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Electron Beam Welding with Activating Flux †

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Abstract

The effect of activating flux in electron beam welding was investigated, and the activating electron beam welding (A-EBW) was proposed. Results clearly showed that activating fluxes affected the penetration capability of electron beam welding for stainless steels. Significant improvement in penetration was observed when electron beam welding was performed both in the conduction mode and the keyhole mode. One of the most likely reasons for the penetration improvement is that the oxygen content through the flux in the weld pool plays an important role in increasing the weld penetration by the reversing of the surface tension gradient in the weld pool from a negative value to a positive value. The change in the surface tension gradient in the weld pool is considered to be the principal mechanism for increased penetration of electron beam welding.

KEY WORDS: (Activating fluxes), (Electron Beam), (Welding)

1. Introduction

Improvement in penetration capability has long been sought in many welding processes. One of the most notable examples is the application of activating flux in tungsten inert gas welding (A-TIG welding) [1~5]. A thin layer of activating flux is placed on the surface of the joint to be welded by means of a brush or a spray before welding. Significant increases in penetration capability of up to 300% compared with the conventional TIG process have been reported when using activating flux[6~7]. Its mechanisms are considered to be the arc constriction or the change in the surface tension of the molten pool[8~10]. The technique has also been demonstrated to increase penetration capability substantially in plasma arc welding and in laser welding[11~12]. D. S. Howse and co-workers[13] have used the A-TIG flux AFP SS1 in electron beam welding. Electron beam melt runs were made to investigate welding without the usual arc or plasma in order to attempt to separate any effects of arc or plasma constriction and surface tension caused by the flux. But the electron beam melt runs did not show major increases in penetration as a result of the A-TIG fluxes. This showed that the A-TIG flux was only effective when the weld pool was produced by an arc or plasma. Where there was no arc or plasma present, the flux had little effect. Heiple and Roper[14] proposed that thermocapillary convection (surface tension driven fluid flow — Marangoni effect) is primarily responsible for the weld shape variations, and that very small changes in material composition (especially of certain surface active elements such as sulfur) will significantly affect the thermocapillary flow. Burgardt and Heiple[15,16] proposed that thermocapillary flow in non arc conduction mode welds (laser and electron beam welds) is qualitatively similar to that in arc welds. However, no attempt was made to quantify the various effects in those studies. To help understand this, conduction mode electron beam welds were made with high sulfur material and low sulfur material by S. W. Pierce and co-workers[17], the results proved that a more concentrated heat source substantially improves weld penetration in high sulfur material, it has little effect in low sulfur material, but the thermocapillary flow reversal behavior was invariably accompanied by some keyhole penetration in the low sulfur material. A defocused electron beam has been used as a heat source to investigate the influence of the minor element on the surface tensional convection by T. Ohji and co-workers[18], it was found that the penetration shape by defocused electron beam is insensitive to the sulfur content in base metal. The result suggested that the minor element effect is peculiar to arc weld pools. In welding, the resulting weld seam geometry may vary significantly even using constant process parameters and steels with the same material number. One likely reason for this is small variations in the concentration of sulfur, phosphorus, oxygen, and other chemical elements that are well within the tolerance of the standard of a specific alloy. These substances act as surfactants and even marginal changes strongly affect the temperature dependent coefficient of surface tension [19]. In simulations of conventional electric

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arc welding and laser heat conduction welding, the effect of the temperature dependent coefficient of surface tension (Marangoni effect) has been identified as one of the primary driving forces of the liquid melt[20,21]. Electron beam welding has long been considered to be appropriate for welding thick plates, owing to its much higher fusion zone depth to width aspect ratio. The concentrated electron beam energy creates a narrow and deep fusion zone in a thick plate due to the keyhole mechanism. Systemic investigations on electron beam welding with activating flux are still very limited. The present study is aimed at the examination of the effects of flux on electron beam welding, it is important to determine if the penetration improvement function of the activating flux can be extended to electron beam welding.

2. Experimental Procedures

Type 304 austenitic stainless steel plates of 10 mm in thickness were investigated in the present study. Four types of activating flux were used: SiO_2 ,TiO_2 ,Cr_2O_3 and FS12. The last one manufactured by us for stainless steels and being composed of SiO_2 ,TiO_2 ,Cr_2O_3 ,ZnO and MnO_2. The specimens were cleaned immediately before welding with alcohol and paper wipes. The activating fluxes were mixed with acetone to form a paste and then brushed onto the desired area of the workpiece before welding. The acetone evaporated, leaving a layer of the flux adhering to the surface of the material to be welded. The welds were made on the plate half coated with the flux and the electron beam moved from an uncoated region to a coated region. **Figure 1** is a schematic illustration of electron beam welding with activating flux. The layer of the flux was less than 0.3 mm thick. Several welds were made along each specimen under the same welding conditions. To avoid preheating effects, the specimens were cooled to room temperature between welds. After welding, weld cross-sections were prepared both with and without the activating flux using standard procedures including grinding, polishing and etching.

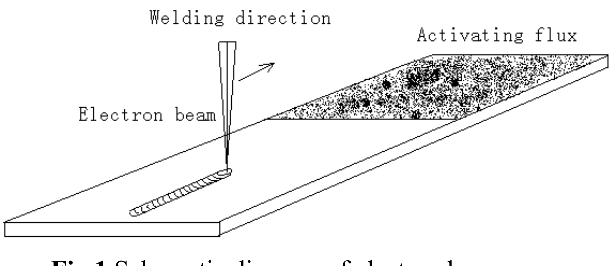


Fig.1 Schematic diagram of electron beam welding with activating flux

The plates were welded with the Torvac CVE63B electron beam welding system in vacuum at 5 to 8×10^{-5} torr. The focused electron beam size was determined to be around 0.2 to 0.5 mm. Beam size and power density were varied in a measurable and reproducible fashion by adjusting the degree of beam defocus. The electron beam power employed was varied from 1500 to 2500 W with weld speeds of 2-8 mm/s, applied voltage of 60 kV and current of 22.5-58.4 mA.

3. Experimental Results

Electron beam welding can be performed in two modes, conduction mode and keyhole mode, depending on electron beam energy density. Conduction mode refers to welds made with sufficiently low power density and the beam power is deposited on the work top surface. In this case, weld shape is determined by normal conduction and convection processes. The width of the welds produced in this manner is usually similar in scale to the depths. A keyhole can be formed when electron beam welding energy density exceeds a critical value. The high energy density in electron beam welding transfers heat from the electron beam source into the material, not to a point on the surface, but to a line extending through the material thickness. Hence, the weld is deep and narrow.

3.1 Effect of activating fluxes on surface appearance

Figure 2 shows the surface appearances of Type 304 stainless steel produced with various activating fluxes. There were significant variations in the bead widths of the welds. The widths with fluxes become narrower than those without them. The weld metal piles up on the boundary of the areas with and without fluxes. **Figure 2a** shows the result of the use of SiO_2, which produced little slag. **Figure 2b** and **2c** show that excessive slag was produced with use of Cr_2O_3 and TiO_2. **Figure 2d** shows no slag defects and the satisfactory surface appearance obtained with use of FS12.

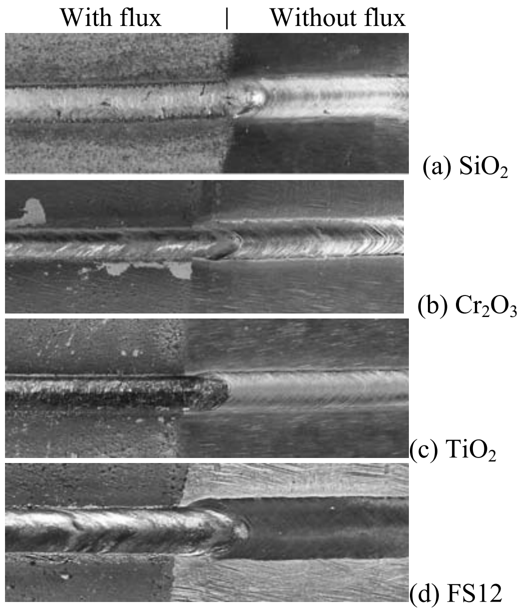


Fig.2 Effect of activating fluxes on surface appearances of EB welding in conduction mode (Weld speed :4 mm/s, Current: 22.5mA)

3.2 Effect of activating fluxes on penetration

Figure 3 shows the relative changes in penetration depths of welds with and without flux, where H is the penetration depth with flux, H_0 is the penetration depth without flux. Increases in penetration were observed with the use of SiO_2, Cr_2O_3 and TiO_2 , respectively.

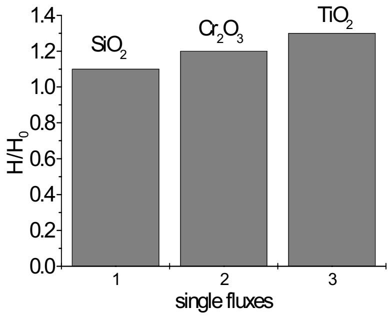
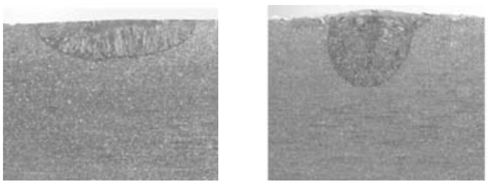


Fig.3 Effect of activating fluxes on weld penetration in conduction mode

Figure 4 shows the cross-sections of electron beam welds produced in stainless steel without and with flux FS12. There are significant increases in weld penetration and decreases in bead width when using the activating flux FS12. In the present study, the activating flux FS12 led to the greatest improvement in penetration capability, up to 200%, compared with the conventional electron beam weld process for Type 304 stainless steel.



(a) Without flux (b) With flux

Fig.4 Cross-sections of electron beam welds made without and with FS12 in conduction mode（Weld speed: 4 mm/s, Current: 22.5mA）

3.3 Effect of current on surface appearance and weld penetration

In addition, the effect of keyhole mode was investigated in electron beam welding of Type 304 stainless steel with activating flux FS12. The flux was selected on the basis of results that led to the greatest improvement in penetration for stainless steel. The focused electron beam size was 0.5 mm. The electron beam welding speed was 8 mm/s. The currents were 38.4mA, 48mA and 58.4mA. Several welds were made circumferentially around each specimen.

Figure 5 shows the surface appearance of Type 304 stainless steel produced in a keyhole mode. There were significant variations in the bead widths of the welds. The widths with flux become narrower than those without it.

Figure 6 shows the cross-sections of electron beam welds produced without and with flux FS12. The current was 48mA. There was significant variation in the penetration of the welds. The increases in weld penetration and the decrease in bead width are significant with the use of the activating flux FS12. The activating flux FS12 led to an improvement in penetration capability up to 120%, compared with the conventional electron beam weld process for Type 304 stainless steel. Compared with the conduction mode, the improvement in penetration was not so distinct. It should be mentioned that there was significant variation in the bead width of the welds. With the flux, the bead width became narrower than that without it, and the form of the welds varied in “radish” shape from “mushroom” shape.

Without flux | With flux

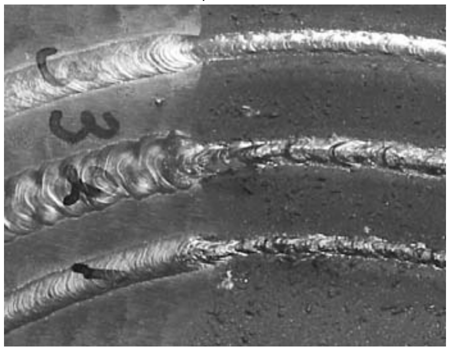
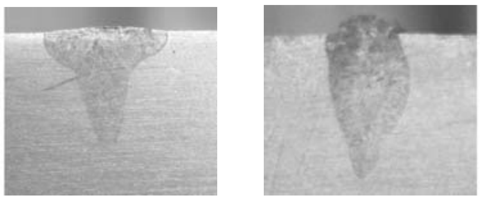


Fig.5 Effect of current on surface appearance in keyhole mode（Weld speed 8: mm/s, Current: 38.4, 48 and 58.4mA）



(a) Without flux (b) With flux

Fig.6 Cross-sections of electron beam keyhole-mode welds made with and without flux（Weld speed 8: mm/s, Current: 48mA）

4. Mechanisms for penetration improvement in electron beam welding

Thermocapillary convection has been widely accepted as the primary mechanism governing weld pool shape variations. Heiple and Roper pointed out that when the sulfur or oxygen concentration exceeded a certain critical value, the temperature coefficient of surface tension changed from a negative to a positive value[14)]. When there was no flux, the surface tension temperature coefficient is negative, the surface tension decreases with increasing temperature, In this case, the surface tension will be greatest in the cooler regions at the edge of the weld pool and this induces a radially outward surface flow which carries hot metal to the edge of the pool where the consequent melt back results in a wide shallow weld. When there was flux, the activating elements in the flux (such as O) can make the surface tension changed from negative to positive, thus the surface tension is greatest in the high temperature region at the centre of the pool and induces a radially inward flow. This, in turn, produces a downward flow in the centre of the weld pool which transfers hot metal to the bottom of the pool where melt back of the metal results in a deep and narrow pool under exactly the same welding conditions. In the conduction mode, the thermocapillary flow in electron beam welding is qualitatively similar to that in arc welding. The oxygen content through the flux in the weld pool plays an important role in increasing the weld penetration by the reverse of the surface tension gradient in the weld pool from a negative value to a positive value. The change in the surface tension gradient in the molten pool is considered to be the principal mechanism for increased penetration of electron beam welding.

In the keyhole mode, the electron beam can produce a high pressure metallic jet on the base metal, which can eject the molten metal to form a cavity. The energy is transferred into the substrate by multiple reflections inside the cavity, while on the surface of the molten pool there exists a radially outward flow, resulting in a wider top portion of the electron beam weld profile as shown in **Fig.6**(a). The flux with activating elements in it can make the surface tension of the molten pool change and induce a radially inward flow. The flow is strong enough to flow from the surface to the bottom of weld pool, resulting in a deep and narrow weld pool as shown in **Fig.6**(b).

5. Conclusions

The effect of activating flux on electron beam welding was investigated. Results clearly showed that activating flux affected the penetration capability of electron beam welding in stainless steels. However, its effect was dependent on welding parameters and the type of activating flux. Significant penetration improvement occurred when electron beam welding was carried out in the conduction mode. The investigation demonstrated not only that activating flux could improve welding penetration in the conduction mode, but also that it was beneficial for electron beam welding in the keyhole mode. One of the most likely reasons for this is that the oxygen content through the flux in the weld pool plays an important role in increasing the weld penetration by reversing the surface tension gradient in the weld pool from a negative value to a positive value. The change in the surface tension gradient in the molten pool is considered to be the principal mechanism for increased penetration of electron beam welding.

Acknowledgements

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