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Low-cycle Fatigue in Welds

The lives of parent and welded specimens of ASTM A-516, grade 55, steel plate are compared

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ABSTRACT—Hour-glass-shaped specimens were made from ASTM A-516, grade 55, steel plates which had been welded together. The specimens were manufactured so that the weld material was at the minimum section. The specimens were strain cycled about zero mean strain and the results were compared with tests conducted on specimens taken from the parent material. When the total strain range vs. cycles to failure was plotted on log-log coordinates, the curves for both the welded and parent-material specimens had nearly the same slope; however, the curve for the welded specimens was displaced downward from that of the parent material. Thus, for a given strain range, the parent-material specimens had lives approximately six times greater than the welded specimens.

Two-level cumulative-damage tests on the welded specimens indicate that using $\Sigma\ n/N = 1.0$ is reasonably accurate.

List of Symbols

ϵ_{pr} = plastic strain range
ϵ_{tr} = total strain range
ϵ_f = fracture ductility
n = actual cycles
N = cycles to failure
nH = number of cycles at the high-strain range
nL = number of cycles at the low-strain range
a, C = material constants

Introduction

Over the past twenty years, considerable effort has been applied to the study of low-cycle fatigue, but only within the last few years has attention been turned to that of low-cycle fatigue in welds. Fall, et al[1] studied the effects of various welding conditions on the low-cycle fatigue strength of selected low-alloy, high-strength-steel weldments. This work showed that weld-bead shape had more effect on life than weld-joint design, filler material, or weld-metal cleanliness. Hersh[2] investigated the effect of discontinuities on fatigue of aluminum welds and found that if the bead was left intact, the tests were of no real value in determining allowable defect sizes, since failure always occurred at the edge of the weld. Gross and Heise,[3] using pressured boxes, found that low-cycle-fatigue life was closely related to total strain range, and that the life of a complex structure was more sensitive to design and fabrication than to material.

Based on the foregoing information, it was decided to run a series of tests on welded specimens in such a manner that the weld material was in the test zone. The purpose was to compare the fatigue lives in the low-cycle region of the parent and welded materials. Furthermore, the welding was to be done under field conditions by a certified welder. The effect of the weld bead was removed by machining the welded specimen smooth.

Method of Investigation

The material used in this investigation was 3/4-in. (19.05-mm)-thick plate of firebox quality, ASTM A-516, grade 55, fine grain steel. Specimens were made from the parent material by cutting 3/4-in. (19.05-mm) strips from the plate and turning on centers. The test section had an hour-glass shape with a minimum diameter of 1/4 in. (6.35 mm). The ends were

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Original manuscript submitted: March 20, 1974. Final version received: August 16, 1974.

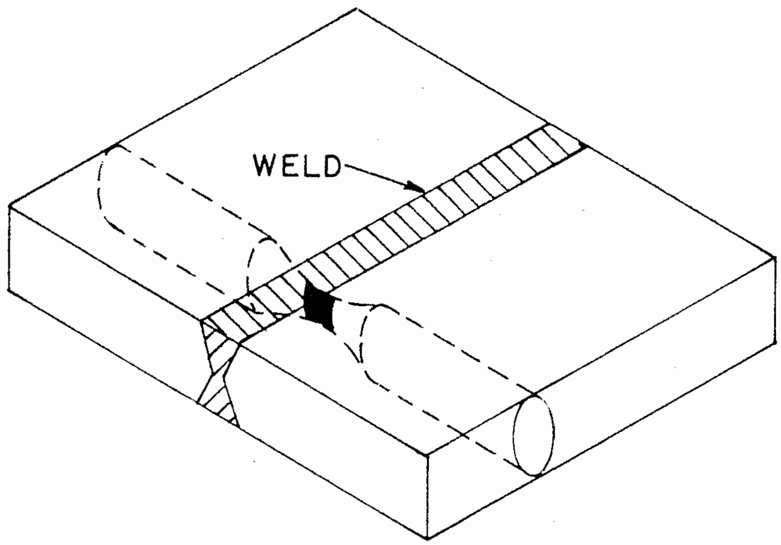

Fig. 1—Specimen orientation in welded plate

turned to 1/2-in. (12.7 mm) and threaded. The welded specimens were made in a similar manner, except the plate was first cut in half, beveled, and welded before the 3/4-in. (19.05-mm) strips were cut. The plate had a double-vee weld applied and the specimen was oriented as shown in Fig. 1. The welds were neither stress relieved nor X-rayed. The filler rod used was P5; the welds were made by a certified welder at the plant of a firm specializing in the construction of pressure vessels.

All tests were conducted at zero mean strain, with specimens made of the parent material being tested first. A diametral extensometer was used for strain measurement, while a load cell in series with the specimen was used to record the load. The second set of tests was on the welded specimens, while the third set of tests was cumulative-damage tests on the welded specimens.

In the cumulative-damage tests, the basic strain ratios, nL/nH, used were 5, 20 and 100, where nL represents the number of cycles at the low-strain range and nH represents the number of cycles at the high-strain range. In approximately half of the tests, the basic strain ratios were followed exactly. For instance, if the ratio was twenty to one, twenty cycles would be executed at the low-strain range followed

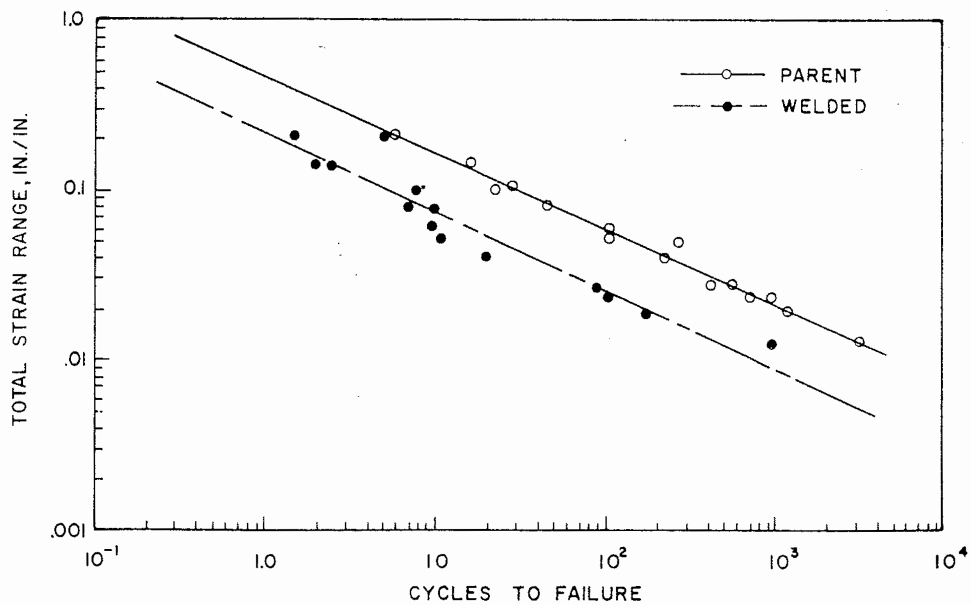

Fig. 2—Completely reversed strain-cycling tests at various constant-strain ranges

by one cycle at the high-strain range. This pattern would be adhered to until failure. The remainder of the tests were varied in that, for example, for the twenty to one ratio, 100 cycles at the low-strain range would be followed by five cycles at the high-strain range.

The basic relation for uniaxial low-cycle fatigue, first proposed by Manson[4] and given by eq (1), is

$$\epsilon_{pr}^{a} N = C \tag{1}$$

where ϵ_{pr} is the plastic strain range, N the cycles to failure, a and C material constants determined by test. Later, Coffin[5,6] proposed the same equation primarily for thermal fatigue.

In the region where the present tests were conducted, the total strain range ϵ_{tr} can be used with little error in eq (1), rather than the plastic strain range ϵ_{pr}. Thus eq (1) becomes

$$\epsilon_{tr}^{a} N = C \tag{2}$$

The material constants a and C in eqs (1) and (2) have different numerical values because of the difference in variables, and they must be determined experimentally.

Experimental Results and Discussion

The results obtained for the reversed-strain tests are shown in Fig. 2. The results are expressed in terms of the total strain range, and the curves were fitted by least squares. Using log-log coordinates, a good linear relationship is observed for both the parent and welded material, although the welded specimens show more scatter. The constants in eq (2) were determined to be, for the parent material,

$$a = 2.23, \qquad C = 0.46$$

and for the welded material

$$a = 2.19, \qquad C = 0.21$$

For the parent material, a good approximation for C has been found to be $\epsilon_f/2$, where ϵ_f is the fracture ductility determined from a tensile test. The value of $2C$ for the parent material agrees quite well with the fracture ductility of 0.93. Two welded specimens were tested to obtain the fracture ductility; the results were 0.27 and 0.77. The value of $2C$ for the welded specimens falls between these two values.

The surfaces of the welded specimens were examined for defects after machining, and small defects were found in all but three. A specimen with a defect is shown in Fig. 3. It was observed that cracks generally originated from the region of the defect; however, if cracks originated elsewhere, they eventually passed through the defect. Of the three specimens without visible defects, two failed at the welded edge.

The specimen shown in Fig. 3 and one without a visible defect were chosen for closer observation than the others during testing. Both were cycled at a total strain range of 0.026 in./in. (.026 m/m), and the extensometer was removed at the end of every ten cycles and the surface examined for cracks. In the specimen with a defect, cracks were first detected on either side of the defect at 120 cycles, with failure occurring at 214 cycles. The defect-free specimen, however, showed two pin-point dots on the surface at two different elevations after 50 cycles. Through these two points, horizontal cracks propagated until 80 cycles, at which time the two cracks were joined by an inclined crack. The predicted life of these specimens was 100 cycles.

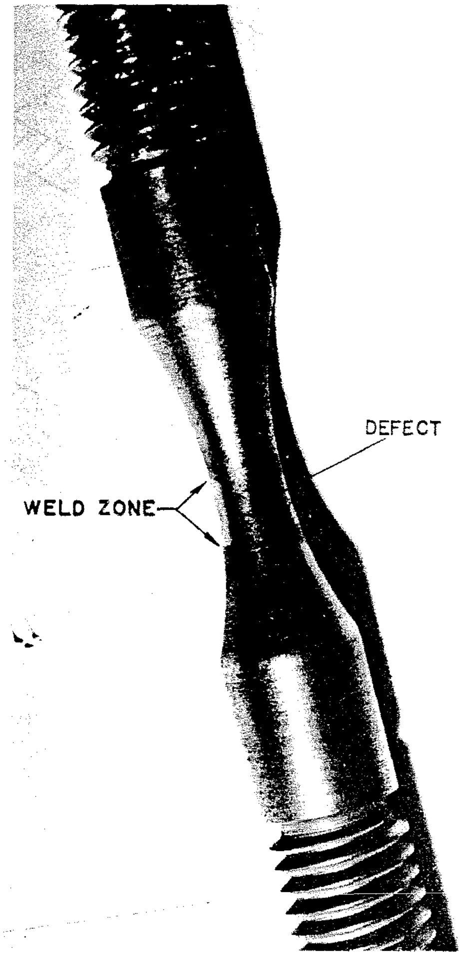

Fig. 3—Specimen with defect

There is no reason to believe that the defects had a preferential orientation, or that there were not other defects beneath the surface. This could explain the manner in which the cracks propagated in the two tests cited, and the reason that the two dots appeared on the surface of the defect-free specimen. The weld defects observed would be considered typical for this class of weld.

The tensile tests show that the welded specimen is less ductile than the parent material; hence, one would expect the curve for the welded specimens to be shifted downward. Examination of Fig. 2 shows that, for a given number of cycles to failure, the welded specimens can tolerate a strain range of

TABLE 1—RESULTS OF CUMULATIVE-DAMAGE TESTS

No.	ϵ_{tr_1}	ϵ_{tr_2}	n_1	N_1	n_2	N_2	n_1/N_1	n_2/N_2	$\Sigma \frac{n}{N}$	nL/nH^1	nL/nH^2
1	.03	.06	21	71	4	16	.296	.250	.546	5	5.25
2	.03	.06	14	71	2	16	.197	.125	.322	5	7.
3	.03	.06	25	71	4	16	.352	.250	.602	5	6.25
4	.016	.04	165	279	30	38	.591	.789	1.380	5	5.5
5	.016	.04	52	279	10	38	.186	.263	.449	5	5.2
6	.016	.04	235	279	47	38	.842	1.237	2.079	5	5.
7	.012	.02	85	523	11	171	.163	.085	.248	5	7.73
8	.012	.02	27	523	5	171	.052	.029	.081	5	5.4
9	.012	.02	331	523	65	171	.632	.380	1.012	5	5.09
10	.03	.06	86	71	4	16	1.211	.250	1.461	20	21.5
11	.03	.06	37	71	1	16	.521	.063	.584	20	37.
12	.03	.06	20	71	2	16	.282	.125	.407	20	10.
13	.016	.04	76	279	3	38	.272	.079	.351	20	25.33
14	.016	.04	600	279	29	38	2.151	.763	2.914	20	20.69
15	.016	.04	103	279	5	38	.368	.132	.501	20	20.6
16	.012	.02	295	523	10	171	.564	.058	.622	20	29.5
17	.012	.02	332	523	15	171	.635	.088	.723	20	22.13
18	.017	.12	185	244	1	4	.758	.250	1.008	100	185.
19	.017	.12	69	244	0	4	.283	.000	.283	100	
20	.017	.12	171	244	1	4	.701	.250	.951	100	171.
21	.012	.08	292	523	2	9	.558	.222	.780	100	146.
22	.012	.08	700	523	7	9	1.338	.777	2.116	100	100.
23	.012	.08	1624	523	16	9	3.105	1.778	4.883	100	101.5
24	.014	.10	701	373	7	5	1.879	1.400	3.279	100	100.14
25	.014	.10	201	373	2	5	.539	.400	.939	100	100.5
26	.014	.10	271	373	2	5	.727	.400	1.127	100	135.5
27	.04	.016	31	38	617	279	.816	2.211	3.027	20	19.9
28	.04	.016	10	38	58	279	.263	.208	.471	20	5.8
29	.04	.016	15	38	243	279	.395	.871	1.266	20	16.2

Superscripts 1 and 2 signify the programmed and actual ratios, respectively.

slightly less than half that of the parent material. Conversely, for the same strain range, the parent material has a life approximately six times longer than that for the welded material. The parent material also strain hardened slightly during testing, while the welded material strain softened slightly.

The results of the cumulative-damage tests are shown in Table 1. The low-strain range was imposed first, except for tests 27, 28 and 29. The average of n/N for the tests is 1.16, while the sample variance is $(1.12)^2$. Based on a sample size of 29, the 95-percent confidence interval on the average of n/N is 0.75 to 1.57.

Conclusions

This study leads to the following conclusions:

1. The slope of the curves for the parent and welded materials is nearly the same.
2. For the same strain range, the parent material has a life approximately six times longer than that of the welded material. Conversely, for a given number of cycles to failure, the welded specimens can tolerate a strain range of slightly less than half that of the parent material.
3. The Manson-Coffin relation is applicable to the welded specimens.
4. More work should be done on smooth welded specimens, with particular attention paid to defect size and orientation.
5. Cumulative damage tests on the welded specimens indicate that $n/N = 1.0$ is reasonably accurate.

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