Embrittlement in Weld Strain-Affected Zone in Carbon Steel

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

BY T. TOYOOKA AND M. WATANABE

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.

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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

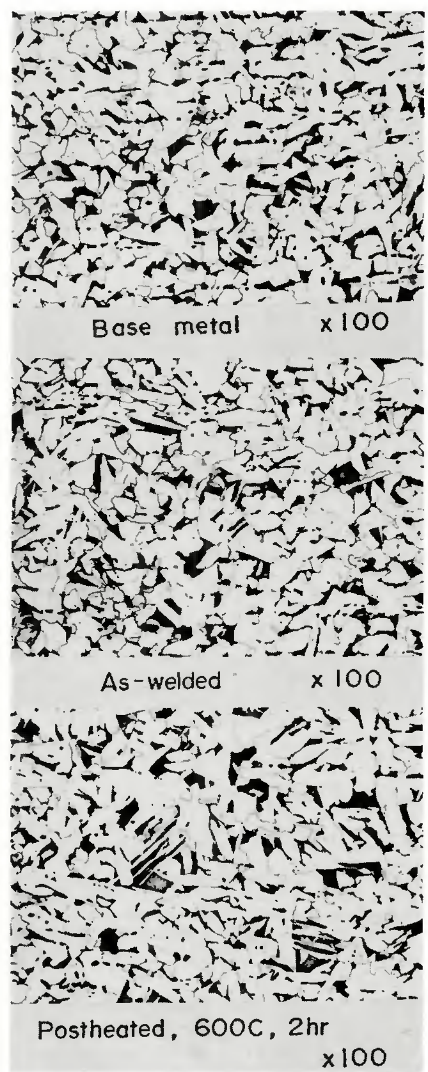


Fig. 1 — Photomicrographs at the tip part of the center notch, reduced 32%

(1112 F) for 2 hr.

Next, the authors tried to reproduce this thermal straining by welding heat; the specimens were heated to the abovementioned peak temperature under uniaxial, biaxial, and triaxial restraint, and also heated without restraint for comparison. These specimens were postheated under various heating conditions and then the material differences were examined, using the tests which were found to be effective for this purpose.

As to the reality of a "weld strain-affected zone," crosswise reddish-brown rust lines at an angle of 45 deg to the weld line and about 1 to 2 in. in width beside the joint, like the Lueder'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.

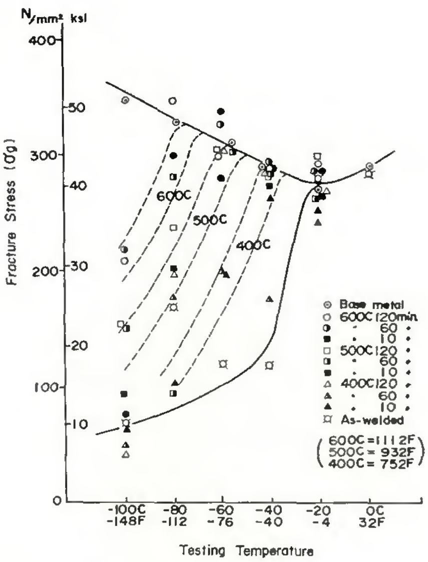


Fig. 2 — Recovery of fracture stress values after various postheat treatments. (from data of the previous report)

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 postheat 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 h to remove possible internal stress.

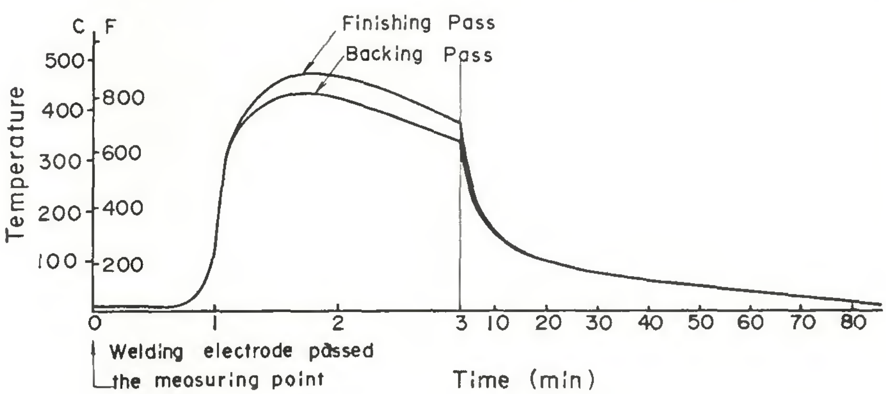


Fig. 3 — Thermal cycle at the tip part of the center notch

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

Steel	C	Si	Mn	P	S	Y.S. N/mm²(b)	T.S. N/mm²	Elong. %
SB42(a)	0.15	0.20	0.66	0.015	0.016	274	451	28

(a) Rolled steel plate for boilers, specified by Japanese Industrial Standards.
(b) 1 N/mm² = 145 psi

Preparation of Weld Specimens

Two 250 × 500 mm (10 × 20 in.) plates were butt welded by submerged arc welding to make a 500 × 500 mm (20 × 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 h

The soaking time of 1 h 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 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
41: Postheat 400 C (752 F), 10 min
42: Postheat 400 C (752 F), 2 h
51: Postheat 500 C (932 F), 10 min
52: Postheat 500 C (932 F), 2 h
61: Postheat 600 C (1112 F) 10 min
62: Postheat 600 C (1112 F) 2 h
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

Rolled steel plate for boilers specified by Japanese Industrial Standards, with a minimum tensile strength of 42 kg/mm² (410 N/mm², 59,700 psi).

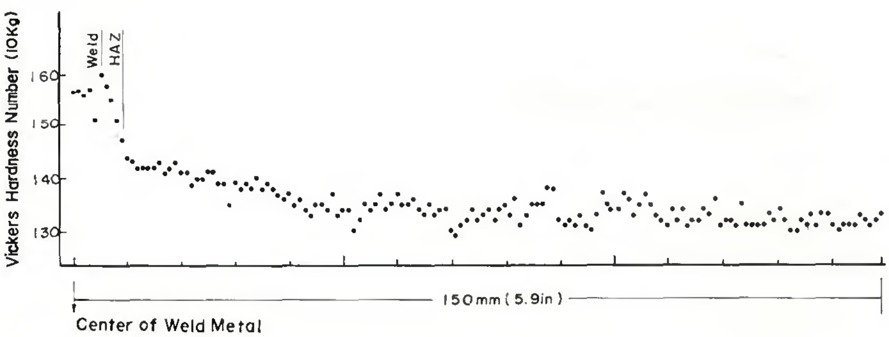


Fig. 4 — Hardness distribution along the mid-thickness line in as-welded specimen

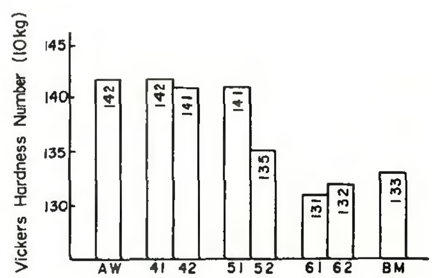


Fig. 5 — Reduction of hardness after various postheat treatments, notch tip area

Finishing pass: 1100 A, 36 V, 33 cm/min (13.0 in./min), and 72 kJ/cm (180 kJ/in.) heat input

Peak temperatures were recorded at about 450 C (842 F), which were different from those in the previous report, 570 C (1058 F) and 590 C (1094 F). Therefore, the peak temperature measurement was carefully repeated several times, and it was confirmed that the peak temperatures were 450 ± 20 C (842 ± 36 F), regardless of the difference in welding conditions in backing pass and finishing pass. The reason for the difference could not be traced out even by careful reexamination. Figure 3 shows the typical thermal cycle at the notch tip.

The peak temperature at the notch tip was below the transformation temperature. It is easily seen from three photomicrographs in Fig. 1 that there were no differences in microstructure at the notch tip among the BM, AW, and 62 specimens.

Figure 4 gives the hardness distribution of AW specimens along the midthickness line at 1 mm (0.04 in.) distances. As shown in this figure, there was a hardened zone outside the heat-affected zone, say between 10 mm (0.39 in.) and about 40 mm (1.57 in.) from the center of weld.

Table 2 — Calculated Correlation Coefficients (R) and Results of the Analysis of Variance

	Corr. coef. R, with fracture stress	Results of analysis of variance[a] for: Heating temp.	Soaking time
Hardness	−0.86	Significant	Not significant
Fracture transition temperature	−0.81	Significant	Not significant
Half-size V notch Charpy impact test	0.40	Not significant	Not significant
Half-size sharp notch Charpy impact test	0.82	Significant	Not significant
Compressive strain	−0.76	Significant	Not significant

(a) At a 5% significance level

Hardness Measurement

The hardness distribution in the thickness direction at the notch tip after various postheat treatments was measured at 1 mm (0.04 in.) distances, and the mean values of these measurements are given in Fig. 5.

These mean hardness values were plotted in a scatter diagram against the fracture stress values at a testing temperature of −80 C (−112 F) and the correlation coefficient (R) between them was calculated, as presented in Table 2. The fracture stress values at −80 C were taken from experiment of the previous report; they showed distinct differences among various temperature levels of postheating. In actual calculation, however, the mean value of three fracture stress values tested at −60 C (−76 F), −80 C (−112 F), and −100 C (−148 F) corresponding to each postheat condition was used. Here, it is assumed that each set of fracture stress values corresponding to each postheat condition was linearly decreasing, or linearly increasing in the base metal case, with decreasing testing temperature within this temperature range. The calculated R (−0.86) showed that the hardness data was highly correlated with the fracture stress values.

Further, the mean hardness values after various postheat treatments were examined by the analysis of variance (ANOVA) of a two-factor and multilevel experimental design model to see the significance of the effect of the heating temperature and the effect of the soaking time. In this calculation, the one factor is the heating temperature with three levels, and the other the soaking time with two levels. A 5% significance level was used in what follows.

The calculated results of the ANOVA are also presented in Table 2. They showed that the effect of the heating temperature of postheat treatments on hardness was significant, while the effect of the soaking time was not significant.

Incidentally, the results of the ANOVA of the previous report showed that the effect of the heating temperature of postheat treatments on fracture stress values was highly significant, while the effect of the soaking time was not significant.

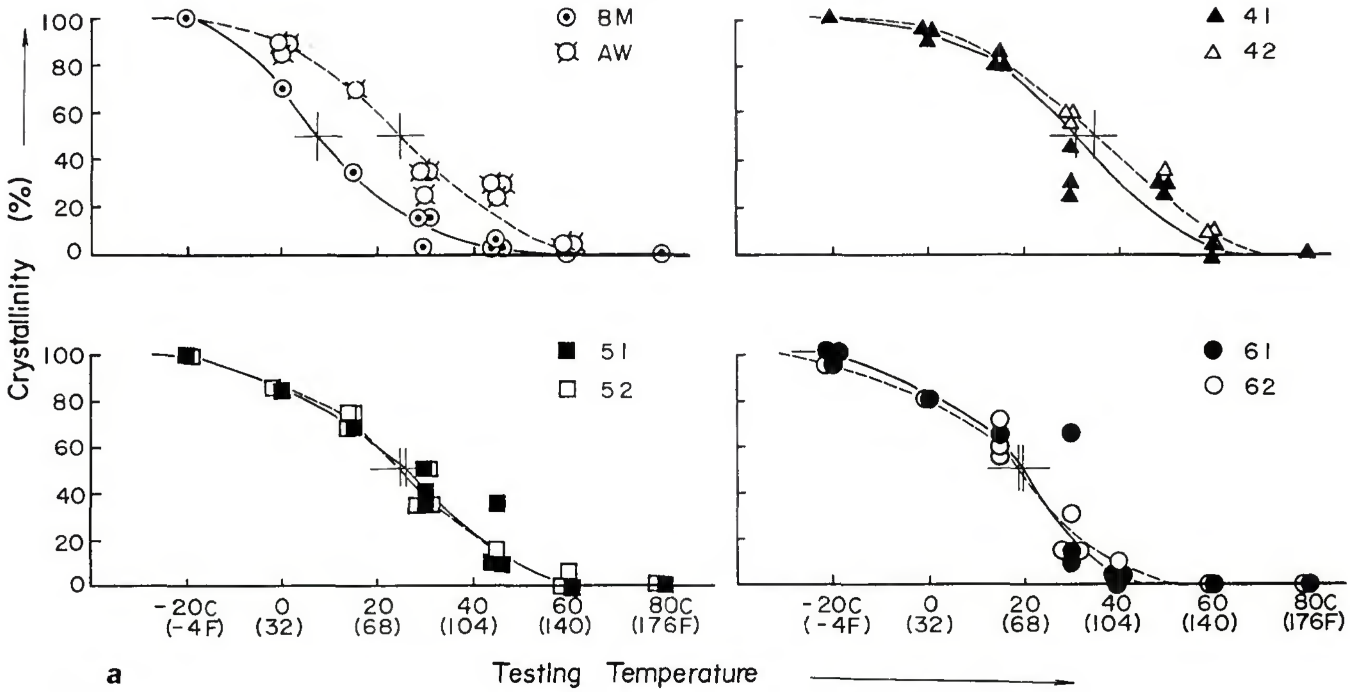
Fracture Transition Temperature

The fracture transition curves and the temperatures at the notch tip after various postheat treatments are given in Figs. 6 (a) and (b).

The R between the transition temperature and the fracture stress, and the results of the ANOVA are 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 (2) as to the response to postheat treatments, 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



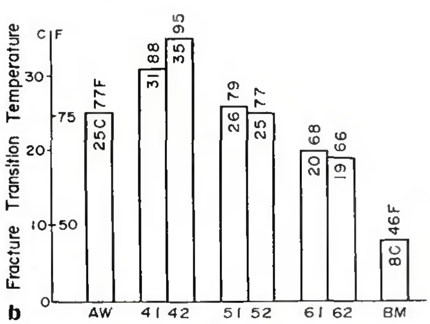


Fig. 6 — (a) Four fracture transition curves after various postheat treatments, notch tip part. (b) Recovery of fracture transition temperature after various postheat treatments, notch tip part

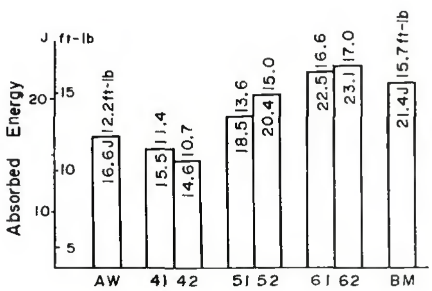


Fig. 7 — Recovery of impact values after various postheat treatments, notch tip part

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

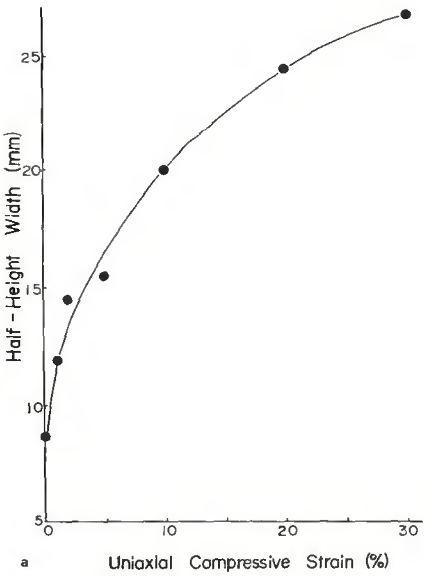
The amounts of plastic strain at the notch tip were measured by x-ray diffractometer. First, the calibration specimens were uniaxially compressed by a tensile testing machine. The amounts of compressive plastic strain of these specimens were: 0,1, 2,5,10,20, and 30%. Each specimen was placed in a goniometer, 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 K_α, 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.

The calculated R and the results of the ANOVA are presented in Table 2. The results showed that: (1) the equivalent uniaxial compressive strain was highly correlated with the fracture stress; and (2) as to the response to postheat treatments, the effect of the heating temperature on the compressive strain was significant, while the effect of the soaking time was not significant.

Crack Opening Displacement

The crack opening displacement at the notch tip after various postheat



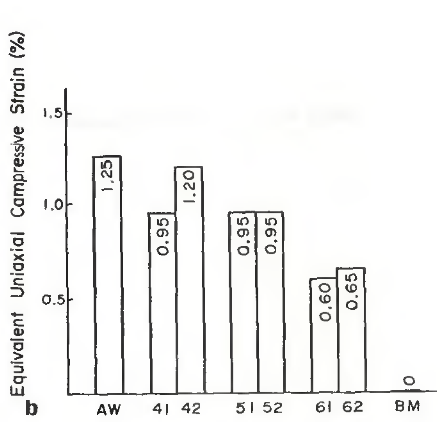


Fig. 8 — (a) Calibration curve, half-height width vs. uniaxial compressive strain. (b) Reduction of equivalent uniaxial compressive strain after various postheat treatments, notch tip part

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 postheat 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 as-thermally-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 R'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

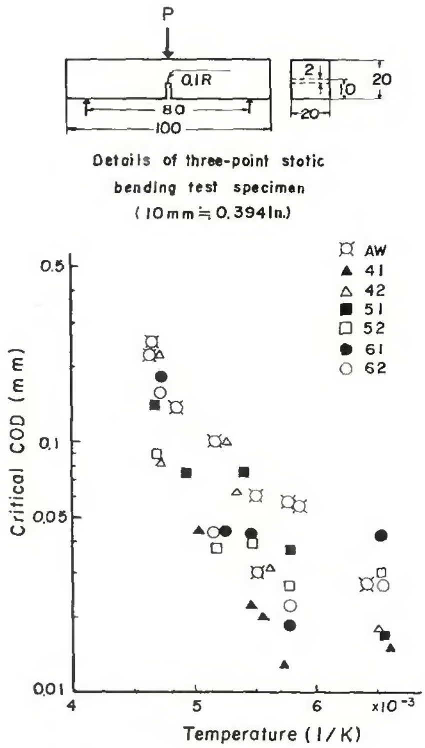


Fig. 9 — Crack-opening displacement after various postheat treatments, notch tip part (Nakatsuji, T.)

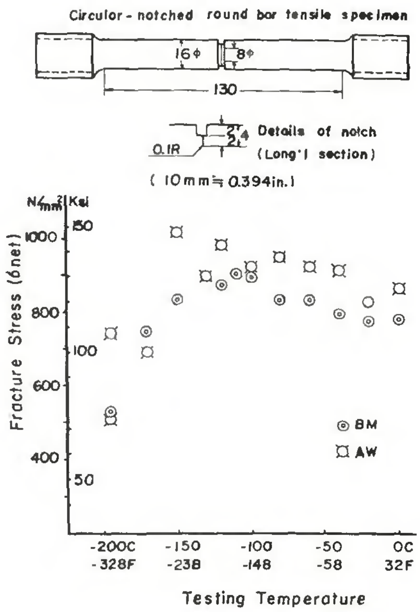


Fig. 10 — Fracture stress by circular-notched round-bar tensile test, notch tip part

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 postheated.

The mean hardness values of ten measurements after various postheat treatments are given as O-Series 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 both the heating temperature and the soaking time were not significant for all sets of data.

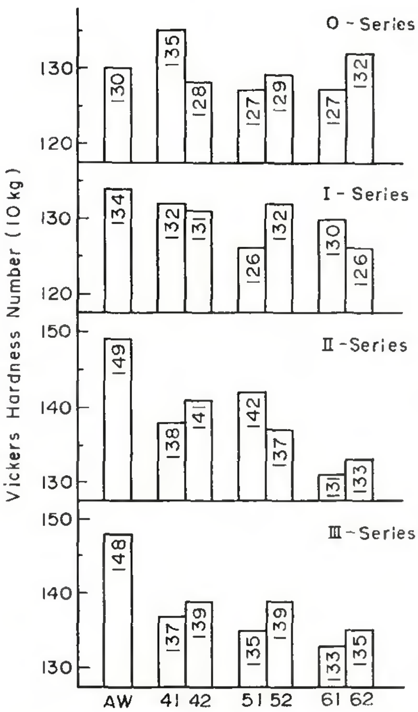


Fig. 11 — Reduction of hardness after various postheat treatments, thermally strained specimens

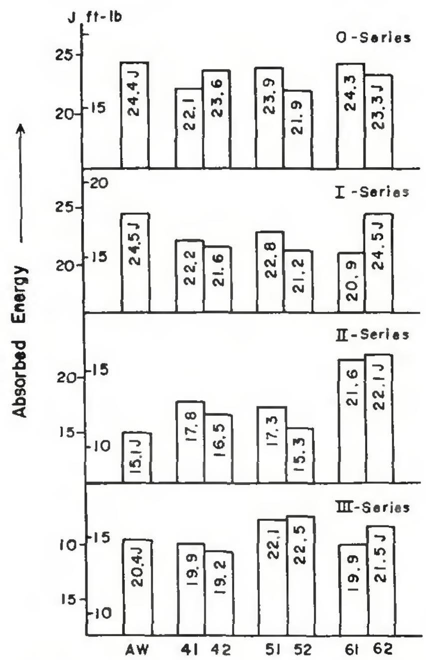


Fig. 12 — Recovery of impact values after various postheat treatments, thermally strained specimens

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

	Correlation coefficent: With fracture stress	Correlation coefficent: With results at notch tip	Results of analysis of variance(a) for: Heating temp.	Results of analysis of variance(a) for: Soaking time
Hardness:				
O-Series	−0.28	0.19	Not significant	Not significant
I-Series	−0.66	0.37	Not significant	Not significant
II-Series	−0.76	0.84	Not significant	Not significant
III-Series	−0.63	0.55	Significant	Significant
Half-size sharp notch Charpy impact test:				
O-Series	−0.03	0.07	Not significant	Not significant
I-Series	−0.09	0.03	Not Significant	Not significant
II-Series	0.65	0.70	Significant	Not significant
III-Series	0.46	0.51	Not significant	Not significant
Compressive strain:				
II-Series	−0.94	0.90	Significant	Not significant
III-Series	−0.67	0.59	Significant	Not significant

(a) At a 5% significance level

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 both 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 were 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 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 thermal expansion at the notch tip were also heated to higher temperatures, and therefore the degree of the restraint 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 temperature. But it was found difficult to hold the heated part within peak temperature 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 temperature range, 450 ± 20 C. These spots were discarded.

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

In the preliminary test, we examined the temperature distribution in the thickness direction at the spot using a number of thermocouples inserted 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 specimen are illustrated in Fig. 13. Figure 14 shows the three-phase, low-frequency spot welding machine used in the experiments.

Straining under Biaxial Restraint

The specimens were heated to the peak temperature in the same manner as explained above. Each specimen was flame cut in the longitudinal direction, and then machined in the transverse direction. These block specimens were variously postheated.

The II-Series experimental results of hardness measurement, mean absorbed 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 presented in Table 3.

The hardness data of the II-Series test was highly correlated with those at the notch tip, and also highly correlated with fracture stress. As regards the response to postheat treatments, 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 significant 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 treatments, 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 heating temperature was highly significant, while the effect of the soaking time was not significant.

In these test results under biaxial restraint, the hardness of II-AW specimens 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 results might come from the difference in heating temperature at the peak range, in holding time, and in the number of repetitions of heating between notch tip parts and these specimens.

Straining under Triaxial Restraint

The specimens were prepared in the same manner as the II-Series test except for the amount of the electrode 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 experimental 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 understood 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 significant, while the effect of the soaking time was not significant.

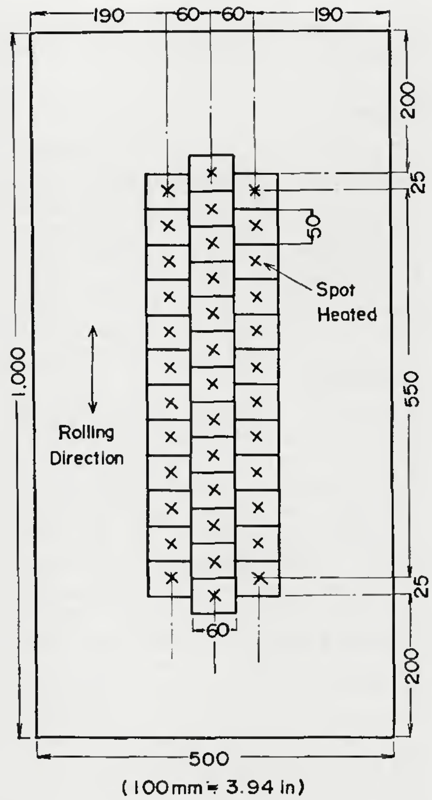


Fig. 13 — Spot heated steel plate specimen

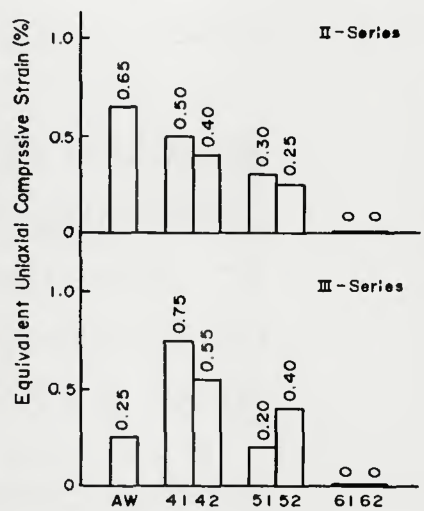


Fig. 14 — Reduction of equivalent uniaxial compressive strain after various postheat treatments, thermally strained specimens

In absorbed energy data, there were no substantial differences among AW and postheated specimens. Such an experimental result is inconsistent 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 tip part of the center notch of welded wide-plate tensile specimen.

Both in the biaxial and triaxial restraint cases, the restraint force in the thickness direction was supplied by an air cylinder of the spot welding machine. It must be emphasized that air is easily compressible. On the other hand, it may require a tremendous amount of force to restrain the cubical thermal expansion of steel, and the thermal expansion of the spot heated part in the thickness direction, 0.3 mm (0.012 in.) at the most, was negligible compared with the stroke of the air cylinder, 25 mm (0.98 in.). Therefore, it is supposed that the effect of the restraint force in the thickness direction in the amount of 16 N/mm^2 (2260 psi) in the biaxial restraint case was the same as that of 125 N/mm^2 (18,060 psi) in the triaxial restraint case. 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.

Further, the reproduced thermal straining test under biaxial restraint may suggest a new testing method to evaluate the properties in the weld strain-affected zone, for example, a thermal cycle and strain cycle simulating test.

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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