Electroslag Welding of High Nickel Alloys

Welded joints made with matching and special filler metals are compared with base metals as to mechanical properties and corrosion resistance

BY N. KENYON, G. A. REDFERN AND R. R. RICHARDSON

Introduction

Electroslag melting techniques are finding increasing application for the refining of stainless steels and nickel base alloys (Ref. 1). Electroslag methods have occasionally been used for welding such alloys but development in this area has been much slower. This is despite the fact that the electroslag welding process can often show great economic and technical advantages over other joining methods. The advantages are obvious when very thick sections are being welded but it has been suggested that cost savings begin to be realized when plate thickness exceeds ⅜ in. (Ref. 2). Moreover, edge preparation requirements are not too stringent, little excess filler metal is used, flux consumption is low, long lengths can be welded and deposition rates can exceed those of any other welding process. The major metallurgical advantage is the refining of the weld metal, and clean, dense deposits are a characteristic feature of the process.

The aim of the present work was to determine the feasibility of electroslag welding two high nickel alloys and to measure the properties of the weldments. The alloys chosen, Inconel* alloy 600 and Incoloy* alloy 800 are widely used in a variety of applications. Moreover it seems particularly appropriate to examine the electroslag welding of these now because of recent interest in using them in heavier sections such as for heavy wall pressure vessels.

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Experimental Procedure

Materials

Welds were made in 1 in. thick Inconel alloy 600 plates and in 1 in. and 4½ in. thick Incoloy alloy 800 plates. All plates were in the hot rolled and annealed condition. Both matching composition and commercial nickel base filler metals were used. Experimental quantities of the matching composition electrodes (⅛ in. diam) were drawn in the laboratory. The commercial wire (Inconel Filler Metal 82) was purchased at ⅛ in. diam. The compositions of base plates and filler metals are given in Table 1.

The flux used was 80%CaF_2 + 20%CaO. It was baked at 600 F for 2 h immediately before use.

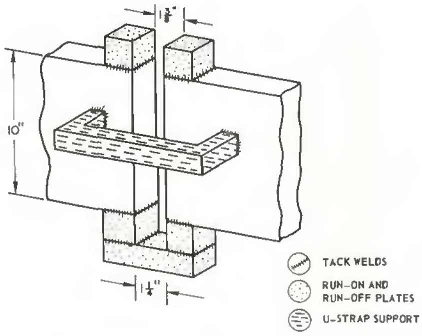


Fig. 1 — Plate setup

Welding Procedure

A general view of the plate setup arrangement is shown in Fig. 1. To start the weld, an arc was struck on a ball of steel wool embedded in flux at the bottom of the weld gap. Once

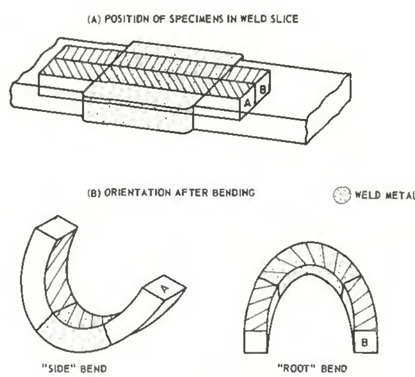
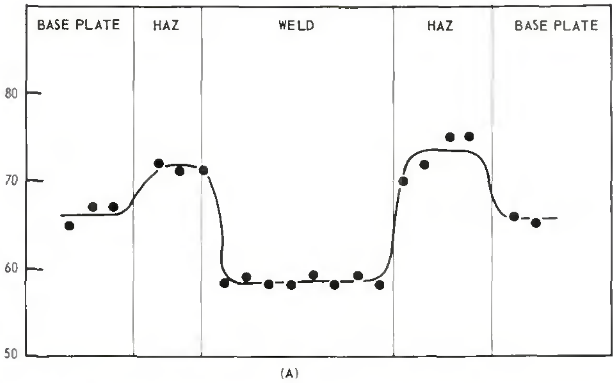


Fig. 2 — Manner of sectioning for bend specimens

Fig. 3 — Longitudinal section (top to bottom) through a vertical electroslag weld made in 4½ in. Incoloy alloy 800 with Inconel filler metal 82



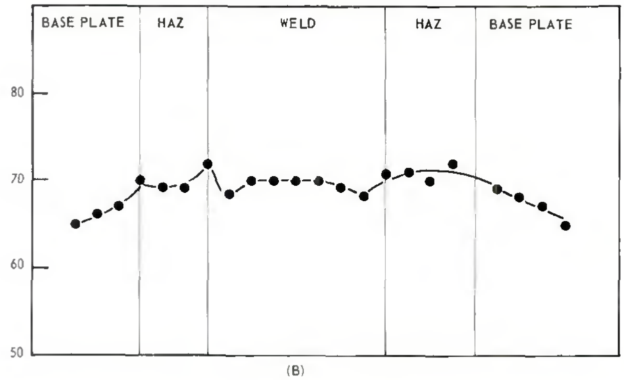


Fig. 4 — Rockwell 'B' hardness traverse across (a) weld made with matching composition filler wire, (b) weld made with Inconel filler metal 82

Table 1 — Compositions of Base Metals and Filler Metals

Alloy	Ni	Fe	Cr	C	Mn	Si	S	Al	Ti
				Chemical composition — weight %					
Base metals									
Incoloy 800, 1 in.	33.2	44.0	20.0	0.04	0.78	0.24	.001	0.44	0.44
Incoloy 800, 4½ in.	32.3	45.1	20.3	0.07	0.90	0.40	—	0.50	0.40
Inconel 600, 1 in.	76.1	7.7	15.5	0.09	0.18	0.22	.002	ND[b]	ND
Filler metals									
Incoloy 800 (matching wire)	31.4	45.0	21.1	0.08	0.84	0.32	—	0.40	0.39
Inconel 600 (matching wire)	76.3	7.5	15.5	0.07	0.20	0.24	.001	ND	ND
Inconel 82[a]	73.3	0.2	20.2	0.02	3.09	0.20	.002	0.03	0.33

(a) Composition includes 2.55 Cb
(b) ND = not determined.

welding was under way, more flux was added to maintain a slag depth of ½ to ¾ in. Slag depth and weld penetration were measured continually by probing with lengths of appropriate filler metal wire. Direct current reverse polarity (DCRP) was used for all the welds. Though the optimum current mode is still a matter of some controversy, DCRP has been found to give the most satisfactory results in our work. The starting conditions were 40 V, 200 A; these were changed to 30 V and 600 A once welding was under way. The vertical rise rate was ⅜ ipm. The volts, amps and travel speed were held constant once a steady wire melt rate was established and the temperature of the copper shoes was also controlled.

For the 4½ in. thick welds the wire feed mechanism was oscillated, but oscillation was not necessary when the 1 in. plates were welded. Full details of the welding procedures are given in Table 2.

Inspection and Testing of Weldments

All the welds were x-rayed. Slices cut from them were also polished and etched, and examined macroscopically for defects. Further tests included chemical analyses of the deposits, hardness traverses, tensile tests from room temperature to 1600 F, bend tests in the as-welded and heat treated conditions, impact toughness tests, stress rupture tests, and tests to determine corrosion and stress corrosion resistance.

The way the bend specimens were cut from the welds is shown in Fig. 2.

Results and Discussion

Welding

No difficulties were encountered in making the welds. Good electroslag welding conditions were easily established and maintained during the welding operation. Radiographically sound welds were made and examination of polished sections revealed no defects. The appearance of a longitudinal section (top to bottom) of a portion of a 4½ in. thick weld is shown in Fig. 3. It is particularly significant that sound joints were produced with filler metal having the same composition as the base metal, because it is known that these are not ideal for welding with other processes (Ref. 3). It was because of this that special filler metal wires, such as the Inconel Filler Metal 82 which was also used in this work, were developed (Ref. 4).

Table 2 — Details of Welding Procedures

1 in. thick welds	
Starting conditions	
50 g $80CaF_2$-$20CaO$ flux and steel wool	
Current	: 200A
Voltage	: 40V
Welding conditions	
Current	: 500A
Voltage	: 30V
Wire Feed	: Approx. 100 ipm (⅛ diam wire)
Vertical Rise	: ⅜ ipm
4½ in. thick welds	
Starting conditions	
250 g $80CaF_2$-$20CaO$ flux and steel wool	
Current	: 200A
Voltage	: 60 V
Welding conditions	
Current	: 600A
Voltage	: 35V
Oscillation time	: 3 s
Oscillation dist.	: 3½ in.
Wire Feed	: 180 ipm (⅛ in. diam)
Vertical Rise	: ⅜ ipm

Chemical Analysis of Weldments

The compositions of the deposits of 1 in. thick welds made in alloy 800 and alloy 600 base plate with both match-

Table 3 — Weld Metal Compositions, wt % (Welds Made in 1 in. Thick Plates)

Weld	Location	Ni	Fe	Cr	C	Mn	Si	S	P	Al	Ti	O	N	Other
Incoloy 800 with	Start (Bottom)	31.7	ND	21.0	.08	.81	.25	.001	.021	.36	.41	.0175	.0290	
matching wire	End (Top)	31.5	ND	20.8	.08	.78	.25	.001	.020	.35	.40	.0135	.0250	
Incoloy 800 with	Start (Bottom)	ND	10.9	20.0	.02	2.42	.21	.001	.007	.12	.26	.0031	.0360	1.87Cb
Inconel filler	Middle	ND	7.6	20.2	.02	2.60	.21	.002	.007	.10	.29	.0035	.0390	2.03Cb
metal 82	End (Top)	ND	8.9	20.1	.02	2.65	.20	.002	.006	.08	.29	.0043	.0415	2.08Cb
Inconel 600 with	Start (Bottom)	ND	8.0	15.2	.06	.18	.21	.002	.011	ND	ND	.0078	.0165	
matching wire	End (Top)	ND	7.9	15.6	.07	.19	.23	.002	.009	ND	ND	.0052	.0135	
Inconel 600 with	Start (Bottom)	ND	1.2	19.7	.03	2.75	.19	.001	ND	.06	.20	.0040	.0360	2.13Cb
Inconel filler	Middle	ND	2.8	18.5	.05	2.22	.19	.001	ND	.07	.26	.0035	.0310	1.68Cb
metal 82	End (Top)	ND	2.4	18.6	.04	2.30	.19	.003	ND	.06	.26	.0040	.0425	2.74Cb

ND = not determined

Table 4 — Impact Toughness (CVN) of the Welds

Weld	Specimen location	Test temp. F	CVN. ft-lb
1 in. Incoloy 800 with matching wire	Weld metal	R.T.	140
	Weld metal	R.T.	132
	Heat-affected zone	R.T.	176
	Heat-affected zone	R.T.	170
1 in. Inconel 600 with matching wire	Weld metal	R.T.	240
	Weld metal	R.T.	240
	Heat-affected zone	R.T.	194
	Heat-affected zone	R.T.	177
4½ in. Incoloy 800 with matching wire	Weld metal	R.T.	225
	Heat-affected zone	R.T.	225
	Heat-affected zone	−320	219
4½ in. Incoloy 800 with Inconel filler metal 82	Weld metal	−320	183
	Heat-affected zone	−320	184

R.T. = room temperature

Table 5 — Tensile Properties of Annealed Base Metals

Plate	Test Temp., F	0.2% Y.S., ksi	U.T.S., ksi	Elong., %	R.A., %
1 in. Inconel alloy 600	R.T.	40.5	102.8	39	61
	1200	28.2	63.1	56	55
	1400	25.8	34.8	89	64
	1600	14.8	21.7	96	73
1 in. Incoloy alloy 800	R.T.	43.0	84.8	43.0	67.0
	1200	30.6	54.0	50.0	63.0
	1400	25.5	35.7	74.0	69.0
	1600	16.0	21.4	82.0	85.0
4½ in. Incoloy alloy 800	R.T.	42.7	86.8	44	—
	1200	29.0	54.0	56	—
	1400	22.6	32.1	84	—

R.T. = room temperature

ing composition and Inconel Filler Metal 82 are shown in Table 3. The weld compositions were quite uniform from top to bottom and reactive elements such as aluminum and titanium were transferred. Where the base metal and filler metal compositions were very different, examination of the deposit chemistry revealed that dilution rates in these 1 in. thick welds were of the order of 25%.

Hardness Traverses

Hardness traverses were taken across both 4½ in. thick alloy 800 electroslag welds. The joint made with matching filler was noticeably softer in the weld zone (Rb 58-59) than the base metal which had a hardness of Rb 65. Highest hardness recorded in the heat-affected zone was about Rb 75. The weld zone in the Inconel Filler Metal 82 joint was slightly harder (Rb 69-70) than the base metal (Rb 65). Heat-affected zone peak hardness was Rb 71-72. The hardnesses of all the zones are shown in Fig. 4.

Bend Tests

Specimens for bend tests that were taken from the 1 in. thick welds were ½ in. square in cross section and were bent through 160 deg over a 1½ in. diam former. Specimens were tested as-welded and after a heat treatment of 1300 F/20 h/AC. All the specimens were crack-free after testing with the exception of one heat treated specimen from the weld made in alloy 600 plate with matching composition filler metal. This sample had one small crack, less than 1/32 in. long.

Bend specimens from the 4½ in. thick welds were tested in the as-welded condition and were crack-free after bending through 160 deg. Again, both "side" and "face" bends were made. The appearance of some of the bend specimens is shown in Fig. 5.

Impact Toughness Tests

Charpy impact toughness tests were run on samples from 1 in. thick welds made with matching composition electrodes (alloy 800 and alloy 600) and also on samples from both 4½ in. thick welds. Tests were made at room temperature and at −320 F. In all cases, the toughness was very high with all the values easily exceeding 100 ft-lb (Table 4).

Tensile Tests

The tensile strengths of the four welds made in 1 in. thick plate are

Table 6 — Tensile Properties of 1 in. Thick Welds (a)

Weld	Test Temp., F	0.2% Y.S., ksi	U.T.S., ksi	Elong., %	R.A., %
Incoloy 800 with matching wire	R.T.	22.8	64.5	41.0	65.0
	1200	14.3	45.9	39.0	65.0
	1400	13.6	33.6	50.0	42.0
	1600	12.4	17.7	61.0	71.0
Incoloy 800 with Inconel filler metal 82	R.T.	31.5	82.9	56.0	55.0
	R.T (b)	32.3	81.8	47.0	55.0
	1200	19.6	48.7	44.0	46.0
	1400	19.0	39.9	49.0	64.5
	1600	16.1	22.1	58.0	72.0
Inconel 600 with matching wire	R.T.	25.6	70.4	54.0	72.0
	1200	17.3	44.9	32.0	41.0
	1400	19.4	37.7	33.0	44.5
	1600	14.6	18.8	49.0	73.0
Inconel 600 with Inconel filler metal 82	R.T.	30.9	82.8	53.0	54.5
	R.T. (b)	33.7	85.1	30.0	39.5
	1200	19.5	53.7	43.0	40.0
	1400	19.1	40.5	36.0	65.0
	1600	17.7	24.6	57.0	85.5

(a) Specimen gage length consisted entirely of weld metal. In other tests, center of gage length was positioned on the fusion line. Very similar tensile properties were measured with failure occurring in either weld or heat-affected zone.
(b) These specimens were tested after a post-weld treatment at 1300 F for 20 hours, air cool. All other specimens were tested in the as-welded condition.
R.T. = room temperature

Table 7 — Tensile Properties of 4½ in. Thick Welds

Weld	Test temp., F	0.2% Y.S. ksi	U.T.S., ksi	Elong., %	R.A., %
Incoloy 800, with matching wire	R.T.	22.3	54.4	52	63
	1200	11.6	39.0	44	68
	1400	11.5	28.0	48	73
Incoloy 800, with Inconel filler metal 82	R.T.	26.7	73.0	60	66
	1200	15.5	47.5	54	55
	1400	15.8	34.9	59	76

R.T. = room temperature

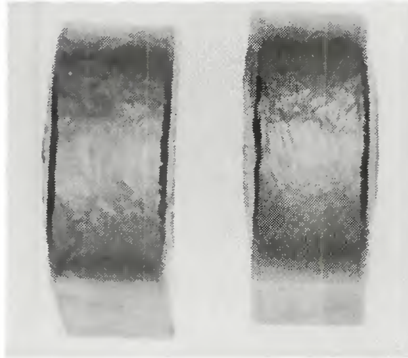


Fig. 5 — U-bend specimens from the welds. Note coarse grained weld zone

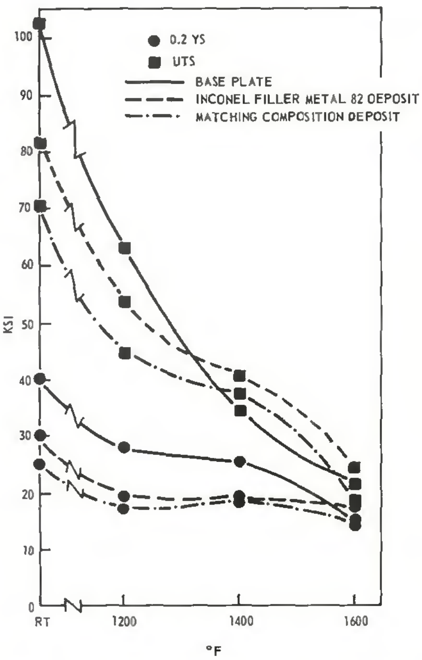


Fig. 6 — Tensile properties of electroslag — weld deposits in Inconel alloy 600 and of annealed alloy 600

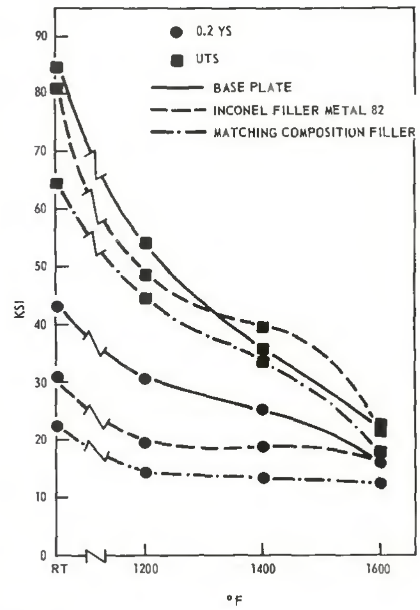


Fig. 7 — Tensile properties of electroslag — weld deposits in Incoloy alloy 800 and of annealed alloy 800

shown in Figs. 6 and 7, and are compared with values for the base metal from room temperature to 1600 F. At the lower temperatures the base plates are noticeably stronger than the welds, but at higher temperatures, welds and plates have similar tensile strengths. In all cases, the welds made with Inconel Filler Metal 82 were stronger than those made with matching composition filler wires. This same relationship was seen in tests on the welds made in 4½ in. thick Incoloy alloy 800. From these tests, it was also noticeable that the strengths of the 4½ in. thick joints were lower than those in the 1 in. thick welds. Details of the tests are given in Tables 5 to 7.

Stress Rupture Testing

Stress rupture tests were made on the 4½ in. thick welds at 1000, 1200 and 1400 F, as shown in Table 8. To some degree the stress rupture strengths followed the same pattern as the tensile strengths. The weld made with matching composition filler metal was weaker than the base metal at 1200 F, but at 1400 F the weld strength approached that of the plate (Fig. 8). The strength of the Inconel Filler Metal 82 weld, even at 1200 F, was close to that of the plate and at 1400 F it exceeded it (Fig. 9).

The fact that joint efficiency increased with test temperature suggests that the very coarse grain size of the weld deposits played an important role in determining weld strength. The coarse grain size of the deposits also manifested itself as an "orange peel" surface in tensile and bend specimens (Fig. 5).

Ductility as measured by percent elongation and reduction of area was unusually high (Ref. 5). In the 1200 to 1400 F range, rupture elongations of 50 to 60% were measured (Table 5).

Corrosion and Stress Corrosion Tests

Samples from the welds made in 4½ in. thick alloy 800 were exposed in Huey and ferric sulfate/sulfuric acid tests to determine their corrosion resistance. Intergranular attack occurred in the heat-affected zone farthest from the weld, with lesser attack in the coarse grained heat-affected zone. The weld metal made with the matching composition electrode showed very little corrosion and, in

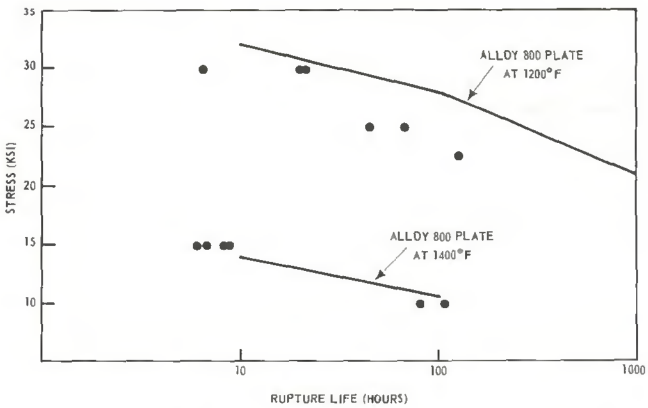


Fig. 8 — The stress rupture strengths of welds made in 4½ in. thick Incoloy alloy 800 plate with matching composition filler wire. The dots are the results of tests on welds at 1200 F and 1400 F. The solid lines represent base plate values included for comparison

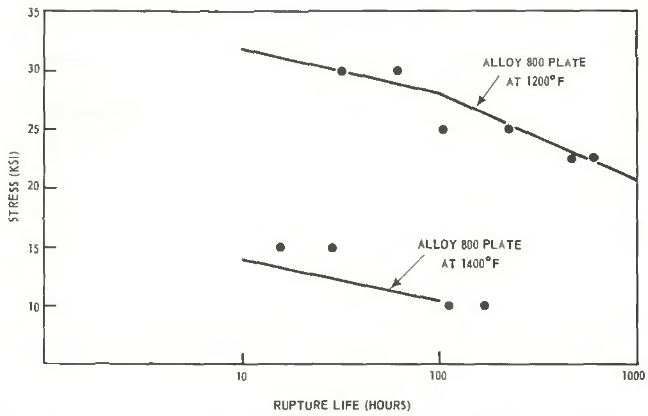


Fig. 9 — The stress rupture strengths of welds made in 4½ in. thick Incoloy alloy 800 plate with Inconel filler metal 82. The dots (•) are the results of tests on welds at 1200 F and 1400 F. The solid lines represent base plate values included for comparison

both tests, the Inconel Filler Metal 82 showed no attack. In this regard, there was a difference in corrosion response between the stabilized Inconel Filler Metal 82 and the matching composition filler wire.

The intergranular corrosion in the heat-affected zone was probably exaggerated by the relatively small size of the plates (approximately 12 in. long × 4 in. wide). This may have resulted in an inadequate heat sink so that regions adjacent to the weld were heated to intermediate temperatures for relatively long times. It is expected that the susceptibility to corrosion would be decreased if the cooling rates were faster.

In stress corrosion tests, U-bends from both alloy 800 welds were exposed over 3%NaCl at 90 C for 90 days. No cracking occurred in these specimens, although a control sample of 304 stainless steel failed after 11 days.

Table 8 — Stress Rupture Properties of 4½ in. Thick Electroslag Welds in Incoloy Alloy 800

Weld	Test temp., F	Stress, ksi	Life, h	Elong. 1 in., %	R.A., %
Incoloy 800 with matching wire	1000	35	291	32	44
	1000	40	97	40	52
	1000	45	52	45	55
	1200	30	21	38	44
	1200	30	21	29	32
	1200	25	45	28	22
	1200	25	68	31	46
	1200	22.5	127	28	48
	1400	15	7	49	72
	1400	15	8	88	85
	1400	15	9	62	68
	1400	10	81	53	82
	1400	10	108	47	57
Incoloy 800 with Inconel filler metal 82	1000	40	1000		
	1000	45	989		
	1000	50	175		
	1200	30	61	52	66
	1200	30	33	54	64
	1200	25	105	70	66
	1200	25	228	54	60
	1200	22.5	609	43	64
	1200	22.5	479	41	47
	1400	15	16	70	87
	1400	15	28	60	77
	1400	10	109	64	83
	1400	10	168	77	79

Conclusions

1. Sound electroslag welds were made without difficulty in 1 in. alloy 600, 1 in. alloy 800 and 4½ in. alloy 800 with both matching composition electrodes and Inconel Filler Metal 82. It is significant that this was possible for matching filler metal because these are often not suitable for use with other welding processes.

2. The electroslag weld deposits had quite uniform analyses from top to bottom and very low sulfur levels.

3. The strengths of weld deposits were lower than those of annealed base metal at room temperature but came close to or exceeded them at elevated temperature. One in. thick welds were stronger than 4½ in. thick welds.

4. The welds had excellent room temperature ductility in both the as-welded condition and after a treatment of 1300 F/20 h/AC.

5. Stress rupture ductilities in the 1000 to 1400 F range were unusually high (approximately 50% elongation).

6. In the as-welded condition parts of the heat-affected zone in the 4½ in. alloy 800 welds were susceptible to intergranular attack. This condition was probably exaggerated by the relatively small size of the plates which resulted in an inadequate heat sink. Little or no attack occurred in the weld metals.

References

1. Elliot, C. F., Evans, D. C., Kennedy, R. L. and Manning, C. R., "Electroslag Remelting of Superalloys — Production Melting Experience," *Metals Engineering Quarterly*, Vol. 10, May 1970, pp 46-50.

2. Burden, C. A., Garstone, J. and Lucey, J. A., "Electroslag Welding of Relatively Thin Plate," *British Welding Journal*, Vol. 11, 1964, pp 148-155.

3. Lingenfelter, A. C., "Varestraint Testing of Nickel Alloys," *Welding Journal*, Vol. 51 (9), Sept. 1972, Res. Suppl., pp 430-s to 436-s.

4. Witherell, C. E., "Welding of Nickel-Chromium-Iron Alloy for Nuclear Power Stations," *Welding Journal*, Vol. 39 (11), Nov. 1960, Res. Suppl., pp 473-s to 478-s.

5. Kenyon, N., "Some Observations on the Stress Rupture Ductility of Welds," *Welding Journal*, Vol. 50 (6), June 1971, Res. Suppl., pp 261-s to 266-s.

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