Fatigue Test of Residual Stress Induced Specimens in Carbon Steel

Embrittlement by thermoplastic straining during welding results in lower fatigue strengths

BY T. TOYOOKA, T. TSUNENARI, R. IDE, AND T. TANGE

ABSTRACT. Fatigue tests were carried out to determine the effect of residual stress on the fatigue strength of carbon steel weldments. The first specimen had three longitudinal bars fixed at both ends, and welding of the middle bar exerted residual stress on the three-bar specimen.

Specimens were postheated to give various levels of residual stress. Then, the specimens were fatigue-tested under pulsating tension. The load vs. strain relationship (measured by strain gages) showed that the tensile residual stress in the middle bar was markedly reduced in the first loading cycle by mechanical stress relief. Even after the marked reduction in residual stress, test results gave fatigue strengths in the following decreasing order: base metal, postheated, and as-welded specimens.

Then, test specimens from the middle bar of three-bar specimens, which were free from residual stress, were prepared. One series of specimens was welded without restraint and the others under restraint, and then variously postheated. The specimens welded without restraint showed scattered fatigue test results. The other specimens gave fatigue test results similar to those obtained with the three-bar specimens. Together with the test results showing an increase in base metal hardness in the specimens welded under restraint, the results indicated that the causes of lower fatigue strength in as-welded and postheated specimens were (1) the embrittlement by thermoplastic straining during welding and (2) the degree of recovery of embrittlement by postheating.

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Introduction

The Bogie Truck Subcommittee of Production Modernization Committee of the Japan Association of Rolling Stock Industries proposed to examine the possibility of omitting the postweld heat treatment on welded carbon steel bogie truck frames. Before taking this step, it was necessary to determine the effect of residual stress on fatigue strength of carbon steel weldment. To accomplish this, the authors carried out a series of fatigue tests with residual stress induced specimens and also with small size specimens free from residual stress.

This paper reports on the results of these tests and assesses the causes for the fatigue behavior of the weldments.

Testing Program

Material Used

All specimens were prepared from 12 mm (0.47 in.) thick carbon steel plate of SM41-B, rolled steel plate for welded structures with minimum tensile strength of 41 kgf/sq mm (402 MPa, 58.3 ksi), as specified by the Japanese Industrial Standards. Mechanical properties of the plate were: tensile strength — 475 MPa (68.9 ksi); yield strength — 319 MPa (46.3 ksi); elongation — 28%; Charpy impact value, V-notch at 0°C (32°F) — 132 J (97 ft-lb).

Chemical analysis of the plate showed its composition to be (%): C — 0.15; Si — 0.17; Mn — 0.72; P — 0.023; S — 0.013; Fe — balance.

All test plates were stress relieved before the fatigue test experiments at 625°C (1157°F) for 1 hour (h) to remove possible internal stress.

Fatigue Tests with the Residual Stress Induced Specimen

Test Specimen. Figure 1 shows the geometry and dimensions of the test specimen. As indicated in Fig. 1, the specimen has three longitudinal bars fixed at both ends. The welding of the middle bar, under the restraint of both side bars, exerts tensile residual stress of approximately yield strength value on the middle bar. The specimen was machined, and a square welding groove with 10 mm (0.39 in.) opening was prepared in the middle bar. The welding groove was welded with a backing strip by GMAW with carbon dioxide shielding gas, since the actual bogie truck frame is welded by the GMAW process.

Welding Conditions. The welding conditions were: welding current — 270 A;

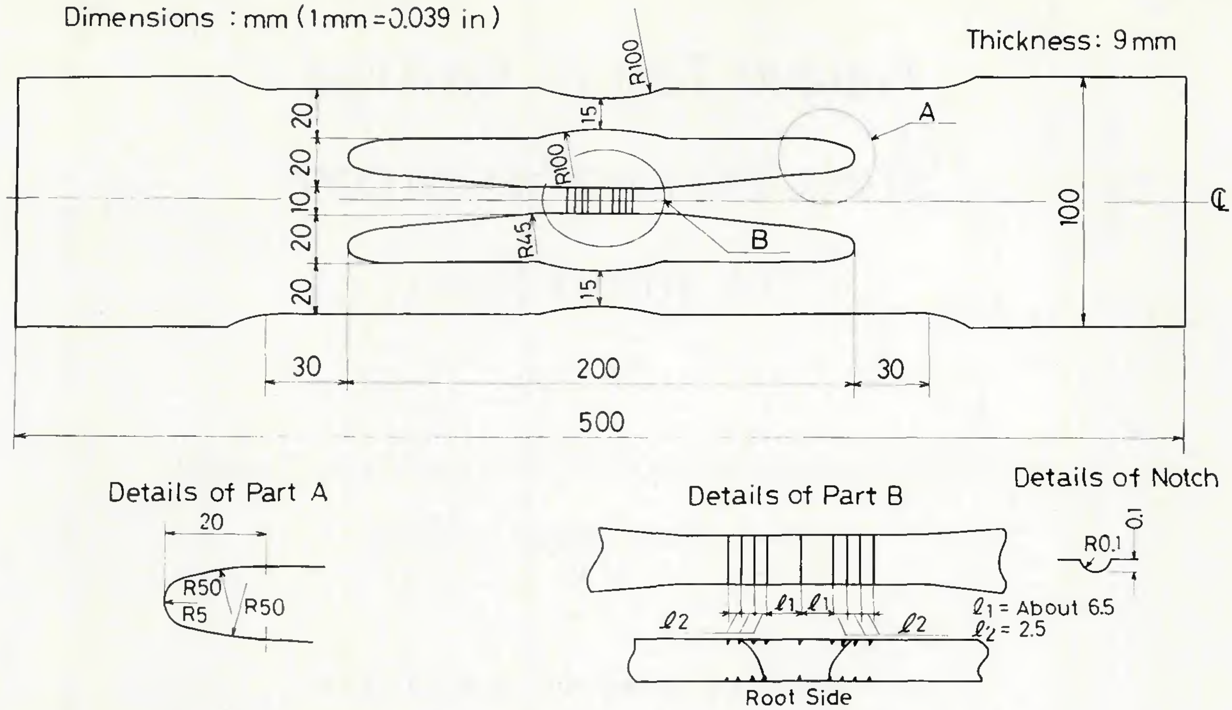

Fig. 1 — Geometry and dimensions for the three-bar test specimen

arc voltage — 30 V; average travel speed — 300 mm/min (12 ipm); shielding gas flow rate — 20 L/min (42.4 cfh). The welding wire was KC 45 1.2 mm (0.047 in.) diameter (Kawasaki Steel Corp.), and the mechanical properties of the all-weld-metal specimen were: tensile strength — 529 MPa (76.8 ksi); yield strength — 431 MPa (62.5 psi); elongation — 33%; Charpy impact value, V-notch at 0°C (32°F) — 138 J (101 ft-lb).

Postweld Heat Treatment. After welding, specimens were postheated using the following combinations of heating temperatures and soaking times to give various levels of residual stress to the specimen: heating temperatures — 400, 500 and 600°C (752, 932 and 1112°F); soaking times — 10 min and 2 h.

In the case of 600°C (1112°F) heating temperature, the soaking time of 1 h was also used.

The postheated specimens were then machined and grinder-finished. On the middle bar, nine small notches were placed on each surface. A total of 18 notches was machine-cut to secure the initiation of fatigue crack in the middle bar. In preliminary tests with specimens without notches, some of the specimens were cracked in the side bar, and the notching was to initiate cracking in the center bar.

The geometry and the location of these small notches are shown in Fig. 1. First, a center notch was cut in the middle of the root surface, which was narrower in width than the weld face. The second and the third notches were cut on both bond lines on the root side of the weld, and another three notches were cut at every 2.5 mm (0.1 in.) distance from both bond lines, six notches in total. The notches on the weld face were cut in the positions symmetrical with respect to the notches on the root surface. The weld face was always wider than the root surface; three or more notches were on the weld face.

Residual Stress Measurement. After various postheat treatments, the tensile residual stress in the middle bar and also the compressive residual stress in both side bars were measured by the stress-relaxation technique. Electric-resistance strain gages were attached to the sur-

Table 1—Residual Stress Measurements, MPa[(a)]

Postheat condition	Middle bar		
	Weld metal	Base metal	Side bar
As-welded	229	231	−74
400°C, 10 min	160	157	−52
400°C, 2 h	147	148	−46
500°C, 10 min	123	121	−37
500°C, 2 h	93	93	−27
600°C, 10 min	52	52	−14
600°C, 1 h	42	41	−14
600°C, 2 h	35	35	−11

(a) 1 MPa = 145 psi.
(b) 400°C = 752°F; 500°C = 932°F; 600°C = 1112°F.

Table 2—Residual Stress Values Measured in Unbroken Specimen after Fatigue Test

Postheat condition	Previous fatigue test		Measured residual stress, MPa[(b)]		
			Middle bar		
	Max. load, kN[(a)]	Cycles (× 10^6)	Weld metal	Base metal	Side bar
As-welded	69	3.14	55	53	−17
500°C, 10 min	69	3.00	75	73	−27
600°C, 10 min	78	7.20	42	42	−10
600°C, 1 h	78	3.15	43	43	−10
600°C, 2 h	78	3.00	40	40	−10

(a) 1 kN = 224.8 lbf.
(b) 1 MPa = 145 psi

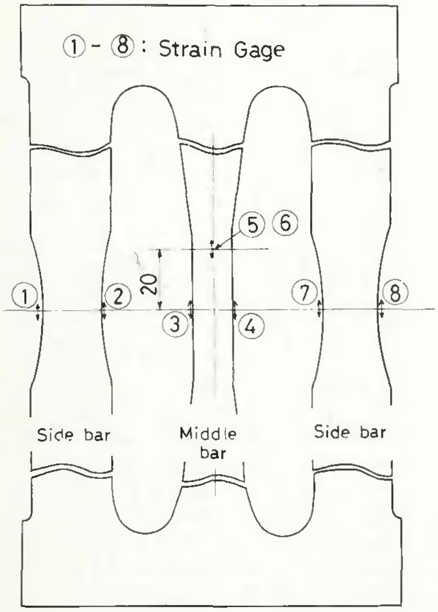

Fig. 2 — Strain measuring points

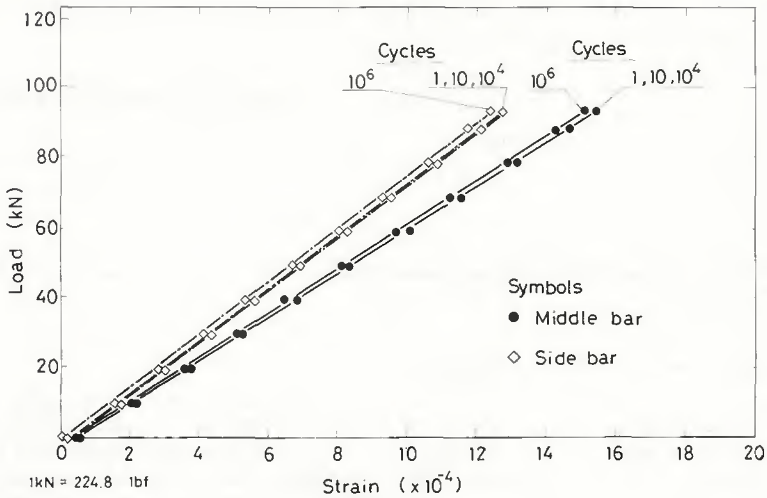

Fig. 3 — Load vs. strain relationship for base metal specimen

faces of middle bar and side bars, then the longitudinal bars were cut off, and the relaxed stresses were measured.

Table 1 gives the results of residual stress measurements; the measured stress values are fairly consistent with the postheating conditions. Table 2 gives the residual stress values measured in unbroken test specimens after fatigue testing. After testing, the remaining residual stress in these unbroken specimens was measured by stress-relaxation technique.

Test Results

Load vs. Strain Relationship

The three-bar specimens were fatigue-tested under pulsating tension, R = 0 (zero to tension). The fatigue testing machine used was of the Rosenhausen type, 392 kN (88,184 lbf) capacity and 550 cpm loading speed.

Figures 3 to 7 show the load vs. strain relationships of base metal, as-welded and postheated specimens in the process of fatigue test. The strain value was measured by strain gages attached to weld metal and base metal of middle bar,

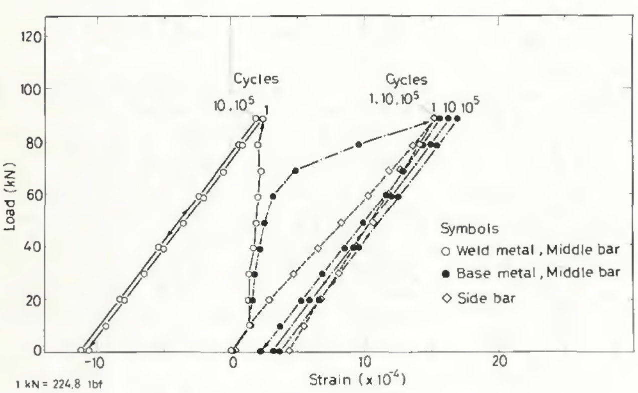

Fig. 4 — Load vs. strain relationship for as-welded specimen

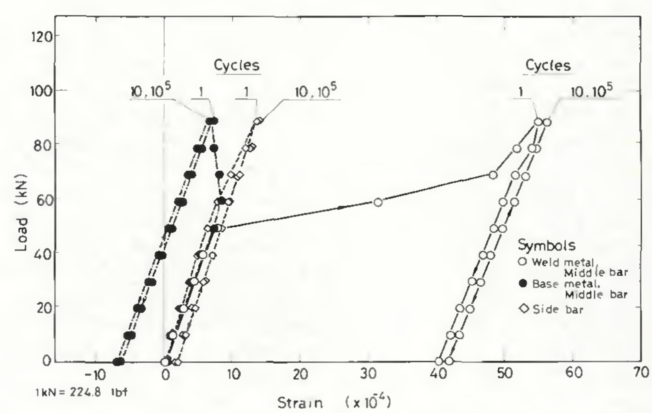

Fig. 5 — Load vs. strain relationships after postheating at 400°C (752°F) for 2 h

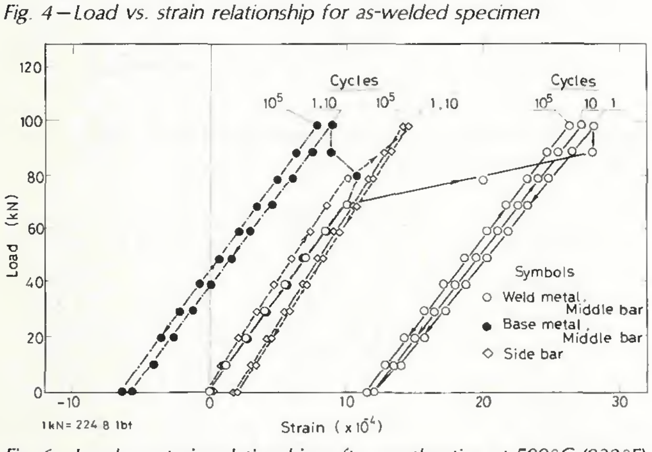

Fig. 6 — Load vs. strain relationships after postheating at 500°C (932°F) for 2 h

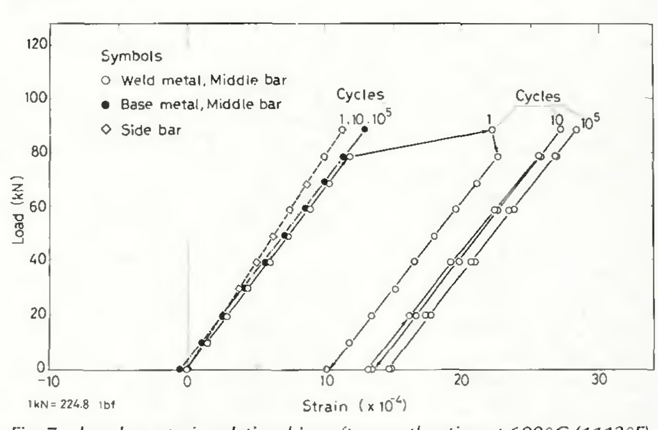

Fig. 7 — Load vs. strain relationships after postheating at 600°C (1112°F) for 2 h

Table 3—Residual Stress Values after the First Loading Cycle

Postheat condition	Applied load, kN[a]	Measured residual stress, MPa[b]		
		Middle bar		
		Weld metal	Base metal	Side bar
As-welded	78	43	42	−14
400°C, 2 h	78	64	62	−21
600°C, 2 h	78	17	15	− 3

(a) 1 kN = 224.8 lbf.
(b) 1 MPa = 145 psi.

and also to the side bars as shown in Fig. 2.

The load vs. strain relationship of the base metal specimen, shown in Fig. 3, gave the elastic behavior throughout the fatigue test. In the cases of as-welded and postheated specimens, the tensile residual stress in the middle bar was markedly reduced in the first loading cycle by the mechanical stress relief process.

As indicated by the as-welded specimen data of Fig. 4, the base metal and weld metal were deformed elastically at the very first step of the loading cycle. Then, at the early stage of loading (about 10 kN or 2248 lbf external load), the other part not measured by strain gage began to yield (presumably, in base metal) with the additional effect of higher tensile residual stress (about 230 MPa or 33.4 ksi) in the middle bar of the as-welded specimen; then the other part was deformed plastically. At the same time, the process of deformation of the measured parts in base metal and in weld metal was stopped.

Next, at the external load of about 60 kN (13,488 lbf), the measured part in base metal began to yield and was deformed plastically. The weld metal showed little deformation up to the maximum load. The load vs. strain relationship in Fig. 4 was shown as an exceptional case. All other as-welded specimens showed clear yielding and plastic deformation in base metal as shown in Figs. 5 and 6.

Figures 5 and 6 depict load vs. strain relationships for the specimens postheated for 2 h at 400 and 500°C (752 and 932°F), respectively; yielding and the plastic deformation took place in weld metal. The yielding of these specimens occurred at external loads of 50 and 70 kN (11,240 and 15,736 lbf), respectively, according to the levels of tensile residual stress in the middle bar, *i.e.,* 148 MPa (21.5 ksi) in the former and 93 MPa (13.5 ksi) in the latter.

With the specimen postheated at 600°C (1112°F) for 2 h (Fig. 7), the weld metal was deformed elastically together with base metal, and then plastically deformed at the final stage of the loading cycle. The residual stress value of this postheated specimen was very low, *i.e.,* 35 MPa (5 ksi).

Typical examples of the load vs. strain relationships are presented here; other tests showed similar behaviors.

Table 3 gives the results of additional residual stress measurements. To confirm the test results that the residual stress was mechanically relieved in the first loading cycle, the three-bar specimen was statically loaded for 1 cycle and up to the yielding load of the middle bar, with the applied load measured by strain gages attached to the middle bar and side bars. After the loading, the middle bar and side bars were cut off, and the residual stress was measured by stress relaxation technique. As shown in Table 3, the tensile residual stress in the middle bar was relieved in the first loading cycle.

Table 4 gives the mean Vickers hardness numbers of weld metal, weld heat-affected zone and base metal in both the as-welded and postheated conditions. The hardness numbers were the mean value of dozens of measurements. As seen in Table 4, the higher hardness numbers of weld metal and of weld heat-affected zone in the as-welded specimen were not reduced by postheating at 400°C (752°F) or 500°C (932°F). On the other hand, the base metal hardness number was reduced by postheating at 400°C (752°F).

These results contradict the abovementioned experimental observations where, in the cases of postheated specimens, the yielding took place in weld metal. Based on the results of tests conducted by a welding wire manufacturer, the tensile and yield strengths of all-weld-metal specimens of KC 45 welding wire were reduced by 36 MPa (5.2 ksi) and by 63 MPa (9.1 ksi), respectively, after postheating at 600°C (1112°F) for 1 h. According to the manufacturer, the marked decrease in yield strength was caused by the reduced effects of interstitially existing carbon and nitrogen associated with postheating.

The mechanical properties of weld metal of three-bar specimens that were subjected to various postheat treatments were not examined. It is assumed, however, that the mechanical behaviors of the weld metal diluted with base metal were similar to those of all-weld-metal specimens, and that the yield strength was reduced by postheating.

The results of postheating tests on rolled steel plate for boilers, which has similar specified minimum tensile strength to SM41B (the material for the authors' tests), showed that postweld heat treatment at 600°C (1112°F) for 1 h reduced tensile strength by 14 to 16 MPa (2.0 to 2.3 ksi); yield strength was not affected substantially (Ref. 1). These test results for postheated specimens explain the reason for premature yielding in weld metal observed in Figs. 5, 6, and 7. In the load vs. strain relationships observed for three-bar specimens, all as-welded specimens yielded in base metal. In the cases of postheated specimens, the yielding was observed as indicated below:

1. For 400°C (752°F), 10 min — 2 specimens in weld metal, and 2 in base metal.
2. For 400°C (752°F), 2 h — 3 in weld metal, and 1 in base metal.
3. For 500°C (932°F), 10 min — 3 in weld metal, and 1 in base metal.
4. For 500°C (932°F), 2 h — 3 in weld metal, and 1 showed obscure behavior.
5. For 600°C (1112°F), 10 min and 1 h cases — all showed elastic behaviors or obscure behaviors. In the 600°C (1112°F), 2 h case, 2 yielded in weld metal, and 2 showed elastic behaviors.

Three-Bar Fatigue Test Results

Figures 8 and 9 show the strain range vs. cycles-to-failure relationships of the

Table 4—Mean Vickers Hardness Numbers Measured

Postheat[a] condition	Weld metal	Heat-affected zone	Base metal
As-welded	152	133	129
400°C, 10 min	158	135	123
400°C, 2 h	153	131	124
500°C, 10 min	156	135	121
500°C, 2 h	153	134	120
600°C, 10 min	138	124	116
600°C, 1 h	144	125	111
600°C, 2 h	142	124	114

(a) 400°C = 752°F; 500°C = 932°F; 600°C = 1112°F.

three-bar specimens measured at weld metal and at base metal, respectively. Here the stress-range, not the absolute stress value, was used, since there was a difference in load distribution between the middle bar and side bars.

Table 5 summarizes the test results; the strain range was taken from the measurement in the 10th cycle of loading. The regression lines of postheated specimens were calculated for each postheating temperature with both test results of 10 min and 2 h soaking times since test results for each postheating temperature seemed to have little relation with the soaking time. All the welded specimens were cracked in the machined notch outside of the bond line, *i.e.,* in the weld heat-affected zone and in base metal outside of the weld heat-affected zone. No fatigue crack was observed in the notches in the weld metal and on the bond line.

As seen in Figs. 8 and 9, the base metal specimens showed the highest fatigue strength. The as-welded specimens had the lowest fatigue strength, and the postheated specimens had a little higher strength, even though the tensile residual stress in the middle bar was markedly reduced in the first cycle of loading.

Fatigue Tests with Small Size Specimens

The previous test results suggest that differences in fatigue strength in base metal, as-welded, and postheated specimens were not caused by residual stresses associated with welding. Instead, they were material changes caused by welding as found in the weld heat-affect-

Table 5—Summary of Fatigue Test Results—Three-Bar Specimen

Postheat condition(a)	Specimen number	Peak load, kN(b)	Nominal stress range MPa(c)	Strain range ($\times 10^{-6}$) in Weld metal	Strain range ($\times 10^{-6}$) in Base metal	Cycles to failure ($\times 10^3$)	Cracked notch, distance from center, mm(d)
Base metal	BM-1	93	259	—	1471	1230	14
	BM-2	88	245	—	1414	4500	6.5
	BM-3	98	272	—	1577	175	14
	BM-4	103	286	—	1860	97	0
							Distance from bond line, mm
As-welded	AW-1	59	167	882	917	>6500	—
	AW-2	74	204	1081	1151	795	4.4
	AW-3	78	218	1159	1242	755	7.6
	AW-4	98	272	1425	1568	143	1.0
	AW-5	69	190	1010	1096	>3140	—
	AW-6	88	245	1267	1331	325	3.2
400°C, 10 min	40-1	88	245	1297	1447	257	7.4
	40-2	98	272	1558	1434	131	0.5
	40-3	78	218	1211	1265	319	3.5
	40-4	69	190	1108	1035	2350	4.2
400°C, 2 h	42-1	98	272	1482	1430	101	5.1
	42-2	88	245	1438	1375	542	2.6
	42-3	78	218	1268	1171	505	4.3
	42-4	69	190	1046	1026	3430	6.3
500°C, 10 min	50-1	88	245	1416	1289	373	0.2
	50-2	98	272	1540	1516	154	4.0
	50-3	78	218	1212	1160	830	2.3
	50-4	69	190	1045	974	>3000	—
500°C, 2 h	52-1	88	245	1336	1317	245	7.3
	52-2	78	218	1191	1127	1020	5.1
	52-3	98	272	1526	1440	145	7.0
	52-4	69	190	1070	1020	>6000	—
600°C, 10 min	60-1	78	218	1234	1204	>7200	—
	60-2	98	272	1427	1425	162	7.8
	60-3	88	245	1287	1307	412	2.6
	60-4	83	231	1227	1206	292	5.2
600°C, 1 h	61-1	88	245	1315	1296	247	8.1
	61-2	98	272	1441	1410	70	3.7
	61-3	78	218	1161	1146	>3150	—
	61-4	83	231	1255	1246	2470	7.4
	61-5	93	259	1406	1386	196	3.5
	61-6	88	245	1357	1339	352	2.5
600°C, 2 h	62-1	88	245	1372	1316	400	2.0
	62-2	78	218	1174	1137	>3000	—
	62-3	98	272	1638	1516	93	0.6
	62-4	93	259	1562	1415	342	5.0

(a) 400°C = 752°F; 500°C = 932°F; 600°C = 1112°F
(b) 1 kN = 224.8 lbf.
(c) 1 MPa = 145 psi.
(d) 1 in. = 25.4 mm.

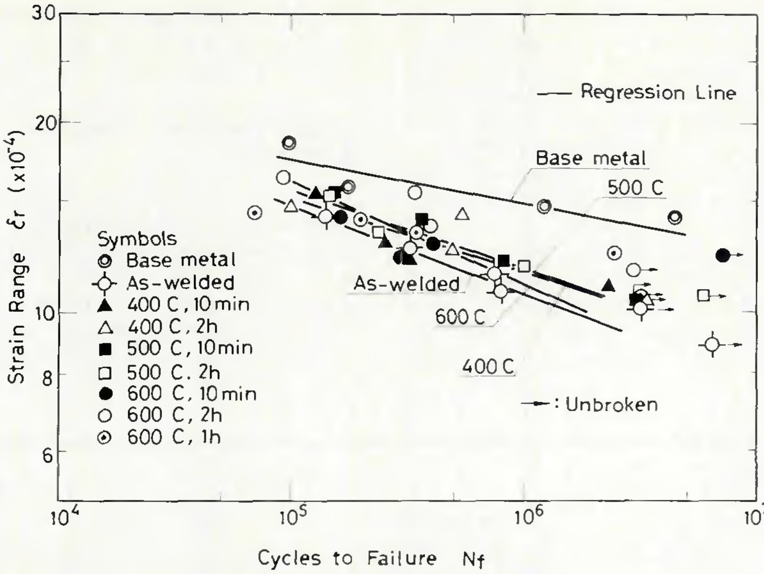

Fig. 8 — Strain range vs. cycles to failure — measured at weld metal

ed zone or so-called "weld strain-affected zone" (Ref. 2). To find the reasons for these test results, further fatigue tests were carried out with small size specimens which were free from residual stress.

Plane Bending Fatigue Test

Fatigue tests were carried out with ordinary plane bending test specimens which had the bottom of round notch in the weld heat-affected zone and in the base metal part outside of the heat-affected zone. The authors found that many fatigue cracks here initiated randomly from the parts off the bottom of round notch, and that there were no consistent test results. Then they tried to determine the location of fatigue crack initiation on smoothly finished surface, and prepared welded plane bending fatigue test specimens as shown by the inset in Fig. 10. Unlike the ordinary test specimen, these specimens had a parallel part for equal chance of crack initiation, and had two welded butt joints on both sides for symmetrization. The welding conditions were similar to those of three-bar specimen.

The test results shown in Fig. 10 indicate little difference in the fatigue strengths for base metal, as-welded and postheated specimens. The fatigue cracks were initiated in weld heat-affected zone and also in base metal outside of the weld heat-affected zone.

Tests with Middle Bar Specimen

After the plane bending fatigue test, a fatigue test with specimens identical to the middle bar of three-bar specimen was carried out under pulsating tension to see the location of fatigue crack initiation, and to find the difference in fatigue behavior between this type specimen and three-bar specimen. In this test, however, the welding was done without restraint. After various postheat treatments, a number of small notches, as shown in Fig. 1, were machine-cut on both surfaces of the specimen.

Figure 11 gives the test results. As shown in Fig. 11, there were practically no differences in fatigue strength among base metal, as-welded and postheated specimens. The straight lines in Fig. 11 are the regression lines taken from the test results for the three-bar specimens shown in Fig. 8. All fatigue cracks were found in the base metal outside of the weld heat-affected zone.

Test with Middle Bar Specimen Welded under Restraint

Fatigue testing was carried out with the middle bar specimens welded under restraint, similarly to the three-bar specimen. The three-bar specimens had been prepared and welded and, after welding, the restraining side bars were discarded. Then, specimens were variously postheated, and a number of small notches were machine-cut on both surfaces.

The results of testing under pulsating

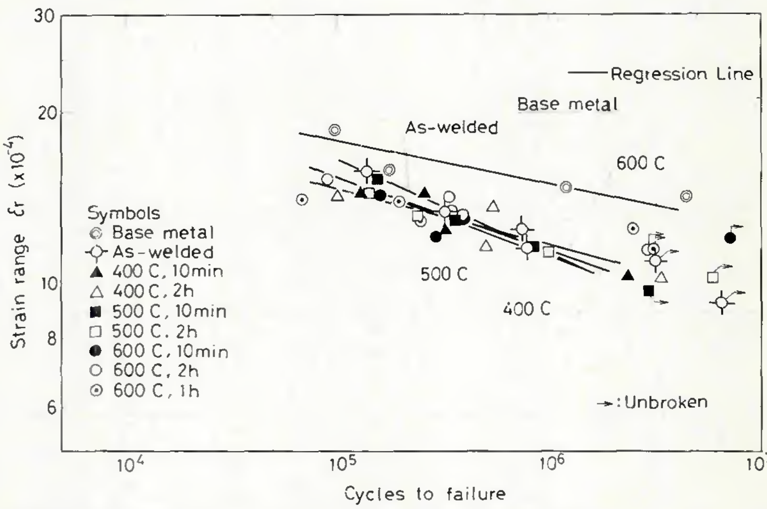

Fig. 9 — Strain range vs. cycles to failure — measured at base metal

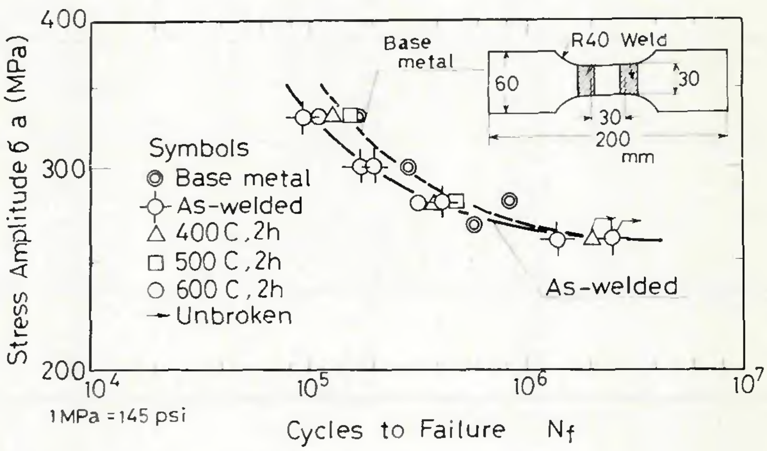

Fig. 10 — Plane bending fatigue test results

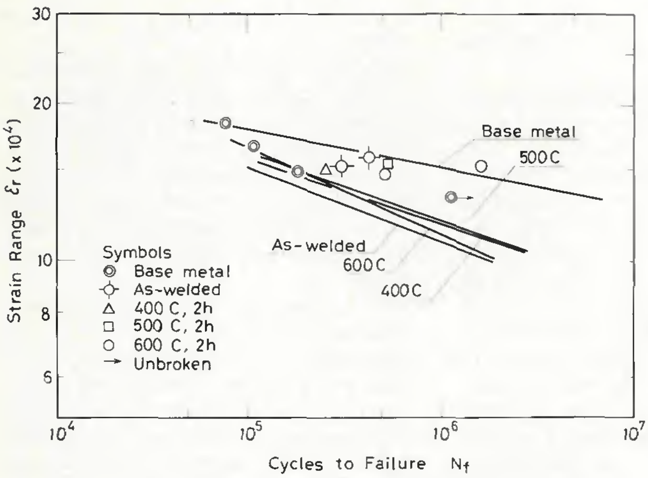

Fig. 11 — *Fatigue test results for middle-bar specimen — welded without restraint*

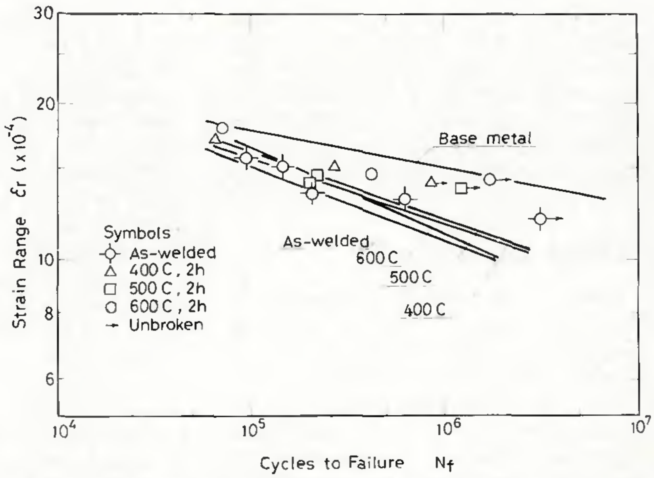

Fig. 12 — *Fatigue test results for middle-bar specimen — welded under restraint*

tension are given in Fig. 12. The straight lines in Fig. 12 are the regression lines taken from Fig. 8. Test results were compared with the regression lines, since the tested specimens for each postheating and as-welded condition were too few to draw an experimental line.

Compared with test results for the three-bar specimen shown in Fig. 8, these fatigue test results produce a similar tendency, *i.e.*, as-welded specimens had the lowest fatigue strength and the post-

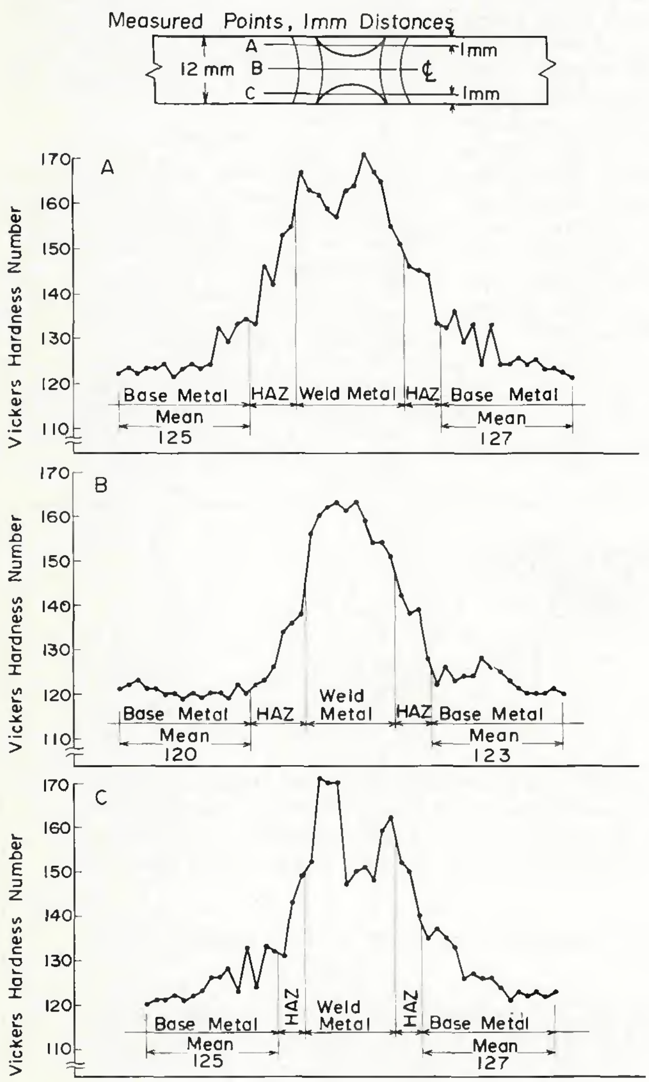

Fig. 13 — *Hardness distributions for welds made without restraint*

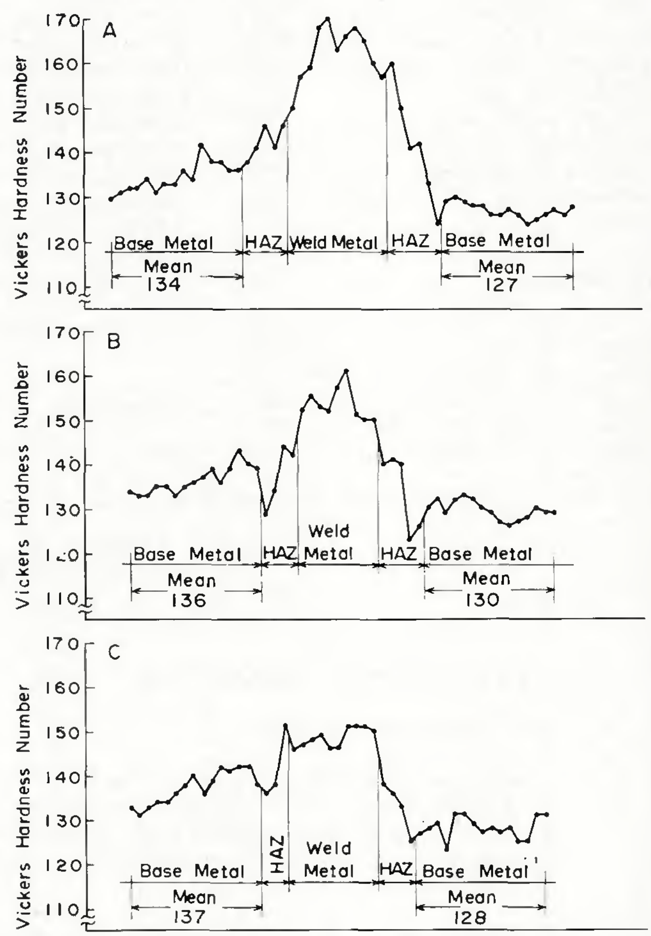

Fig. 14 — *Hardness distributions for welds made under restraint*

heated specimen had improved fatigue strength. All fatigue cracks were found in the weld heat-affected zone and in the base metal outside of the weld heat-affected zone, except for one crack found in the weld metal in a postheated specimen heated at 600°C (1112°F) for 2 h.

Hardness Measurements

Figures 13 and 14 depict Vickers hardness distributions for the middle bar specimens welded without restraint and welded under restraint, respectively. In Figs. 13 and 14, the mean hardness for 15 measurements in the base metal part is also given. As shown, the mean hardness numbers on the left side of the restrained specimen were about 10 points higher than those of the freely welded specimen.

The results indicate that the left side of the restrained specimen was hardened by thermoplastic straining and that strain-hardening was concentrated on the left side of the specimen. The reason for this concentrated hardening is not clear. However, it may come from the uneven heating by manual welding and resulting uneven distortion.

In the weld heat-affected zone, there was no substantial difference in hardness between the specimen welded without restraint and that welded under restraint.

Discussion

The above fatigue test results may indicate that the lower fatigue strength of the as-welded and postheated specimens comes from embrittlement by thermoplastic straining during welding. In the case of the postheated specimens, this embrittlement was to some extent recovered by postheating, but recovery was not complete.

In a structural weld joint, there exists a weld heat-affected zone and also a so-called "weld strain-affected zone" (Ref. 2). The weld joint in the middle bar of the three-bar specimen was very small in dimensions: 12 mm (0.47 in.) in thickness and 10 mm (0.39 in.) in width. Such a small weld could not bring about enough thermoplastic straining to cause embrittlement if the welding is done without restraint. Thus, the fatigue test results of freely welded specimens did not show any difference in fatigue strength between base metal, as-welded or postheated specimens. On the other hand, the middle-bar specimen, welded under restraint, was given a sufficient amount of thermoplastic straining to cause embrittlement, and the fatigue test results showed a difference between the three conditions.

In fatigue testing, the external load or applied stress is comparatively high, since the purpose of the test is to see differences in fatigue strength in a limited period of testing. In the authors' fatigue tests with residual stress induced specimens, the applied load was also high, and the residual stress was markedly reduced by a mechanical stress relief process. In addition, there are some reports that the residual stress is relieved by fatigue loading (Ref. 3). However, the authors' experimental results indicate a negative effect of residual stress on fatigue strength, and the importance of thermoplastic straining which produces the residual stress.

Conclusion

From the experimental results stated above, the following conclusions may be drawn:

1. In a series of fatigue tests with residual stress induced specimens, the tensile residual stress in the specimens was reduced at the first loading cycle, and the level of tensile residual stress had no distinct effect on the fatigue strength of as-welded and postheated specimens as compared to the base metal specimens.

2. It appeared that the cause of lower fatigue strength in the as-welded and postheated specimens compared to the base metal specimens was the embrittlement by thermoplastic straining during welding, and the degree of recovery from this embrittlement by postheating.

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