Root Weld Formation in Modified Refractory Flux One-Sided Welding: Part 2 — Effect of Joint Geometry

Relationships between the shape of the root weld and variations in joint geometry were established

BY V. MALIN

ABSTRACT. Experiments were conducted using modified refractory flux welding developed for use in the field. The effects of joint geometry (root opening, included angle, root face, and plate misalignment) on root (backside) welds, including the root bead (deposit inside the groove) and the root reinforcement (deposit outside the groove), were studied. The effects of arc blow and tack welds were also studied. Modified refractory flux (MRF) welding is a one-sided welding method that utilizes submerged arc welding, thermosetting backing flux, direct current electrode negative polarity, and a specially designed portable backing system (Ref. 1). Formation of root welds in MRF welding was studied in 17.5-mm-thick, single-V-groove, steel butt joints at wide variation of groove geometry, including 0–9.5-mm root openings, 30–45 deg included angles, 0–4.8-mm root faces and misalignments of 0–4.0 mm. It was found if the root beads have a specific shape, defects may develop in the following fill weld. Also, the shape of the root weld is significantly affected by the groove geometry, arc blow, and tack welds.

Introduction

Refractory flux one-sided welding is little known in the United States, and is described in Ref.1. It has long been successful in Japan (Refs. 2, 3).

Modified refractory flux (MRF) welding is a one-sided welding method (Ref. 1) that features a new portable backing system designed to allow application in the field where a wide variation in root openings is typically encountered.

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Experiments (Ref. 1) found the root bead shape is crucial to the integrity of the entire groove weld because it may be related to incomplete fusion in the following fill weld. These experiments (Ref. 1) were conducted at constant joint geometry. Indications were strong that variations in joint geometry encountered in the field might have a serious effect on the shape of the root weld. Unfortunately, very little data exists describing this effect. Therefore, the objective of this investigation was to establish the relationships between the shape of the root weld and widely varied (or abnormal) joint geometry typical of the field environment, including root opening (RO), included angle (ß), root face (RF), and plate misalignment (MA). To eliminate the effect of the welding variables, the latter were kept constant. The effects produced by arc blow and tack welds were also studied.

KEY WORDS

One-Sided Welding
Submerged Arc Welding (SAW)
Carbon Steel
Thermosetting Backing Flux
Joint Geometry
Root Weld Geometry
Arc Blow
Tack Welds

Experimental Procedure

Standard two-electrode SAW equipment and a specially designed backing system used for MRF welding are described in Ref. 1. Two steel plates (17.5 mm x 305 mm x 1219 mm) were oxyfuel cut, beveled at 22.5 or 15 deg, and assembled to form a single-V-groove butt joint. To simulate joint inaccuracy typical in field erection, joint geometry was varied in a controlled setting with 0–9.5-mm root opening, 30–45 deg included angle, 0–4.8-mm root face, and 0–4.0-mm misalignment, welding variables being constant. The root welds were deposited using the leading electrode only. A layer of iron powder was placed into the groove prior to welding. The basic welding conditions are given in Table 1, except those specified otherwise.

A number of transverse specimens were cut from each weldment, including the areas affected by arc blow and tack welds. The cross section of each specimen was polished and etched to reveal the weld profile. The profile was reproduced and enlarged. To characterize quantitatively and compare the shape of different root welds, root weld geometry was defined as a combination of characteristic dimensions and cross-sectional areas, as well as the specific calculated geometric criteria. They were determined by measuring the enlarged reproductions taken from the transverse specimens, as illustrated in Fig. 4 of Ref. 1.

Results and Discussions

Effect of Root Opening

Many one-sided welding methods are used under shop conditions. These conditions are favorable because they allow the root opening to be kept as small and uniform as possible. This arrangement is one of the most important requirements for quality of the root welds and can be strictly enforced only in a shop. However, in the field (at erection stage of ship

Table 1 — Basic Welding Conditions Used for Root Welds in MRF Welding

Plate thickness T	(mm)	17.5
Joint type	single-V butt	
Included angle ß	(deg)	45 ± 5
Root opening RO	(mm)	6.4 ± 0.4
face RF	(mm)	0
Electrode diameter	(mm)	4.0
polarity (leading[a])	DCEN	
diameter	(mm)	4.0
inclination α	(deg)	15 (drag)
extension	(mm)	41 ± 3
Backing flux type	thermoset	
Iron powder height f	(mm)	11.1 ± 0.5
volume IR[b]	(%)	50 ± 2.5
Current I	(A)	600 ± 50
Voltage U	(V)	23.5 ± 0.5
Travel speed V	(cm/min)	39.6 ± 2.5

(a) Experiments were conducted using the leading electrode only. Trailing electrode (if used) operated on AC in tandem with the leading electrode.
(b) IR = F_i/F_g x 100%, where F_i is a cross section of the groove filled with iron powder and F_g is a cross section of the groove.

construction), variations in root openings may be significant.

The results presented in Part 1 of this research (Ref. 1) describe the effect of welding variables on root weld geometry obtained with a root opening of 6.4 mm. In the current study, the root opening varied from 0 to 9.5 mm. The results showed root opening is one of the most influential factors in MRF one-sided welding, comparable to current.

Root Opening vs. Groove Cross Section and Root Bead Geometry

Variations in the root opening changes the groove cross section and, thus, the amounts of filler metal deposited for the root weld and the following fill weld. Root bead geometry may also be affected, as well as root edge penetration. This situation is illustrated in the following examples:

Assume a weld is deposited in a 17.5-mm-thick, single-V-groove butt joint with included angle of 30 deg. Also, assume the root opening increases along the joint from 1.6 to 6.4 mm. As the RO increases along the joint, groove cross section (F_g) increases from 109 to 192 mm^2. In other words, 76% more metal would be needed to fill the groove.

Assume the root bead has no crown. Then, the height of the root bead is equal to the height of root fusion (h_{rf}). Assume also h_{rf} = 9.5 mm and is maintained constant, while RO varies from 1.6 to 6.4 mm. Then, the root bead cross section (F_{rb}) increases from 39 to 85 mm^2. This means 115% more metal would be required to keep h_{rf} constant.

Assume that F_{rb} = 85 mm^2, RO = 6.4 mm and h_{rf} = 9.5 mm. In production, F_{rb} remains the same because welding conditions and deposition rate are practically constant along the joint. If RO decreases to 1.6 mm, then the height of the root bead, h_{rf}, increases up to 15 mm (60%). This may have a serious impact on the shape of the root head and its fusion characteristics.

As discussed in Ref. 1, to obtain an adequate root reinforcement, the arc must first completely penetrate through the root edges. At wider root openings, lower current is needed for adequate penetration and vice versa. For example, 600 A is sufficient at RO = 6.4 mm for adequate root edge penetration, while 550 A is not. However, at RO = 3.2 mm, 700 A is sufficient, while 600 A is not.

Effect of Root Opening on Fusion Characteristics of Root Bead

This complex and current dependent effect was studied by varying the current from 600 to 900 A and the root opening from 0 to 6.4 mm. Other conditions are given in Table 1.

The root fusion height h_{rf} was found

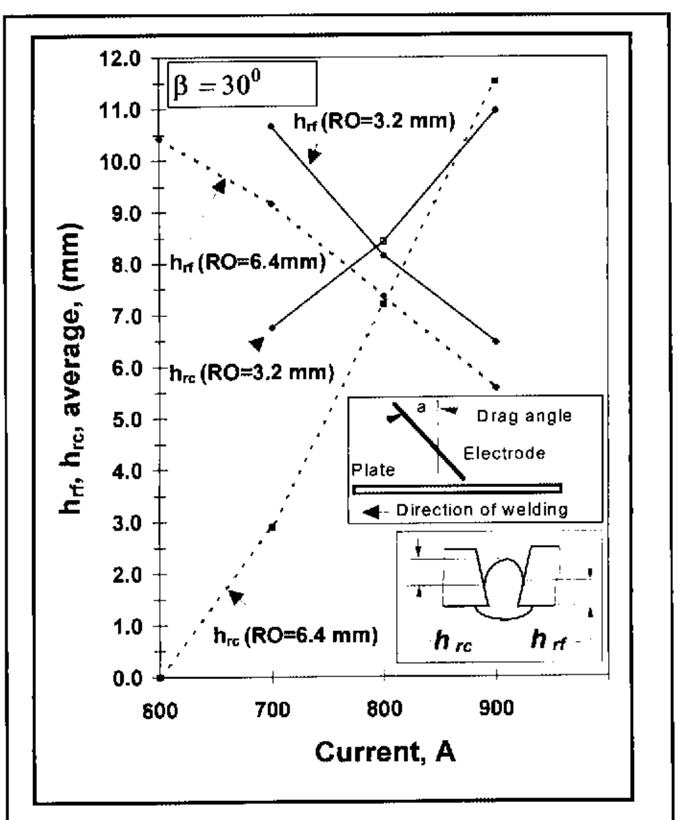

Fig. 1 — Effect of the root opening at various currents on fusion characteristics of the root bead.

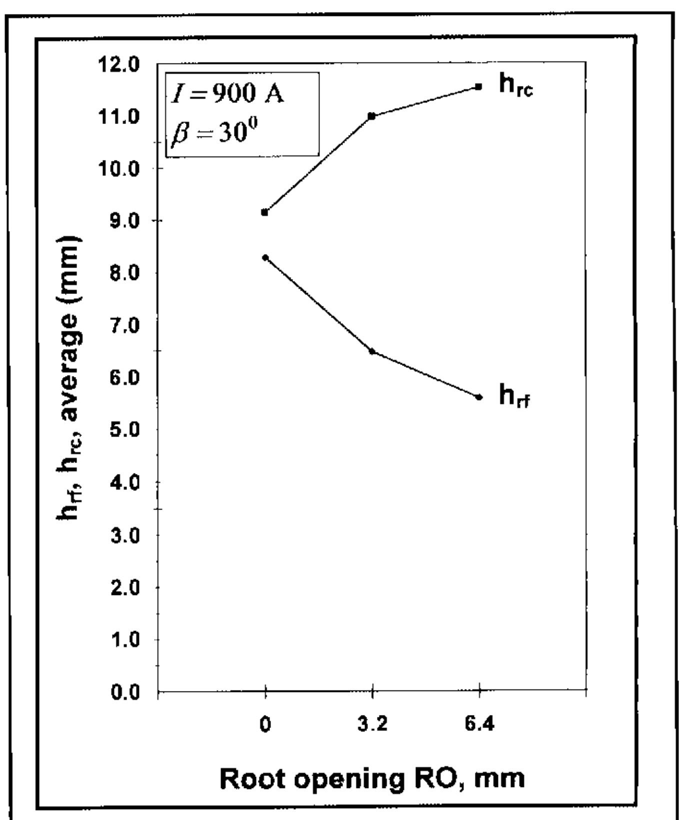

Fig. 2 — Effect of the root opening at 900 A on fusion characteristics of the root bead.

(Ref. 1) to be dependent on the current at a constant root opening. The experiments conducted in Ref. 1 at 6.4-mm root opening and 45-deg included angle showed the best root fusion is achieved at critical current I_{cr} = 600 A. As the current increased above I_{cr}, h_{rf} decreased. A similar trend was observed in this study at ß = 30 deg for both RO = 6.4 mm and RO = 3.2 mm, as illustrated in Fig. 3. (No data are shown for 600 A and RO = 3.2 mm because the root edges are not completely fused). For example, as current increased from 700 to 900 A at RO = 3.2 mm, h_{rf} decreased 39% from 10.7 to 6.5 mm.

Comparing the data for RO = 3.2 mm and 6.4 mm in Fig. 1, it is obvious that h_{rf} at RO = 3.2 mm is higher over the entire range of the current explored. For example, at 700 A, h_{rf} is higher by 16% (10.7 vs. 9.2 mm). At 900 A, h_{rf} is higher by 15%. The fact h_{rf} decreased as RO increased is illustrated in Fig. 2 for the root welds made at 900 A. Thus, root fusion deteriorates due to increased current and root opening.

The height of the root crown h_{rc} was also found to be dependent on the current at a constant root opening (Ref. 1). The experiments conducted in Ref. 1 at RO = 6.4 mm and ß = 45 deg showed that the lowest root crown and, thus, the slag pockets developed on both sides of the groove are also achieved at 600 A. As the current increased, h_{rc} also increased. That meant the slag pockets developed on both sides of the groove grew larger. If the slag pockets become too deep, the following fill weld may not remelt them and incomplete fusion may occur. A similar trend is observed in this study at ß = 30 deg for RO = 6.4 mm and 3.2 mm, as illustrated in Fig. 1. As the current increased from 700 to 900 A at RO = 3.2 mm, h_{rc} increased from 6.8 to 11.0 mm (62%).

Comparing the data in Fig. 1 for RO = 3.2 mm and 6.4 mm at 700 A, it is obvious h_{rc} at RO = 3.2 mm is much higher than for RO = 6.4 mm (6.8 vs 2.9 mm). In other words, at 700 A, wider root openings resulted in smaller slag pockets. However, at I > 700 A, this favorable trend came into conflict with the opposite trend of increased current. As a result, h_{rc} is diminished and even reversed at 900 A — Fig. 1. This reverse trend at 900 A is illustrated in Fig. 2, which shows wider root openings result in larger root crowns and deeper slag pockets. In fact, the largest crowns and the deepest slag pockets were observed in root welds deposited at RO ≥ 6.4 mm and I ≥ 900 A. For example, in the completed weld shown in Fig. 3, the root weld was made at RO = 9.5 mm and 900 A. Very deep slag pockets developed in the root weld, especially on the right side, creating incomplete fusion on the right side. Thus, if welding has to be performed at high currents, root openings less than 6.4 mm are recommended because smaller slag pockets develop. Still, lower currents are preferable because lower h_{rc} values can be obtained regardless of the root opening. Compare the lowest h_{rc} value (9.2 mm) obtained at RO = 0 and 900 A (Fig. 2) with the highest h_{rc} value (6.8 mm) obtained at RO = 3.2 mm and 700 A — Fig. 1.

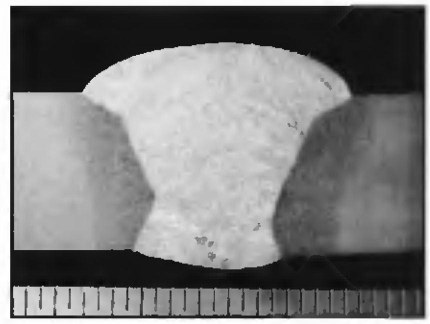

Fig. 3— A cross section of the root weld deposited at RO = 9.5 mm and 900 A. Note incomplete fusion on the right sidewall.

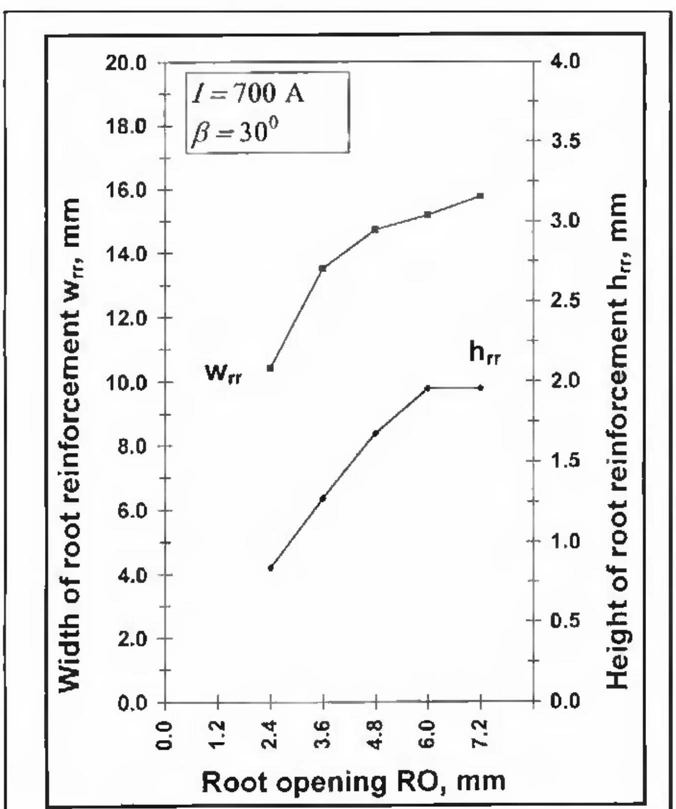

Fig. 4 — Effect of root opening on the geometry of root reinforcement.

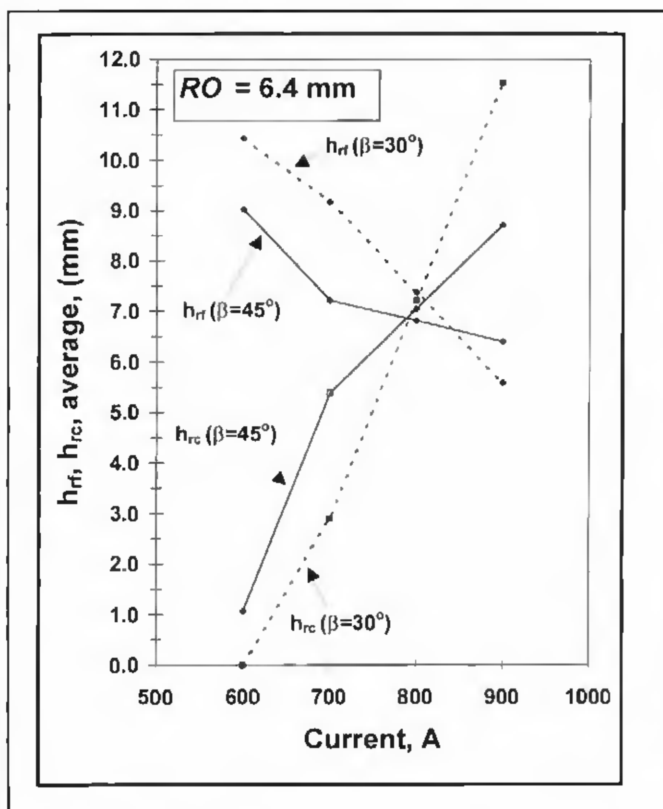

Fig. 5 — Effect of included angle at various currents on fusion characteristics of the root bead.

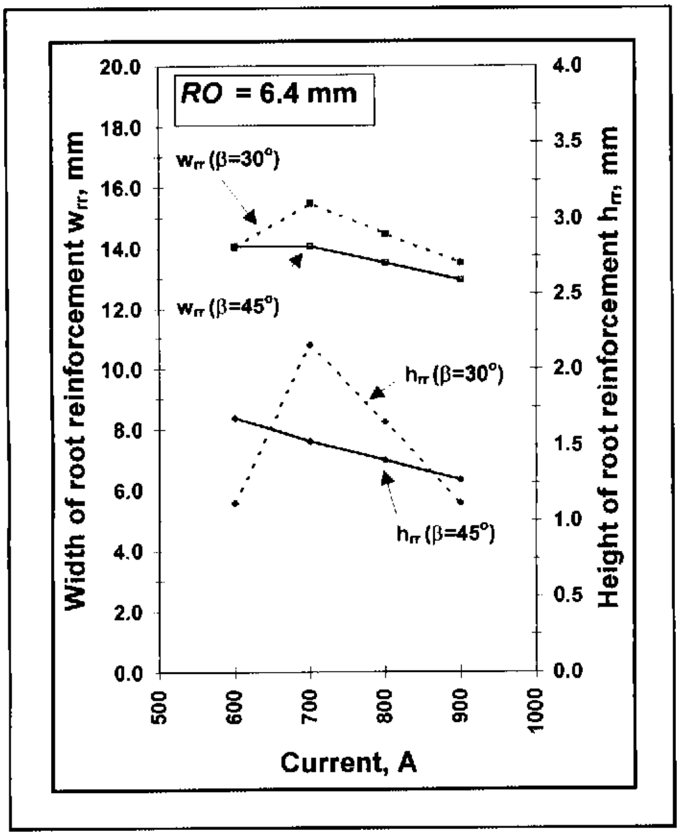

Fig. 6 — Effect of included angle at various currents on the geometry of root reinforcement.

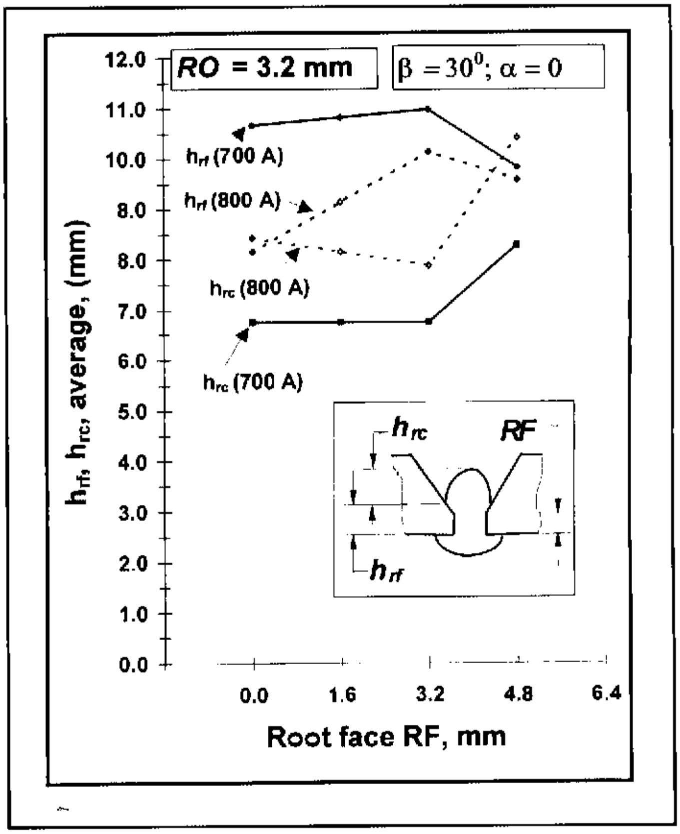

Fig. 7 — Effect of the root face at various currents on fusion characteristics of the root bead.

Effect of Root Opening on Shape of Root Reinforcement

This effect was studied by depositing the root weld in a groove with the root opening varying from 1.6 to 8.0 mm at 700 A. Other conditions are given in Table 1. The samples were cut and measured at locations corresponding to RO = 2.4–7.2 mm at an interval of 1.2 mm. The results are illustrated in Fig. 4.

The height of root reinforcement increased as RO increased — Fig. 4. This increase is beneficial because a low-profile reinforcement is typical for MRF welding. A minimum h_{rr} = 0.8 mm was considered acceptable in this study. At RO < 2.4 mm, the root edges were not sufficiently fused and no root reinforcement developed (no data are shown). A small reinforcement appeared at RO = 2.4 mm. Further increase in root openings from 2.4 to 7.2 mm resulted in h_{rr} increasing from 0.8 to 2.0 mm (133%), a trend opposite the current. As discussed in Ref. 1, h_{rr} decreased as the current increased above 700 A. Thus, h_{rr} improves due to increase of root opening and deteriorates due to increase of current.

The width of the root reinforcement w_{rr} also increased as RO increased — Fig. 4. For example, increasing the root opening from 2.4 to 7.2 mm resulted in an increase of w_{rr} from 10.4 to 15.8 mm (51%). This trend differs from that produced by increasing the current. According to Ref. 1, w_{rr} did not change much as current increased above I_{cr}.

Effect of Included Angle

In one-sided welding, including the MRF method, plates are typically beveled and assembled to form a single-V-groove butt joint with an included angle. Such joints allow better access to root edges and deeper penetration, which facilitates formation of the root reinforcement.

To study the effect of the included angle on the shape of the root weld, two series of root welds were made at 45- and 30-deg included angles. The root welds were made in V-grooves at 600–900 A, with a root opening of 6.4 mm. All other conditions are given in Table 1.

Effect of Included Angle on Fusion Characteristics of Root Beads

Figure 5 shows the effect of the included angle on the heights of root fusion (h_{rf}) and root crown (h_{rc}) Here, the graphs corresponding to the welds made at 45 and 30 deg are shown in solid and dashed lines, respectively.

The height of root fusion is affected by the included angle, but it depends on the current as well. For example, at I_{cr} = 600 A and 45 deg, h_{rf} = 9.0 mm, while at 30 deg, h_{rf} = 10.4 mm (increase of 16%). At the higher current of 700 A and 45 deg, h_{rf} is reduced from 9.0 to 7.2 mm (20%). This trend is expected at $I > I_{cr}$, as described in Ref. 1. However, by reducing the angle from 45 to 30 deg, h_{rf} can be restored from 7.2 to 9.2 mm (increase of 27%) even at 700 A. In other words, the reduction in root fusion (due to increase of the current from 600 to 700 A) can be compensated by reducing the included angle from 45 to 30 deg. In this respect, the effect of the reduction of the included angle is similar to that of increasing the inclination (drag) angle of the leading electrode described in Ref. 1. This favorable trend is diminished at a further increase in current. For example, at 800 A, the reduction of the included angle has no effect and at 900 A this trend may even be reversed in favor of the 45-deg angle.

The height of the root crown h_{rc} was reduced as the included angle decreased from 45 to 30 deg at 600–700 A — Fig. 5. This favorable trend diminished and even reversed in favor of 45 deg at further current increase.

Thus, a 30-deg included angle at lower (700 A) current is recommended because it improves the root fusion characteristics in comparison with that of 45 deg. However, if high (900 A) current has to be used, a 45-deg included angle is more beneficial.

Effect of Included Angle on Shape of Root Reinforcement

This effect is illustrated in Fig. 6. The height of root reinforcement also depends on the current. At 600 A and 45 deg, a higher h_{rr} was obtained than at 30 deg because a larger angle provides a deeper root edge penetration. However, at 700 A, 30 deg is more beneficial. In fact, the maximum h_{rr} of 2.2 mm is reached at 700 A and 30 deg. As the current increased, h_{rr} decreased at both included angles. However, it remained acceptable (> 0.8 mm) within the explored current range (600–900 A).

The width of root reinforcement did not change much as the current increased at both angles of 45 and 30 deg (Fig. 6), although it is slightly wider at 30 deg.

Effect of Root Face

In one-sided welding, plates are typically beveled with a small root face (RF) or without it. Such joints allow closer access to the root edges and deeper root edge penetration facilitates formation of root reinforcement. To study the effect of the root face on the shape of root welds produced by the MRF method, the root welds were deposited at 700 and 800 A in joints with RF = 1.6–4.8 mm. Other welding conditions are given in Table 1, except that RO = 3.2 mm, and $\alpha = 0$. The data were compared with those obtained from similar welds with RF = 0.

Effect of Root Face on Fusion Characteristics of Root Beads

This effect is illustrated in Fig. 7. The height of root fusion h_{rf} increased at both currents as RF increased from 0 to 3.2 mm. However, at RF > 3.2 mm, h_{rf} sharply decreased. Comparing welds made at 700 and 800 A, it is obvious root fusion was lower at 800 A. Thus, presence of the root face did not change the trend of h_{rf} decrease as the current increased.

The height of the root crown h_{rc} remained practically the same at both currents as RF increased from 0 to 3.2 mm. However, at RF > 3.2 mm, h_{rc} dramatically increased. In fact, at RF = 4.8 mm, the crown became so tall (h_{rc} = 60% T) it stood above the plate top surface and became uneven along the joint. Comparing welds made at 700 and 800 A, it was obvious the root crown was taller and slag pockets were deeper at 800 A. This also confirmed the trend that as the current increased, h_{rc} increased.

Thus, the root face " 3.2 mm offers no advantage at 700 A and results in unfavorable changes in the root fusion characteristics at 800 A, although deterioration is relatively minor. At RF > 3.2 mm, the root fusion characteristics deteriorated at both 700 and 800 A, namely h_{rf} decreased and h_{rc} increased.

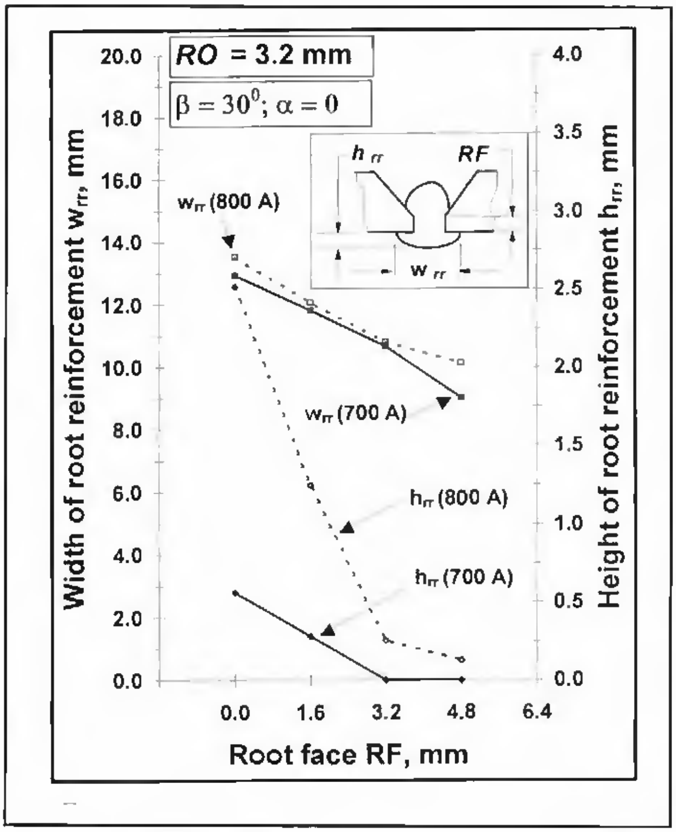

Fig. 8 — Effect of the root face at various currents on geometry of the root reinforcement.

Effect of Root Face on Shape of Root Reinforcement

It is known that root face reduces penetration through the root edges. This reduction is especially noticeable in the MRF method in which the arc operates using DCEN polarity, which is known for its low penetrating characteristic. As a result, the presence of a root face produces a detrimental effect on the root reinforcement. This effect is illustrated in Fig. 8 for welds made at 700 and 800 A.

The height of root reinforcement h_{rr} sharply decreased at both currents as RF increased from 0 to 4.8 mm. In fact, at 700 A and RF ≥ 1.6 mm, inadequate or no reinforcement was observed, although the root was completely fused. At 800 A and RF ≥ 3.2 mm, an inadequate reinforcement was formed. Better penetration may be achieved at an increase in current (900 A). However, this result is counterproductive because the crown grows extremely tall and uneven.

The width of root reinforcement sharply decreased at both currents as RF increased from 0 to 4.8 mm. For example, at 700 A, w_{rr} dropped from 12.9 to 9.0 mm as RF increased from 0 to 4.8 mm.

A

B

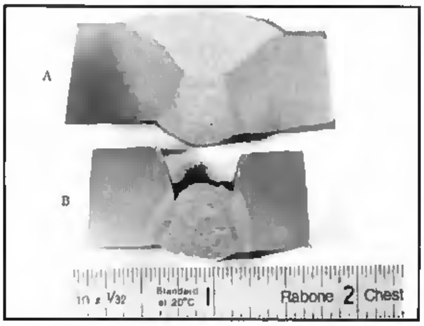

Fig. 9 — Cross sections of completed welds produced by MRF welding in 17.5-mm-thick steel. Plates assembled with root opening of 6.4 mm and misalignment. A — MA = 4.8 mm; B — MA = 2.4 mm.

In conclusion, despite moderate improvements in root fusion characteristics, the overall effect of the root face on root weld geometry cannot be considered favorable. Since considerable cost is involved in preparing a uniform root face in the field, its preparation is not recommended for MRF welding.

Effect of Plate Misalignment

Flux-backing, one-sided welding

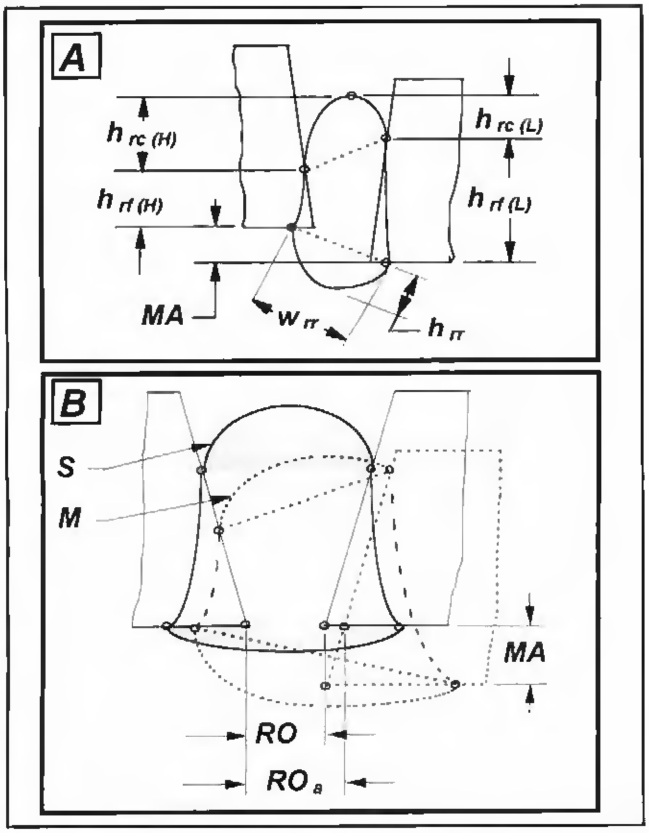

Fig. 10 — Characteristic areas and dimensions of the root weld at plate misalignment.

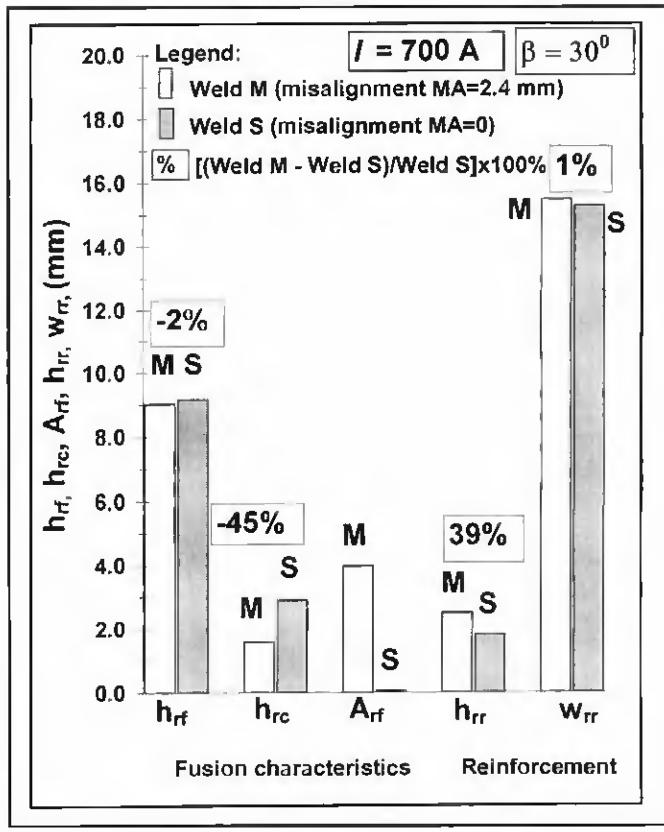

Fig. 11 — Effect of 2.4-mm plate misalignment on fusion characteristics of the root bead and geometry of the root reinforcement.

methods are known to be tolerant to misalignment (MA) of plate edges, while copper-backing methods are not. The reason is powder flux under pressure acts similar to liquid and can adjust very well to any surface. This behavior is true for the MRF welding method because the thermosetting backing flux is also powder prior to being heated by the arc.

In fact, MRF welding is very tolerant of misalignment, as illustrated in Fig. 9A. The picture shows a cross section of a completed weld made at 700 A, RO = 6.4 mm, and ß = 30 deg. It was cut from a joint that was assembled with a misalignment of 4.8 mm. (Misalignment after welding may differ slightly due to welding distortion.)

For 17.5-mm-thick plates, 4.8 mm represents a fairly large misalignment, 27% of plate thickness. The picture shows an adequate root reinforcement can be obtained in plates even if misalignment is that large. However, an analysis of root weld cross sections shows misalignment distorts the shape of the root weld, as schematically shown in Fig. 10A. Here, the root fusion characteristics on the high and low sides of the groove are identified by letters H and L, respectively.

Effect of Misalignment on Fusion Characteristics of Root Bead

This effect is illustrated on the bar chart shown in Fig. 11. The plates were assembled with misalignment of 2.4 mm (14% T). The root weld (identified as M and shown in Fig. 9B) was deposited at 700 A. Other conditions are given in Table 1. The electrode was set in the center of the groove. The data for weld M (Fig. 11) are compared with those results shown in Fig. 1 (points taken at 700 A and RO = 6.4 mm). The data in Fig. 1 correspond to a symmetrical weld (identified as S), which was made without misalignment using the same welding conditions as those conditions reported for weld M.

The height of root fusion in weld M on both sides of the groove was not even, namely, $h_{rf(H)} < h_{rf(L)}$. In other words, the high side of the groove was fused much less than the low side (7 vs. 11 mm). A comparison of asymmetrical weld M (MA = 2.4 mm) with symmetrical weld S (MA = 0) is demonstrated in Fig. 11. It shows the average heights of root fusion in both welds are almost the same (9.0 vs. 9.2 mm), the difference being only 2%. This indicates misalignment does not change the root fused area much but makes it fairly asymmetric.

The height of the root crown in weld M on both sides of the groove were not even, but the effect was the opposite, $h_{rc(H)} > h_{rc(L)}$ This behavior means the slag pocket on the high side of the groove is deeper (2.0 vs. 1.1 mm). A comparison of asymmetrical weld M with symmetrical weld S (Fig. 11) showed the average h_{rc} in weld M was smaller by 45% (1.6 vs. 2.9 mm). Thus, misalignment reduced the root crown area and the slag pockets.

Effect of Misalignment on Shape of Root Reinforcement

Misalignment distorted the shape of root reinforcement, making it asymmetric, as shown in Fig. 9. To determine the degree of distortion, the pertinent data shown (Fig. 11) for weld M (MA = 2.4 mm) were compared with those in Fig. 4 (points taken at RO = 6.4 mm). The data in Fig. 4 corresponded to the same symmetrical weld S made using the same welding conditions as those for weld M (I = 700 A, RO = 6.4 mm, ß = 30 deg, and the rest per Table 1), except that MA = 0.

The height of the root reinforcement in weld M (measured as shown in Fig. 10A) is greater (by 39%) than in weld S (2.5 vs.

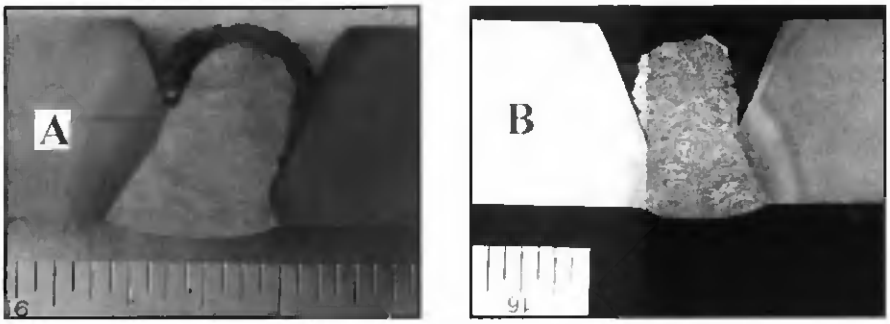

Fig. 12. — Cross sections of the root welds affected (A) and not affected (B) by arc blow (RO = 6.4 mm; I = 900 A).

Fig. 13 — A cross section of a completed weld in which the root weld was affected by arc blow (RO = 6.4 mm; I = 900 A). Note incomplete fusion on the right side of the fill weld.

1.8 mm), according to Fig. 11. Even greater h_{rr} (4.0 mm) was obtained in the weld shown in Fig. 9A (MA = 4.8 mm). Thus, h_{rr} increased as MA increased.

The width of the root reinforcement w_{rr} in welds M and S are almost the same (15.5 vs. 15.4 mm). In the weld shown in Fig. 9A, w_{rr} = 15.5 mm, too. Thus, w_{rr} did not change as MA increased.

Analysis of Root Weld Geometry

The data discussed above show plate misalignment produced noticeable changes in geometry of the root weld by 1) causing fusion asymmetry, 2) increasing the size of the reinforcement, and 3) decreasing the size of the crown and the slag pockets. The analysis of these changes, its implications and possible explanations, are discussed below and illustrated in Figs. 10A and B.

Root fusion asymmetry A_{rf} and A_{rc} developed in the root weld as a result of misalignment. (For A_{rf} and A_{rc} definitions, see Fig. 10.) Assume root weld S is made in a joint with constant root opening and no misalignment. It is shown in Fig. 10B by solid lines. The weld is symmetrical, that is

$$h_{rf(H)} = h_{rf} = h_{rf(L)} \text{ and } h_{rc(H)} = h_{rc} = h_{rc(L)}$$

Assume also a portion of the joint is assembled with misalignment while RO remains the same. The resulting weld M (shown in Fig. 10B by dashed lines) became uneven, that is

$$h_{rf(H)} < h_{rf} < h_{rf(L)} \text{ and } h_{rc(H)} > h_{rc} > h_{rc(L)}$$

In other words, symmetrical weld S developed asymmetry of root fusion A_{rf} = 4 mm (23% T), as illustrated in Fig. 11. The root crown developed much smaller asymmetry, A_{rc} = 0.9 mm (5% T). Obviously, the root-fused area in weld M was reshaped at the top, as if the deposited metal flowed toward the low side of the groove. The effect produced by misalignment seems similar to that of electrode offset in the same direction (toward the low side). As a result, the following fill weld may be susceptible to incomplete fusion on the high side of the groove. For this reason, the electrode should be shifted toward the high side if the plates are assembled with misalignment.

The height of root reinforcement increased due to misalignment, which is a favorable trend for MRF welding. One of the reasons may be the following:

If plates are assembled with a root opening, the actual root opening (RO_a) increases due to misalignment MA — Fig. 10B. For example, if MA = 3.2 mm and RO = 6.4 mm, then RO_a = 7.2 mm (13% increase). Once the root opening increased, h_{rr} increased, according to Fig. 4.

The size of the root crown and the slag pockets decreased due to misalignment, which is a favorable trend. A possible reason may be that the cross section of the deposited metal (root crown, fused area, and reinforcement) along the same root weld is constant because the deposition rate is constant. Since the root reinforcement becomes larger due to misalignment, this increase may occur at the expense of the root crown (and possibly root-fused area to a lesser degree).

Effect of Arc Blow

Arc Blow Phenomenon in MRF Welding

Arc blow is expected in MRF welding because the root weld is deposited using DC current. Figure 12A shows a cross section of the root weld affected by arc blow cut from the end portion of the joint. The centerline of the crown and the groove are practically in line in this weld. This situation indicated the electrode was in the center of the groove. However, the arc was severely deflected to the left side at the bottom of the groove. As a result, the height of root fusion measured on the left side was higher than that on the right side. The opposite was true for the height of the root crown, which developed a much deeper slag pocket on the right side of the groove. This behavior means arc blow causes asymmetry of the root bead. The asymmetry makes the following fill weld more susceptible to incomplete fusion because it may not reach the bottom of the deepest slag pocket, as illustrated in Fig. 13.

In contrast, Fig. 12B shows a cross section of the root weld made using the same welding conditions cut from the central portion of the joint and not affected by arc blow. It was evident the root bead was fairly symmetrical in the groove and, thus, less sensitive to incomplete fusion.

The following were noticed during the experiments:

1) Root bead asymmetry was typically greater near tack welds and at the ends of the joint, where arc blow is known to occur most frequently.

2) It was typically greater at higher current and voltage, which are known to intensify arc blow.

3) It was absent when AC was used with the leading arc. Thus, a severe root bead asymmetry may serve as an indirect indication of arc blow during welding.

Effect of Arc Blow on Fusion Characteristics of Root Weld

This effect is illustrated on a bar chart shown in Fig. 14. Here a cross section of a root weld affected by a severe arc blow (Fig. 12A, identified as no. 1) was measured. The root weld was made at 900 A and the included angle was 45 deg. Other welding conditions are given in Table 1. Similar data for the root weld made under the same welding conditions, but not affected by arc blow (Fig. 12B, no. 2), are given for comparison.

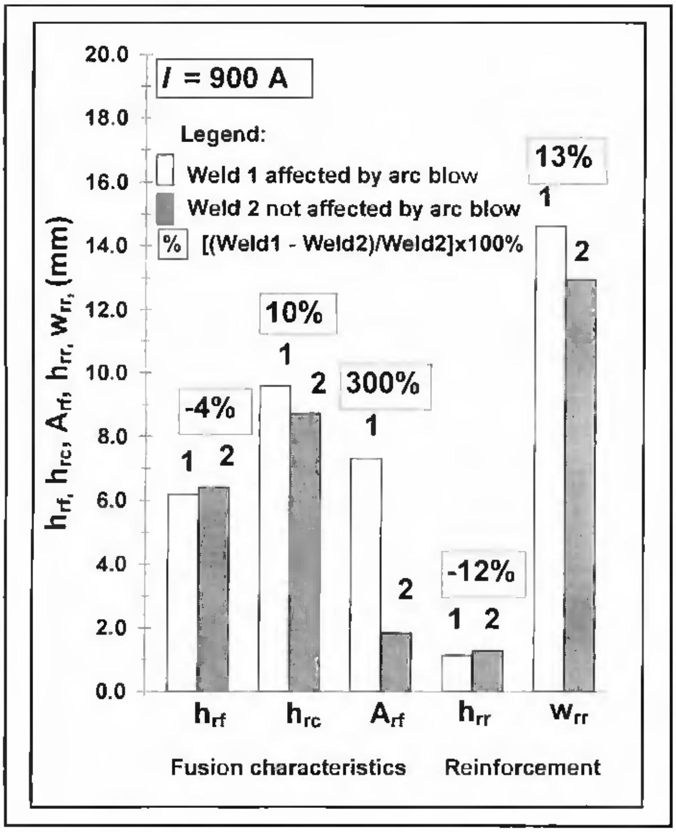

Fig. 14 — Effect of arc blow on fusion characteristics of the root bead and geometry of the root reinforcement. 1 — Root weld affected by arc blow; 2 — root weld not affected by arc blow. Percentage is the difference between 1 and 2.

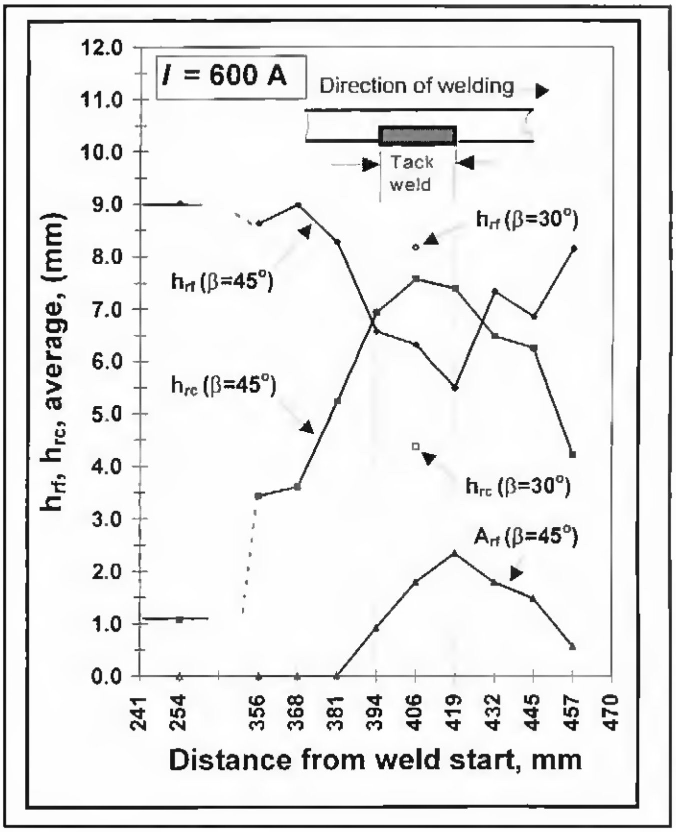

Fig. 15 — Fusion characteristics of the root bead in the tack weld affected zone (TWAZ).

Weld 2 is slightly asymmetrical due to a normal small offset of the electrode or slight lack of straightness of the root edges along the joint.

The height of root fusion measured on the left and the right sides of the groove in root weld 1 affected by arc blow was extremely uneven (9.8 vs. 2.5 mm). This result is obvious from Fig. 12A. The arc blow caused the arc to favor the left side of the groove in weld 1. As a result, the right sidewall was not fused adequately, in contrast to weld 2, where both sides fused fairly evenly — Fig. 12B. However, according to Fig. 14, the average height of root fusion measured in root welds 1 and 2 was almost the same (4% difference in favor of weld 2).

The height of the root crown, measured on both sides of the groove in root weld 1 was also uneven — Fig. 12A. As a result, an extremely deep slag pocket was formed on the right sidewall. To remelt the slag pocket reliably with the following fill weld may not be possible without melting through the entire root weld. Despite that, the root crown was extremely uneven in weld 1, the average height of the root crown did not differ much from that in weld 2 (10% in favor of weld 1), according to Fig. 12.

Root bead asymmetry developed as a result of arc blow. For example, root fusion asymmetry (A_{rf}) in weld 1 was significant (7.3 mm or 62% T). Such high A_{rf} can be categorized as severe in comparison with that developed as a result of misalignment (23% T) described earlier. Comparing root welds 1 and 2 (Fig. 14), it is obvious A_{rf} differs dramatically (by 300%) in favor of weld 1.

Besides arc blow, other factors may also cause root bead asymmetry, including misalignment, electrode offset, or lack of straightness of the root edges. These factors may reduce or increase the effect of arc blow depending on the direction of each phenomenon. What makes the effect of arc blow different is it develops locally (at tack weld), and it is much more severe. In any case, arc-blow prevention measures, a strict control of electrode offset, and plate edge straightness are required for root welds in MRF welding.

Effect of Arc Blow on Shape of Root Reinforcement

Comparing the height and width of the root reinforcements in root welds 1 and 2, it is evident there is no dramatic difference, according to Fig. 14. Weld 1, affected by arc blow, was slightly shallower and wider. Arc blow did not affect the shape of the root reinforcement or its appearance. They remained as good as in welds not affected by arc blow. This makes arc blow a treacherous phenomenon because its effect is difficult to recognize during or after welding. However, there are some visual signs that may manifest this phenomenon. For example, sudden erratic fluctuations of arc voltage and current may be the indications of arc blow. Also, after severe arc blow, the root reinforcement may deviate from straight line and make a relatively sharp local zigzag.

Effect of Tack Welds

All one-sided welding methods are sensitive to tack welds, including MRF welding. Normally, the shape of the root weld along the joint remains uniform, except for small deviations resulting from fluctuations of welding variables and joint geometry. However, this is not true when the arc approaches a tack weld.

Tack weld phenomenon was observed when the arc approached and passed over a tack weld. In MRF welding, the shape of the root weld in areas above and around the tack weld are severely affected and differ from the rest of the weld. These areas will be called the "tack weld affected zone" (TWAZ) to facilitate the discussion below.

A tack weld affects the root weld directly because it is remelted by the leading arc and integrated into the root weld. However, the following fill weld is also affected despite the fact the root weld solidifies and takes shape before the trailing arc has reached it. This effect is indirect and manifests itself through development of internal defects in the fill weld. Thus, the entire weld may be affected by tack welds. The effect of tack welds on the shape of the root weld was found to be extremely detrimental.

The experimental procedure for studying the TWAZ was as follows:

A root weld was deposited at 600 A to produce the best shape. Other welding conditions are given in Table 1, except the included angle was 45 deg. The plates were assembled with a root opening of 6.4 mm using tack welds deposited by GMAW on a copper bar. The tack weld was 6.4 mm thick and 25 mm in length. The backside of each tack weld was ground flush with the plates. The tack weld started at a distance of 394 mm from the start of the joint and ended at 419 mm. The root weld containing the tack weld was cut out. It was sectioned transversely every 13 mm along the joint and the weld cross sections were measured. The obtained data are plotted on graphs shown in Figs. 15 and 16. A regular root weld not affected by the tack weld was cut for comparison. Its cross section was located at 254 mm or 140 mm ahead of the tack weld relative to the direction of welding.

Effect of Tack Welds on Root Fusion Characteristics

The effect is shown in Fig. 15. Typically, cross sections of a regular (unaffected) root bead outside of the TWAZ were uniform along the joint. The fusion characteristics of the weld taken at 254 mm are the height of root fusion = 9 mm, the height of the root crown = 1.1 mm, and the asymmetry of root fusion = 0. These characteristics changed dramatically in the TWAZ. The difference in the TWAZ is best characterized at the start, the extreme point, and the end.

The height of root fusion began to decrease suddenly at 368 mm, namely, ahead of the tack weld. The maximum deterioration of root fusion occurred at the end of the tack weld, where h_{rf} dropped from 9 to 5.5 mm (a decrease of almost 40%). After having reached the minimum, h_{rf} rose to that of the regular root bead. This behavior happened at some distance behind the tack weld.

The height of the root crown rose suddenly ahead of the tack weld. This was the true beginning of the TWAZ. The highest root crown developed in the middle of the tack weld. Here, h_{rc} rose dramatically, from 1.1 to 6.5 mm (increased by a factor of six). After that, it decreased to that of the unaffected root bead at some distance behind the tack weld.

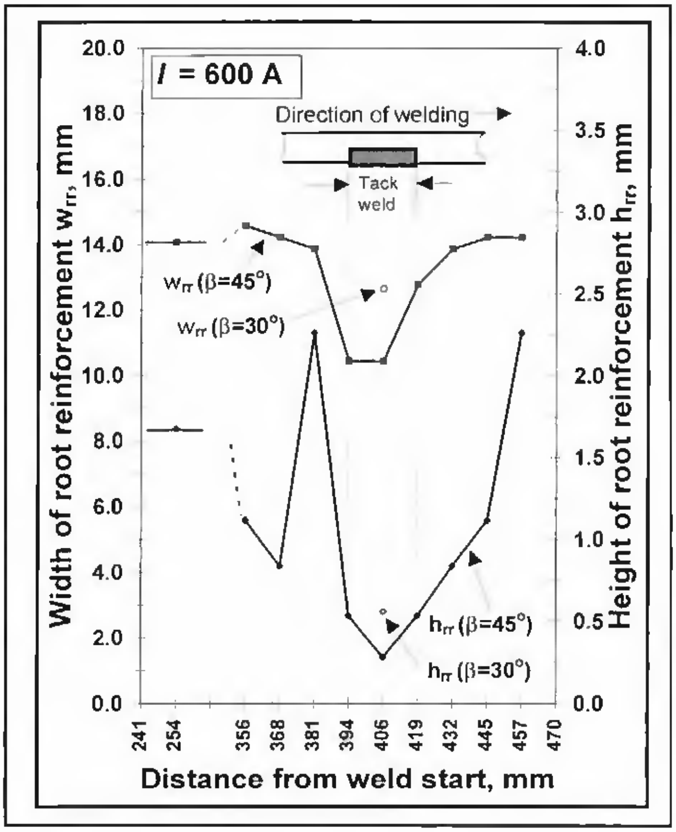

Fig. 16— Geometry of the root reinforcement in the tack weld affected zone.

The asymmetry of root fusion appeared suddenly at 381 mm, that is, 13 mm ahead of the tack weld. The regular root weld ahead of this point fused evenly on both sides of the groove (A_{rf} = 0). Then, a sudden event took place that changed this uniform fusion pattern and caused asymmetry of root fusion. A_{rf} reached the maximum (2.3 mm) at the end of the tack weld (at 419 mm). After the arc passed the tack weld, the asymmetry decreased and disappeared. Such an uneven fusion of the sidewalls of the groove within the length of the tack weld can be developed only by a sudden deflection of the arc, caused by a phenomenon like arc blow. The implication is the following fill weld could be susceptible to incomplete fusion in the TWAZ.

Effect of Tack Welds on Shape of Root Reinforcement

This effect was found to be especially detrimental, as illustrated in Fig. 16. Normally, the height and width of root reinforcement outside of the TWAZ were fairly uniform along the joint. In the TWAZ, they changed significantly. Also, sudden zigzags of root reinforcement in the vicinity of the tack weld may be observed due to arc blow provoked by the tack weld.

The height of the root reinforcement was changed in the TWAZ in a peculiar way. At first, it formed a dent at 368 mm and then a bump at 381 mm, both of which looked like a "wave" ahead of the tack weld. In the dent, h_{rr} suddenly dropped from 1.7 mm (in the regular weld) down to 0.8 mm (50% drop). In the bump, h_{rr} abruptly rose up to 2.3 mm (increase by 36%). After the bump, h_{rr} dropped sharply again in the middle of the tack weld, down to 0.3 mm (a huge 84% drop due to lower arc penetration). Then, h_{rr} gradually increased to the regular height.

The width of the root reinforcement was also affected negatively. When the arc approached the tack weld, w_{rr} decreased. The minimum was reached in the middle of the tack weld, where w_{rr} = 10.4 mm (vs. 14.1 mm in the regular weld). Then, w_{rr} increased gradually to the regular width.

Mechanism of Detrimental Effect of Tack Welds

As described above, a tack weld produced negative effects on the root weld geometry, namely, it deteriorated the root fusion characteristics, decreased the size of the root reinforcement, and caused root fusion asymmetry. The reason for this behavior is that the effect of a tack weld on the weld pool and the arc is similar to combined effects produced by increasing the amount of iron powder and arc blow.

The effect of iron powder was similar to that of a tack weld because each reduced the root edge penetration and, thus, impaired the shape and size of the root reinforcement. In fact, a 6.4-mm-thick tack weld placed in a groove with a 30-deg angle and 6.4-mm root opening occupies a cross-section area of 51 mm². The same amount (by weight) of iron powder would occupy a cross-section area of 132 mm² due to lower density. This situation is equivalent to IR = 68%. (IR is the percentage of the groove cross section occupied by iron powder.) Most of the experiments described above were conducted at optimal IR = 50%, the height of iron powder being 11.1 mm. This means a 4.8-mm layer of iron powder covering a 6.4-mm-thick tack weld is the equivalent of extra IR = 32%. Thus, IR over the tack weld jumps suddenly from 50 to 100%. According to Ref. 1, the height and width of the root reinforcement drop dramatically at IR = 100%. If the 4.8-mm-thick layer of iron powder is removed from only the tack welds, h_{rr} and w_{rr} improve, but not much, because IR is still 68%. However, this improvement is not practical and can be risky because a melt-through can occur at the border between iron powder and the tack weld.

The mechanism of the wave (dent and bump) formation in the root reinforcement ahead of the tack weld is not fully understood. Possibly, the stable flow of the weld pool is disturbed when a sizeable amount of extra metal is suddenly thrown into the tail portion of the pool.

Arc blow may be provoked by the tack weld when the arc approaches it. Thus, a tack weld may be responsible for root fusion asymmetry. The reason is, during welding, the current flows through the plates assembled with a root opening (a gap), which creates magnetic fields during welding (Ref. 4). The magnetic lines behind the arc go through solidified weld metal. The magnetic lines ahead of the arc have to cross the air gap. This situation creates a constant imbalance of the magnetic field and a resulting force deflects the arc. Since the deflection is constant, the arc does not deviate from its initially selected path along the joint. However, when the arc approaches a tack weld, more and more lines, which previously crossed the air gap, go through metal. As a result, the new imbalance deflects the arc from its initial path. When the tack weld is consumed, the lines cross the air gap again and the arc returns to its initial path.

Effect of Other Variables and Factors on TWAZ

Welding variables and groove geometry may affect the shape of regular root welds for better or worse, as discussed in Ref. 1. In a similar fashion, they may influence the harmful effect produced by tack welds in the TWAZ.

Decreasing the included angle from standard 45 to 30 deg produces a positive effect on fusion characteristics of a regular root bead made at 600 and 700 A, as was shown in Ref. 1. This result is true for the TWAZ, as illustrated in Fig. 15, where the data are presented for welds made at 45 deg and 600 A. Two extra points are plotted on the graph for comparison. These data were obtained from a weld made at equal welding conditions, except the angle was 30 deg and the current was 700 A. The weld was cut in the middle of a tack weld. These extra points show the root fusion in the TWAZ is improved at 30 deg and 700 A, namely, h_{rf} is higher while h_{rc} is lower, despite the increase in the current. Similar improvements are seen in the shape of the root reinforcement — Fig. 16.

Effect of tack weld's size on the TWAZ is direct. The larger the cross section of the tack weld, the more pronounced negative effect it has on the root weld geometry. Thus, the tack weld size should be minimized, depending on the welded structure and its material. In heat-sensitive steel, local preheating would be useful to allow the use of smaller tack welds, while avoiding HAZ cracks, if smaller tack welds would be adequate to support a particular structure during assembly.

Conclusions

This study makes the following conclusions:

1) The root opening (RO) produces a mixed effect on the shape of the root bead. As the RO increases, the effect is harmful for root fusion regardless of the current because the height of root fusion (h_{rf}) decreases. As far as the height of root crown (h_{rc}) is concerned, the effect depends on the current. Increasing RO is beneficial at lower currents ($I \leq 700$ A) because the root crown and, thus, the slag pockets grow smaller. However, at $I > 700$ A, this favorable trend comes into conflict with the opposite trend produced by the increase of the current, which prevails. As a result, the slag pockets grow deeper. Still, lower h_{rc} values are obtained at lower current regardless of RO. An increase in RO produces a beneficial effect on the shape of the root reinforcement because its height (h_{rr}) and the width (w_{rr}) increase.

2) The included angle (ß) produces a moderate effect on the shape of the root weld, but this effect depends on the current. A moderate improvement in root head fusion can be obtained by reducing the angle from 45 to 30 deg, but only in a narrow current range (I = 600–700 A). Thus, 30 deg is more beneficial with lower currents, while 45 deg is more beneficial with higher currents. The best root reinforcement is obtained also at 700 A and 30 deg.

3) The effect of the root face (RF) on the root fusion characteristics is marginally favorable until RF reaches 3.2 mm. At a further increase of RF, the root fusion characteristics deteriorate, namely, h_{rf} decreases and h_{rc} increases. As RF increases, both the height and the width of the root reinforcement sharply decrease. At RF ≥ 3.2 mm, the arc does not penetrate at all through the root edges (at 700 A) or penetrates inadequately (at 800 A). Since the root face preparation in the field incurs extra costs and is associated with some difficulties, it is not recommended for MRF welding.

4) Plate misalignment (MA) produces noticeable changes in geometry of the root weld by causing fusion asymmetry, decreasing the size of the crown (and the slag pockets) and increasing the size of the reinforcement. The shape of the root bead on the high side of the groove deteriorates in comparison with those in similar welds without misalignment, while that on the low side actually improves. As a result, the high side may be more susceptible to incomplete fusion in the following fill weld. To avoid this situation, the electrode should be offset toward the high side if the plates are assembled with misalignment. The appearance of root reinforcement is not negatively affected, even at 4.8 mm misalignment.

5) Arc blow is especially detrimental in MRF welding. Arc blow affects average fusion characteristics of the root head very little, but causes severe asymmetry of root fusion (A_{rf}). As a result, a very deep slag pocket may be developed locally on one or another side of the groove. Such a weld is more difficult to complete without incomplete fusion or slag inclusions. In this respect, arc blow prevention measures, and stricter control of electrode offset and root edge straightness are required for MRF welding. Surprisingly, arc blow does not negatively affect the shape of the root reinforcement or its appearance.

6) A tack weld produces a highly detrimental effect on the shape and fusion characteristics of the root weld. It represents an abrupt and undesirable change in groove configuration. In the tack weld affected zone (TWAZ), root fu-

sion deteriorates, root crown grows larger, and root fusion asymmetry occurs, making the following fill weld vulnerable to incomplete fusion. The effect of tack welds on the root reinforcement is especially harmful. Its height and width decrease, and its appearance becomes irregular and less attractive in the TWAZ. The larger the thickness and length of the tack weld, the more harmful its effect on root weld geometry.

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Appendix

h_{rf} = height of root fusion
h_{rc} = height of the root crown (slag pocket)
h_{rr} = height of root reinforcement
w_{rr} = width of root reinforcement
A_{rf} = root fusion asymmetry
A_{rc} = root crown asymmetry
ß = included angle
I = current
I_{cr} = critical current
MA = misalignment
MRF = modified refractory flux
RO = root opening
RF = root face
TWAZ = tack weld affected zone
IR = percentage of groove cross section occupied by iron powder
T = plate thickness

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