WELDING RESEARCH

SUPPLEMENT TO THE WELDING JOURNAL, DECEMBER 1977
Sponsored by the American Welding Society and the Welding Research Council

Effects of Process Parameters on Thermal Distribution During Electroslag Welding

Data that should prove useful to fabricators and code bodies in the design, qualification and testing of electroslag weldments are derived from tests on 1 and 4 in. thick ASTM A588 Grade A steel plates

BY P. J. KONKOL

ABSTRACT. A series of eight weldments were made in 24 in. (0.61 m) wide ASTM A588 Grade A steel plates by using the consumable-guide electroslag welding process. The variables studied were shoe type (water-cooled copper shoe vs. solid copper), guide-tube type (single oscillating vs. two fixed), plate thickness, and weldment length. Temperatures were monitored during and after welding by means of thermocouples imbedded at various distances from the groove face.

Peak temperatures were highest at the top (finish) of the weldments. In weldments cooled with water-cooled shoes, peak temperatures at the midheight were often lower than those at the bottom (start); however, in weldments cooled with solid shoes, peak temperatures increased with increasing distance along the joint. Higher peak temperatures were generally produced in 4 in. (102 mm) thick weldments made with two fixed guide tubes than in weldments made with a single oscillating guide tube at similar energy inputs. The 1 in. (25.4 mm) thick weldments exhibited peak temperatures in the heat-affected zones that were significantly lower than those of the 4 in. thick weldments. Peak temperatures were similar for weldment lengths of 18 and 42 in. (0.46 and 1.07 m) made with a single guide tube and water-cooled shoes.

The cooling time in the transformation-temperature range of 800 to 500 C (1472 to 932 F) was generally shorter at the midheight than at the top or bottom of the joint, was shorter for water-cooled than for solid shoes, and was shorter for single oscillating than for two fixed guide tubes.

Introduction

The thermal distribution during electroslag welding differs considerably from that accompanying other structural welding processes. There are three reasons for this:

1. The heat input is much higher.
2. The heat is generated across the full weldment thickness.
3. The copper shoes or dams (either water-cooled or solid) used to contain the molten metal also extract heat in a controlled manner.

In any process, the cooling rate after welding controls the weld integrity and influences the mechanical properties of the weld metal and the weld-

---

P. J. KONKOL is with the Research Laboratory, United States Steel Corporation, Monroeville, Pennsylvania.

It is understood that the material in this paper is intended for general information only and should not be used in relation to any specific application without independent examination and verification of its applicability and suitability by professionally qualified personnel. Those making use thereof or relying thereon assume all risk and liability arising from such use or reliance.

The opinions and conclusions expressed or implied in this paper are those of the research agency. They are not necessarily those of the Transportation Research Board, the National Academy of Sciences, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, or of the individual states participating in the National Cooperative Highway Research Program.

heat-affected zone. For this reason a study was made of the thermal distribution during electroslag welding, and of the relation between the thermal distribution and the properties and characteristics of the welds. The variables studied included plate thickness, joint length, guide-tube type, and shoe type.

This work was done as part of NCHRP Project 10-10, "Acceptance Criteria for Electroslag Weldments in Bridges," sponsored by the National Cooperative Highway Research Program.[1]

The data generated in this study should be useful to fabricators and code bodies in the design, qualification, and testing of electroslag weldments. The results of this study are described herein.

Materials and Experimental Work

Materials

The 1 and 4 in. (25 and 102 mm) thick plates used in this study were obtained from production-size heats of ASTM A588 Grade A steel. The electrode was 3/32 in. (2.4 mm) diameter solid bare wire conforming to AWS Classification E70S-3. The guide tubes were ⅝ in. (16 mm) diameter flux-coated consumable guide tubes. A commercial flux was used during startup and welding.

Table 1—Description of Weldments in Thermal-Distribution Study

Weldment no.	Plate thickness, in.[a]	Weld length, in.[a]	Guide-tube type	Shoe type
6	1	42	One fixed	Water-cooled
6A	1	18	One fixed	Water-cooled
8	4	42	One osc.	Water-cooled
8A	4	18	One osc.	Water-cooled
9	4	42	Two fixed	Water-cooled
14	1	24	One fixed	Solid
15	4	24	One osc.	Solid
16	4	24	Two fixed	Solid

[a] 1 inch = 25.4 mm.

Experimental Work

Eight weldments were fabricated in order to study the effects of several process parameters on the thermal distribution and subsequent mechanical properties of electroslag weldments. The weldments contained embedded thermocouples at various locations in the base metal so that the thermal histories of the weldments could be measured and compared.

The eight weldments are described in Table 1. They were selected to show the effects of plate thickness (weldments 6, 6A, and 14 vs. 8, 8A, 9, 15, and 16), joint length (weldments 6 vs. 6A and 8 vs. 8A), guide-tube type—single oscillating versus two fixed—(weldments 8 vs. 9 and 15 vs. 16), and shoe type (weldments 6 vs. 14, 8 vs. 15, and 9 vs. 16).

The plates were oxygen-cut to 24 in. (0.61 m) wide by the lengths shown in Table 1 and shot-blasted on one face to enable photographing of the heat-tint patterns after welding. For one plate of each weldment, holes for thermocouples were drilled to the plate midthickness at ½, 1, 1½, 2, 4, 8, 12, 18, and 24 in. (13, 25, 38, 51, 102, 203, 305, 457, and 610 mm) from the groove face of the joint. The thermocouple holes at ½ and 1 in. (12.7 and 25.4 mm) from the groove face were drilled at an angle so that the copper shoes would not interfere with the thermocouples, as shown in a corner detail example in Fig. 1. The holes were drilled at the

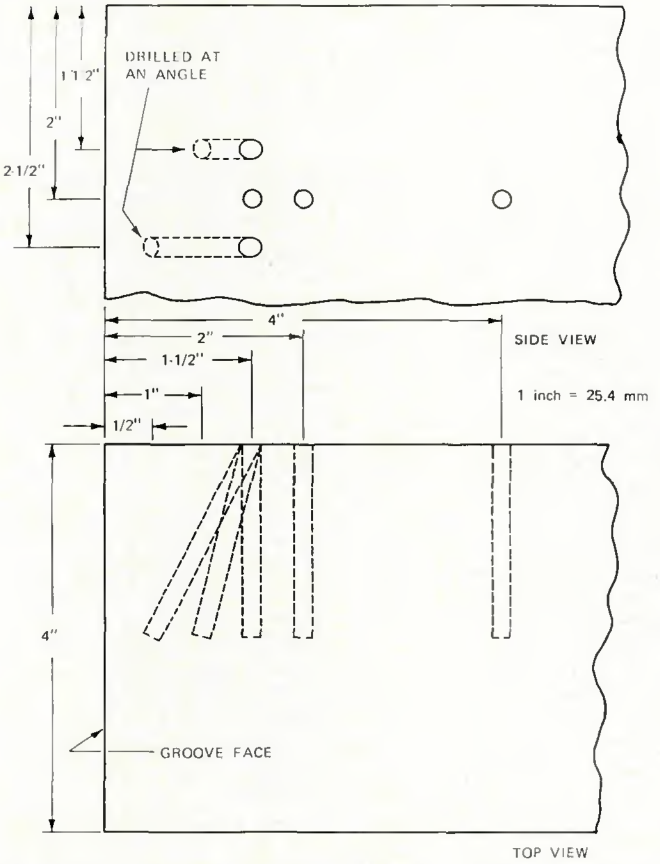


Fig. 1—Position and orientation of thermocouple holes for the top corner location in the 4 in. (102 mm) thick plate

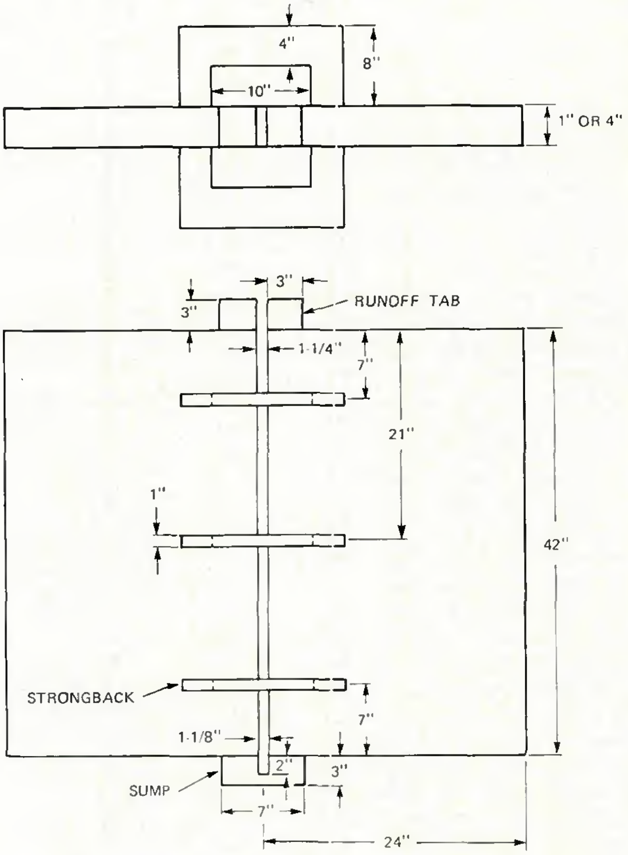


Fig. 2—Fixturing for 42 in. (1.07 m) long weldments

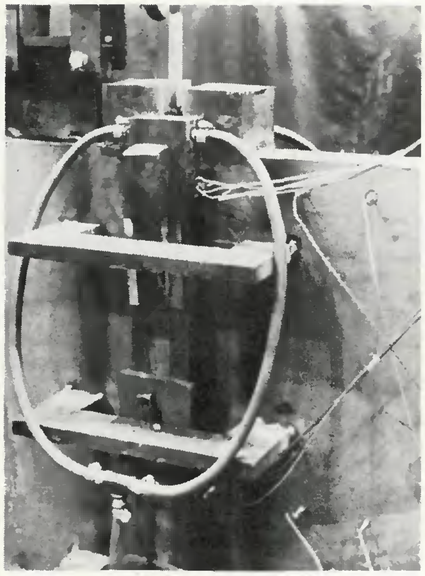


Fig. 3—Completed 4 in. (102 mm) thick electroslag weldment with thermocouples attached

Table 2—Welding Conditions

Weldment no.	Electrode feed speed, ipm[a]	Current per electrode, A	Voltage, V	Fill rate, ipm[a]	Energy input, kJ/in.[a]	Flux consumed, grams
6	140	500	37	0.799	1390	280
6A	141	500	37	0.846	1310	180
8	240	650	50	0.409	4760	800
8A	244	650	50	0.396	4930	400
9	135	450	44	0.505	4700	600
14	140	500	37	0.916	1210	80
15	244	650	50	0.388	5025	600
16	135	450	44	0.520	4560	450

[a] 1 ipm = 0.423 mm/s; 1 kJ/inch = 0.0394 kJ/mm

following locations relative to the length of the joint: 2 in. (51 mm) from the bottom (start) end of the joint, at midheight, and 2 in. (51 mm) from the top (finish) end of the joint. Chromel-alumel thermocouples were capacitor-discharge-welded to the plate at the bottom of the holes and connected to a high-speed recorder.

The joint geometry was a square butt with a root opening of 1⅛ in. (29 mm) at the bottom and 1¼ in. (32 mm) at the top. Strongbacks were used to hold the plates and copper shoes in position. The joint geometry and location of strongbacks for a 42 in. (1.1 m) long weldment are shown in Fig. 2. The middle pair of strongbacks was eliminated for the 24 in. (0.61 m) long weldments. For the 18 in. (0.46 m) long weldments, two pairs of strongbacks were positioned 4 in. (102 mm) from the top and bottom of the joint.

No preheat was used, and all plates were at room temperature at the time welding was started. When water-cooled copper shoes were used, the water was not turned on until welding commenced; the outlet water temperature was monitored and the flow rate adjusted so that the outlet temperature did not exceed 65 C (150 F). Temperatures during and after welding were recorded at various time intervals that were as short as 20 seconds (s) when temperatures were changing rapidly. A photograph of a weldment with thermocouples in place is shown in Fig. 3. The welding conditions used during fabrication are shown in Table 2.

Results and Discussion

Temperature readings of the embedded thermocouples in the eight weldments were recorded at various time intervals. The maximum temperature attained by each thermocouple, the cooling rate of the weldment at 540 C (1000 F) for those thermocouples that exceeded the ferrite-to-austenite transformation temperature (about 705 C or 1300 F), and the time to cool through the transformation-temperature range (approximately 800 to 500 C or 1472 to 932 F) were also recorded.

A typical thermal history of a 4 in.

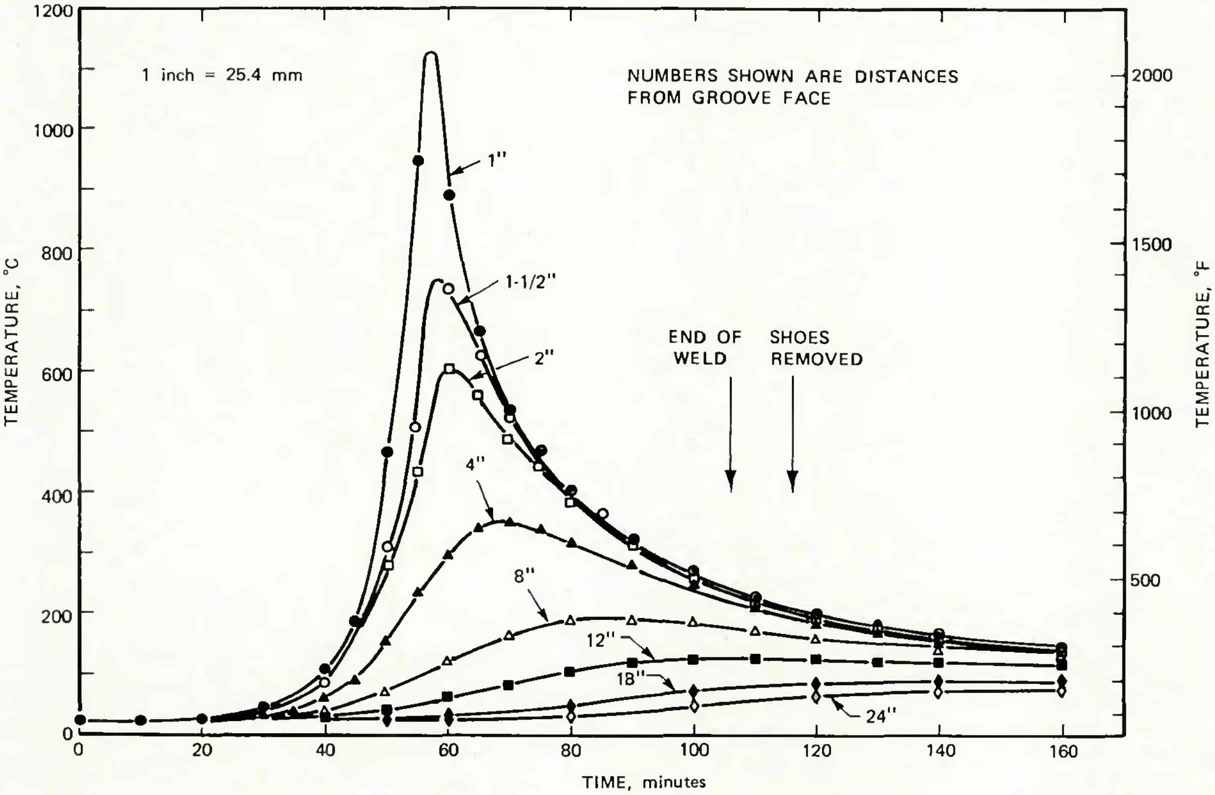


Fig. 4—Thermal history at midheight of 4 in. (102 mm) thick electroslag weldment 8

Table 3—Peak Temperatures Observed in Various Weldments, °C[a]

Weldment code	Thickness, in.[a]	Length, in.[a]	Shoe Type[b]	Guide Tube[c]	T.C. Location	Distance From Groove Face, in.[a] ½	1	1½	2	4	8	12	18	24
6	1	42	W	ST	Top	—	535	395	320	189	85	$>52^{+}$	$>33^{+}$	>27[d]
					Mid	—	324	251	207	118	58	40	$>30^{+}$	>29[d]
					Bot	—	576	400	318	175	76	45	30	>27[d]
6A	1	18	W	ST	Top	719	467	458	345	188	76	$>46^{+}$	$>24^{+}$	>18[d]
					Mid	413	369	365	277	150	58	48	$>27^{+}$	>23[d]
					Bot	536	444	394	307	168	67	40	$>28^{+}$	>24[d]
8	4	42	W	OT	Top	>1766	>1766	1160	857	487	238	151	104	88
					Mid	>1766	1132	755	606	350	192	129	96	84
					Bot	>1766	1328	870	624	339	173	111	78	73
8A	4	18	W	OT	Top	>1766	1016	759	624	369	195	130	90	83
					Mid	>1766	927	670	542	326	170	138	96	90
					Bot	>1766	910	—	567	334	180	124	96	88
9	4	42	W	2T	Top	>1766	>1766	>1766	1044	526	266	172	129	123
					Mid	>1766	>1766	>1766	874	438	226	154	124	118
					Bot	>1766	>1766	1054	696	397	199	129	105	101
14	1	24	S	ST	Top	646	623	544	394	232	109	70	44	38
					Mid	640	554	494	387	216	—	78	45	40
					Bot	—	493	445	351	204	106	68	44	39
15	4	24	S	OT	Top	>1766	1142	838	722	441	239	159	111	102
					Mid	>1766	1060	793	579	430	216	149	116	106
					Bot	>1766	1110	714	591	373	205	140	110	101
16	4	24	S	2T	Top	>1766	>1766	1173	854	438	232	151	106	95
					Mid	>1766	1185	861	646	371	194	152	110	100
					Bot	>1766	1117	700	600	353	190	133	105	93

[a] °F = (9/5°C) + 32; 1 in. = 25.4 mm.

[b] W—water cooled; S—solid copper.

[c] ST—stationary tube; OT—oscillating tube; 2T—two stationary tubes.

[d] Peak temperature not reached at end of recording.

(102 mm) thick weldment (No. 8) is shown in Fig. 4. The general shape of this pattern is similar to that in a weldment made by the conventional arc-welding process except that the time and distance parameters are greater. It should be noted that the location 12 in. (305 mm) from the joint face was heated only a slight amount before the weld metal and the heat-affected zone had cooled to temperatures below which most metallurgical reactions would occur (800 to 500 C or 1472 to 932 F). Thus the thermal distributions in the 24 in. (610 mm) wide plates used in this program were similar to those that would be expected in wider plates. Other work has shown that the use of plates as narrow as 12 in. (305 mm) should be adequate for welding-procedure qualification.

Table 3 lists the peak temperature observed at each thermocouple location in each of the weldments. In many of the locations close to the groove face in the 4 in. (102 mm) thick weldments, the peak temperatures exceeded the melting point of the steel, and the thermal histories were lost because the recorder did not record temperature after the thermocouple exceeded 1766 C (3211 F).

The reproducibility of the thermal data in Table 3 may be questionable because, as can be seen in the Fig. 5 photographs of the heat-tint patterns on the weld surfaces, the weld-heat-affected regions are often nonsymmetrical. This is probably caused by variations in shoe contact with the plate surfaces and by variations in wire cast or in alignment of the consumable guide tubes. This variability must be considered when comparisons of thermal distributions among the weldments are made.

Effect of Plate Thickness

As shown in Table 3, the peak temperature observed in 1 in. (25.4 mm) thick weldments 6, 6A, and 14 at any distance from the groove face was much lower than that observed in the 4 in. (102 mm) thick weldments; this indicated a much narrower heat-affected zone in the 1 in. (25.4 mm) thick weldments.

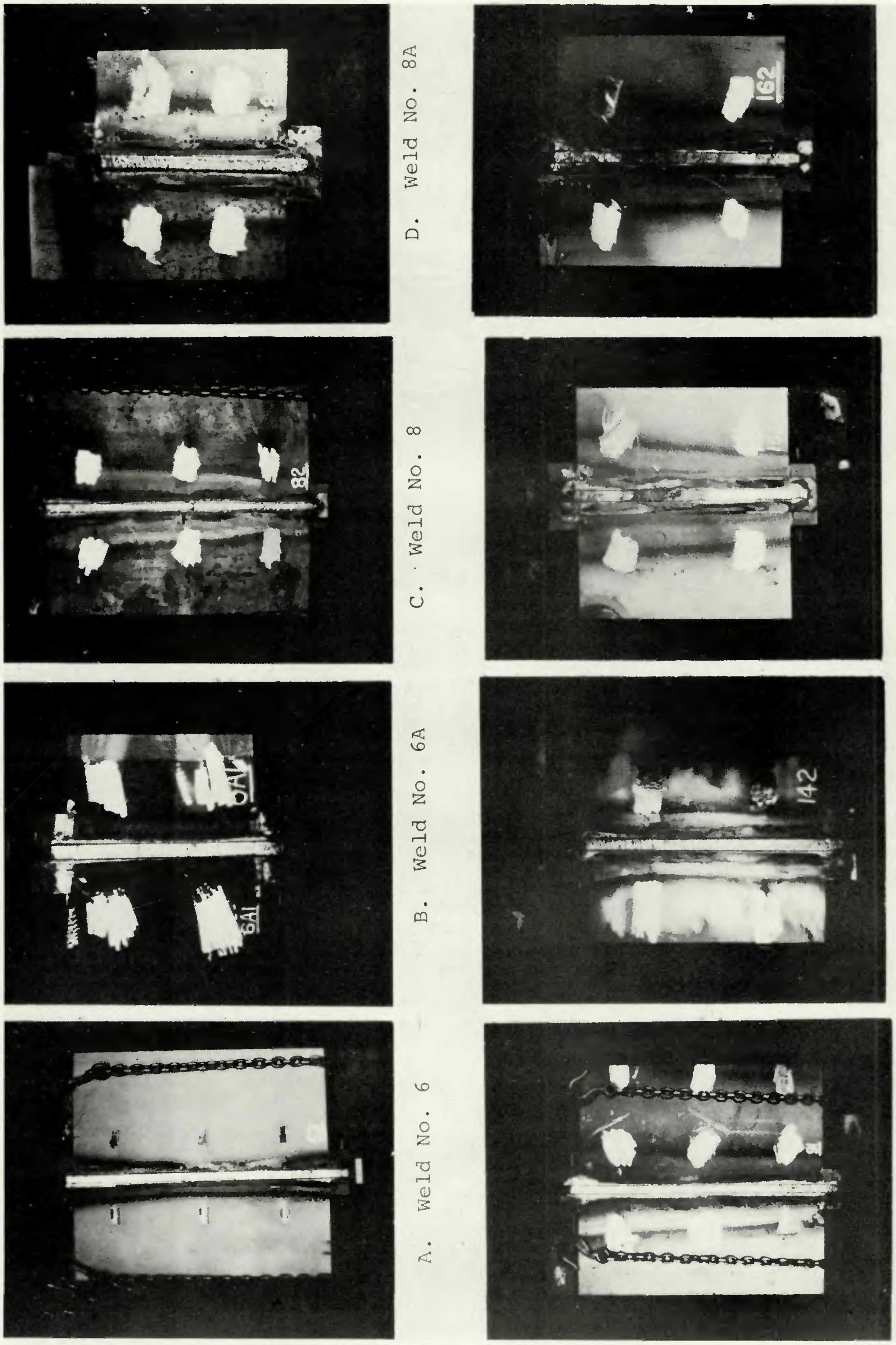
The average energy input of the 1 in. (25.4 mm) thick weldments with consumable guide tubes was about one-fourth that of the corresponding 4 in. (102 mm) thick weldments. Therefore, the energy input per inch of plate thickness was similar for both thicknesses of weldments. Thus, in a thinner weldment, proportionately more of the welding energy was extracted by means of the copper shoes. Other work has shown that in 2 and 4 in. (51 and 102 mm) thick electroslag weldments, 56 and 49%, respectively, of the weld energy was extracted by the water-cooled copper shoes.

Temperature Distribution Along Weldment Length

As shown in Table 3, in weldments made with water-cooled shoes, there was usually little change (and sometimes a decrease) in peak temperature at the midheight of the joint as compared with that at the bottom. The peak temperatures near the top of the joint were usually somewhat higher than at the bottom or midheight, probably because there was no heat sink above the top of the weld.

During welding, heat is extracted from the liquid pool by the copper shoes, by the base metal, and by the cooled weld metal below the liquid pool. At the top of the weld, however, the base metal above the liquid pool is not available to act as a heat sink; in addition, the heat generated by welding into the runoff tabs is conducted down through the top of the weld. Similarly, the slightly higher peak temperatures often observed near the bottom of the joint (compared with those at the midheight) may have been caused by heat conduction upward from the sump.

Poor shoe contact could also be a factor. Shoe contact appeared to be best under the strongbacks, which were located 7 in. (178 mm) from the top and bottom, and at the midheight—Fig. 5. Also, the unrestrained ends of the shoes may not have been



A. Weld No. 6

B. Weld No. 6A

C. Weld No. 8

D. Weld No. 8A

E. Weld No. 9

F. Weld No. 14

G. Weld No. 15

H. Weld No. 16

Fig. 5—Heat-tint patterns on welds used for thermal study

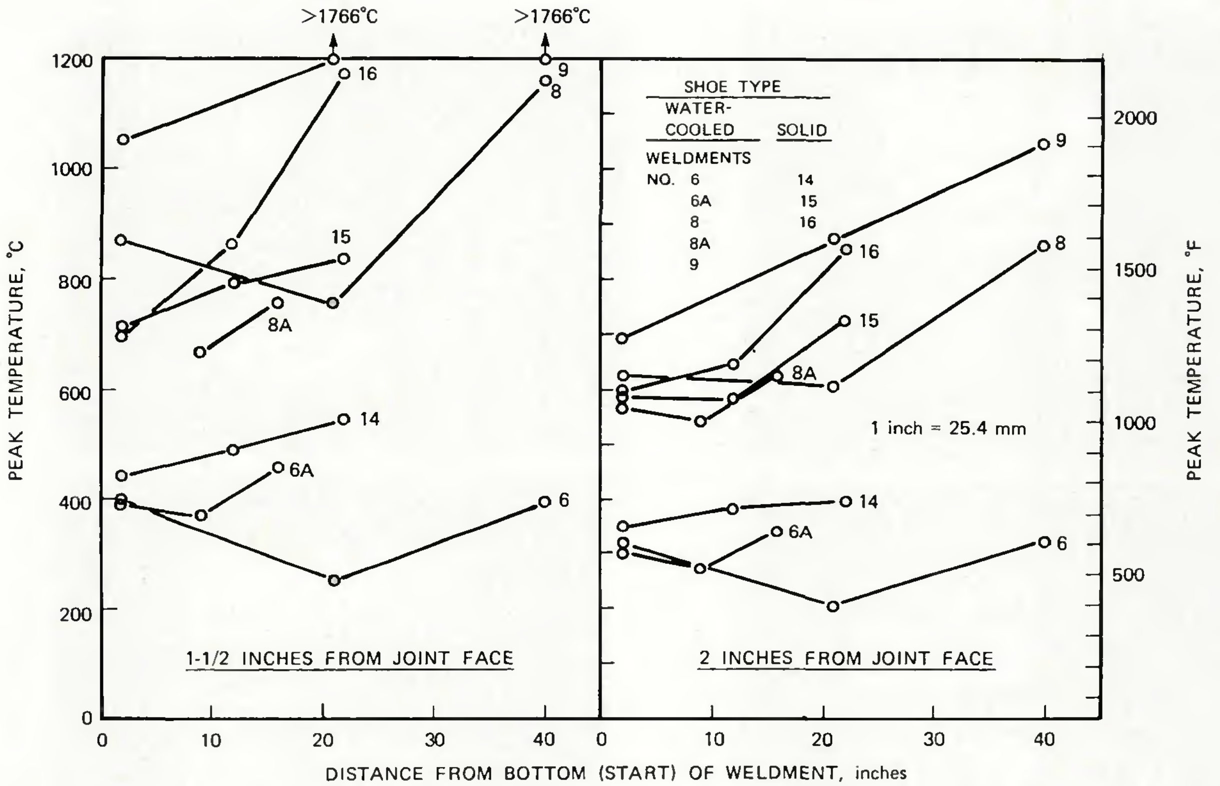


Fig. 6—Effect of weld length on peak temperatures at 1½ and 2 in. (38 and 51 mm) from the groove face

in intimate contact with the plates; therefore, poorer heat transfer would be obtained at the top and bottom of the weld.

The variations in heat distribution along the length of the weld are shown in the photographs of the heat-tint patterns—Fig. 5. The dark band on either side of the weld bead is the result of a very thin oxide film that resulted from heating of the surface. The colors range from faint straw, which corresponds to about 205 C (400 F), through peacock (280 C or 540 F), to light blue (340 C or 640 F).[2] These colors correlate reasonably well with the peak temperatures measured by means of the attached thermocouples.

The effect of position along the length of the weldment on peak temperature at distances of 1½ and 2 in. (38 and 51 mm) from the groove face is shown graphically in Fig. 6 for each of the eight weldments. (Too few data were available at distances of ½ and 1 in. because of melted thermocouples.) In all of these cases, the highest peak temperatures occurred at the top of the weldment. Weldment 9 exhibited by far the highest peak temperatures at all locations (Table 3 and Fig. 6), although its energy input was similar to that of the other weldments. The reason for this observation is not known.

In general, weldments 14, 15, and 16 made with the solid copper shoes did not exhibit a decrease in peak temperature at the midheight of the weldment. However, they often exhibited a nearly linear rise in peak temperature with distance along the weld at thermocouple locations up to 8 to 12 in. (0.2 to 0.3 m) away from the groove face—Table 3. This effect is also shown in the heat-tint patterns of welds 15 and 16—Fig. 5.

These observations may be the result of the preheating effect of the solid copper shoes on the unwelded base plate. They may also result from the fact that, because the shoes became progressively hotter during welding, the rate of heat extraction from the weld region during cooling is lowered. On the other hand, the water-cooled copper shoes remain at a relatively constant temperature during welding; therefore, a linear rise in peak temperature along the length of the weld is not encountered.

Effect of Weldment Length

The effect of weldment lengths of 18 in. or 0.46 m (weldments 6A and 8A) vs. 42 in. or 1.07 m (weldments 6 and 8) on the peak temperatures is presented in Table 3 and plotted for the top location at various distances from the joint face in Fig. 7. For the 1 in. (25.4 mm) thick weldments (6 and 6A), little effect of weldment length was observed, probably because of the dominant effect of the water-cooled copper shoes on peak temperature in the thinner plates.

For the 4 in. (102 mm) thick weldments, the 42 in. (1.07 m) long weldment (weldment 8) exhibited significantly higher peak temperatures at the top of the joint than did the 18 in. (0.46 m) long weldment (weldment 8A). However, as can be seen in Fig. 5, weldment 8A was terminated about ¾ in. (19 mm) from the top because of a breakout of the molten pool. Thus, the peak temperatures near the top of the shorter weld would have been higher and probably equivalent to that of weldment 8 if the weld had gone to completion.

As can be seen in Fig. 6 and Table 3, the peak temperatures at the bottom and middle of weldment 8 are not significantly higher than those for the bottom and middle of weldment 8A. This implies that the temperature distribution along the length of the weldments made with water-cooled shoes and a single guide tube reaches a steady state regardless of weld length, with a significant temperature rise at the top end due to the aforementioned end effects. However, in weldment 9 made with two fixed guide tubes, peak temperatures increased with distance along the weld, although the energy input was similar to that of weldment 8—Table 2.

The weldments made with solid copper shoes (weldments 14, 15, and 16) generally exhibited increasing peak temperatures along the length of the 24 in. (0.61 m) long joint—Fig. 6. This temperature rise indicated that the 4

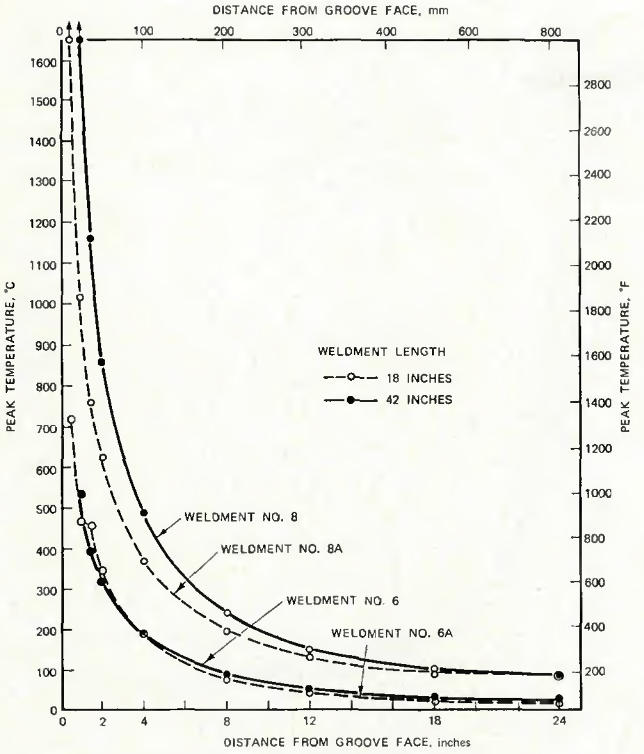


Fig. 7—Effect of weldment length on peak temperatures near top (end)

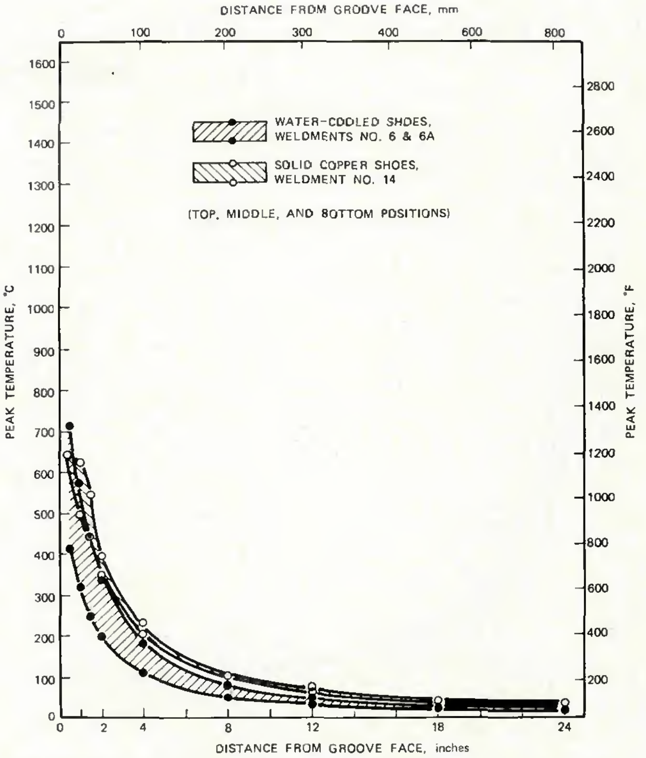


Fig. 8—Effect of shoe type on peak temperatures—1 in. (25.4 mm) thick weldments

in. (102 mm) wide by 1½ in. (38 mm) thick solid shoes used in this program were of insufficient size to absorb and redistribute the heat generated during welding, particularly in the 4 in. (102 mm) thick weldments. This could result in an excessively large fused zone in relatively long weldments; thus, the use of more massive solid shoes or water-cooled shoes is recommended for long weldments in thick plate.

Effect of Shoe Type

The effects of water-cooled copper shoes vs. solid copper shoes on thermal distribution were confounded by differences in weldment length—24 in. (0.61 m) for the solid shoes vs. 18 and 42 in. (0.46 and 1.07 m) for the water-cooled shoes. The range in peak temperatures observed in 1 in. (25.4 mm) thick weldment 14 made with solid shoes is compared with the range observed in similar 18 and 42 in. (0.46 and 1.07 m) long weldments 6A and 6 made with water-cooled shoes—Fig. 8 and Table 3.

There was much scatter in peak temperatures at ½ and 1 in. (12.7 and 25.4 mm) from the groove face. This was probably caused by the variations in fusion-zone symmetry. However, at distances beyond 1 in. (25.4 mm) from the groove face, the use of solid shoes resulted in a small but consistently higher peak temperature than did the use of water-cooled shoes in the 1 in. (25.4 mm) thick weldments.

Figures 9 and 10 and Table 3 compare the effect of solid and water-cooled shoes on peak-temperature ranges for 4 in. (102 mm) thick weldments 8, 8A, and 15 made with an oscillating guide tube and weldments 9 and 16 made with two fixed guide tubes, respectively. The ranges of peak temperatures showed considerable overlap. The effect of shoe type in the 4 in. (102 mm) thick weldments was less pronounced than in the 1 in. (25.4 mm) thick weldments, probably because proportionately less heat is extracted by the shoes as plate thickness is increased.

The use of solid copper shoes did not significantly affect the peak temperatures in the heat-affected zone of the 4 in. (102 mm) thick weldments at the midthickness of the joints. However, the shoes heated considerably during welding and were cooled with compressed air to minimize the possibility of their melting into the molten puddle or breakout of the molten pool from behind the shoes. It is unlikely that this technique significantly affected the thermal distribution at the thermocouple location. This overheating would not be a problem in shorter weldments or if more massive shoes were used.

Effect of Single Oscillating Guide vs. Two Fixed Guide Tubes

The ranges of peak temperatures observed in 4 in. (102 mm) thick weldments with water-cooled shoes and with either a single oscillating consumable guide tube (weldment 8) or two fixed consumable guide tubes (weldment 9) are shown in Fig. 11. A similar comparison for weldments 15 and 16, made with solid copper shoes, is shown in Fig. 12. Both of the two-tube weldments exhibited higher peak temperatures close to the joint face, although they were made with slightly lower energy inputs—Table 2.

Effect of Process Parameters on Cooling Rate

In low-hardenability steels, the austenite-to-ferrite transformation upon continuous cooling usually occurs in the temperature range near 540 C (1000 F). The cooling rate through this transformation-temperature range determines the resulting microstructure and this, in turn, may determine the mechanical properties. To determine the differences in cooling rates in the weld region as a result of variations in process parameters, the cooling rate at 540 C (1000 F) was measured at each thermocouple location that was in the austenite region (above about 705 C or 1300 F). The results are summarized in Table 4.

For the 1 in. (25.4 mm) thick weldments, only one peak temperature greater than 705 C (1300 F) was obtained, and a cooling rate at 540 C (1000 F) of 1.05 C/s (1.89 F/s) was measured. In the 4 in. (102 mm) thick weldments cooling rates ranged from 0.17 to 0.53 C/s (0.31 to 0.95 F/s). Because of the limited data and the

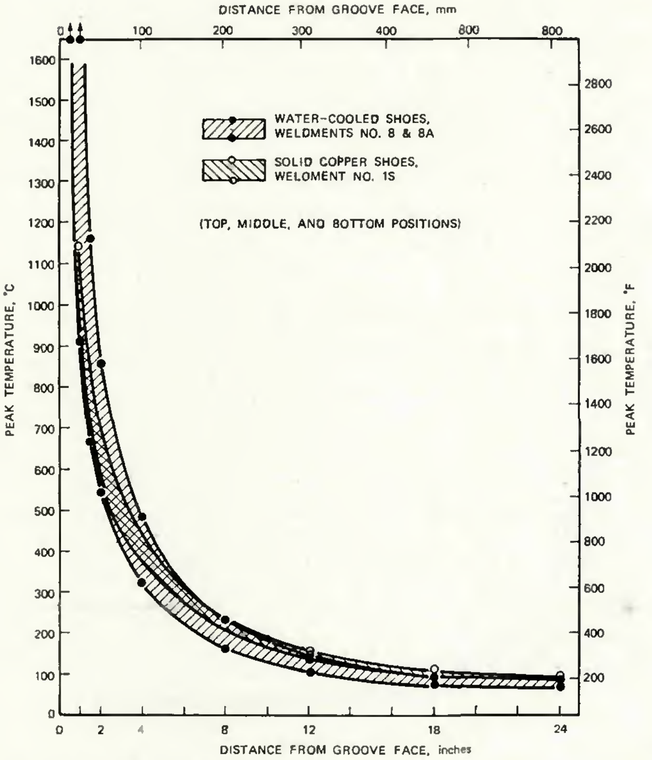


Fig. 9—Effect of shoe type on peak temperatures—4 in. (102 mm) thick weldments, oscillating guide tube

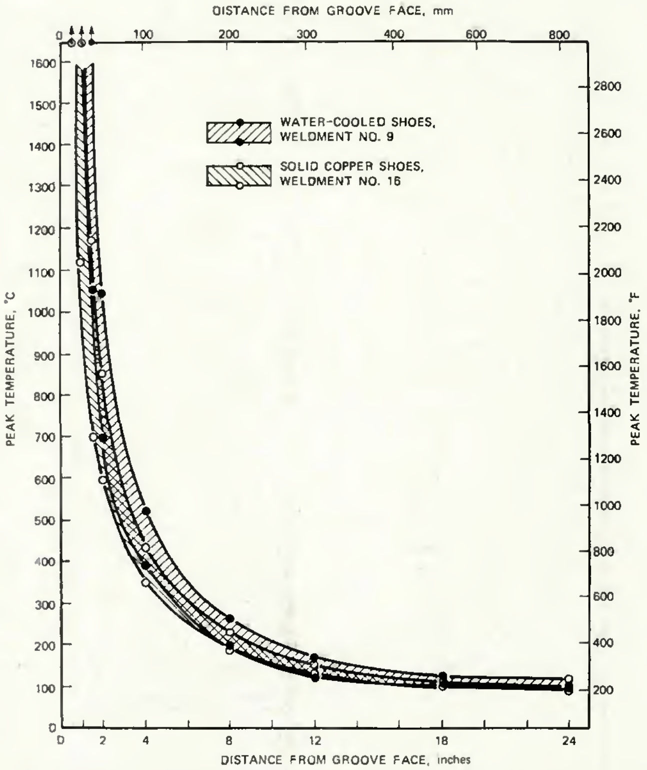


Fig. 10—Effect of shoe type on peak temperatures— 4 in. (102 mm) thick weldments, two guide tubes

scatter involved, definite correlations of cooling rates with process parameters could not be made.

Part of the scatter may have occurred because the cooling rate at 540 C (1000 F) was also a function of the peak temperature, as can be seen in Fig. 4. A more meaningful measure of cooling rate might be the time elapsed in cooling through the entire transformation-temperature range of about 800 to 500 C (1472 to 932 F). These data are shown in Table 5 for peak temperatures that exceeded 800 C (1472 F). Although there was considerable scatter in the available data, some general observations could be made:

1. Faster cooling was obtained at the midheight than at either the bottom or top of the weld.
2. The solid shoes resulted in signif-

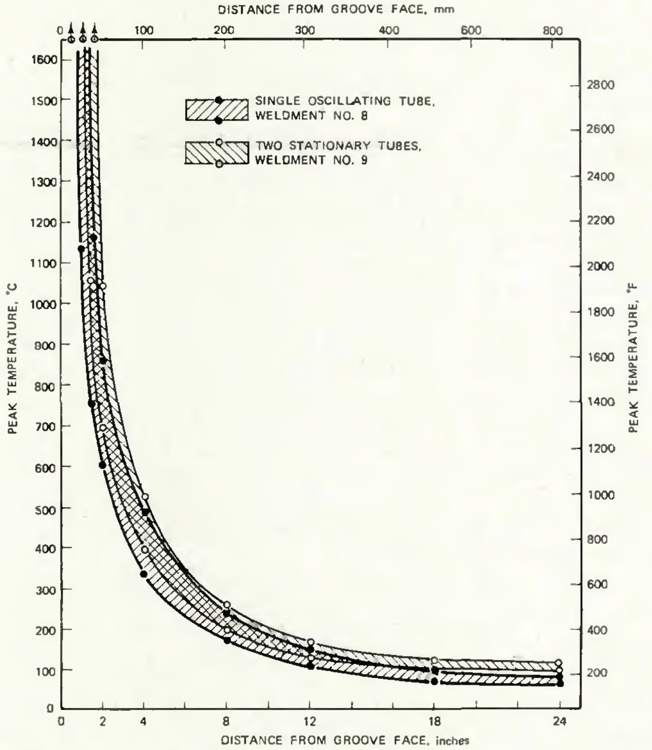


Fig. 11—Effect of guide-tube type on peak temperatures in 4 in. (102 mm) thick weldments with water-cooled shoes

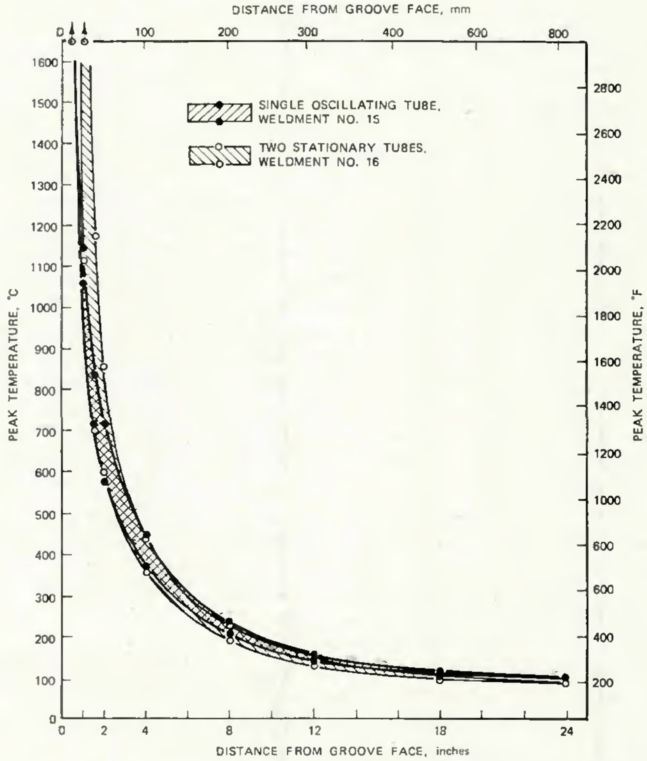


Fig. 12—Effect of guide-tube type on peak temperatures in 4 in. (102 mm) thick weldments with solid copper shoes

icantly longer cooling times (weldments 15 and 16) than did the water-cooled shoes (weldments 8, 8A, and 9) in the heat-affected zone close to the groove face.

3. The use of two fixed tubes (weldments 9 and 16) resulted in longer cooling times than did the use of a single oscillating tube (weldments 8, 8A, and 15).

As to the effects of variations in cooling rate on microstructures and mechanical properties of the weld region, the two most significant effects are the lower yield and tensile strengths resulting from a change from water-cooled to solid shoes, and a trend toward lower notch toughness at the extreme top and bottom of the weldments.

Summary

The results of the present investigation to study the effects of process parameters on thermal distribution during electroslag welding can be summarized as follows:

1. The 24 in. (0.61 m) plates used to fabricate the electroslag weldments were sufficiently wide to simulate the weld thermal cycles expected to be obtained in wider plates.
2. Variations in the geometry of the fusion zone and in the resultant thermal cycles were encountered within individual weldments.
3. The 1 in. (25.4 mm) thick weldments exhibited peak temperatures in the heat-affected zones (HAZ) that were significantly lower than those of the 4 in. (102 mm) thick weldments.
4. Peak temperatures were highest at the top of the weldments. In weldments cooled with water-cooled copper shoes, peak temperatures at the midheight were often lower than those at the bottom; however, in weldments cooled with solid copper shoes, peak temperatures increased with increasing distance along the joint.
5. Peak temperatures were similar for weldment lengths of 18 and 42 in. (0.46 and 1.07 m) in 1 and 4 in. (25.4 and 102 mm) thick weldments made with a single oscillating guide tube and by using water-cooled shoes.
6. The use of solid vs. water-cooled copper shoes resulted in higher peak temperatures in the HAZ of 1 in. (25.4 mm) thick weldments but not in the HAZ at the midthickness of the 4 in. (102 mm) thick weldments. However, the 4 by 1½ in. (102 by 38 mm) solid copper shoes tended to overheat and had to be cooled by compressed air during welding.
7. Higher peak temperatures generally resulted in 4 in. (102 mm) thick weldments made with two fixed guide tubes than in weldments made with a single oscillating guide tube at similar energy inputs.
8. Little correlation was found between process parameters and cooling rate at 540 C (1000 F) in the HAZ. However, the cooling time in the transformation-temperature range 800 to 500 C (1472 to 932 F) was generally shorter at the midheight than at the top or bottom of the joint, was shorter for water-cooled than for solid shoes, and was shorter for single oscillating than for two fixed guide tubes.

Table 4—Cooling Rates at 540°C at Positions With Peak Temperature in Excess of 705°C

Weldment no.	Thermocouple location along weld	Cooling rate, °C/s,[a] for indicated distance[a] from groove face, in.[b] ½	1	1½	2
6A	Top	1.05	—	—	—
8	Bottom	—	0.31	0.53	0.48
	Middle	—	0.30	0.26	—
	Top	—	—	0.24	0.21
8A	Bottom	—	0.25	—	—
	Middle	—	0.26	—	—
	Top	—	(0.42)[c]	(0.53)[c]	—
9	Bottom	—	—	0.23	—
	Middle	—	—	—	0.20
	Top	—	—	—	0.19
15	Bottom	—	0.19	—	—
	Middle	—	0.26	0.26	—
	Top	—	0.22	0.17	—
16	Bottom	—	0.22	—	—
	Middle	—	0.29	0.25	—
	Top	—	—	0.23	0.19

[a] °F/s = (9/5) (°C/s).
[b] 1 in. = 2.54 mm.
[c] Weld terminated prematurely.

Table 5—Cooling Times Through Transformation-Temperature Range for Positions With Peak Temperature in Excess of 800°C (1472°F)

Weldment no.	Shoe type	Guide-tube type	Thermocouple location along weld	Time to cool from 800 to 500°C at indicated distance from groove face, s 1 in.[a]	1½ in.[a]	2 in.[a]
8	Water-cooled	Osc.	Bottom	692	769	—
			Middle	695	—	—
			Top	—	822	843
8A	Water-cooled	Osc.	Bottom	838	—	—
			Middle	749	—	—
			Top	(429)[b]	—	—
9	Water-cooled	Two fixed	Bottom	—	906	—
			Middle	—	—	1024
			Top	—	—	1034
15	Solid	Osc.	Bottom	1071	—	—
			Middle	873	—	—
			Top	928	1032	—
16	Solid	Two fixed	Bottom	909	—	—
			Middle	822	908	—
			Top	—	892	921

[a] 1 in. = 25.4 mm. [b] Weld terminated prematurely.

Acknowledgment

This work was sponsored by the American Association of State Highway and Transportation officials, in cooperation with the Federal Highway Administration, and was conducted as one of the projects in the National Cooperative Highway Research Program which is administered by the Transportation Research Board of the National Research Council.

References

1. Benter, Jr., W. P., Konkol, P. J., Kapadia, B. M., Shoemaker, A. K., and Sovak, J. F., "Acceptance Criteria for Electroslag Weldments in Bridges," Phase I, Final Report, NCHRP Project 10-10, National Cooperative Highway Research Program, April 1, 1977.
2. *Metals Handbook,* 1948 edition, American Society for Metals, p. 730.