WELDING RESEARCH

SUPPLEMENT TO THE WELDING JOURNAL, FEBRUARY, 1982

Sponsored by the American Welding Society and the Welding Research Council

Effects of Ferrite Content in Austenitic Stainless Steel Welds

The elevated-temperature mechanical properties of weld metal with a wide delta ferrite range are determined following their deposition using E308-16 covered electrodes

BY D. HAUSER AND J. A. VANECHO

ABSTRACT. The effects of delta ferrite level on tensile and creep-rupture behavior of E308-16 shielded metal-arc stainless steel weld metal were determined. The all-weld-metal deposits had measured delta ferrite levels of 2, 6, 10, and 16 FN. Most of the creep-rupture tests were conducted at 1000 and 1200°F so that the results could be compared with prior results of tests conducted at 1100°F. The data obtained included initial and final elongation, rupture time, reduction of area, minimum creep rate, time to attain 0.5, 1.0, 2, 5, and 10% creep strain, and the strain and time to the initiation of third stage creep.

The results of the creep-rupture tests include the following:

- The 2 FN and 6 FN as-deposited weld metals have similar stress-rupture properties at all three test temperatures.
- At 1000°F, there is a convergence of the creep-rupture curves resulting in almost a common strength level at about the 1000 to 3000 hour (h) time period for all four as-deposited weld metals.
- At 1200°F, there is a divergence of the creep-rupture curves producing a widening of strength level among the four as-deposited weld metals, with the 6 FN material having the highest strength and the 16 FN material having the lowest strength.
- Solution annealing (1950°F/2 h, water-quenched) produces no change in the short time (about 100 h) creep-rupture strength of the 6 FN material at 1100°F and reduces the 1000 h strength level from about 34 to 30 ksi. Solution annealing the 16 FN material results in essentially no change in creep-rupture strength at either short or long times.

Based on minimum creep rate data, the following observations were made:

- The 2 FN weld metal has the highest creep strength at all three test temperatures.
- At 1100 and 1200°F, the creep strength of the 6 FN weld metal is nearly equal that of the 2 FN weld metal.
- At 1200°F and at low creep rates at 1100°F, the 16 FN weld metal has the lowest creep strength. At 1000°F and at high creep rates at 1100°F, the 10 FN weld metal tends to have the lowest creep strength.
- Solution annealing lowers the creep strength of the 2 FN weld metal at 1100°F. Similar treatment of the 16 FN weld metal produces essentially no change.
- Prior exposure for 2500 h at 1100°F produces little change in the 2 FN and 6 FN weld metals and slightly increases the creep strength of the 10 FN and 16 FN weld metals.

The results of the short-time tensile tests indicate that:

- Solution annealing the 6 FN weld metal reduced the yield strength by about 50% at 80 and 1100°F and 60% at 600°F, when compared with the as-deposited condition. Solution annealing the 16 FN weld metal reduced its yield strength by about 30% at 80° F, 45% at 600°F, and 40% at 1100°F.
- The ultimate strength was only mildly affected by solution annealing. It was reduced by approximately 10% at 80 and 600°F and essentially unchanged at 1100°F.
- The ductility of both the 6 FN and 16 FN weld metals was increased significantly by solution annealing. The elongation values of the 6 FN weld metal increased by about 35-40% and of the 16 FN weld metal by about 20-30% at the three test temperatures (80, 600, and 1100°F). Reduction in area values were increased to a lesser extent ranging from about 25% at 600°F to no change at 80°F for the 16 FN weld metal. For the 6 FN weld metal, the increase ranged from about 10 to 20%.
- In general, the yield and ultimate strengths of all four weld metals at 80 and 1100°F are about 5 to 10% lower in the longitudinal direction than in the transverse direction. The ductility, as evidenced by the elongation and reduction in area values, is 10 to 15% higher, on the average, for the longitudinal specimens. Elastic modulus values are lower in the longitudinal direction by about 10 to 20%, with the greatest difference at 1100°F.

Table 1–Metric Conversions

80°F = 27°C = 300 K
600°F = 315°C = 588 K
1000°F = 538°C = 811 K
1100°F = 593°C = 866 K
1200°F = 649°C = 922 K
1950°F = 1066°C = 1339 K
MPa = ksi/6.9
N = lbf/4.5

Paper sponsored by the Metal Properties Council at the 62nd AWS Annual Meeting held in Cleveland, Ohio, during April 5-10, 1981.

D. HAUSER is Senior Researcher and Group Leader, Fabrication and Quality Assurance Section, and J. A. VANECHO is Staff Metallurgist, Physical Metallurgy Section, Battelle-Columbus Laboratories, Columbus, Ohio.

Metallographic examinations of failed creep-rupture specimens indicated that the formation of sigma phase was promoted by higher weld metal ferrite level, test temperature, and rupture time. Solution annealing prior to creep-rupture testing suppressed the formation of sigma phase, even at high as-deposited ferrite levels.

Introduction

Ferrite in austenitic stainless steel weld metal has been investigated extensively. The characteristics of its formation and morphology and its influences on mechanical properties, weldability (solidification cracking tendencies), and corrosion resistance have been widely reported (Ref. 1-8). A need was recognized, however, for the determination of the elevated-temperature mechanical properties of weld metal deposited by the shielded metal-arc process using E308-16 electrodes and having a wide range of delta ferrite content. In performing this investigation, carefully controlled preparation and metallurgical characterization of the weld metals was planned in order to maximize understanding of the results obtained and to permit comparisons with the results of other investigators.

The objective of this study was to determine the effects of delta ferrite level in E308-16 shielded metal-arc austenitic stainless steel weld metal on mechanical properties. This program was a continuation of a previous program, the results of which were published (Ref. 9).

Referring to Table 1 for metric conversion data, the specific mechanical properties of interest were measured by the following tests:

1. Single transverse tensile tests at 80, 600, and 1100°F for ferrite levels of 6 and 16 FN after solution annealing at 1950°F for 2 hours (h).
2. Transverse tensile tests at 600°F for ferrite levels of 2, 6, 10, and 16 FN in the as-deposited condition.
3. Single transverse creep rupture tests at 1000 and 1200°F to produce failure in 100 and 2500 h. Specimens of all four ferrite levels were tested in the as-deposited condition.
4. Duplicate transverse creep rupture tests at 1100°F to produce failure in 100 and 2500 h following solution annealing at 1950°F for 2 h in argon. Only weld metals having ferrite levels of 6 and 16 FN were included in these tests.
5. Single transverse creep rupture tests at 1100°F to produce failure in 100 h following annealing at 1100°F for 2500 h.

In addition, representative samples from the tested specimens were examined metallographically. Emphasis was placed on specimens tested at 1200°F to document microstructural changes that occurred as a result of the different thermal and strain histories.

Materials and Test Requirements

Table 2 gives the test requirements and the particular specimens assigned to each. In addition to the tests of as-deposited weld metal, tests were made on solution-anneal (1950°F/2 h, W.Q., i.e., water-quenched), and exposed (1100°F/2500 h) weld metals. Requirements for both creep-rupture and short-time tensile tests are given in Table 2. A total of six tests were initially scheduled for the 2 FN and 10 FN weld metals and 11 tests for the 6 FN and 16 FN weld metals. One additional creep-rupture test was actually made on each material. These were short-time (10 h) tests at 1000°F made for the purpose of aiding in the selection of stresses for the long-term tests.

Weld-Metal Property Characterization

Creep-Rupture Tests

Final creep-rupture test results are summarized in Table 3. Data reported include initial and final strain, rupture time, reduction in area, minimum creep rate, time to attain 0.5, 1.0, 2, 5, and 10% creep strain, and initiation of third stage creep (strain in percent and time in hours or h).

The rupture times for all tests are presented versus the stress on log-log plots in Fig. 1 and the minimum creep rates are plotted vs. the stress in Fig. 2. Results for all three temperatures (1000, 1100, and 1200°F) and all ferrite levels are given on the same plot in order to show the strength relationships for all weld metals at all three temperatures. The creep-rupture data also were plotted as Larson-Miller (L-M) curves for all four ferrite levels.

An optimum but different constant was derived for each weld metal. However, it was desirable to have a constant common to all four weld metals, in order to compare their rupture strengths. The

Table 2—Test Requirements for E308 Weld Metal Program

	Delta ferrite levels, FN			
Material identity	2 FN D(63)	6 FN A(78)	10 FN B(79)	16 FN C(80)
		As-deposited		
Creep rupture tests	1000°F/10 h (DT-23)	1000°F/10 h (AT-23)	1000°F/10 h (BT-27)	1000°F/10 h (CT-19)
	1000°F/100 h (DT-21)	1000°F/100 h (AT-7)	1000°F/100 h (BT-23)	1000°F/100 h (CT-24)
	1000°F/2500 h (DT-27)	1000°F/2500 h (AT-25)	1000°F/2500 h (BT-25)	1000°F/2500 h (CT-25)
	1200°F/100 h (DT-22)	1200°F/100 h (AT-8)	1200°F/100 h (BT-24)	1200°F/100 h (CT-1)
	1200°F/2500 h (DT-24)	1200°F/2500 h (AT-24)	1200°F/2500 h (BT-32)	1200°F/2500 h (CT-32)
		Solution annealed (1950°F/2h)		
Creep rupture tests	—	1100°F/100 h (AT-27)	—	1100°F/100 h (CT-28)
	—	1100°F/2500 h (AT-28)	—	1100°F/2500 h (CT-27)
		Annealed (1100°F/2500 h)		
Creep rupture tests	1100°F/100 h (DT-25)	1100°F/100 h (AT-32)	1100°F/100 h (BT-33)	1100°F/100 h (CT-33)
		As-deposited		
Short time tensile tests	600°F (DT-26)	600°F (AT-26)	600°F (BT-26)	600°F (CT-26)
		Solution annealed (1950°F/2 h)		
Short time tensile tests	—	80°F (AT-29)	—	80°F (CT-29)
	—	600°F (AT-30)	—	600°F (CT-30)
	—	1100°F (AT-31)	—	1100°F (CT-31)
Total tests required (no. specimens)	7	12	7	12

most appropriate constant for this purpose, based on visual comparisons of the plotted data, appeared to be 25. This constant was used in Fig. 3 that shows the comparative strength relationship of the weld metals at four ferrite levels. Based on the various L-M curves, the creep-rupture strength values given in Table 4 were calculated. These values do not necessarily agree with log stress-log time curves presented in Fig. 1. The L-M values are a collective representation of all temperatures (1000, 1100, and 1200°F) and all rupture times. The log-log curves of Fig. 1 are based on a limited number of tests conducted at each temperature.

Because only two tests were made on each as-deposited weld metal at 1200 F, it is not possible to develop a trend other than linear. Therefore, the values developed from the L-M curves (Table 4) were used to reconstruct the log-log curves in Fig. 4. In addition to the values given in Table 4, the L-M curves permit the determination of stress values for other temperatures and rupture times. These are calculated by inserting the desired temperature (T, absolute) and time (t, hours) in the equation $T(25 + \log t) \times 10^{-3}$. The intersection of this calculated value with the appropriate L-M curve gives the stress.

Based on the creep-rupture data obtained for the various material and test conditions:

- The very low (2 FN) and low ferrite (6 FN) as-deposited weld metals have similar stress-rupture properties at all three test temperatures (1000, 1100, and 1200°F).
- At 1000°F, there is a convergence of the creep-rupture curves resulting in almost a common strength level at about the 1000 to 3000 h time period for all four as-deposited weld metals.
- At 1200°F, there is a divergence of the creep-rupture curves producing a widening of strength levels among the four as-deposited weld metals, with the 6 FN material having the highest strength (19.5 ksi to rupture in 10,000 h) and the 16 FN material having the lowest strength (15 ksi to rupture in 10,000 h).
- Solution annealing (1950°F/2 hr, W.Q.) produces no change in the short time (about 100 h) creep-rupture strength of the 6 FN weld metal at 1100°F and reduces the 1000 h strength level from about 34 to 30 ksi. Solution annealing the 16 FN weld metal results in essentially no change in creep-rupture strength at either short or long times.
- The solution annealed specimens (AT-27 and CT-28) initially deformed 9.59 and 4.06%, respectively, when stressed to 40 ksi at 1100°F (Table 3). This is understandable in that the yield strength was greatly reduced by solution annealing. The yield strength of the 6 FN weld metal (AT-27) dropped from 39.8 (Ref. 9) to 22.3 ksi (Table 7) and the yield strength of the 16 FN (CT-28) weld metal dropped from 42.6 (Ref. 9) to 25.6 ksi (Table 7). The 40 ksi stress on the AT-27 and CT-28 specimens was approximately 60% over

Table 3—Summary Data on Creep and Rupture Properties of E308 Weld Metal at 1000, 1100, and 1200°F (538, 593, and 649°C)

Specimen number	Stress, ksi	Hours to indicated percent creep deformation 0.5	1.0	2.0	5	10	Initial strain, %	Rupture time, h	Elongation in 2 in., %	Reduction of area, %	Minimum creep rate, %/h	Initiation of third stage creep %	h
							AS-WELDED CONDITION						
							1000°F						
							Extra-low delta ferrite						
DT-23	52	21	36	63	109	–	3.708	142.6	15.6	40.5	0.020	3.9	10
DT-21	47	35	45	162	335	–	1.210	400.8	12.4	20.7	0.012	3.3	170
DT-27	42.5	145	460	1500	–	–	0.334	2093.3	7.7	22.5	0.0009	2.7	1820
							Low delta ferrite						
AT-23	54	0.7	1.3	2.4	5	–	7.103	9.8	24.9	47.4	0.67	7.7	1
AT-7	47	18	35	66	160	240	1.542	283.5	19.2	33.7	0.032	5.0	110
AT-25	42.5	65	164	490	1400	–	0.742	1769.2	12.8	30.7	0.0029	4.5	1100
							Medium delta ferrite						
BT-27	50	2.2	4	8	15	20	3.370	24.7	21.7	49.7	0.17	3.8	2
BT-23	43	31	74	200	480	700	0.358	813.2	19.6	39.4	0.0075	2.3	250
8T-25	41	65	185	610	1560	2230	0.355	2526.1	16.6	28.9	0.0022	2.8	830
							High delta ferrite						
CT-19	53	1.2	2.7	7.7	20	–	2.853	35.8	14.9	37.2	0.20	6.0	13
CT-24	47	10	23	56	194	340	0.530	430.2	19.0	29.3	0.021	5.0	175
CT-25	43.5	30	75	210	550	800	0.308	871.2	14.0	25.4	0.0077	2.6	250
							1200°F						
							Extra low delta ferrite						
DT-22	30	17	29	41	65	88	0.294	119.0	26.0	27.4	0.026	0.6	10
DT-24	23.5	960	1075	–	–	–	0.122	1127.4	4.1	13.4	0.00026	0.35	575
							Low delta ferrite						
AT-8	31.5	3.5	6.5	11	19	26	0.225	34.0	27.9	47.6	0.11	0.6	3
AT-24	22	2300	2600	–	–	–	0.145	2748.3	5.9	10.9	0.00009	0.34	1000
							Medium delta ferrite						
BT-24	27.5	15	28	45	72	103	0.187	122.8	20.0	38.6	0.027	0.4	5
BT-32	20.5	1460	1840	–	–	–	0.161	2032.8	5.1	12.7	0.00017	0.42	725
							High Delta Ferrite						
CT-1	26.5	12	27	40	97	147	0.166	153.8	14.1	27.9	0.033	0.7	13
CT-32	17.5	1290	2080	–	–	–	0.118	2267.6	3.4	6.0	0.00022	0.48	850
							SOLUTION ANNEALED CONDITION (1950°F/2 h, W.Q.), 1100°F						
AT-27	40	1.0	2.5	6.0	22	39	9.589	46.8	22.5	25.6	0.17	–	–
AT-28	30	10	35	160	780	980	3.330	1004.3	12.3	19.8	0.0042	7.0	540
CT-28	40	0.4	1.0	2.7	8.8	20	4.059	39.1	26.4	33.2	0.43	–	–
CT-27	27.5	12	125	1070	2250	–	0.310	2278.0	6.4	12.7	0.00027	2.6	1400
							EXPOSED CONDITION (2500 h at 1100°F)						
							1100°F						
DT-25	40	3	8	20	47	75	1.390	99.8	21.7	35.0	0.081	4.5	34
AT-32	40	2	4	11	33	52	1.536	87.9	29.3	49.2	0.12	5.2	25
BT-33	40	0.7	3	5.5	24	43	0.909	79.6	34.0	45.5	0.20	7.0	28
CT-33	40	1.5	4.5	16	40	65	0.455	79.5	17.0	28.5	0.096	3.3	25

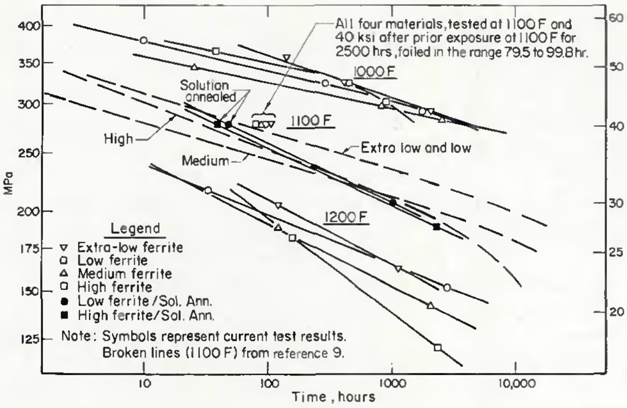

Fig. 1—Stress-rupture curves for E308 weld metal containing different ferrite levels tested at 1000, 1100, and 1200°F (538, 593, and 649°C)

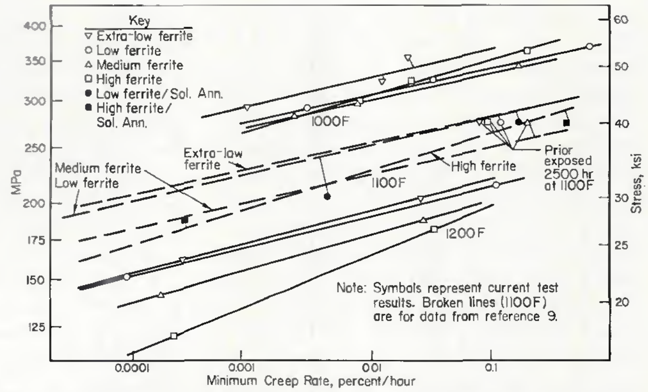

Fig. 2—Stress vs. minimum creep rate curves for E308 weld metal tested at 1000, 1100, and 1200°F (538, 593, and 649°C)

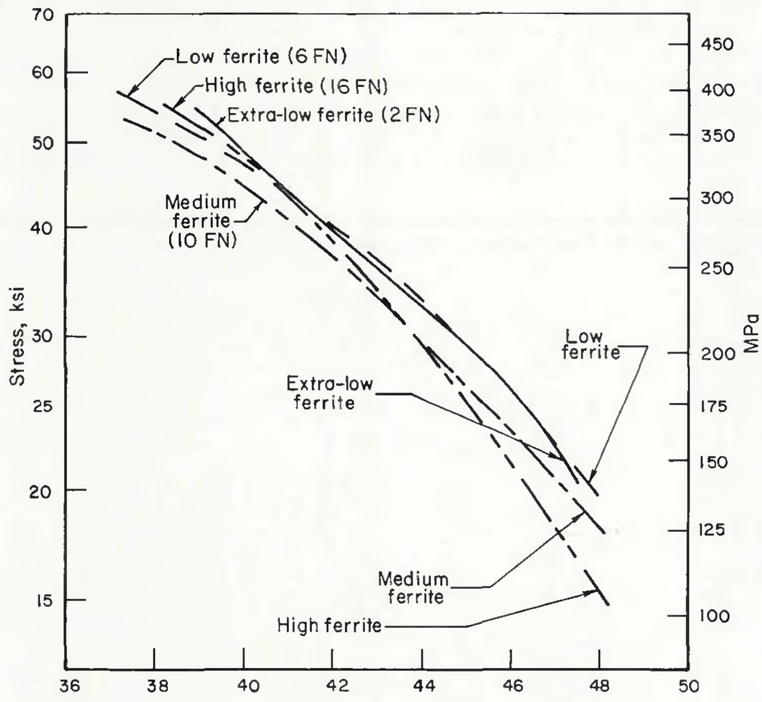

Fig. 3—Larson-Miller comparison of stress-rupture properties of E308 weld metal

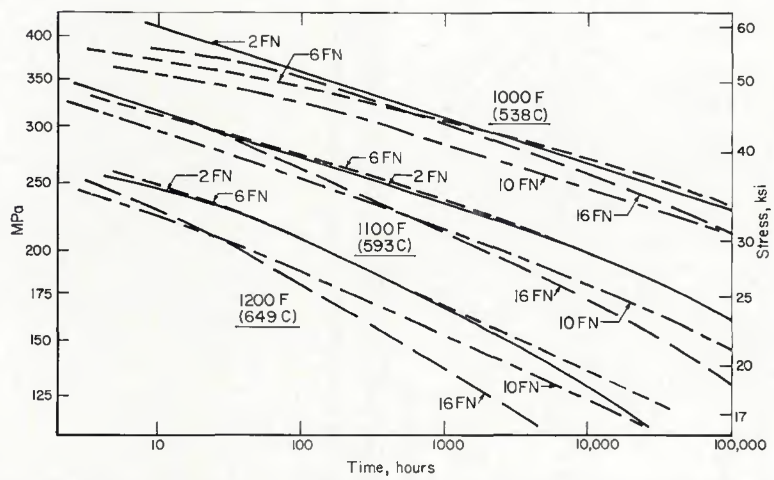

Fig. 4—Stress-rupture curves for E308 weld metal with different ferrite numbers tested at 1000, 1100, and 1200°F as based on Larson-Miller data

each weld metal's yield strength.

- There are only minor differences between the two log-log plots (Figs. 1 and 4) of creep-rupture strength properties of the four weld metals. The relationships established by individual tests (Fig. 1) are about the same as those (Fig. 4) reconstructed from the L-M curves. The major difference, and advantage, of the reconstructed plot is that the creep-rupture curves extend to 100,000 h at 1000 and 1100°F, and beyond 10,000 h at 1200°F.

The stresses required to produce various minimum creep rates (0.1 to 0.0001%/h) were taken from the log-log plots in Fig. 2 and are shown in Table 5. Based on these values and on the curves in Fig. 2, the following observations were made:

- The 2 FN weld metal has the highest creep strength at all three test temperatures (1000, 1100, and 1200°F).
- At 1100 and 1200°F, the 6 FN weld metal has approximately the same strength as the 2 FN weld metal.
- At 1200°F and at low creep rates at 1100°F, the 16 FN weld metal has the lowest creep strength. At 1000°F and at high creep rates at 1100°F, the 10 FN weld metal tends to have the lowest creep strength.
- Solution annealing lowers the creep strength of the 2 FN weld metal at 1100°F. Similar treatment of the 16 FN weld metal produces essentially no change.
- Prior exposure for 2500 h at 1100°F produces little change in the 2 FN and 6 FN weld metals and slightly increases the creep strength of the 10 FN and 16 FN weld metals.

The effect of solution annealing and prior exposure on the ductility of the four weld metals is shown in Figs. 5 and 6. Rupture elongation (Fig. 5) is lowered only slightly by either of the heat treatments. Reduction in area values (Fig. 6) are lowered by an average of about 5% by the two heat treatments.

Comparison of Creep-Rupture Properties of Weld-Deposited, Cast, and Wrought Stainless Steels

The results of weld-metal creep-rup-

Table 4—Stress-Rupture Values for Four Ferrite Levels of E308 Weld Metal Based on L-M Curves

Ferrite level	Stress, ksi, to produce rupture in times indicated in hours				
	10	100	1000	10,000	100,000
			1000°F		
2 FN	60	52	44.5	38	33
6 FN	54	49	44	39	33.5
10 FN	51.5	46.5	41	35.5	30.5
16 FN	55.5	50.2	43.3	37	30.2
			1100°F		
2 FN	46	39.5	33.5	28.5	23
6 FN	45	39.5	34	28.5	23
10 FN	42.5	36.5	31	25.5	21
16 FN	45.5	38	31	24.5	18.7
			1200°F		
2 FN	35.5	30	24	18.5	–
6 FN	36	30	24	19.5	–
10 FN	32.5	27	21.8	17.7	–
16 FN	33	26	19.5	15	–

Table 5—Stress vs. Creep Rate Values for Four Ferrite Levels of E308 Weld Metal Based on Log-Log Plots

Ferrite level	Stress, ksi, to produce minimum creep rates indicated in %/hour			
	0.1	0.01	0.001	0.0001
		1000°F		
2 FN	53	48	43	–
6 FN	49.5	44.5	40.5	–
10 FN	48.5	43.5	39.5	–
16 FN	50.5	44.5	39	–
		1100°F		
2 FN	41	37	33.5	30
6 FN	41	36.5	33	29
10 FN	36.5	32.5	29.5	26.5
16 FN	38.5	33.5	28.5	25
		1200°F		
2 FN	32	28.5	25	22
6 FN	31	28	24.5	22
10 FN	29.5	26	22.5	20
16 FN	29	24	19.5	16.5

ture tests at 1100°F are replotted in Fig. 7.

The adjusted average creep-rupture values for Types 304 and 304H wrought stainless steels reported by Smith (Ref. 10) are similar to the results from this program for the medium-ferrite weld metal at rupture times beyond 1000 h. For times to rupture less than 1000 h, the results for the high-ferrite weld metal are close to the values reported by Smith (Ref. 10). The expected minimum creep-rupture values for Type 304 stainless steel published in the 1977 ASME Code Case N-47-12 (1592-12) also are plotted in Fig. 7. The rupture times from this Code Case (Ref. 11) are significantly shorter than those measured for the ferrite containing weld metals.

Also plotted in Fig. 7 are results reported by Voorhees (Ref. 12) and given in Table 6 for CF8 castings at two ferrite levels. Compared to the weld metal, the castings have the following creep-ruptuce properties:

- Lower strength.
- Lower secondary creep rate.
- Higher elongation and reduction of area at fracture, especially at the longer rupture times.

The CF8 having a calculated ferrite level of 3% was significantly stronger than CF8 having a calculated ferrite level of 16%.

Short Time Tensile Tests

Ten short time tensile tests were conducted on the four weld metals at the conditions described in Table 2. Results of these tests include yield and ultimate strength, elongation, reduction in area, and elastic modulus and are given in Table 7. These values are presented graphically in Figs. 8 and 9 together with those presented in the literature (Ref. 9).

All tensile tests were conducted in a Baldwin Universal hydraulic tensile machine having a capacity of 60,000 pounds. Temperatures were obtained by means of an electric-resistance furnace and controlled by means of Chromel-Alumel thermocouples attached to the gage section of the specimens. Strain was recorded on an autographic stress-strain recorder. A Class B-1 extensometer was used for all tests (ASTM Standard E83-74). The extensometer was calibrated prior to making the tests to ensure that the maximum error was within the prescribed limits. Accuracy of the extensometer is within ±10%. After holding the specimens at the test temperature for 30 min, the specimens were pulled at a strain rate of 0.002 ipm.

The short-time tensile test results indi-

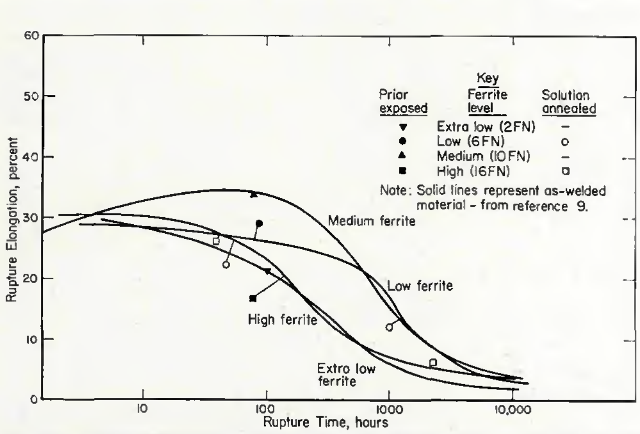

Fig. 5—Relationship of elongation and rupture time in creep-rupture tests at 1100°F (593°C) for E308 weld metal

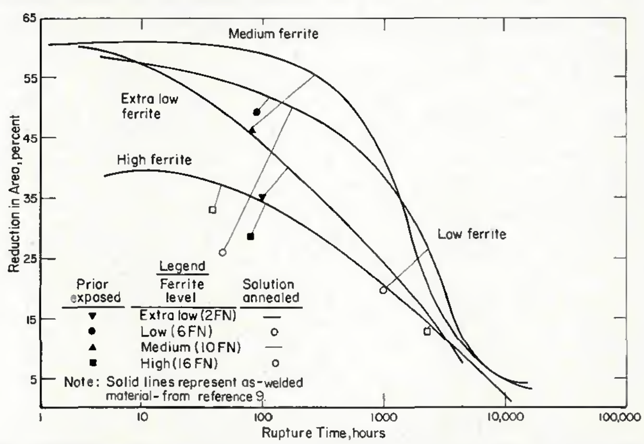

Fig. 6—Relationship of reduction in area (593°C) and rupture time in creep-rupture tests at 1100°F (593°C) for E308 weld metal

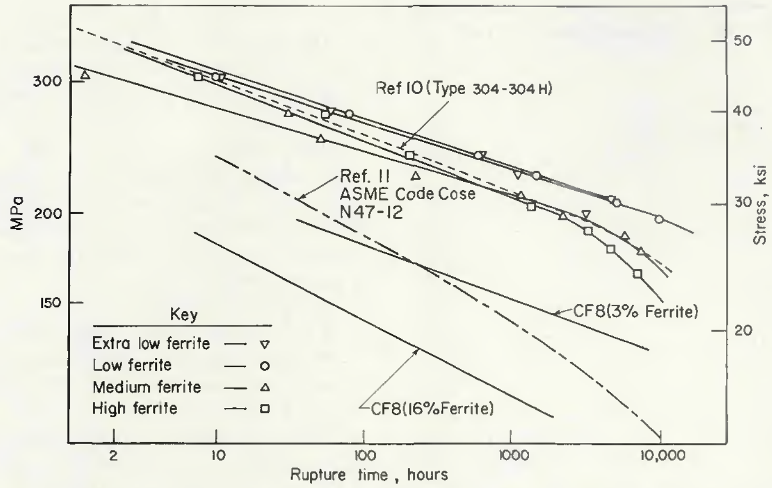

Fig. 7 — Stress rupture curves for E308 weld metal and CF8 castings at 1100°F (593°C) with different ferrite levels

cate that:

- The data on the as-deposited weld metal obtained at 600°F are generally consistent with the established trend except for some values for the 16 FN weld metal. The yield strength and elastic modulus for the 16 FN specimens appear slightly higher and the elongation and reduction in area tend to be lower than the trend would indicate.
- Solution annealing the 6 FN weld metal reduced the yield strength by about 50% at 80 and 1100°F and 60% at 600°F, when compared with the as-deposited condition. Solution annealing the 16 FN weld metal reduced its yield strength by about 30% at 80°F, 45% at 600°F, and 40% at 1100°F.
- The ultimate strength was only mildly affected by solution annealing. It was reduced by approximately 10% at 80 and 600°F and essentially unchanged at 1100°F.
- The ductility of both the 6 FN and 16 FN weld metals was increased significantly by solution annealing. The elongation values of the 6 FN weld metal increased by about 35-40% and of the 16 FN weld metal by about 20-30% at the three test temperatures (80, 600, and 1100°F). Reduction in area values were increased to a lesser extent ranging from about 25% at 600°F to no change at 80°F for the 16 FN weld metal. For the 6 FN weld metal, the increase in reduction of area ranged from about 10 to 20%.
- Nearly all short-time tensile tests were made transverse to the welding direction. At 80 and 1100°F, tests were made also in the weld direction (longitudinal) on all four weld metals. The results are presented in Figs. 8 and 9. In general, the yield and ultimate strengths of all four weld metals at 80 and 1100°F are about 5 to 10% lower in the longitudinal direction than in the transverse direction. The ductility, as evidenced by the elongation and reduction in area values, is 10 to 15% higher, on the average, for the longitudinal specimens. Elastic modulus values are lower in the longitudinal direction by about 10 to 20%, with the greatest difference at 1100°F.

Fractographs of several failed stress-rupture bars are shown in Fig. 10. These are typical of the failures seen in all test bars. No specimen displayed any unusual appearance.

Table 6—Creep-Rupture Properties of CF8 Castings (Ref. 12)

				Secondary creep period							
				Start		Rate	End				
Spec. no.	Temp., °F	Stress, ksi	Total strain on loading, %	Creep, %	Time, h	%/h	Creep, %	Time, h	Rupture life, h	Elong., %/4D	R.A., E. %
CF8, Lot D-4. Ingersoll-Rand Co., Ht. No. 6876. (2050° F, 3½ h, W.Q.)									*3% calculated ferrite.*		
D4-47	1100	25	16.1	3.2	63	0.012	4.2	146	172.9	24.5	34.4
D4-49	1100	22.5	10.45	1.8	160	0.00265	2.7	500	763.0	16	18.8
D4-62	1100	20	7.25	2.3	1080	0.00083	3.2	2160	4794.1	21	36.0
CF8, Lot D-10. Esco Corp., Ht. No. 40S-25976.									*16% calculated ferrite.*		
D10-28	1100	25	6.2	4.0	4.8	(0.40)	–		15.8	21.5	35.6
D10-65	1100	20	3.0	4.9	50	0.037	7.3	115	182.1	19	23.0
D10-23	1100	16		2.2	78	0.0059	6.0	720	1108.4	17.5	22.5
D10-53	1100	12.5	0.13	1.1	1070	0.00055	1.8	2320	(2.66% creep/3360 h)		
D10-63	1100	10	0.27			[0.00017 to 0.91%/3168 h]					

Table 7—Short-Time Tensile Properties of E308 Weld Metal in As-Welded and Solution-Annealed Conditions[a]

Spec.	Temperature, deg °F	°C	Yield strength 0.2% offset, ksi[b]	Ultimate strength, ksi[b]	Elongation, %	Reduction of area, %	Elastic modulus, 10^6 psi
				As-welded condition			
DT-26	600	315	53.7	71.5	27.5	45.9	20.1
AT-26	600	315	53.4	70.2	28.0	45.5	22.6
BT-26	600	315	55.0	72.4	29.0	44.0	21.9
CT-26	600	315	61.7	79.4	23.0	35.1	27.5
				Solution-annealed condition (1950°F/2 h, W.Q.)			
AT-29	80	27	37.6	82.6	62.0	58.3	25.5
CT-29	80	27	53.3	94.5	50.0	49.6	27.8
AT-30	600	315	21.2	66.2	42.0	55.4	20.8
CT-30	600	315	34.1	72.1	34.0	48.1	22.2
AT-31	1100	593	22.3	54.0	40.0	52.2	24.8
CT-31	1100	593	25.6	55.9	33.5	46.0	23.8

(a) All Specimens were taken transverse to weld direction.
(b) 1 ksi = 6.9 MPa.

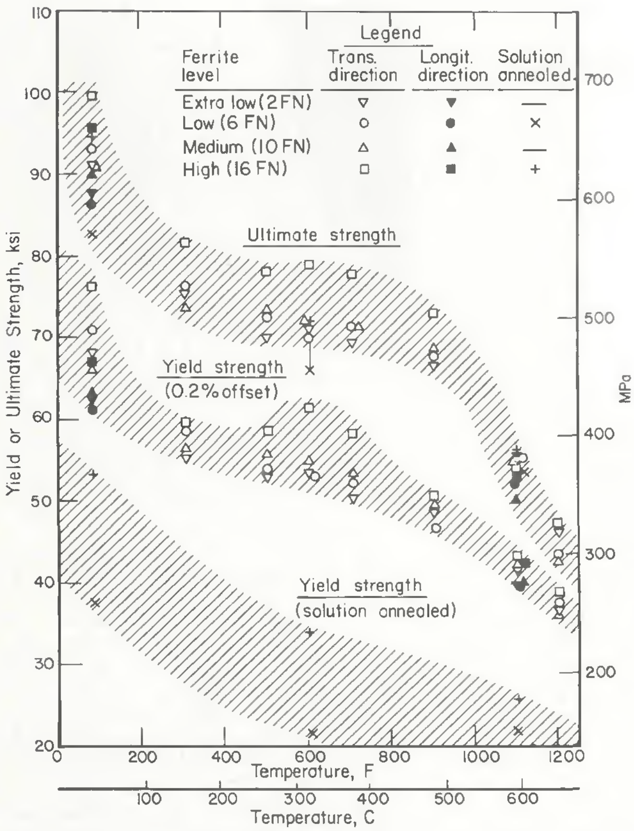

Fig. 8 — Yield strength and ultimate strength values for E308 weld metal in as-welded and solution-annealed conditions

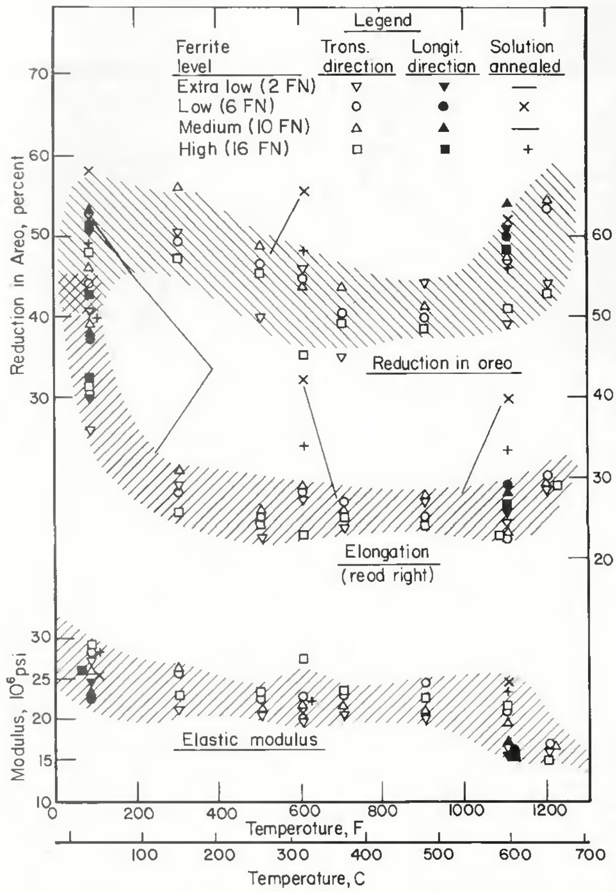

Fig. 9 — Elastic modulus, elongation, and reduction-in-area values for E308 weld metal in as-welded and solution-annealed conditions

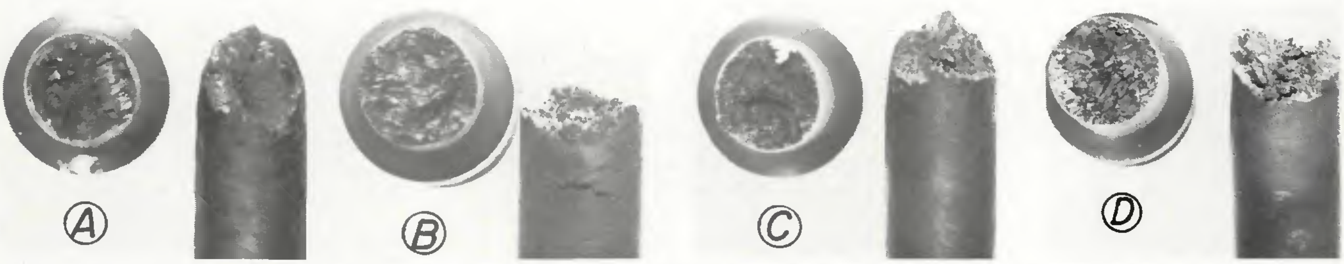

Fig. 10 — Fractographs of E308 weld metal specimens: A — specimen DT-25 (2 FN), 1100°F/40,000 psi, rupture time — 100 h; B — specimen AT-24 (6 FN), 1200°F/22,000 psi, rupture time — 2748 h; C — specimen BT-25 (10 FN), 1000°F/41,000 psi, rupture time — 2526 h; D — specimen CT-27 (16 FN), 1100°F/27,500 psi, rupture time — 2278 h

Metallography

Selected creep-rupture specimens were chosen for a metallographic examination. The main purpose of this examination was to determine whether and to what extent sigma phase had formed during the creep-rupture tests. A rather extensive metallographic study has already been performed on the four ferrite levels of E308 weld metal (Ref. 8). Therefore, the current study was aimed at material and/or test conditions not included in the previous work. All specimens examined were oriented transverse to the welding direction. The sections viewed were all parallel to the specimen length and in the vicinity of the fracture. The specimens were etched in NaCN for 5 seconds(s) to bring out the sigma phase, if present.

Fig. 11 — Creep-rupture specimen AT-25 (6 FN) after failure in 1769 h at 1000°F/42.5 ksi. NaCN treatment. A — X100; B — X1000 (reduced 35% on reproduction)

Figures 11 and 12 show the microstructure of two specimens after testing in the as-deposited condition. Specimen AT-25 (Fig. 11) was tested at 1000°F and 42.5 ksi and failed in 1769.2 h. Specimen AT-24 (Fig. 12) was tested at 1200°F and 22 ksi and failed at 2748.3 h. No sigma was found in the specimen (AT-25) tested

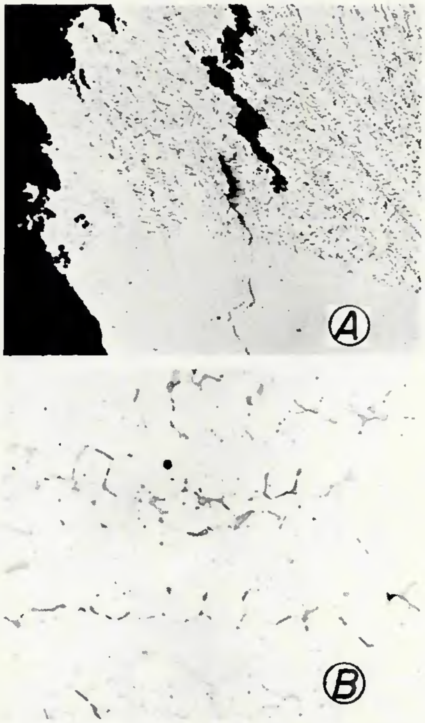

Fig. 12—Creep ruture specimen AT-24 (6 FN) after failure in 2748 h at 1200°F/22 ksi. NaCN treatment. A—×100; B—×1000 (reduced 37% on reproduction)

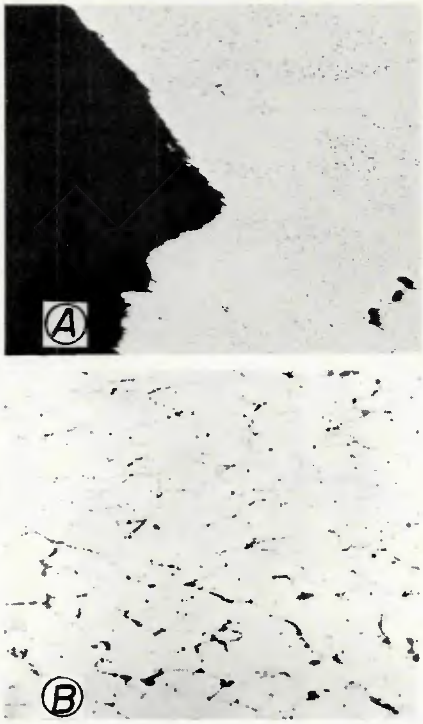

Fig. 13—Creep-rupture specimen BT-33 (10 FN) after failure in B0 h at 1100°F/40 ksi. NaCN treatment. A—×100; B—×1000 (reduced 38% on reproduction)

Fig. 14—Creep-rupture specimen CT-27 (16 FN) after failure in 2278 h at 1100°F/27.5 ksi. NaCN treatment—prior solution annealing at 1950°F for 2 h and water-quenched. A—×100; B—×1000 (reduced 38% on reproduction)

at 1000°F. The phase visible in Fig. 11 at both ×100 and ×1000 is believed to be delta ferrite. Sigma phase, appearing dark gray, was present in the specimen (AT-24) tested at 1200°F and shown in Fig. 12. The varying appearance of the phases in the microstructure seen in Fig. 12 at ×100 was noted in nearly all of the specimens examined. It is believed to be due to dendrite orientation rather than differences in ferrite level.

The microstructure in Fig. 13 is that of specimen BT-33 (10 FN) that had been prior exposed at 1100°F for 2500 h. In addition, it was in test at 1100°F and 40 ksi resulting in failure in 79.6 h. Sigma phase was found in this specimen, seen in the ×1000 photomicrograph as the darkly stained areas. Specimen CT-27 (16 FN), which failed in 2278 h after creep-rupture testing at 1100°F and 27.5 ksi, is seen in Fig. 14. This specimen was solution annealed at 1950°F for 2 h and water quenched prior to testing. The microstructures of the 6 FN and 16 FN weld metals following solution annealing showed no sigma phase. After creep exposure for 2278 h, the microstructure shown in Fig. 14 had developed. As shown here at ×1000, a significant amount of sigma phase had formed in this weld metal during the 2278 h at 1100°F.

Although photomicrographs are not shown, an examination was made of several other tested creep-rupture bars. Specimens AT-27 (6 FN) and CT-28 (16 FN) that had been solution annealed and tested at 1100°F failed in only 47 and 39 h, respectively, and no sigma phase formed. Specimen AT-28 (6 FN), also solution annealed before testing at 1100°F, was also examined metallographically. After creep exposure for 1004.3 h, however, no sigma was evident. The difference between this specimen and specimen CT-27, which showed the sigma phase, is the lower ferrite content (6 FN vs. 16 FN) and also the shorter creep exposure time (1004 vs. 2278 h).

Acknowledgments

The authors acknowledge the financial support of the Metal Properties Council and the technical guidance provided by the Task Force on the Properties of Weld Metal, Dr. W. D. Doty, Chairman, and the Subcommittee I, Engineering Properties of Boiler and Pressure Vessel Metals, Dr. M. Semchyshen, Chairman.

References

1. DeLong, W. T. 1974. Ferrite in austenitic stainless steel weld metal. *Welding Journal* 53 (7): 273-s to 286-s.

2. Lundin, C. D.; Chou, C.-P. D.; and Sullivan, C. J. 1980. Hot cracking resistance of austenitic stainless steel weld metals. *Welding Journal* 59 (8): 226-s to 232-s.

3. Gooch, T. G., and Honeycombe, J. 1980. Welding variables and microfissuring in austenitic stainless steel weld metal. *Ibid*: 233-s to 241-s.

4. Castro, R., and deCadenet, J. J. 1974. *Welding metallurgy of stainless and heat-resisting steels*. Translated by R. C. Jain, Babcock & Wilcox Co., Mt. Vernon, Indiana. Cambridge University Press.

5. Arata, Y.; Matsuda, F.; and Katayama, S. 1977. Solidification crack susceptibility in weld metals of fully austenitic stainless steels (report II). *Transactions of JWRI* 6 (1): 10S-116.

6. Astrom, H.; Loberg, B.; Bengtsson, B.; and Easterling, K. E. 1976. Hot cracking and micro-segregation in 18-10 stainless steel welds. *Metal Science* 10 (7): 225-234.

7. Thomas, R. D., Jr. 1978. Effect of delta ferrite content of E308-16 stainless steel weld metal—weld metal preparation. *Proceedings of the symposium on properties of steel weldments for elevated temperature pressure containment applications*, ed. G. V. Smith, pp. 1-16. Metal Properties Council publication MPC-9.

8. Edmonds, D. P.; Vandergriff, D. M.; and Gray, R. J. 1978. Effect of delta ferrite content of E308-16 stainless steel weld metal—supplemental studies. *Ibid*: 47-61.

9. Hauser, D., and Van Echo, J. A. 1978. Effect of delta ferrite content of E308-16 weld metal—mechanical property and metallographic studies. *Ibid*: 17-46

10. Smith, G. V. 1969 (Feb.). *An evaluation of the yield, tensile, creep, and rupture strengths of wrought 304, 316, 321, and 347 stainless steels at elevated temperatures*. ASTM data series DS 5S2 prepared for the Metal Properties Council. Philadelphia: American Society of Testing and Materials.

11. ASME. 1977 (July). *1977 code cases, nuclear components*, 1977 ed., case N-47-12 (1592-12), appendix 1-14, table 1-14.6A, p. 152. New York.

12. Voorhees, H. R. 1979 (Jan. 8). *Interim data summary*. Metal Properties Council contract no. 174-1, project D.