Process Modifications to Improve HAZ Toughness in High Deposition Arc Welds

Practical modifications of basic submerged arc welding makes it possible to use existing steels in applications requiring both high deposition and improved low-temperature toughness

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SUMMARY. With the purpose of improving heat-affected zone toughness, several modifications of high-deposition submerged-arc welding procedures were examined to determine techniques of depositing equivalent amounts of filler metal at faster cooling rates. The following modifications produced the desired results: multiple-head submerged-arc welding (SAW), long-stickout SAW, small-diameter twin-electrode SAW, SAW using cored electrodes and a process utilizing a gas metal-arc welding (GMAW) head and a SAW head spaced 12 in. (305 mm) apart.

Multiple-head welding gave faster cooling than single-head welding for identical nominal heat inputs. For the other four modifications, the desired fill and penetration could be maintained using lower heat inputs, the result being faster cooling. With the faster cooling provided by these five modifications, HAZ toughness was substantially higher than that obtained using standard procedures.

Introduction

The increasing use of structural steels with excellent low-temperature toughness means that good toughness must be achieved in the heat-affected zone. Because of the relatively slow cooling rates, traditional high-deposition processes often produce low HAZ toughness at low temperatures. Toughness deterioration can be avoided by lowering the heat input to increase the cooling rate. On the other hand, if no other modifications are made, the result is more welding passes, hence lowered productivity. The present study tested existing and possible techniques that would likely overcome these problems. Testing and evaluation resulted in the selection of five techniques, as discussed.

Procedure

Using the commonly applied dc reverse-polarity (dc+) single-solid-electrode process as a basis for comparison, the following modifications of the submerged-arc process were considered:

- Two and three heads and various combinations of dc+, dc− and ac power
- Long stickout
- Small-diameter twin electrodes
- Cored electrodes
- A combination process in which a gas metal-arc electrode is followed by a submerged-arc electrode (GMAW + SAW).

All ac-ac welds were made with the heads Scott-connected. The following dependent variables were measured:

- Thermal cycle.
- Deposition rate (weight/arc time).
- Fill (weight/weld length).
- Penetration.

For the first four modifications, cooling curves were determined by plunging a W-5% Re/W-26% Re thermocouple into the weld pool immediately behind the electrode. For measuring the cooling curve of the first weld in the GMAW + SAW process, a hole was made in which the thermocouple was placed before welding so that the thermocouple tip would lie just within the weld metal after welding—Fig. 1. The wire electrode feed speed was directly measured for each electrode of each weld using a meter with digital read-out. The amount of fill and the deposition rate were then determined according to the following equations:

$$\text{Fill}\left(\frac{\text{weight of filler metal deposited}}{\text{length}}\right) = \frac{\rho\ AV_e}{S},$$

$$\text{Deposition rate}\left(\frac{\text{weight of filler metal deposited}}{\text{arc time}}\right) = \rho\ AV_e,$$

where ρ = the density of steel, A = electrode cross-sectional area, S = travel speed, and V_e = wire feed speed.

All welding was done on ¾ in. (19 mm) carbon-manganese plate and with the double-V joint configuration shown in Fig. 2. Welding with solid electrodes was done using an electrode/flux combination meeting AWS classification F72-EA3. Electrodes 5⁄32 in. (4 mm) in diameter were employed for all modifications except the small-diameter twin technique (5⁄64 in. (2 mm) electrodes). The cored electrodes, consumables meeting AWS classification F86-ECF1-F1, were 5⁄32 in. (4 mm) in diameter.

Initially, all welds were made at a heat input of 90 kJ/in. (3.5 kJ/mm). The amperage and voltage were 1200 A and 40 V, respectively, and the travel speed was selected to obtain the desired heat input.

In some cases, the choice of 1200 A and 40 V produced beads whose shape

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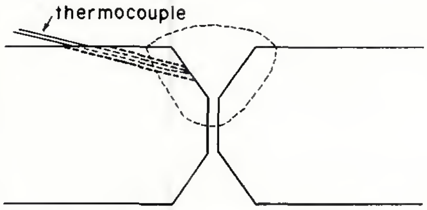

Fig. 1—Method of preplacing thermocouple

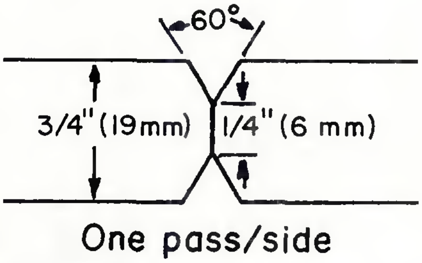

Fig. 2—Welding procedure

would not normally be acceptable, but the desire at this stage of the program was to avoid having amperage and voltage as additional variables. However, once the effects of the process modifications were determined, the amperage and voltage for each head were modified to produce a desirable bead shape for a given heat input. Finally, the heat input for each process modification was reduced in order to bring the amount of fill to a level similar to that of our standard 90 kJ/in. (3.5 kJ/mm) dc+ procedure. The purpose was to increase the cooling rate, a step designed to produce a tougher HAZ microstructure.

A normalized low-sulfur carbon-manganese grade (0.10% C, 1.5% Mn) was selected for welding tests in which the HAZ toughness produced by these modifications was to be measured. To approximate the minimum HAZ toughness, measurements were made at the fusion line (the intersection of the two weld beads) and at 1 and 2 mm from the fusion line.

Table 1—Effect of Number of Heads on Dependent Parameters[a]

No.	Type	Fill, lb/ft (kg/m)	Deposition rate, lb/h (kg/h)	Penetration, in. (mm)	Cooling time, 800-500°C, seconds
1	dc+	0.245 (0.365)	39 (18)	0.52 (13.2)	38
2	dc + /ac	0.225 (0.335)	73 (33)	0.49 (12.4)	31
3	dc + /ac/ac	0.235 (0.350	113 (51)	0.49 (12.4)	25

[a]Welding conditions: 1200 A, 40 V/head, and travel speed adjusted to give 90 kJ/in. (3.5 kJ/mm).

Results

The following results are presented in terms of the effect of each process modification on the dependent parameters—thermal cycle, deposition rate, fill, and penetration—and on the toughness of the heat-affected zone.

Effect of Process Modifications on Dependent Parameters

Number of Heads. In tandem and triple-arc welding the function of the lead electrode is to provide most of the penetration. The trail electrode fills the groove and provides a favorable weld bead shape. The second of a three-wire system performs a portion of both functions. Although currents and voltages are rarely the same from electrode to electrode because different electrodes have different purposes, current and voltage were not varied in the first stage of the program for the reason already mentioned. References to multiple-electrode welding go back about 30 years;[1] a recent summary article is that by Uttrachi.[2]

Table 1 shows the effect of the number of heads when one and then two ac-powered electrodes followed a dc+ electrode. The total heat input

Table 2—Effect of Stickout on Dependent Parameters[a]

No. of heads	Type	Stickout, in., (mm)	Fill, lb/ft, (kg/m)	Deposition rate, lb/h (kg/h)	Penetration, in. (mm)	Cooling time, 800-500°C, seconds
2	dc + /ac	1½/1½ (38/38)	0.225 (0.335)	73 (33)	0.49 (12.4)	31
2	dc + /ac	1½/3½ (38/89)	0.295 (0.440)	94 (43)	0.45 (11.4)	27
3	dc + /ac/ac	1½/1½/1½ (38/38/38)	0.235 (0.350)	113 (51)	0.49 (12.4)	25
3	dc + /ac/ac	1½/1½/3½ (38/38/89)	0.271 (0.404)	130 (59)	0.44 (11.2)	25
3	dc + /ac/ac	1½/3½/3½ (38/89/89)	0.296 (0.441)	142 (65)	0.41 (10.4)	N.D.[b]

[a]Welding conditions: 1200 A, 40V/head, and travel speed adjusted to give 90 kJ/in. (3.5 kJ/mm).
[b]N.D. = Not Determined.

Table 3—Effect of Small-Diameter Twin Electrodes on Dependent Parameters[a]

Process	Type	Stickout, in. (mm)	Fill, lb/ft (kg/m)	Deposition rate, lb/h (kg/h)	Penetration, in. (mm)	Cooling time, 800-500°C, seconds
Conventional	dc + /ac	1½/1½ (38/38)	0.236 (0.352)	75 (34)	0.48 (12.2)	37
Long stickout	dc + /ac	1½/2¾ (38/70)	0.291 (0.434)	93 (42)	0.45 (11.4)	33
Twin	dc + /twin ac	1½/1½ (38/70)	0.289 (0.431)	92 (42)	0.46 (11.7)	37

[a]Welding Conditions: 1200 A, 40V/head, 64 ipm (27 mm/s) travel speed, and 90 kJ/in. (3.5 kJ/mm) total heat input.

Table 4—Effect of Electrode Type on Dependent Parameters[a]

Electrode	Heat input, kJ/in. (kJ/mm)	Current, A	Volts, V	Travel speed, ipm (mm/s)	Fill, lb/ft (kg/m)	Deposition rate, lb/h (kg/h)	Penetration, in. (mm)	Cooling time, 800-500°C, seconds
Solid[b]	90 (3.5)	1200	42	32 (14)	0.245 (0.365)	39 (18)	0.52 (13.2)	38
Solid[b]	75 (3.0)	800	35	22 (9)	0.190 (0.283)	21 (10)	0.40 (10.1)	27
Cored[b]	75 (3.0)	800	35	22 (9)	0.304 (0.453)	34 (15)	0.39 (9.9)	33
S/C[c]	75 (3.0)	1200 800	32 40	56 (24)	0.282 (0.421)	79 (36)	0.40 (10.1)	28

[a] DC+ used in all cases.
[b] Single-head process.
[c] Two head process: dc+ solid electrode lead, ac cored electrode trail.

was assumed to be the sum of the heat inputs of each individual head. Note that, for the same nominal total heat input, the cooling time decreased i.e., the cooling rate increased, with the number of heads.

For most structural steels HAZ toughness increases with cooling rate over the normal range of welding conditions. Consequently, by virtue of its role in increasing the cooling rate, multiple-head welding is a modification that can be introduced to improve this property.

Table 1 also indicates that fill is virtually unchanged and that the deposition rate increases in proportion to the number of heads. Along with the expected improvement in HAZ toughness resulting from increased cooling rates, these higher deposition rates would provide economy in terms of reduced welding time.

Long Stickout. Long-stickout (electrode extension) welding increases the amount of metal deposited at a given amperage,[3] and practical applications of this process have been discussed in the literature.[4] The data of Table 2 show the effect of using electrodes with long stickout to follow an electrode with normal stickout. The first electrode was always used with normal stickout in order to maintain good penetration. Results similar to those in Table 2 were found with ac/dc- and ac/ac/dc- welds.

These data demonstrate that long stickout used in this way increases fill and deposition rate at some expense to penetration. Changes in cooling time were small. The implication of the data is that adequate fill can be maintained with lower heat input. The resulting increase in cooling rate should produce better toughness.

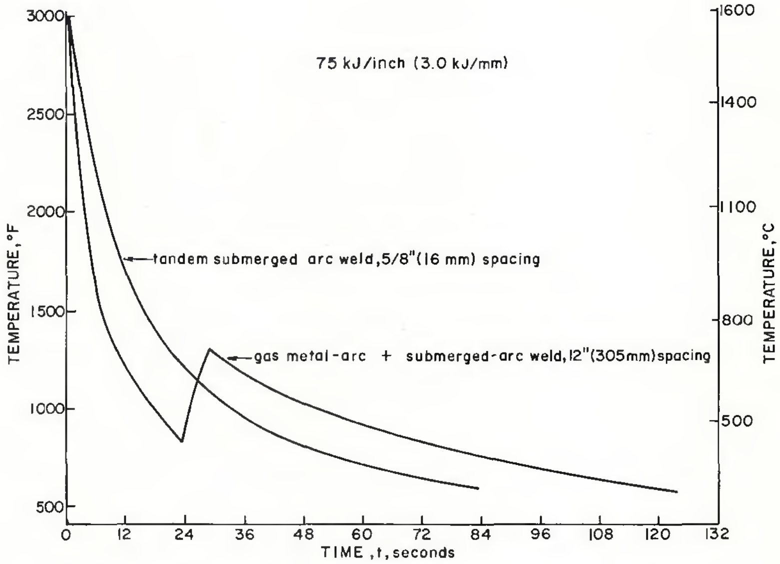

Fig. 3—Time-temperature curve for SAW and GMAW + SAW welds

Small-Diameter Twin Electrodes. This process has been used for several years and was discussed in some detail in a 1976 article.[5] In this process, one head is equipped with a double set of drive rolls so that two electrodes are fed simultaneously through the head at the same rate.

Table 3 shows that this process increases fill and deposition rate with some loss in penetration. These changes are similar to those obtained with long stickout and indicate that the use of lower heat inputs with the small-diameter twin process should produce a tougher HAZ without any loss in deposition.

Cored Electrodes. At a given current, cored electrodes give a much higher deposition rate than is possible with solid electrodes. However, because of the rapid meltback of the wire, high currents cannot be attained with cored electrodes. As seen in Table 4, even when a relatively low current (800 A) and a heat input of 75 kJ/in. (3.0 kJ/mm) were employed, the amount of fill obtained with the cored electrode was substantially greater than that obtained with solid wire at 1200 A

Table 5—GMAW + SAW Process: Effect on Dependent Parameters

Process[a]	Head	Current, A	Volts, V	Travel speed, ipm (mm/s)	Fill, lb/ft (kg/m)	Deposition rate, lb/h (kg/h)	Penetration, in. (mm)	Cooling time, 800-500°C, seconds
Single-wire SAW	dc+	800	35	19 (8)	0.223 (0.332)	21 (10)	0.44 (11.2)	39
GMAW + SAW (12 in. spacing)	dc+ ac	800 700	30 30	30 (13)	0.297 (0.442)	46 (21)	.44 (11.2)	34

[a] 90 kJ/in. (3.5 kJ/mm) total heat input was used in both cases.

Table 6—Welding Conditions for Welds Made to Determine Effect of Modification on HAZ Toughness

Code	Head, comments[a]	Current, A	Volts, V	Travel speed, ipm (mm/s)	Heat input, kJ/in. (kJ/mm)
1	dc+	800	35	19 (8)	90 (3.5)
2	dc+	1200	32	60	70
	ac	800	40	(25)	(2.8)
3	dc+	1200	32	91	70
	ac	1000	36	(38)	(2.8)
	ac	800	40		
2L	dc+, stickout 1½ in. (38 mm)	1200	32	64	66
	ac+, stickout 4½ in. (83 mm)	800	40	(27)	(2.6)
3L	dc+, stickout 1½ in (38 mm)	1200	32	98	65
	ac, stickout 3¼ in. (83 mm)	1000	36	(42)	(2.6)
	ac, stickout 4½ in. (114 mm)	800	40		
2T	dc+, one 5/32 in. (4 mm) electrode	1200	32	64	66
	ac, two 5/64 in. (2 mm) electrodes	800	40	(27)	(2.6)
SC	dc+, solid electrode	1200	32	64	66
	ac, cored electrode	800	40	(27)	(2.6)
GS	dc+, GMAW head	800	30	38	71
	ac, SAW head, 12 in. (305 mm) behind	700	30	(16)	(2.8)

[a]Unless noted, all electrodes are 5/32 in. (4 mm) solid electrodes with 1.5 in (38 mm) stickout. Tandem and three-head SAW welding heads have 5/8 in. (16 mm) spacing.

Table 7—Effect of Number of Heads on HAZ Toughness

Code	Heads	Heat input, kJ/in. (kJ/mm)	Fill, lb/ft (kg/m)	Deposition rate, lb/h (kg/h)	Penetration, in. (mm)	Cooling time 800-500°C, seconds	Minimum HAZ energy,[a] ft-lb at −50°F (J at −46°C)
1	dc+	90 (3.5)	0.226 (0.337)	21 (10)	0.44 (11.2)	39	7 (9)
2	dc+/ac	70 (2.8)	0.220 (0.328)	66 (30)	0.41 (10.4)	20	26 (35)
3	dc+/ac/ac	70 (2.8)	0.214 (0.319)	97 (41)	0.40 (10.2)	19	37 (50)

[a]Minimum of fusion line, 1 mm and 2 mm positions.

and 90 kJ/in. (3.5 kJ/mm). In addition, the cooling rate was lower with the cored electrode.

Multiple-head welding using only cored electrodes was not beneficial, because lead head currents high enough to produce desired penetration were not achievable. Thus, currents much higher than 800 A without burnback could not be obtained. However, by combining a solid lead electrode with a cored trail electrode we were able to obtain approximately double the deposition rate of a single cored electrode weld for the same fill.

GMAW + SAW. With two electrodes spaced a considerable distance apart, the weld metal and HAZ thermal cycle can be altered favorably by significantly reducing the amount of time spent at high austenitizing temperatures. The submerged-arc process cannot be used for both heads when the spacing exceeds about 6 in. (150 mm), because slag from the first head will already be solidified when the second head reaches it. To avoid the problems this situation would create, the GMAW process was employed with the first head. Japanese researchers have recently looked at this process as well as at a two-head GMAW process.[6,7]

A comparison of the thermal cycles produced by a tandem submerged-arc weld and the GMAW + SAW process is shown in Fig. 3. With the former the spacing between electrodes was ⅝ in. (16 mm); with the GMAW + SAW it was 12 in. (305 mm). Although the generally accepted measure of cooling rate, time from 800 to 500°C (1472 to 932°F), was not significantly affected, the time spent above high austenitizing temperature was. For example, the time above 1100°C (2000°F) was reduced from 8 down to 3 seconds (s). This shorter time is responsible for a less coarse HAZ.

GMAW + SAW welds were made using submerged-arc equipment with a specially designed gas shield for the GMA weld. The results shown in Table 5 were generated with the spacing held at 12 in. (305 mm). Again, the increased fill at 90 kJ/in. (3.5 kJ/mm) suggested that sufficient weld metal would be deposited at a lower heat input thus providing a faster-cooling, tougher weld.

Effect of Process Modifications on HAZ Toughness

In the testing done to this point, the welding conditions were deliberately restricted. In the next stage of the work, we were able to move to a more realistic range of conditions. The strong points of each technique were utilized in such a way as to produce welds of acceptable shape. The heat input was adjusted to provide a fill roughly equivalent to a single-electrode dc+ weld made with a 5/32 in. (4 mm) solid wire and 800 A, 35 V and 90 kJ/in. (3.5 kJ/mm), i.e., roughly 0.23 lb/ft (0.34 kg/m). Welding conditions for these welds are given in Table 6.

The HAZ toughness of each weld was then determined at the three locations previously described. In the following sections we cite the lowest of the values at the three locations. In all cases, these were either at the fusion line or at the 1-mm location.

Number of Heads. Changing from a single- to a multiple-head system produced the greatest increase in HAZ

Table 8—Effect of Long Stickout on HAZ Toughness

Code	Head polarity, stickout, inches (mm)	Heat input, kJ/in. (kJ/mm)	Fill, lb/ft (kg/m)	Deposition rate, lb/h (kg/h)	Penetration, in. (mm)	Cooling time, 800-500°C, seconds	Minimum HAZ energy,[a] ft-lb at −50°F (J at −46°C)
1	dc+	90	0.226	21	0.44	39	7
	1½ (38)	(3.5)	(0.337)	(10)	(11.2)		(9)
2	dc+/ac	70	0.220	66	0.41	20	26
	1½ (38)/1½ (38)	(2.8)	(0.328)	(30)	(10.4)		(35)
2L	dc+/ac	66	0.224	72	0.41	15	28
	1½ (38)/4½ (114)	(2.6)	(0.334)	(33)	(10.4)		(38)
3	dc+/ac/ac	70	0.214	97	0.40	19	37
	1½ (38)/1½ (38)/1½ (38)	(2.8)	(0.319)	(44)	(10.2)		(50)
3L	dc+/ac/ac	65	0.218	107	0.40	14	44
	1½ (38)/3¼ (83)/4½ (114)	(2.6)	(0.325)	(48)	(10.2)		(60)

[a]Minimum of fusion line 1 mm and 2 mm positions.

Table 9—Effect of Small-Diameter Twin on HAZ Toughness

Code	Heads	Heat input, kJ/in. (kJ/mm)	Fill, lb/h (kg/m)	Deposition rate, lb/h (kg/h	Penetration, in. (mm)	Cooling time, 800-500°C, seconds	Minimum HAZ energy,[a] ft-lb at −50°F (J at −46°C)
1	dc+	90	0.226	21	0.44	39	7
		(3.5)	(0.337)	(10)	(11.2)		(9)
2	dc+/ac	70	0.220	66	0.41	20	26
		(2.8)	(0.328)	(30)	(10.4)		(35)
2T	dc+/twin ac	66	0.224	72	0.42	18	42
		(2.6)	(0.334)	(33)	(10.7)		(57)

[a]Minimum of fusion line, 1 mm and 2 mm positions.

Table 10—Effect of Cored Electrodes on HAZ Toughness

Code	Heads	Heat input, kJ/in. (kJ/mm)	Fill, ft/lb, (kg/m)	Deposition rate, lb/h (kg/h)	Penetration, in. (mm)	Cooling time, 800-500°C, seconds	Minimum HAZ energy,[a] ft-lb at −50°F (J at −46°C)
1	dc+, solid	90	0.226	21	0.44	39	7
		(3.5)	(0.337)	(10)	(11.2)		(9)
2	dc+/ac	70	0.220	66	0.41	20	26
		(2.8)	(0.328)	(30)	(10.4)		(35)
SC	dc+, solid/	66	0.226	72	0.210	15	32
	ac, cored	(2.6)	(0.337)	(33)	(10.2)		(43)

[a]Minimum of fusion line, 1 mm and 2 mm positions.

toughness. In general, other modifications, when combined with multiple-head welding, further increased the toughness, but this initial jump was the most dramatic. In other situations—a different grade or a slower initial cooling rate, for example—the additional benefits provided by these other modifications might prove to be of greater significance than was the case here.

The data for single-, two- and three-head welds are shown in Table 7. The increase is primarily due to the ability to use much higher currents in the lead head than those possible with single-head welding. Deposition rate is, of course, greatly increased with the multihead welds, another feature that makes their application attractive.

Long-Stickout SAW. Table 8 presents a comparison between single-head and multiple-head SAW with normal stickout (electrode extension) on all electrodes and multiple-head SAW with a long stickout on the trail electrode or electrodes.

As Table 8 shows, the long-stickout process provided a substantially higher HAZ toughness than was possible with the single-head process. The long-stickout process also gave a modest increase in HAZ toughness over what the normal stick-out multiple-head SAW provided. In addition, the deposition rate with long stickout was about 10% higher than with normal stickout.

Small-Diameter Twin Electrodes. Table 9 gives data from:

1. standard single-electrode welding.
2. DC+/ac welding with single electrodes on each head.
3. DC+/ac welding in which two small-diameter ⁵⁄₆₄ in. (2 mm) electrodes were used in the ac head.

It is seen that HAZ toughness was improved when the small-diameter twin process was employed. The deposition rate was also further improved over that obtained with the standard two-head process.

Cored Electrodes. The effect of cored electrodes can be seen in Table 10, which shows that HAZ toughness was greater than that obtained with a single electrode or with tandem welding using two solid wires. Again, the deposition rate increased.

GMAW + SAW. Table 11 would seem to indicate that the GMAW + SAW process is no better

Table 11—Effect of GMAW + SAW Modification on HAZ Toughness

Code	Heads	Heat input, kJ/in. (kJ/mm)	Fill, lb/ft (kg/m)	Deposition rate, lb/h (kg/h)	Penetration, in. (mm)	Cooling time, 800-500°C, seconds	Time above 1100°C, seconds	Minimum HAZ energy,[a] Ft-lb at −50°F (J at −46°C)
1	dc+	90 (3.5)	0.226 (0.337)	21 (10)	0.44 (11.2)	39	N.D.[b]	7 (9)
2	dc+/ac (both SAW)	70 (2.8)	0.220 (0.328)	66 (30)	0.41 (10.4)	20	8	26 (35)
GS	GMAW-dc+/ SAW-ac	71 (2.8)	0.231 (0.345)	45 (20)	0.40 (10.2)	23	3	28 (38)

[a]Minimum of fusion line, 1 mm and 2 mm positions.
[b]N.D. = not determined.

than standard tandem welding. However, since the low lead head current, 800 A, was the result of equipment limitations, equipment designed for currents of 1200 A or more would permit further decreasing the heat input to maintain the desired fill and thereby improve toughness.

Concluding Remarks

This study has shown how existing steels can be used in applications requiring improved low-temperature toughness, with good HAZ toughness being maintained through practical modifications of basic submerged-arc welding.

Where the user is limited to one head, a switch from solid to cored electrodes will produce an immediate increase in deposition, allowing the use of lower heat inputs and hence improved toughness. Joint configuration may have to be modified to counter the slight penetration loss. Where multipass welding is required, maximum penetration can be achieved in the first pass with traditional conditions followed by fill passes using either cored electrodes or long stickout.

With only slight modifications, single-electrode submerged-arc welding equipment can be adapted to the small-diameter twin process. This process, which has about the same deposition characteristics as the long-stickout process, does not have the starting and burnback problems often associated with long-stickout welding, but does provide equivalent improvements in toughness.

When multihead capability is available, its utilization can greatly improve toughness properties by permitting the use of lower heat input. The added advantages of cored electrodes, long-stickout welding and the small-diameter twin process can be achieved by using them as the trail head in a multiple-head process.

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