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TECHNICAL NOTE

Vaporization of Mn Element in Electron Beam Weld Metals of Fe-Mn Binary Steels†

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KEY WORDS: (Vaporization) (Manganese) (Electron Beam Welding) (Weld Metals)

In recent years electron beam (EB) welding has often been performed on high strength steels containing a considerable amount of manganese (Mn) and on high Mn austenitic stainless steels such as Fe-21Cr-6Ni-9Mn[1]. Moreover, it is well known that Mn, one of the main alloying elements, is liable to evaporate during EB welding of steels[2]. There are, however, few systematic data on the vaporization of Mn and its effect on weldability and the formation of defects such as spikes, concavity, porosities, etc.

Therefore, in this fundamental study, the evaporated Mn contents in EB weld metals were investigated with the help of the XMA (X-ray micro-probe analyser) by using five kinds of Fe-Mn binary steels. The effect of the Mn content on the morphology of the EB fusion zones was also examined.

The Mn contents in Fe-Mn steels were about 0.51, 2.17, 5.34, 10.3 and 20.1 wt%. EB spot and bead welding were conducted on plates of about 15 mm thickness at t(spot time) = 0.3, 0.5, 1, 2 and 5 sec and v_b (welding speed) = 200, 400 and 1,000 mm/min, respectively, under the welding conditions of V_b (acceleration voltage) = 150 kV, I_b (welding current) = 20 mA and a_b (active beam parameter) = 1.0 ($a_b = D_O/D_F$; D_O: object distance, D_F: focal length). A vacuum of less than 1×10^{-4} mmHg was maintained during welding.

Figure 1 shows schematic examples of cross-sectional morphology of EB fusion zones in Fe-Mn steels with different Mn contents after spot welding. Penetration depth (h_p), fusion zone diameter (d_s) and concavity depth (d_c) are expressed as numerals in mm. **Figure 2** indicates the effect of Mn on h_p, d_s and penetration-to-diameter ratio (h_p/d_s) of fusion zones at t = 0.3 – 5 sec in spot welding. As might be expected, with an increase in spot time both penetration depth and fusion zone diameter increase, and the penetration-to-diameter ratio approaches the value of 1. Moreover, in the Mn content range of about 0.5 to 5% the morphology of penetration is very similar, but above 5%, weld penetration significantly

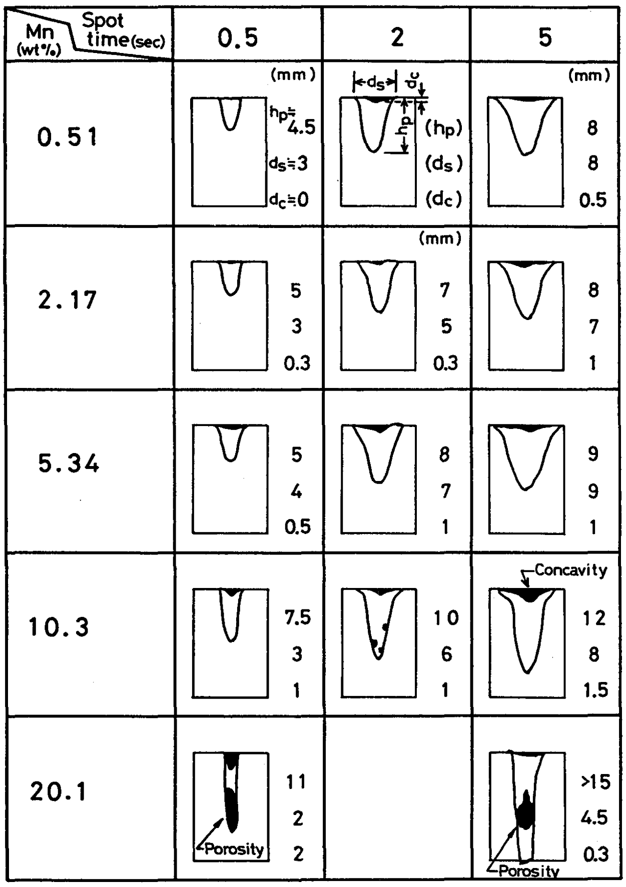

Fig. 1 Schematic morphology of electron beam weld nuggets in Fe-Mn steels containing 0.51, 2.17, 5.34, 10.3 and 20.1 wt% Mn at spot time of 0.5, 2 and 5 sec, and numerals meaning penetration depth, spot weld diameter and concave depth.

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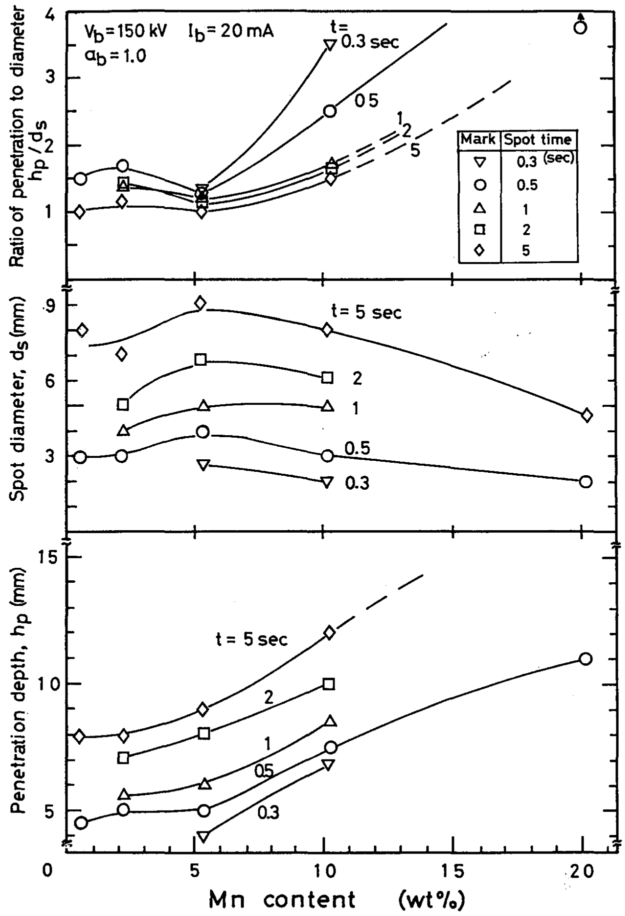

Fig. 2 Effect of Mn content on penetration depth, fusion zone diameter and penetration-to-diameter ratio of Fe-Mn steels in electron beam spot welding.

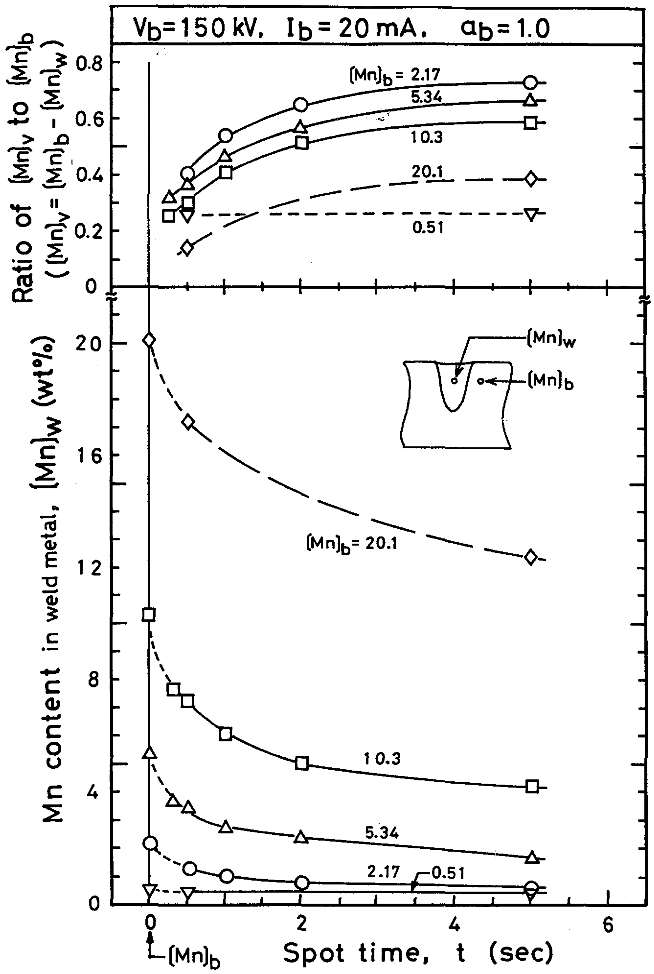

Fig. 3 Variation in Mn content in weld metal and ratio of evaporated Mn content to initial Mn content in base metal with time in spot welding of Fe-Mn steels.

becomes deeper with an increase in the Mn contents.

From a multiple linear-regression analysis of the 17 data shown in Fig. 2, the equation to predict penetration depth (h_p) of spot weld nugget was obtained as follows:

$$h_p = 5.15\,[\mathrm{Mn}]_b^{0.194}\,t^{0.228}\ (\mathrm{mm}) \qquad (1)$$

where $[\mathrm{Mn}]_b$ is Mn content (wt%) in each base metal and t is spot time (sec).

Then the standard deviation (σ) and the correlation coefficient (R) are 1.2 mm and 0.87, and thus the penetration will be roughly estimated by the equation (1).

Weld surfaces are characterized by their concave shape in spot welding, and the degree of the concavity increases as the Mn contents increase. Porosities were realized at 10.3% Mn and t = 2 sec, and at 20% Mn and t = 0.5 and 5 sec. Therefore, it should be noted that porosities are liable to form in EB spot welding of high Mn steels.

Mn contents in EB weld metals were investigated by the XMA method. **Figure 3** exhibits a summary of XMA results on Mn contents in EB spot weld metals. As spot time passes in the range of 0.3 or 0.5 to 5 sec, the Mn contents in weld metals decrease gradually down to about 0.4, 0.6, 1.8, 4.2 and 12.4% at t = 5 sec from the contents in base metals of 0.51, 2.17, 5.34, 10.3 and 20.1%, respectively; and therefore the evaporated Mn contents ($[\mathrm{Mn}]_v = [\mathrm{Mn}]_b - [\mathrm{Mn}]_w$) are larger at larger contents of Mn (where $[\mathrm{Mn}]_b$ and $[\mathrm{Mn}]_w$ are Mn content in base metal and in weld metal, respectively). Moreover, the tendency of Mn contents lost with the lapse of time is similar except for 0.51% Mn; however, the Mn losses are about 15 to 40% at t = 0.5 sec and 25 to 70% at t = 5 sec, and the degree of the evaporated ratio of Mn contents is greater than at lower contents of Mn in the range of 2 to 20%.

The equation to predict Mn content (wt%) in spot weld metal ($[\mathrm{Mn}]_w$) was obtained from a multiple linear-regression analysis of the data shown in Fig. 3 as follows:

$$[\mathrm{Mn}]_w = 0.386\,[\mathrm{Mn}]_b^{1.186}\,t^{-0.267}\ (\mathrm{wt\%}) \qquad (2)$$

where $[Mn]_b$: Mn content in base metal (wt%),
t: spot time (sec).

$[Mn]_b$ and t are in the range of 2.17 to 20.1% and 0.3 to 5 sec, respectively, (except for 20.1% at t = 5 sec). The standard deviation and the correlation coefficient are about 0.31% and 0.998. Consequently this equation is regarded as sufficient expression in predicting the Mn content in EB spot weld metal.

Figure 4 indicates schematic cross-sectional morphology of EB weld beads in Fe-Mn steels. Penetration depth (h_p), bead width (d_B) and convexity height (h_c) are expressed in mm. Penetration depth and bead width apparently increase with a decrease in welding speed. In addition an increase in Mn content has an effect of making weld penetration deeper and bead width a little narrower. In EB bead welding, weld surfaces are characteristic of convex shape, which is different from the feature of EB spot weld surfaces. The degree of the convexity increases with increasing Mn contents.

Figure 5 shows the effect of welding speed on Mn content in weld metals after EB bead welding and evaporated loss ratio of Mn. The reduced Mn content is observed to be in the range of 0.4 to 0.9% at v_b = 1,000 mm/min and 0.6 to 1.3% at v_b = 200 mm/min and to increase with a decrease in welding speed, and its degree is greater as Mn content is larger. On the other hand the loss ratio is in the range of about 5 to 17% at v_b = 1,000 mm/min and 7 to 28% at v_b = 200 mm/min, and contrary to the case of the decreased Mn content, the degree of the reduced ratio is greater at lower contents of Mn in the range of 2.17 to 20.1%. Moreover, it is found by comparing Fig. 5 with Fig. 3 that the evaporated Mn contents in bead welding are apparently smaller than those in spot welding.

From all the above-mentioned results it is confirmed that Mn is very liable to evaporate during EB welding, especially in spot welding. It is revealed in EB spot and bead welding that the evaporated amount or weight of Mn increases with an increase in Mn content in base metal but on the contrary that the ratio of the evaporated Mn

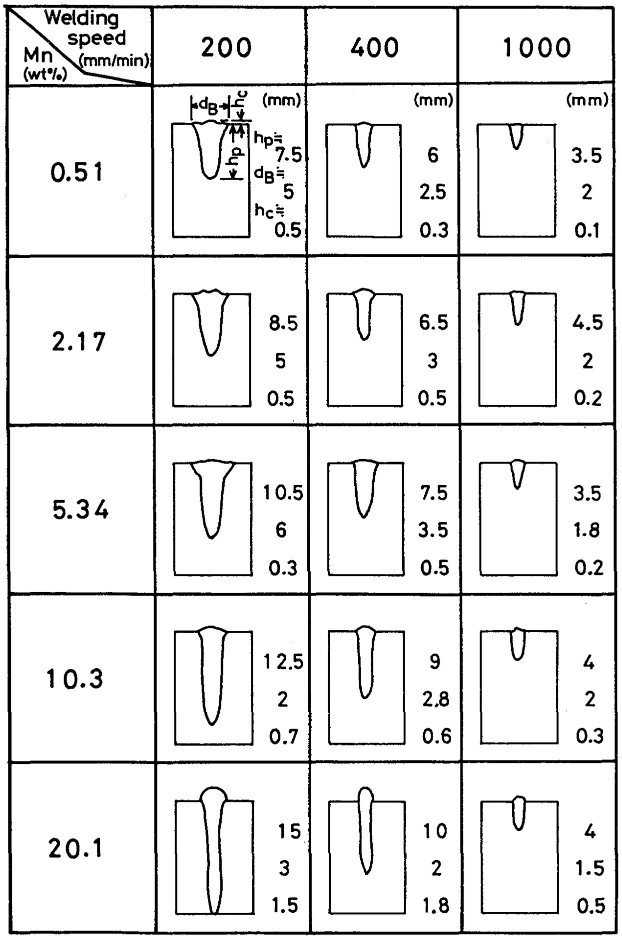

Fig. 4 Schematic cross-sectional morphology of weld beads in different Fe-Mn steels after electron beam bead welding at speed of 200, 400 and 1,000 mm/min.

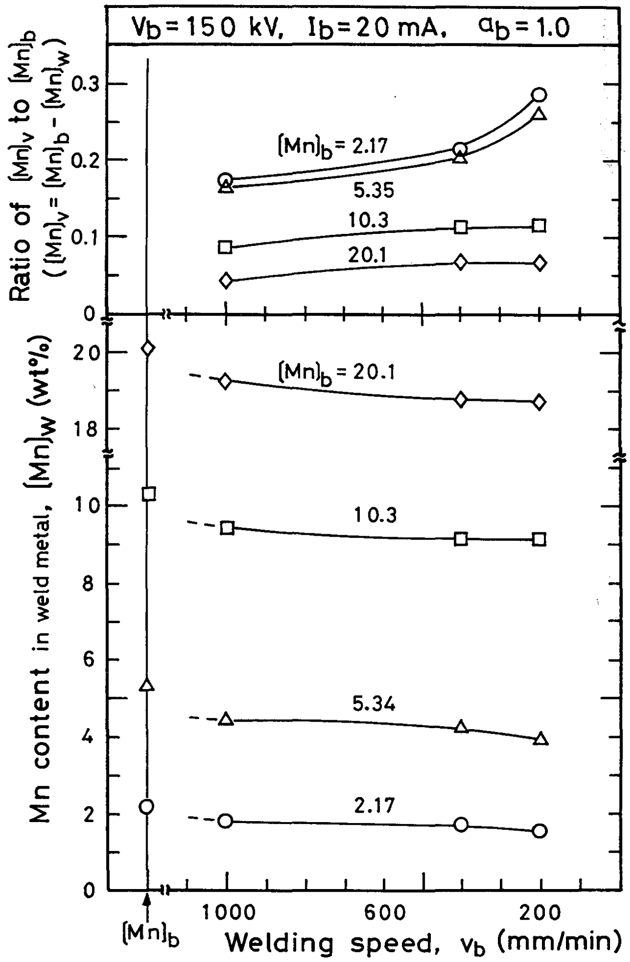

Fig. 5 Effect of welding speed on Mn content in weld metal and ratio of vaporized Mn content to initial Mn content in electron beam bead welding of various Fe-Mn steels.

content to the initial Mn content in base metal becomes smaller with an increase in the initial Mn content in the range of about 2 to 20%. An increase in Mn content is conducive to deeper penetration, in particular, above 5% Mn. It was noted that porosities were brought about in EB spot weld metals of high Mn steels.

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