr>
<td>3% Bending Pre-Strain T</td>
<td>15°C</td>
<td>7°C</td>
<td>-6°C</td>
</tr>
</tbody>
</table>

because, though the tensile residual stresses are developed at the specimen surfaces as illustrated in Figs. 13 and 14, there are compressive residual stresses produced at the middle of the plate thickness and, thus, the residual stresses as distributed through the full plate thickness are considered to exert no deleterious effect for practical purposes.

4.2 Evaluation of Notch Toughness

In order to determine notch toughness of KEN and K5E steels, it is considered reasonable to evaluate the results of V-notch Charpy test, brittle fracture initiation test, and brittle fracture propagation arrest test in the following manner.

The 50% crystallinity transition temperature, $T_r$, will be used as an acceptance criterion for evaluating the results of V-notch Charpy test.

For evaluating the results of brittle fracture initiation test, the critical temperature for brittle fracture initiation $T_{b-s}$ for the applied stress of 12.5 kg/mm² (1/2 X yield point at the room temperature) and allowable critical surface-crack depth of 3 mm will be used as an acceptance criterion for the KEN steel test specimens while the critical temperature for brittle fracture initiation $T_{c-w}$ for the applied stress of 16.0 kg/mm² (1/2 X yield point at the room temperature) and allowable critical crack length of 20 mm (or C = 10 mm) will be used as an acceptance criterion for the K5E steel test specimens.

For evaluating the results of brittle fracture propagation arrest test, the temperature satisfying the NK requirements will be used as acceptance criteria: for the KEN steel test specimens, the temperature $12.5 T_{b-s}$ for the applied stress of 12.5 kg/mm² and critical crack length of 240 mm for propagation arrest, or $K_c = 343$ kg√mm/mm², and for the K5E steel test specimens, the temperature $16 T_{c-w}$ for the applied stress of 16.0 kg/mm² and critical crack length of 240 mm for propagation arrest, or $K_c = 439$ kg√mm/mm².

It is considered that for KEN, K5E, or any other similar steels, $T_r$ will show a scatter of less than 20°C and $12.5 T_{b-s}$, $16 T_{c-w}$, $12.5 T_{b-s}$, and $16 T_{c-w}$ a scatter of less than 10°C each as against the standard calculated value. Therefore, if each of the calculated values shifts to the high-temperature region beyond the limit of the expected scatter, then it should be interpreted that the bending-or tensile-cold-work combined with welding to adversely affect the notch toughness of the steel.

$T_{b-s}$, $12.5 T_{b-s}$, $16 T_{c-w}$, $12.5 T_{b-s}$, and $16 T_{c-w}$ determined for each of the KEN and K5E steel test specimens are shown in Figs. 15 and 16 though $T_r$.
was obtained from test on the specimen removed from the surface layer of each test specimen. It will be seen from Figs. 15 and 16 that all the bending-prestrained type B specimens and tensile-prestrained types T and T' specimen do not show any telltale sign of deterioration in notch toughness attributable to the combined effects of cold-work and welding.

**Conclusions**

The brittle fracture initiation and propagation arrest tests were conducted on cold-worked-and-bead-welded K5E 50 kg/mm² high-tensile and KEN mild steel test specimens to determine how the cold-working and welding would combine together to affect the brittle fracture strength of the grade E gunwale plating, with the following results.

1. Welding on the grade E steel gunwale plating cold-worked in bending up to about 3~5% or tensile cold-worked up to about 3% will not impair the brittle fracture strength of the gunwale plating so seriously as to prevent its practical use.
2. Welding lifting eyes, etc., to the cold-bent gunwale plating for large ships will pose no problem from a practical standpoint.

**Acknowledgement**

This project was suggested by the Shipbuilding Process Research Committee of The Society of Naval Architects of Japan and conducted by the 111 Research Committee of The Japan Shipbuilding Research Association to which the authors belong. The authors wish to express their heartfelt thanks to the members.
of both committees for fruitful discussions and coopera-
tions, and also to the technical staffs of the Depart-
ment of Structural Engineering, Nagasaki University
and The Nagasaki Technical Institute of Mitsubishi
Heavy Industries, Ltd., who kindly assisted the
authors for carrying out the various test.

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