On the Effects of Postweld Heat Treatment

Two carbon steels are tested to determine the effects of temperature and soaking time on selected mechanical properties and residual stresses

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ABSTRACT. The authors carried out experiments with two kinds of carbon steel plates upon: (1) the recovery of impact values and reduction of hardness with specimens prestrained and later postheated in various combinations of heating temperature and soaking time; (2) the recovery of fracture stress values of longitudinally welded and center notched wide-plate tensile specimens after various postheat treatments; and (3) actual residual stress measurements of longitudinally welded wide-plate specimens after various postheat treatments.

Each set of these experimental data was examined by the analysis of variance model to determine the significance of the effect of the heating temperature and the effect of the soaking time.

Further, the experimental results on the recovery of fracture stress of wide-plate tensile tests were examined with respect to the effect of various factors, i.e., the residual stress values, recovery of impact values and reduction of hardness. Each set of these experimental data was plotted in scatter diagrams and the correlation coefficient was calculated.

The conclusions are: (1) the low fracture stress values of as-welded, longitudinally welded and center notched wide-plate tensile specimens were 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) it appears that the recovery of fracture stress values had no distinct relationship with residual stress values; and (3) it appears that the recovery of fracture stress values was highly correlated with the reduc-

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

Designation by J I S [b]	Chemical analysis, wt %: C	Si	Mn	P	S	Mechanical properties: Y. S., Kg/mm²	T. S., Kg/mm²	Elong., %	vEo, [c] Kg-m/cm²
SM41B (preliminary test)	0.15	0.26	0.89	0.018	0.017	36	48	28	6.6
SB42 (main test)	0.15	0.20	0.66	0.015	0.016	28	46	28	Not specified

(a) Thickness of the plates: 25 mm
(b) J I S: Japan Industrial Standard
(c) vEo: Absorbed energy at 0 C

tion of hardness of strain-hardened specimens.

Introduction

The effects of postweld heat treatment on carbon steel are: (1) reduction of residual stress value, (2) removal of strain-aging embrittlement, (3) reduction of heat-affected zone hardness, and (4) dimensional stability.

As for the reduction of weld heat-affected zone hardness and dimensional stability, the causes of these phenomena are well known. On the other hand, as for the reduction of residual stress value and the removal of strain-aging embrittlement, they take place simultaneously in postweld heat treatment: it is difficult to separate the effects of these two factors on embrittlement of the as-welded joint. Further, as to residual stress, it is generally accepted that it is one of the most potent factors in brittle fracture at low temperature.

To estimate separately the effect of residual stress and the effect of strain-aging embrittlement, the authors carried out experiments with two kinds of carbon steel plates upon:

1. The recovery of impact values and reduction of hardness with specimens prestrained and later postheated in various combinations of heating temperature and soaking time.
2. The recovery of fracture stress values of longitudinally welded and center notched wide-plate tensile specimens after various postheat treatments.
3. Actual residual stress measurements of longitudinally welded wide-plate specimens after various postheat treatments.

The experimental results on the recovery of fracture stress values of wide-plate tensile tests were examined with respect to the effects of various factors, i.e., residual stress values, recovery of impact values and reduction of hardness using the techniques of statistics.

The Steels Used

The carbon steels used in experiments were SM41B* plates of 25 mm (about 1 in.) in thickness for the preliminary experiments, and SB42** plates of 25 mm in thickness for the main experiments. Chemical analysis and mechanical properties of these steels are given in Table 1. In Table 1, the yield strength of SM41B plates is comparatively high; however, according to the explanation of the steel manufacturer, this high yield strength is within the tolerance range of the manufacturer, and depends on the lower roll-finishing temperature.

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

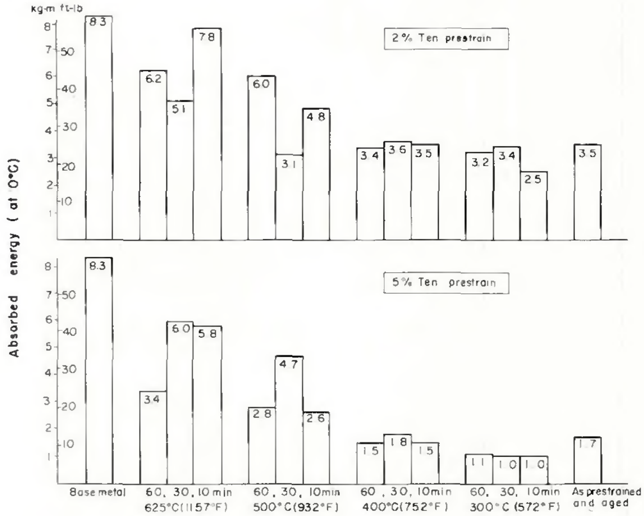


Fig. 1 — Recovery of impact values after postheating of various grades (preliminary test)

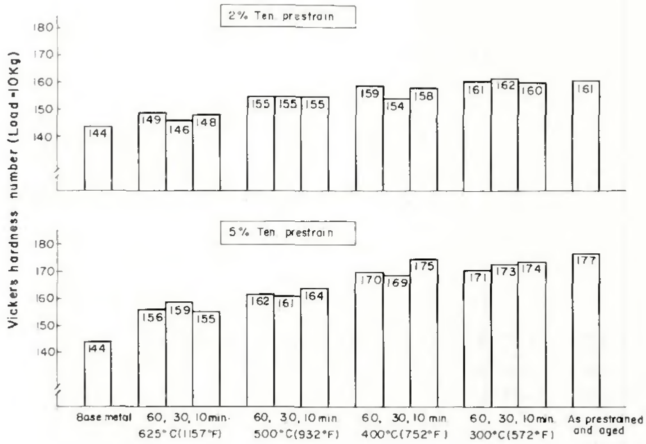


Fig. 2 — Reduction of hardness after postheating of various grades (preliminary test)

Table 2 — Residual Stress Values for As-Welded and Postheated Specimens

Test	As-welded, kg/mm²	Heating temperature C	After soaking times of 10 min, kg/mm²	30 min, kg/mm²	60 min, kg/mm²	120 min, kg/mm²
		625	5.1	—	1.5	—
Preliminary	17.1	500	11.5	4.7	2.9	—
		600	15.4	—	3.2	3.6
					3.8	4.5
Main	22.4	500	19.7	—	14.0	6.3
						11.9
		400	19.5	—	15.6	16.7

Recovery of Strain-Aging Embrittlement

Preliminary Test

In preliminary tests with SM41B steel, the amount of prestraining was taken as 2% and 5% each in tension; after prestraining, the specimens were artificially aged at 250 C (482 F), for 1 hr. The specimens then were postheated using all combinations of the following heating temperatures and soaking times.

* Rolled steel plate for welded structure specified by Japan Industrial Standard, with a minimum tensile strength of 41 kg/mm² (about 58,300 psi.).

** Rolled steel plate for boilers specified by Japan Industrial Standard, with a minimum tensile strength of 42 kg/mm² (about 59,700 psi.).

Table 3 — Fracture Stress Values After Postheat Treatments Indicated

Preliminary test

No.	Postheat treatment	Test temperature, C	Width, mm	Load, tons	Fracture Stress (gross) kg/mm²
1	Base metal	−98	500	497	39.8
2	As-welded	0	470	368	31.3
3	As-welded	−30	500	422	33.8
4	As-welded	−102	500	50	4.0
5	625 C, 60 min	−100	500	505	40.4
6	500 C, 60 min	−102	494	193	15.6
7	500 C, 30 min	−100	500	384	30.7
8	500 C, 10 min	−98	500	341	27.3
9	625 C, 10 min	−100	495	558	45.1
10	625 C, 10 min	−100	495	456	36.8
11	500 C, 60 min	−95	495	320	25.9
12	500 C, 60 min	−100	494	347	28.1
13	500 C, 60 min	−105	494	348	28.2
14	500 C, 10 min	−100	495	425	34.3

Main test

No.	Postheat treatment	Test temperature, C	Width, mm	Load, tons	Fracture Stress (gross) kg/mm²
1	Base metal	0	508	375	29.5
2	Base metal	−20	507	350	27.6
3	Base metal	−40	505	372	29.5
4	Base metal	−55	509	404	31.7
5	Base metal	−78	508	425	33.5
6	Base metal	−98	508	450	35.4
7	As-welded	0	484	350	28.9
8	As-welded	−20	486	348	28.6
9	As-welded	−40	496	150	12.1
10	As-welded	−60	490	150	12.2
11	As-welded	−80	485	210	17.3
12	As-welded	−100	485	86	7.1
13	600 C, 120 min	−20	496	370	29.8
14	600 C, 120 min	−40	491	360	29.3
15	600 C, 120 min	−60	485	370	30.5
16	600 C, 120 min	−80	492	435	35.4
17	600 C, 120 min	−100	487	260	21.4
18	600 C, 60 min	−20	487	354	29.1
19	600 C, 60 min	−40	489	365	29.9
20	600 C, 60 min	−60	493	410	33.3
21	600 C, 60 min	−80	487	350	28.7
22	600 C, 60 min	−100	490	275	22.4
23	600 C, 10 min	−20	487	355	29.2
24	600 C, 10 min	−40	491	360	29.3
25	600 C, 10 min	−60	500	430	34.4
26	600 C, 10 min	−80	485	370	30.5
27	600 C, 10 min	−100	487	95	7.8
28	500 C, 120 min	−20	494	375	30.4
29	500 C, 120 min	−40	493	354	28.7
30	500 C, 120 min	−60	490	380	31.0
31	500 C, 120 min	−80	490	295	24.1
32	500 C, 120 min	−100	496	195	15.7
33	500 C, 60 min	−20	495	333	26.9
34	500 C, 60 min	−40	495	360	29.1
35	500 C, 60 min	−55	493	380	30.8
36	500 C, 60 min	−80	490	120	9.8
37	500 C, 60 min	−100	490	190	15.5
38	500 C, 10 min	−20	490	331	27.0
39	500 C, 10 min	−38	495	345	27.9
40	500 C, 10 min	−60	488	350	28.7
41	500 C, 10 min	−80	485	251	20.7
42	500 C, 10 min	−100	495	120	9.7
43	400 C, 120 min	−20	497	341	27.4
44	400 C, 120 min	−40	486	355	29.2
45	400 C, 120 min	−60	490	380	31.0
46	400 C, 120 min	−80	487	245	20.1
47	400 C, 120 min	−100	490	51	4.2
48	400 C, 60 min	−20	492	303	24.6
49	400 C, 60 min	−40	492	220	17.9
50	400 C, 60 min	−60	490	250	20.4
51	400 C, 60 min	−80	487	220	18.1
52	400 C, 60 min	−100	487	62	5.1
53	400 C, 10 min	−20	490	314	25.6
54	400 C, 10 min	−40	486	325	26.7
55	400 C, 10 min	−60	495	250	20.2
56	400 C, 10 min	−80	490	130	10.6
57	400 C, 10 min	−100	487	84	6.9

1. Heating temperatures: 300 C (572 F), 400 C (752 F), 500 C (932 F) and 625 C (1157 F)
2. Soaking times: 10 min, 30 min and 60 min

The heating temperature level of 625 C was chosen as the mean of the temperature range of postweld heat treatment required by Japanese regulations for boilers and pressure vessels, 600 to 650 C (1112 to 1202 F).

The specimens were tested by V-notch Charpy impact test at 0 C (32 F), and the recovery of impact values after postheating of various grades was examined by the mean value of three impact specimens.

At the same time, the specimens were tested by Vickers hardness measurement, and the reduction of hardness of strain-hardened specimens after postheating of various grades was examined by the mean value of ten measurements.

The results of the impact tests and the hardness measurements are given in Fig. 1 and Fig. 2 respectively. It seems from the figures that the recovery of impact values and reduction of hardness were substantially affected by the heating temperature, but not practically affected by the soaking time, in the cases of 2% and 5% prestrain.

Further, these experimental results were examined by the analysis of variance 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 four levels, and the other the soaking time with three levels, and the replication is two, as the effect of postheating appears same in 2% and 5% prestrain cases.

The calculated results, described in Table 4, can be summarized as follows:

1. In the case of the recovery of impact values in tensile prestrain, the effect of the heating temperature was highly significant at a 1% significance level, while the effect of the soaking time was not significant even at a 10% significance level.*
2. In the case of the reduction of hardness in tensile prestrain, the effect of the heating temperature was highly significant at a 1% significance level, while the effect of the soaking time was not significant even at a 10% significance level.

It should be noted that in the calculation of engineering data, a 5% significance level is usually adopted.

Main Test

In the main test with SB42 steel, the amount of prestraining was taken as 2% and 5% each in tension and in compression, and, after prestraining, the specimens were artificially aged. The specimens then 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: 0 min, 10 min, 60 min and 120 min

In the case of zero min soaking time, the specimen was heated to a desired level of heating temperature and then furnace cooled as soon as the temperature of the specimen reached that level. The heating temperature level of 600 C, instead of 625 C, as in the preliminary test, was adopted to keep the temperature differences constant.

The specimens were tested by V-notch Charpy impact test at 20 C (68 F), since the transition temperature of this steel was comparatively high, and, at the same time, the specimens were tested by Vickers hardness measurement in the same manner as the preliminary test.

The results of the impact test and the hardness measurement are given in Figs. 3 and Fig. 4 respectively. Figure 4 shows tendencies similar to the preliminary test, while in Fig. 3, the impact values in compressive prestrain case are slightly different from those of the preliminary test. In Fig. 3, the impact values in tensile prestrain shows tendencies similar to the preliminary test.

The calculated results of the analysis of variance, tabulated in Table 4, can be summarized as follows:

1. In the case of the recovery of impact values in tensile prestrain, the effect of the heating temperature was highly significant at a 1% significance level, while the effect of the soaking time was not significant even at a 10% significance level.
2. In the case of the recovery of impact values in compressive prestrain, both the effect of the heating temperature and the effect of the soaking time were highly significant at a 1% significance level, and the interaction of the heating temperature and the soaking time was significant at a 5% significance level.
3. In the case of the reduction of hardness in both tensile and compressive prestrain, the effect of the heating temperature was highly significant at a 1% significance level, while the effect of the soaking time was not significant even at a 10% significance level.

Residual Stress Measurement

Preliminary Test

Two 250 mm x 500 mm (about 10 x 20 in.) steel plates of SM41B were butt

Table 4 — Results of the Analysis of Variance

Preliminary test	Heating temperature [a]	Soaking time [a]
Impact values, tensile prestrain	Highly significant, at 1% SL	Not significant, at 10% SL
Hardness, tensile prestrain	Highly significant, at 1% SL	Not significant, at 10% SL
Main test		
Impact values, tensile prestrain	Highly significant, at 1% SL	Not significant, at 10% SL
Impact values, compressive prestrain	Highly significant, at 1% SL	Highly significant, at 1% SL
Hardness, tensile prestrain	Highly significant, at 1% SL	Not significant, at 10% SL
Hardness, compressive prestrain	Highly significant, at 1% SL	Not significant, at 10% SL
Residual stress values	Significant, at 5% SL	Significant, at 5% SL
Fracture stress values of wide plate tensile test.	Highly significant at 1% SL	Not significant, at 10% SL

(a) SL = Significance level

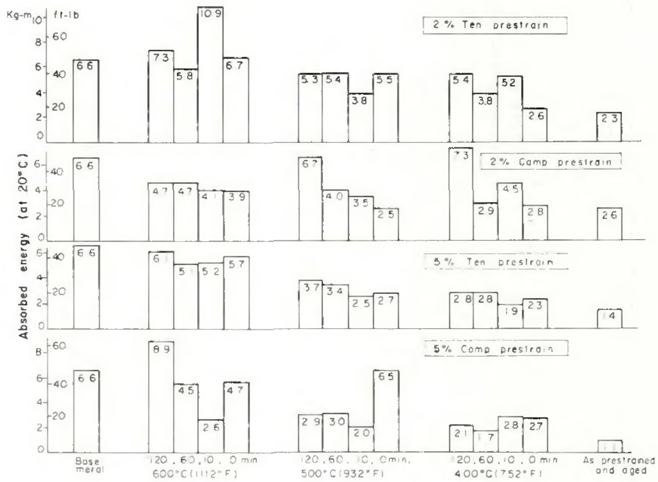


Fig. 3 — Recovery of impact values after postheating of various grades (main test)

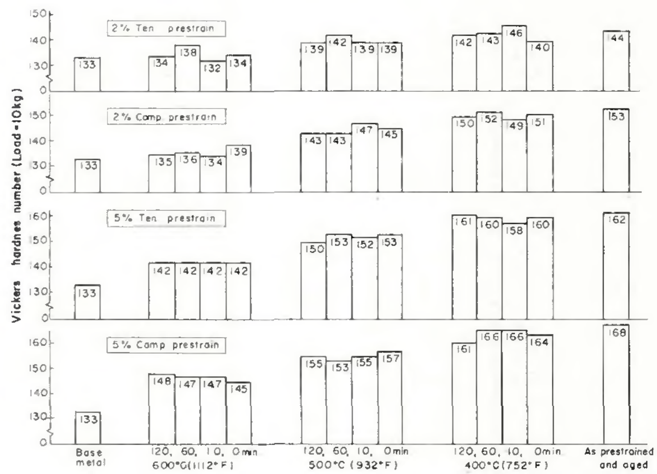


Fig. 4 — Reduction of hardness after postheating of various grades (main test)

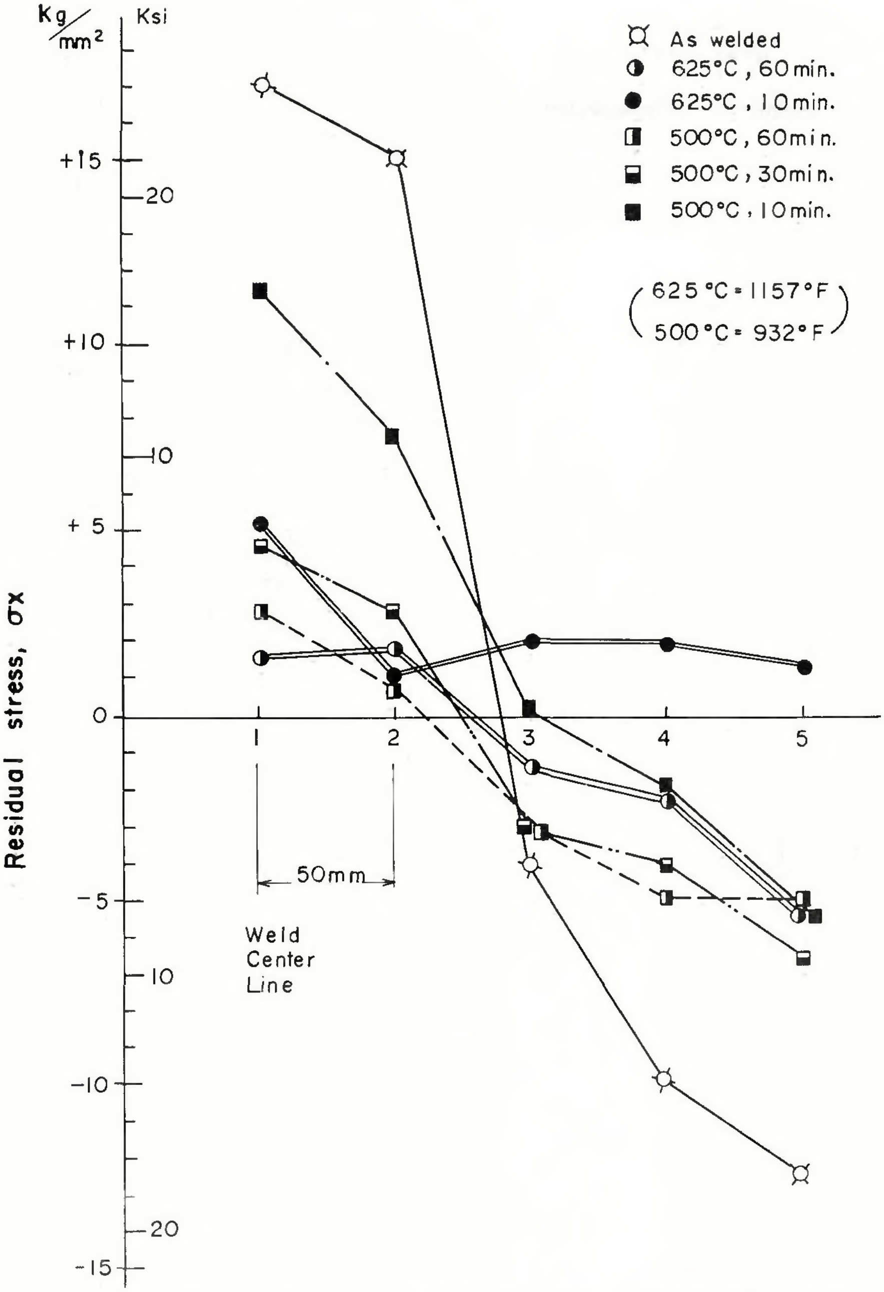


Fig. 5 — Distribution of residual stress after postheating of various grades (preliminary test)

welded by submerged arc welding to make a 500 mm x 500 mm (about 20 x 20 in.) welded specimen. The edge preparation and the welding conditions were the same as the conditions of longitudinally welded and center-notched wide plate tensile specimen shown in Fig. 9.

The welded specimens then were postheated at 500 C (932 F) for soaking times of 10, 30, and 60 min, and at 625 C (1157 F) for soaking times of 10 and 60 min.

The heating temperature levels of 200 C, 300 C, and 400 C are not reported, since the test of significance of the recovery of impact values and the reduction of hardness showed that postheating at these temperatures was generally not very significant when compared with postheating at the 500 C and 625 C temperature levels.

Residual stress in the longitudinal direction was measured at the transverse line at the center of the weld by the strain gage and cut-out method.

The results of residual stress measurement are tabulated in Table 2, and illustrated in Fig. 5. In Fig. 6, residual stress values and soaking time are plotted in logarithmic scale at each heating temperature level. In this figure, three measured points at 500 C temperature level were on a straight line.

Main Test

Welded specimens of SB42 steel plates of 500 mm x 500 mm in size were prepared in the same manner as the preliminary test. The specimens were postheated at 400 C, 500 C and 600 C using soaking times of 10, 60 and 120 min.

The zero minute soaking time in impact test and hardness measurement was neglected, since the heating and cooling speeds of the furnace used for postheating of these comparatively large specimens were so slow, that the zero minute soaking time has no substantial difference with the 10 min soaking time.

The measurement of residual stress was carried out in the same manner as the preliminary test. The results of the measurement are tabulated in Table 2, and illustrated in Fig. 7. In Fig. 8, residual stress values and soaking time are plotted in logarithmic scale at each heating temperature level. As shown in this figure, three measured points at 400 C temperature level were on a straight line, while some of the measured points at 500 C and 600 C temperature level showed considerable deviations from the assumed line, and these points were reexamined.

These results were again examined by the analysis of variance. In this calculation, at the measured points of reexamination, the mean value of two measurements was adopted. Table 4 gives the calculated results which show that, for residual stress measurement, both the effect of the heating temperature and the effect of the soaking time were significant at a 5% significance level. It should be noted that the interaction of the heating temperature and the soaking time cannot be calculated, since the replication is one.

Recovery of Fracture Stress Values

Preliminary Test

Two 250 mm x 500 mm steel plates of SM41B were butt welded by submerged arc welding to make a 500 mm x 500 mm welded specimen. The edge preparation and the welding conditions were the same as the specimens used in a series of wide plate tensile tests by Professor Kihara, et al., and as shown in Fig. 9. After welding, the specimens were postheated at 500 C (932 F) for soaking times of 10, 30 and 60 min, and at 625 C (1157 F) for soaking times of 10 and 60 min.

After postheating, a very sharp center notch, as shown in Fig. 9, was machine cut with a jeweler's saw. The shape and dimensions of the center notch were identical with that used by Professor Kihara, et al,[1] since it was confirmed by his preparatory experiment that the parts at the tip of the center notch was most embrittled by the heat of submerged arc welding.[2] Two measured peak temperatures at the tip of the center notch during welding were 570 C (1058 F) and 590 C (1094 F).

The center-notched tensile specimens were tested by a tensile testing machine of 1200 tons capacity. The subzero cooling of the specimen was carried out by attaching four cooling boxes containing liquid nitrogen along the center transverse line of the specimen. The temperature of the specimen was measured by attaching thermocouples along the center transverse line of the specimen.

The experimental results are shown in Table 3 and illustrated in Fig. 10. As shown in this figure, the recovery of the fracture stress values after various postheat treatments was substantially affected by the heating temperature, but not at all affected by the soaking time.

It should be noted that the extremely low testing temperature of −100 C (−148 F) of the wide plate tension test was adopted for the following reason. The authors had prepared only three as-welded specimens, and the test results of the two specimens at the testing temperature of 0 C (32 F) and of −30 C (−22 F) did not show the low fracture stress value, i.e. embrittlement. The authors then decided to carry out the test at this extremely low testing temperature to secure the low fracture stress value.

Main Test

Longitudinally welded wide-plate tensile specimens of SB42 steel, 500 mm x 500 mm in size, were prepared in the same manner as the preliminary test. The specimens were postheated at temperatures of 400, 500 and 600 C and held for soaking times of 10, 60 and 120 min at each temperature.

After postheating, a very sharp center notch was machine cut, and the center-notched tensile specimens were tested in a testing machine of 1200 tons capacity in the same manner as the preliminary test. The testing temperatures of the main test were 0 C (32 F), −20 C (−4 F), −40 C (−40 F), −60 C (−76 F), −80 C (−112 F) and −100 C (−148 F) each.

The experimental results are tabulated in Table 3, and illustrated in Fig. 11. It seems from the figure that the recovery of fracture stress values after postheating was substantially affected by the heating temperature, but not affected by the soaking time. However, the experimental results in

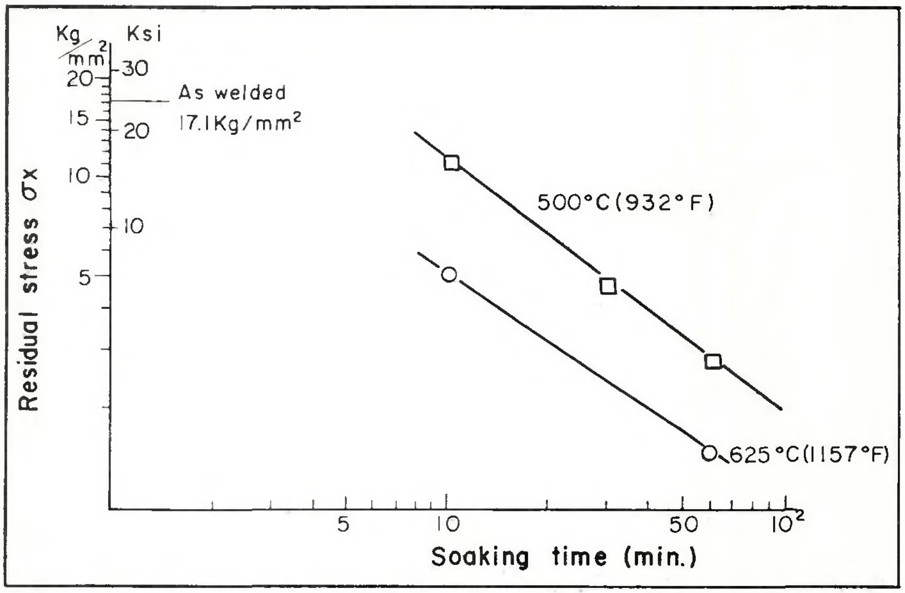


Fig. 6 — Reduction of residual stress after postheating of various grades (preliminary test)

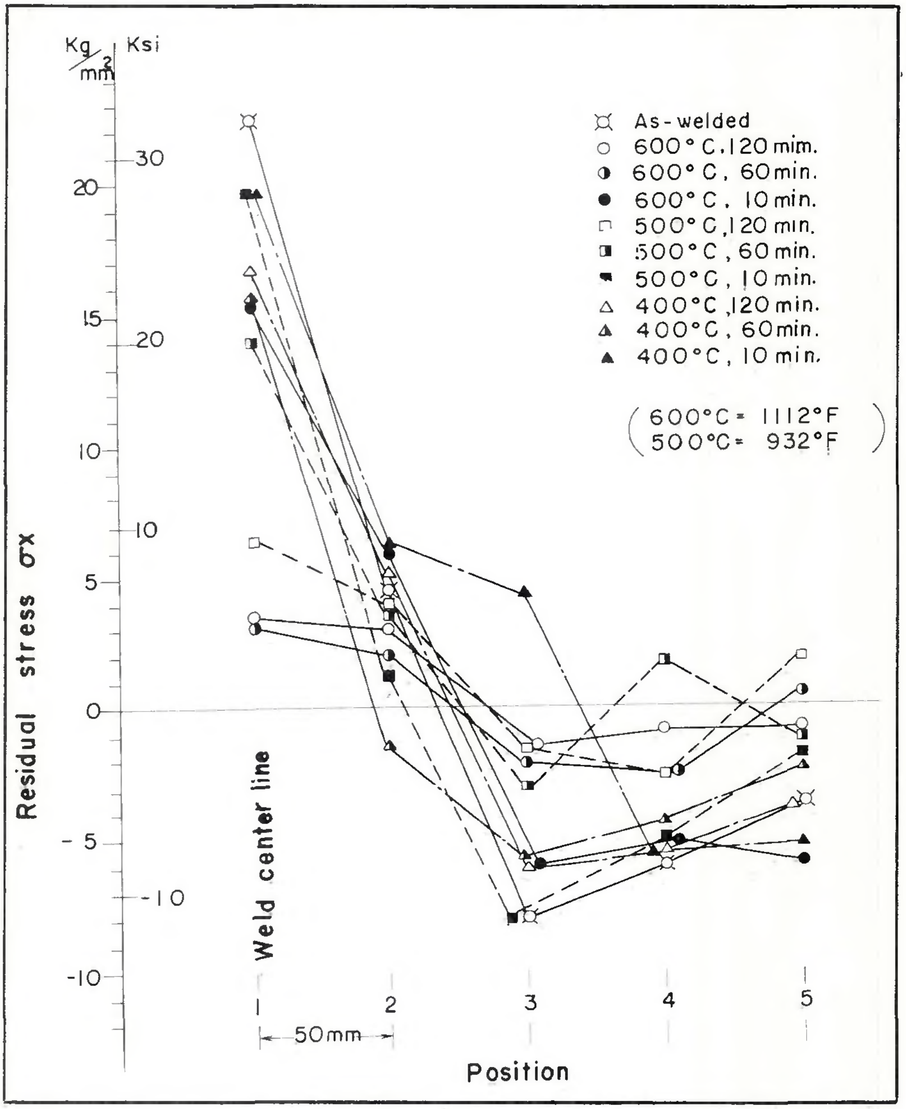


Fig. 7 — Distribution of residual stress after postheating of various grades (main test)

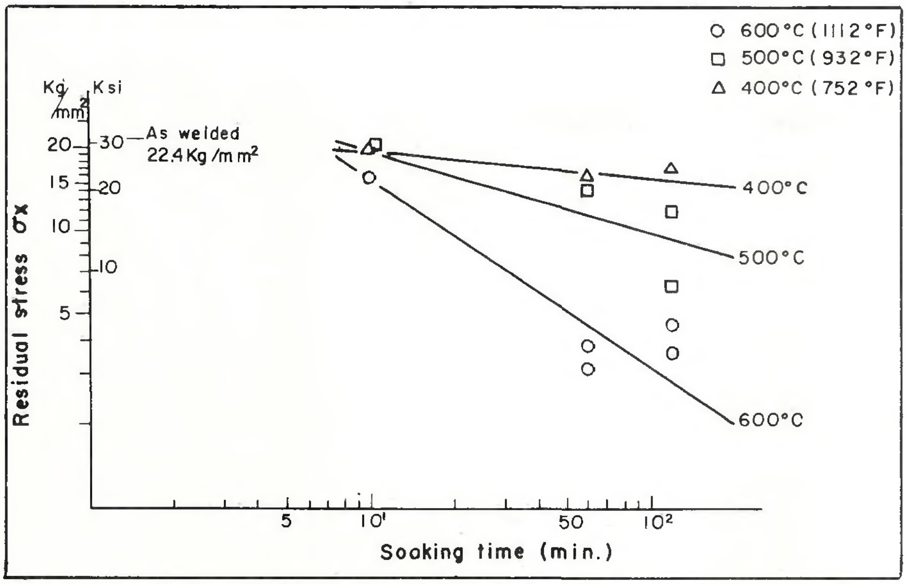
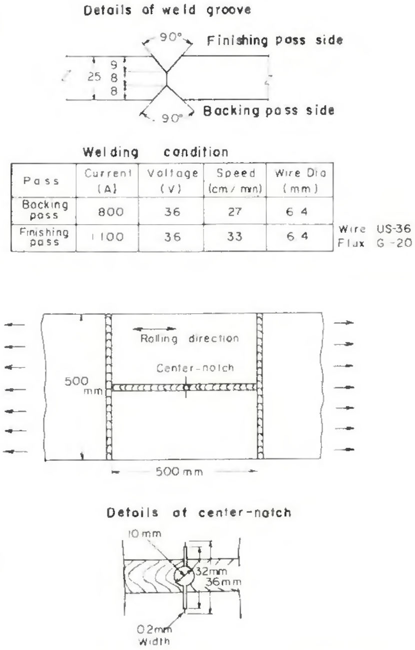


Fig. 8 — Reduction of residual stress after postheating of various grades (main test)



Pass	Current (A)	Voltage (V)	Speed (cm/min)	Wire Dia (mm)
Backing pass	800	36	27	6.4
Finishing pass	1100	36	33	6.4

Fig. 9 — Longitudinally welded and center-notched wide plate tensile specimen

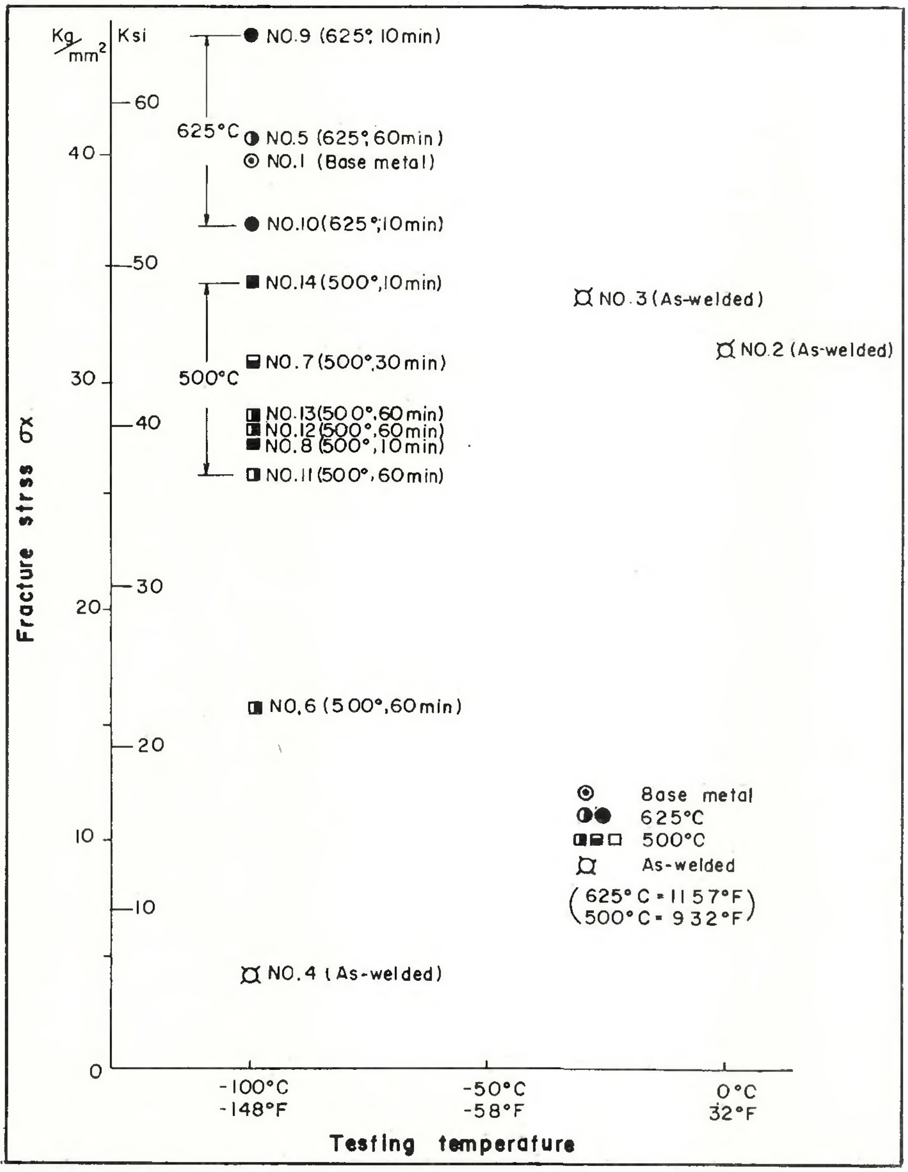


Fig. 10 — Recovery of fracture stress values after postheating of various grades (preliminary test)

the main test showed some scattering compared with the results obtained in the preliminary test. In Fig. 11, the dotted lines show the assumed recovery range at each heating temperature level.

These experimental results were examined by the analysis of variance of a two-factor and multilevel experimental design model to see the significance of the effect of heating temperature and the effect of soaking time, as the replication of the testing temperature is three, i.e., −60 C, −80 C and −100 C.

The calculated results are given in Table 4, and are summarized as follows. In the case of the recovery of fracture stress values of wide plate tensile tests after various postheat treatments, the effect of heating temperature was highly significant at a 1% significance level, while the effect of soaking time was not significant even at a 10% significance level.

Remarks on the Results

The above experimental results on the recovery of fracture stress values of wide-plate tensile tests have been examined with respect to the influence such factors as (1) reduction of residual stress values, (2) recovery of impact values, and (3) reduction of hardness. Each set of these experimental data was plotted in a scatter diagram and the correlation coefficient was calculated. The calculated correlation coefficients are presented in Table 5.

In the main test, the experimental results of the recovery of fracture

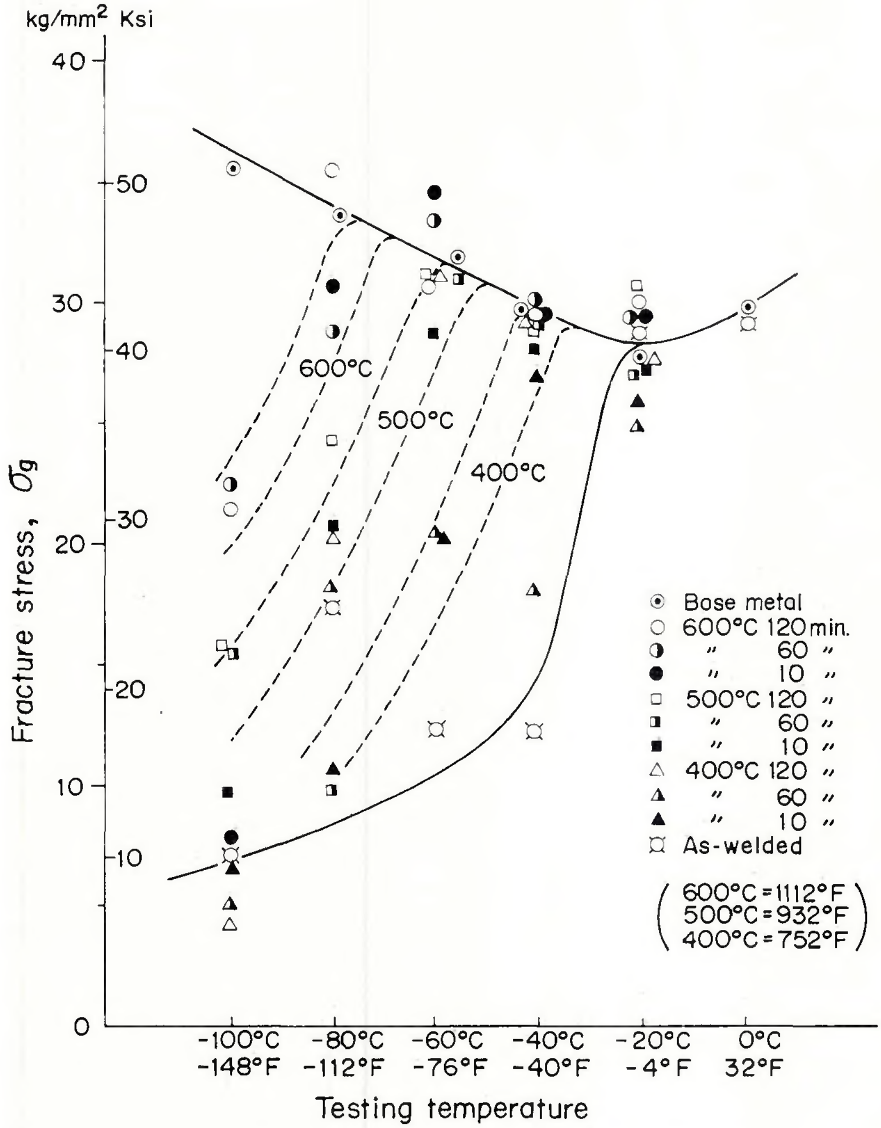


Fig. 11 — Recovery of fracture stress values after postheating of various grades

Table 5 — Correlation Coefficients Between Fracture Stress Values and Affecting Factors

Preliminary test	Prestrain	Correlation coefficient
Impact values	2% tensile	0.57
	5% tensile	0.71
Hardness	2% tensile	−0.87
	5% tensile	−0.88
Residual stress values		−0.49

Main test		Correlation coefficients −100 C	−80 C	−60 C
Impact values	2% tensile	0.21	0.58	0.69
	2% compressive	0.14	0.20	0.56
	5% tensile	0.71	0.83	0.75
	5% compressive	0.76	0.64	0.41
Hardness	2% tensile	−0.47	−0.88	−0.71
	2% compressive	−0.72	−0.74	−0.77
	5% tensile	−0.75	−0.77	−0.73
	5% compressive	−0.73	−0.69	−0.87
Residual stress values		−0.87	−0.67	−0.63

stress values of wide-plate tensile tests showed some scattering; the correlation coefficients between the experimental data of affecting factors and three sets of fracture stress data tested at −60 C, −80 C, and −100 C also showed some scattering.

Conclusions

From the experimental results stated above, and the calculated results of the analysis of variance and the correlation coefficients, the following conclusions may be stated.

1. The low fracture stress values of as-welded, longitudinally welded and 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. It appears that the recovery of fracture stress values had no distinct relationship with residual stress values.
3. It appears that the recovery of fracture stress values was highly correlated with the reduction of hardness of strain-hardened specimens.

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(1) Kihara, H., Masubuchi, K., Iida K., and Oba H., "Effect of Stress Relieving on Brittle Fracture Strength of Welded Steel Plate," *Document No. X-218-59,* 1959 Meeting of International Institute of Welding.

(2) Kihara, H., Yoshida, T., and Oba, H., "Initiation and Propagation of Brittle Fracture in Welded Steel Plate," *Document No. X-217-59,* 1959 Meeting of International Institute of Welding.

Correction:
In the May Research Supplement, pages 200-s and 201-s were reversed. Please read page 200-s as 201-s and vice-versa.