Embrittlement in Weld Strain-Affected Zone in Carbon Steel

As measured by various tests, embrittlement is reproduced by thermal straining under restraint

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ABSTRACT. Based on the work of an earlier report (Ref. 1), the authors have tried to find the cause of embrittlement in the strain-affected zone of carbon steel weldments using postheating conditions as a parameter. First, various properties at the tip of the center notch of welded wideplate tensile specimens (Ref. 1) were investigated to find effective tests for revealing the material-differences between as-welded and postheated specimens. Experiment showed that the following tests are effective: (1) hardness, (2) fracture transition temperature by Charpy impact test, (3) absorbed energy by modified half-size sharp notch Charpy impact test, and (4) amount of plastic strain by the x-ray diffraction method.

Next, to reproduce the embrittlement in the weld strain-affected zone by thermal straining, the specimens were heated to the peak temperature, 450 ± 20 C (842 ± 36 F), under uniaxial, biaxial, and triaxial restraint, and also heated without restraint. These specimens were then postheated under various heating conditions, and their properties were investigated using the abovementioned tests. This data was compared with that at the notch tip and with the fracture stress data of the previous report using statistical methods.

Introduction

Results of the earlier work (Ref. 1) showed that: (1) the low fracture stress values of as-welded center notched wide-plate tensile specimens have recovered by postweld heat treatment even in short soaking time. The recovery of fracture stress values after postweld heat treatment was substantially affected by the heating temperature level, but not by the soaking time, (2) the recovery of fracture stress values had no distinct relationship with residual stress values, and (3) the recovery of fracture stress values was highly correlated with the reduction of hardness of strain-hardened specimens.

From these experimental results, it is conjectured that the cause of the embrittlement of as-welded joints is the thermal straining by welding heat, i.e. the embrittlement in so-called "weld strain-affected zone" (Ref. 2). In other words, the tip area of the center notch is heated by the welding, but free thermal expansion and contraction of this area are restrained by the adjacent material. Thus, the tip area is subjected to thermal straining and the amount of this straining depends on the peak temperature.

The measured peak temperature at the notch tip of welded wide-plate tensile specimen was 450 ± 20 C (842 ± 36 F). Therefore, as shown in Fig. 1, there were no differences in microstructure at the notch tip among the specimens of base metal, as-welded, and postheated at 600 C.
width beside the joint, like the Lueer's lines, are frequently observed on the surface of abandoned welded specimens or structures in an open place. Our results will indicate the importance of the weld strain-affected zone.

Properties at the Tip of the Center Notch

The authors investigated the various properties at the tip part of the center notch of longitudinally welded wide-plate tensile specimens used in the previous report in order to find effective tests for measuring the material differences between as-welded and postheated specimens. The tests made here were: (1) peak temperature measurement during welding, (2) hardness, (3) fracture transition temperature by V-notch Charpy impact test, (4) absorbed energy by modified half-size sharp notch Charpy impact test, (5) the amount of plastic strain by the x-ray diffraction method, (6) crack opening displacement by three-point notched static bending test, and (7) fracture stress by circular-notched round-bar tensile test.

Fig. 2, from data of the previous report, shows the fracture stress of longitudinally welded and center notched wide-plate tensile test after various postheating treatments. Experimental results in this report will always be compared with those of Fig. 2.

The Steel Used

The carbon steel used in experiments was SB42 plates of 25 mm (0.98 in.) in thickness. These steel plates were the same melt as those used in the main tests of the previous report. Chemical analysis and mechanical properties of this steel are given in Table 1.

All plates were stress relieved before experiment at 625 C (1157 F) for 1 hour to remove possible internal stress.

Preparation of Weld Specimens

Two 250 X 500 mm (10 X 20 in.) plates were butt welded by submerged arc welding to make a 500 X 500 mm (20 X 20 in.) weld specimen. The edge preparation and the welding conditions were the same as those of the welded wide-plate tensile specimens used in the previous report.

Then the welded specimens were postheated using all combinations of the following heating temperatures and soaking times.

1. Heating temperature: 400 C (752 F), 500 C (932 F), and 600 C (1112 F)
2. Soaking time: (a) 10 min, (b) 2 hr

The soaking time of 1 hour used in the previous report was neglected, since we were only interested in the effect of soaking time in extreme cases.

All specimens for this investigation were cut in the transverse direction to the weld axis, i.e., transverse to the rolling direction, and taken from the middle part in the thickness direction. As for the notched specimens, the notches were machine cut in the thickness direction and in parallel with the weld axis at the notch tip.

In what follows, we will use the abbreviations:

BM: Base metal
AW: As-welded, or as-thermally-strained
AW: As-welded, or as-thermally-strained
AW: As-welded, or as-thermally-strained
41: Postheat 400 C (752 F), 10 min
42: Postheat 400 C (752 F), 2 hr
51: Postheat 500 C (932 F), 10 min
52: Postheat 500 C (932 F), 2 hr
61: Postheat 600 C (1112 F), 10 min
62: Postheat 600 C (1112 F), 2 hr
R: Correlation coefficient
ANOVA: Analysis of variance

Peak Temperature Measurement

The peak temperature during submerged arc welding at the tip part of the center-notch, 18 mm (0.71 in.) from the center of weld, was measured by thermocouples attached at the mid-thickness on both sides of the weld joint. The welding conditions were:

Backing pass: 800 A, 36 V, 27 cm/min (10.6 in./min), and 64 kJ/cm (160 kJ/in.) heat input

Table 1 — Chemistry and Mechanical Properties of the Steel Plates Used

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Y.S. N/mm² (b)</th>
<th>T.S. N/mm²</th>
<th>Elong. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB42(a)</td>
<td>0.15</td>
<td>0.20</td>
<td>0.66</td>
<td>0.015</td>
<td>0.016</td>
<td>274</td>
<td>451</td>
<td>28</td>
</tr>
</tbody>
</table>

(a) Rolled steel plate for boilers specified by Japanese Industrial Standards.
(b) 1 N/mm² = 145 psi
Values at -80°C were taken from an temperature of -80°C (-112°F) and translation, and the mean values of these thickness direction at the notch tip in the heat-affected zone, say between them was calculated, as presented in Table 2. These calculated results can be summarized as follows: (1) The fracture transition temperature was highly correlated with the fracture stress and the effect of the heating temperature on fracture transition temperature was highly significant, while the effect of the soaking time was not significant.

Besides the transition temperature measurement, the half-size V notch Charpy impact test was carried out, since, in later thermal straining tests under biaxial and triaxial restraint, the uniformly heated part was too small for full size impact specimens. In this case, to examine the material differences, the absorbed energy only at a fixed testing temperature, 20°C (68°F), was measured, since the transition temperature measurement requires a large number of specimens. The absorbed energy values by this test, however, did not show a high correlation with the fracture stress as shown in Table 2; the R was 0.40.

It is generally accepted that the sharper notch is more sensitive to...
material differences. Thus the impact test was conducted with modified half-size sharp notch Charpy impact specimens. The notch was 0.2 mm (0.008 in.) in width, 0.1 mm radius (0.004 in.) at notch tip, and 2 mm (0.078 in.) in depth, in the place of V notch. Mean absorbed energy values of five tests at 20 C (68 F) after various postheat treatments are given in Fig. 7.

The results of statistical calculations, tabulated in Table 2, can be summarized as follows: (1) the absorbed energy values of modified half-size sharp notch Charpy impact test were highly correlated with the fracture stress, and (2) as to the response to postheat treatments, the effect of the heating temperature on absorbed energy was highly significant, while the effect of the soaking time was not significant. It should be noted, however, that the differences among mean values of absorbed energy were very small, as shown in Fig. 7.

Plastic Strain Measurement

The amounts of plastic strain at the notch tip were measured by x-ray diffractometer. First, the calibration specimens were uniaxially compressed by a tensile testing machine. The amounts of compressive plastic strain of these specimens were: 0, 1, 2.5, 10, 20, and 30%. Each specimen was placed in a goniometer, exposed to x-ray, and the distribution of the intensity of diffracted x-ray on (220) plane was plotted on a chart. From this chart, the half-height width was determined, and then the determined values were plotted in a diagram as ordinates against the amounts of compressive plastic strain as abscissa. The resulting calibration curve is illustrated in Fig. 8 (a). The test conditions of the x-ray measurement were: (1) x-ray used: Co Kα, 30 kVP, 10 mA, Fe filter, (2) goniometer scanning speed: 1/4 deg/min, (3) time constant: 4, and (4) chart traveling speed: 20 mm/min (0.79 in./min).

Next, the specimens taken from the notch tip part and postheated under various heating conditions were investigated in the same manner as the calibration specimens, and the half-height width of each specimen was measured. From the abscissa of the calibration curve corresponding to each measured value, the amount of the equivalent uniaxial compressive strain was determined. Figure 8 (b) shows the experimental results.

Crack Opening Displacement

The crack opening displacement at the notch tip after various postheat
treatments was measured by the three-point static bending test. The details of the specimen are illustrated in Fig. 9. These tests were carried out by Mr. T. Nakatsuji at Osaka University using the same welded plate. The results are given in Fig. 9. It is easily seen from the figure that there were no distinct differences among BM, AW, and postheated specimens.

Circular-Notched Round-Bar Tensile Test

The measurement of fracture stress by circular-notched round-bar tensile test of BM and AW specimens was carried out as a preliminary test. The details of the specimen and the results of this test are given in Fig. 10. As shown in Fig. 10, there was no substantial difference in fracture stress between BM and AW specimens, and thus further tests with postheated specimens were omitted. Also, AW specimens always showed higher fracture stress values than BM ones. It might come from the plastic constraint caused by higher peak hardness in heat-affected zone, which was near the circular notch, in AW specimens.

Remarks

Throughout the above investigations, it appeared that the following experimental measurements were effective in revealing material differences at the tip part of the center notch of longitudinally welded wide-plate tensile specimens after various postheating treatments: (1) hardness, (2) fracture transition temperature by V-notch Charpy impact test, (3) absorbed energy by modified half-size sharp notch Charpy impact test, and (4) the amount of plastic strain by the x-ray diffraction method.

Reproduced Thermal Straining Tests

In reproduced thermal straining tests, the specimens from the same steel plate were heated to the peak temperature, 450 ± 20 C (842 ± 36 F), under uniaxial, biaxial, and triaxial restraint, and also heated without restraint for comparison. The holding time at the peak temperature was 30 s for all specimens. The reason for this level will be explained later. The heated specimens were postheated using all combinations of the following heating temperatures and soaking times.

1. Heating temperature: 400 C (752 F), 500 C (932 F) and 600 C (1112 F)
2. Soaking time: (a) 10 min, (b) 2 h

The postheated and the asthermally-strained specimens were examined by the following testing methods: (1) hardness measurement, (2) absorbed energy by modified half-size sharp notch Charpy impact test, and (3) the amount of plastic strain by the x-ray diffraction method. Each set of these experimental results were compared with the fracture stress of the previous report, and with the experimental outcomes of the corresponding test at the notch tip; the F's were also calculated. Further, to see the response to the postheat treatments, these data were examined by the ANOVA.

In these tests, the following abbreviations will be used:

- O: Heated without restraint
- I: Thermally strained under uniaxial restraint
- II: Thermally strained under biaxial restraint
- III: Thermally strained under triaxial restraint

Heating Without Restraint

Round bar specimens, 11.5 mm (0.45 in.) diam and 83 mm (3.27 in.) long, taken from the same steel plate in the direction transverse to the rolling direction, were placed in a weld...
thermal-cycle simulating machine with a load applying device. The specimens were heated to 450°C (842°F) in a one-end-free state with a high frequency inductor coil, and then post-heated.

The mean hardness values of ten measurements after various postheat treatments are given in Table 3. In Fig. 11. Figure 12 shows the mean absorbed energy of three modified half-size sharp notch Charpy impact specimens tested at 20°C (68°F). The equivalent uniaxial compressive strain of the O-AW specimen was zero, and thus the plastic strain measurement with postheated specimens was neglected.

The calculated R's with the fracture stress and also with the data of the corresponding test at the notch tip, and the result of the ANOVA of each set of experimental data are presented in Table 3. As expected, there were practically no differences in hardness and absorbed energy among AW and postheated specimens. A slight effect of softening in hardness and slight improvement in absorbed energy were observed. The statistical calculations showed that: (1) the R's of all sets of data were lower, and (2) as to the response to postheat treatments, the effects of the heating temperature and the soaking time were not significant for all sets of data.

Straining Under Uniaxial Restraint

The same round bar specimens as the O-Series test were heated to 450°C (842°F) and cooled to room temperature in a both-ends-fixed state, otherwise in the same manner as the O-Series test. Later the specimens were postheated.

The I-Series experimental results of the hardness measurement and mean absorbed energy are given in Figs. 11 and 12, respectively. The calculated R and the results of the ANOVA of each set of these experimental data are given in Table 3.

In I-Series experimental results, there were no substantial differences in hardness and absorbed energy data among AW and postheated specimens. A slight effect of reduction in hardness and slight improvement in absorbed energy were observed. The equivalent uniaxial compressive strain of I-AW specimen was zero, and thus further experiment with postheated specimens was neglected.

Statistical calculations showed that: (1) the R's of all sets of data were lower except the R between hardness and fracture stress, and (2) as to the response to postheat treatments, the effects of the heating temperature and the soaking time were not significant for all sets of experimental data.

Resistance Heating

The central part of a 500 × 1000 mm (20 × 40 in.) plate was spot heated to the peak temperature by a large resistance spot welding machine. In this case, the spot heated part is surrounded by cold and rigid metal, and therefore the free thermal expansion and contraction of the heated part are restrained biaxially. By applying the electrode force of the spot welding machine to the spot heated, the free thermal expansion and contraction of the heated part were restrained triaxially. In the biaxial restraint case, however, a small electrode force of 4.9 kN (1100 lb) was applied to secure the electrical contact between electrode and steel plate. The diameter of the electrode was 20 mm (0.79 in.), and therefore the restraint stress in the thickness direction was 16 N/mm² (2260 psi). In the triaxial restraint case, the maximum electrode force of 39.2 kN (8820 lb) was applied, and this produced a restraint stress of 125 N/mm² (18,060 psi) in the thickness direction.

The holding time at the peak temperature was 30 s throughout the

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**Table 3 — Calculated Correlation Coefficients and the Results of the Analysis of Variance**

<table>
<thead>
<tr>
<th></th>
<th>With fracture stress</th>
<th>With results at notch tip</th>
<th>Results of analysis of variance&lt;sup&gt;(a)&lt;/sup&gt; for: Heating temp.</th>
<th>Soaking time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O-Series</td>
<td>-0.28</td>
<td>0.19</td>
<td>Not significant</td>
<td>Not significant</td>
</tr>
<tr>
<td>I-Series</td>
<td>-0.66</td>
<td>0.37</td>
<td>Not significant</td>
<td>Not significant</td>
</tr>
<tr>
<td>II-Series</td>
<td>-0.76</td>
<td>0.84</td>
<td>Not significant</td>
<td>Not significant</td>
</tr>
<tr>
<td>III-Series</td>
<td>-0.63</td>
<td>0.55</td>
<td>Significant</td>
<td>Significant</td>
</tr>
<tr>
<td>Half-size sharp notch Charpy impact test:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O-Series</td>
<td>-0.03</td>
<td>0.07</td>
<td>Not significant</td>
<td>Not significant</td>
</tr>
<tr>
<td>I-Series</td>
<td>-0.09</td>
<td>0.03</td>
<td>Not Significant</td>
<td>Not significant</td>
</tr>
<tr>
<td>II-Series</td>
<td>0.65</td>
<td>0.70</td>
<td>Significant</td>
<td>Not significant</td>
</tr>
<tr>
<td>III-Series</td>
<td>0.46</td>
<td>0.51</td>
<td>Not significant</td>
<td>Not significant</td>
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<tr>
<td>Compressive strain:</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>O-Series</td>
<td>-0.94</td>
<td>0.90</td>
<td>Significant</td>
<td>Not significant</td>
</tr>
<tr>
<td>I-Series</td>
<td>-0.67</td>
<td>0.59</td>
<td>Significant</td>
<td>Not significant</td>
</tr>
</tbody>
</table>

<sup>(a)</sup> At a 5% significance level

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**Fig. 11 — Reduction of hardness after various postheat treatments, thermally strained specimens**

**Fig. 12 — Recovery of impact values after various postheated treatments, thermally strained specimens**
thermal straining tests. As seen in Fig. 
2, the thermal cycle curve at the notch 
tip showed that the time at the peak 
temperature was fairly long. With the 
progress of the molten pool and with 
the elapse of time, however, the cold 
and rigid parts that restrain the ther-
mal expansion at the notch tip were 
also heated to higher temperatures, 
and therefore the degree of the re-
straint at the notch tip might become 
lower in the later period of the peak 
temperature.

The operation of the spot welding 
machine to heat the specimen and to 
hold the heated part within the peak 
temperature range, 450 ± 20 C (842 
± 36 F), was manually controlled by a 
skilled operator observing the temperature of the spot by means of an 
inserted thermocouple and pyrometer. At first, a 1 min. holding 
time was tried at the peak temper-

ture. But it was found difficult to hold 
the heated part within peak tempera-
ture range for 1 min, and so the holding time was reduced to 30 s. 
Even with a 30 s holding time, some of 
the spots exceeded the peak tempera-
ture range, 450 ± 20 C. These spots 
were discarded.

The spot heating conditions were: 
(1) welding current: 12,000 A, (2) cur-
rent-on cycle: 4/60 s, and (3) current-
off cycle: 3/60 s.

In the preliminary test, we ex-
amined the temperature distribution 
in the thickness direction at the spot 
using a number of thermocouples in-
serted in various positions. It was 
found that a portion about 7 mm (0.28 
in.) in thickness in the middle of the 
thickness direction was uniformly 
heated at the peak temperature.

Details of the spot heated plate 
 specimens are illustrated in Fig. 13. 
Figure 14 shows the three-phase, low-
frequency spot welding machine used 
in the experiments.

Straining under Triaxial Restraint

The specimens were heated to the peak temperature in the same man-
ner as explained above. Each spec-
imen was flame cut in the longitudi-

al direction, and then machined in the 
transverse direction. These block 
 specimens were variously post-
heated.

The II-Series experimental results 
of hardness measurement, mean ab-
sorbed energy, and the amount of the 
equivalent uniaxial compressive 
strain are given in Figs. 11, 12, and 14, 
respectively. The calculated R and the 
results of the ANOVA of each set of 
these experimental data are pre-

sented in Table 3.

The hardness data of the II-Series test 
was highly correlated with those 
at the notch tip, and also highly cor-
related with fracture stress. As re-
ards the response to postheat treat-
ments, the effects of both the heating 
temperature and the soaking time 
were not significant. However, the 
hardness data show that the effect of 
the heating temperature was signif-
icant at a 10% significance level.

In absorbed energy data, the R with 
those at the notch tip was relatively 
high, 0.70, and the R with the fracture 
stress was also relatively high, 0.65.

As to the response to postheat treat-
ments, the effect of the heating 
temperature was highly significant, 
while the effect of the soaking time 
was not significant.

The equivalent uniaxial compressive 
strain data was highly correlated 
with those at the notch tip, and also 
highly correlated with the fracture 
stress. As to the response to postheat 
treatments, the effect of the heat-
ting temperature was highly signif-
icant, while the effect of the soaking 
time was not significant.

In these test results under biaxial 
restraint, the hardness of II-AW spec-
imens was higher than that of the 
notch tip. On the other hand, the 
amount of plastic strain of II-AW 
 specimens was smaller than that of 
the notch tip. Such inconsistent re-

sults might come from the difference 
in heating temperature at the peak 
range, in holding time, and in the 
number of repetitions of heating be-

between notch tip parts and these 
 specimens.

Straining under Biaxial Restraint

The specimens were prepared in 
the same manner as the III-Series test 
except for the amount of the elec-

trode force applied. The III-Series 
experimental results of hardness 
measurement, mean absorbed 
energy, and the amount of equivalent 
uniaxial compressive strain are given 
in Figs. 11, 12, and 14, respectively. 
The calculated R and the results of the 
ANOVA of each set of these experi-
mental data are presented in Table 3.

The hardness data of III-Series test 
show the calculated R with those at 
the notch tip was 0.55, and the R with 
fracture stress was even higher at 
-0.63. As to the response to postheat 
treatments, the effects of both the 
heating temperature and the soaking 
time were significant. In this case, 
however, the hardness values of 41, 
51, and 61 specimens were always 
lower than those of 42, 52, and 62 
 specimens. Therefore, it might be un-
derstood that the effect of the soaking 
time was indifferent between the 
10 min and 2 h cases.

In the experimental results of 
equivalent uniaxial compressive 
strain, the calculated R with those at 
the notch tip was higher at 0.59, and 
the R with fracture stress was even 
higher at -0.67. As to the response to 
the postheat treatments, the effect of 
the heating temperature was signif-
icant, while the effect of the soaking 
time was not significant.

In absorbed energy data, there 
were no substantial differences 
among AW and postheated spec-
imens. Such an experimental result is 
consistent with those of hardness 
and compressive strain. The reason 
for this, however, could not be traced 
out. The R's of the absorbed energy 
data with those at the notch tip and 
with the fracture stress were not so 
high, and the results of the ANOVA 
showed that the effects of both the
heating temperature and the soaking time were not significant.

Remarks

Through the reproduced thermal straining tests under uniaxial, biaxial, and triaxial restraint, it appeared that the thermal straining under biaxial restraint with a small amount of restraint force in the thickness direction could reproduce the embrittlement at the notch tip part, although experimental evidences were still insufficient for confirming it.

Further, the reproduced thermal straining test under biaxial restraint may suggest a new testing method to evaluate the properties in the welded wide-plate tensile specimen. From this supposition, our conjecture is that the thermal straining under triaxial restraint could reproduce the embrittlement at the notch tip part, although experimental evidences were still insufficient for confirming it.

Conclusions

1. The main cause of the embrittlement of carbon steel weldment, shown by longitudinally welded and center notched wide-plate tensile test, was thermal straining under restraint, i.e., embrittlement in the weld strain-affected zone.

2. It appears that the thermal straining under biaxial restraint with a small amount of restraint force in the thickness direction could reproduce the embrittlement at the tip part of the center notch of longitudinally welded wide-plate tensile specimen.

3. It appears that the following experimental methods were effective in evaluating the material differences in the weld strain-affected zone: (1) hardness, (2) fracture transition temperature by V notch Charpy impact test, (3) absorbed energy by modified half-size sharp notch Charpy impact test, and (4) the amount of plastic strain by the x-ray diffraction method.

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References


Standard Procedures for Calibrating Magnetic Instruments To Measure the Delta Ferrite Content Of Austenitic Stainless Steel Weld Metal, AWS A4.2-74

Ferrite is useful in preventing or minimizing cracking and fissuring in austenitic stainless steel weld metals. In a few special situations, it can be detrimental to corrosion resistance and to mechanical properties if it transforms to sigma phase due to exposure to temperatures above 900 F (480 C). Within a weld pad, the ferrite content is variable, and it is even more so from pad to pad or when the welding conditions are changed.

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