A MECHANISM OF DEEP WELD PENETRATION IN GAS TUNGSTEN ARC WELDGING WITH ACTIVATING FLUX

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ABSTRACT

The dramatic increase in the depth of a weld bead penetration has been demonstrated by welding a stainless steel in GTA (Gas-Tungsten-Arc) process with activating flux which consists of oxides and halides. However, there is no commonly agreed mechanism for the effect of flux on the process.

In order to make clear the mechanism, each behavior of the arc and the weld pool in GTA process with activating flux is observed in comparison with a conventional GTA process. A constricted anode root is shown in GTA process with the activating flux, whereas a diffuse anode root is shown in the conventional process. These anode roots are related strongly to metal vapor from the weld pool and the metal vapor is also related to temperature distributions on the weld pool surface. Furthermore, it is suggested that a balance between the Marangoni force and the drag force of the cathode jet should dominate the direction of re-circulatory flow in the weld pool. The electromagnetic force encourages the inward re-circulatory flow due to the constricted anode root in the case with flux. The difference in flow direction in the weld pool changes the geometry or depth/width ratio of weld bead penetration.

KEYWORDS

mechanism, weld penetration, GTA, arc, welding, flux, surface tension, cathode jet

1. Introduction

In order to increase the weld bead penetration in GTA welding, the concept of using a flux which consisted of oxides and halides was first proposed by the Paton Welding Institute in the Ukraine [1, 2]. A simple process of applying a thin coating of the flux to the surface of a base metal before arcing produces a dramatic increase in the penetration depth by between 1.5 to 2.5 times as much as the depth produced with the conventional GTA process [2]. Therefore, the GTA welding process with flux should bring about large benefits to the productivity, and then intense interest has been shown towards this process recently. On the other hand, the presence of surface active impurities such as oxygen, sulfur, tellurium and so on in the base metal has been known to affect the geometry of the weld bead [3]. These surface active elements also increase the penetration depth [1]. Therefore, the same mechanism for the effect of flux might be proposed on the surface active impurities in the base metal. However, there is no commonly agreed mechanism of the increase in the penetration depth in spite of several mechanisms proposed in many articles [2, 4-12].

The purpose of this paper is to make clear a mechanism for the effect of the flux on GTA welding process. This paper presents the experimental observations of interactive phenomena between the arc and the weld pool in GTA process with the activating flux in comparison with the conventional GTA process.

2. Experimental procedures

GTA welding was performed on the stainless steel SUS 304 (150 mm $\times$ 50 mm $\times$ 10 mm) as the base metal. Three different welding currents, 100 A, 150 A and 200 A, were used. The W-2% La_2O_3 electrode (diameter 3.2 mm with tip angle 60°) was used with a 5 mm arc length. The helium was employed as shielding gas at flow rate of 30 L/min because observations of the weld pool surface was able to become easy in comparison with the argon due to the lower electron density of helium plasma. The base metal backed by a water cooled copper block was run by a carriage. A welding travel speed was 200 mm/min. The bead-on-plate welds were made with or without the activating flux.

The pure TiO_2 was only employed as the flux, because simple composition of the flux should be easy for discussions about the mechanisms and the TiO_2 was one of the main elements of several flux on the market [2, 7]. The flux was mixed with acetone and applied manually with a brush in a layer thick enough to prevent visual observation of the base metal.

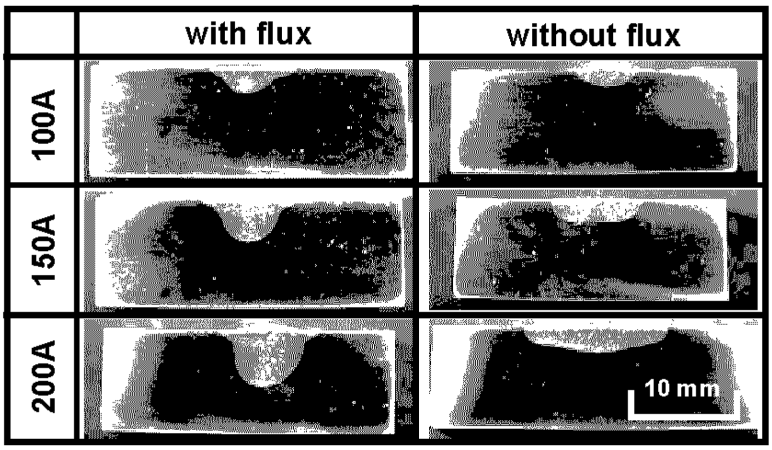

Fig. 1 Cross section of welds with and without flux.

3. Results and Discussion

Figure 1 shows cross section of welds made with and without flux in three different welding currents. The depth/width ratio of welds with flux is obviously higher than that of welds without flux independent of welding current. Figure 2 shows characteristic appearances of the arc in helium GTA welding with and without flux under the condition of 200 A in welding current. In the case without flux, there is a large wide region of blue luminous plasma in the lower part of the arc. The blue luminous plasma is mainly composed of metal vapor from the weld pool, which was confirmed by the results of spectroscopic measurements. Therefore, this blue luminous plasma should be similar to the *metal plasma* [13]. In the case with flux, the region of blue luminous plasma is constricted at the center in the lower part of the arc, and then the anode spot can be observed at the center of the weld pool surface.

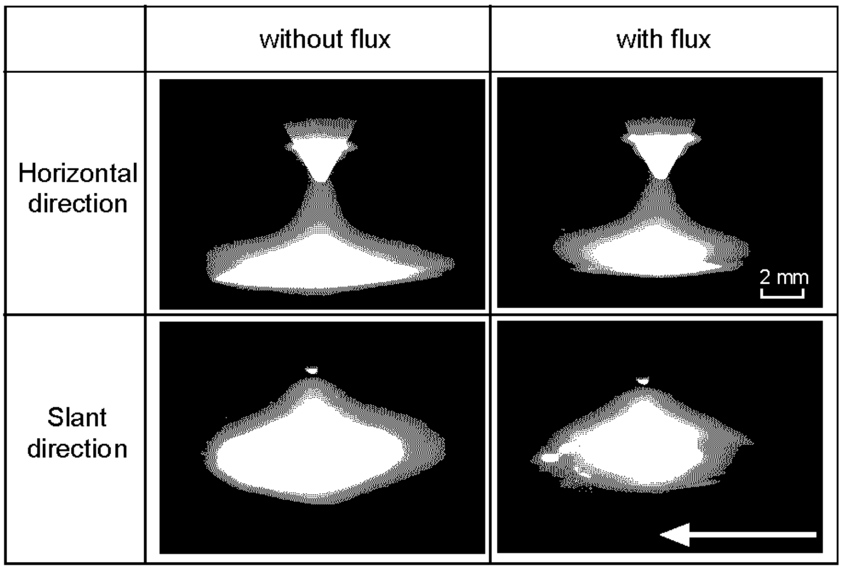

Fig. 2 Characteristic appearances of the arc in helium GTA welding with and without flux under condition of 200 A in welding current.

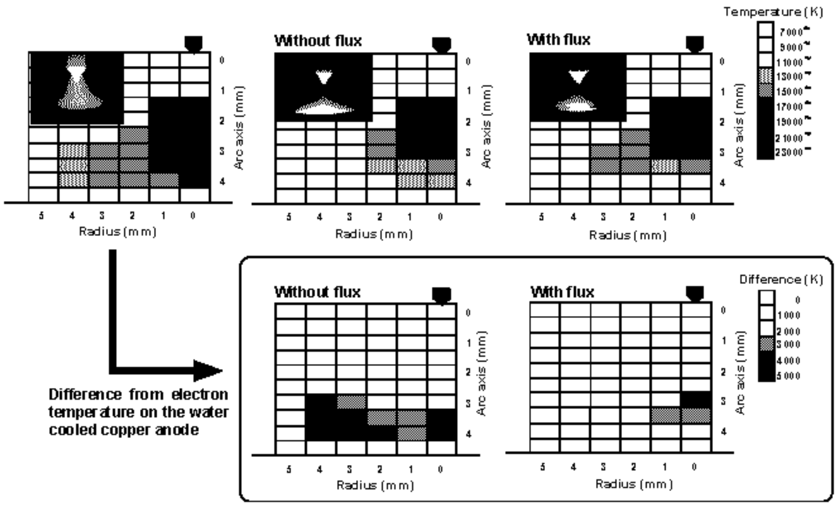

Fig. 3 Electron temperature distributions with and without flux compared to the pure helium GTA plasma on the water cooled copper anode under conditions of 200 A.

In order to investigate the physical state in the metal plasma, electron temperature distributions were measured by using of line-profile analysis of the laser scattering method, namely, Thomson scattering method. The experimental setup is described in detail by our previous paper [14]. Figure 3 shows the results of electron temperature distributions of arc plasmas in GTA welding with and without flux under the same condition with Fig. 2. Figure 3 includes a result of electron temperature distribution in pure helium GTA plasma on the water cooled copper anode, which was carried out under the conditions of 200 A in arc current and 5 mm in arc length. Each electron temperature is also indicated by gray scale in Fig. 3. In the case without flux, the electron temperature in the lower part of the arc remarkably decreases compared with the pure helium GTA plasma. This region of the reduced temperature is quite agreement with the region of the metal plasma in Fig. 2. This result suggests that the metal vapor from the weld pool should reduce the electron temperature. In the case with flux, the region of the reduced temperature is only observed at the center in the lower part of the arc, which is also quite agreement with the region of the metal plasma in Fig. 2. It can be considered that the metal vapor increases the electrical conductivity in the helium plasma due to much lower ionization potential compared with that of helium atom and decreases the electric field strength in the plasma and consequently reduces the electron temperature. Since the current path should be formed in the region of higher electrical conductivity [15], the metal plasma is closely related to an electric current path. Therefore, from above results, it is presumed that the current path in the case without flux expands widely on the whole weld pool surface, whereas the current path in the case with flux is constricted on the center.

It is well known that the metal vapor depends on surface temperature of the weld pool [16-18]. We measured the surface temperature by using of the pyrometer with similar technique to Kraus [19, 20]. Figure 4 shows the radius temperature distributions on the weld pool surface with and without flux. In the case without flux, surface temperature decreases gently from center to edge of the weld pool. On the other hand, in the case with flux, surface temperature at center of the weld pool reaches approximately 2350 K which is higher than the temperature without flux, while it becomes lower than the temperature without flux in the outer radius of about 1.5 mm. It means that surface temperature gradient with flux is much higher than that without flux, which was suggested theoretically by Zacharia [21].

Since Heiple [8] and David [10] suggested that the surface tension was an important element for the mechanism of increase in the penetration depth, we tried to measure the surface tension of the weld pool by using of the weld pool oscillation [22]. Figure 5 shows a relationship between the surface tension and the coating density of flux (TiO_2). The surface tension decreases sharply with the coating density and approximately reaches a constant when the density reaches only about 1 mg/cm^2. Figure 6 shows a relationship between the penetration depth and the coating density of flux (TiO_2). The penetration depth increases sharply with the coating density and approximately reaches a constant when the density reaches only about 1 mg/cm^2. The change in the surface tension of Fig. 5 is quite similar to the change in the penetration depth in Fig. 6. From

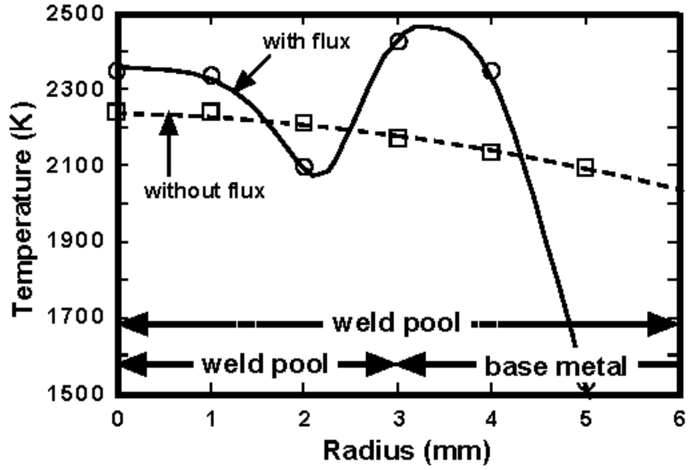

Fig. 4 Surface temperature distributions of weld pool with and without flux under condition of 200 A in welding current.

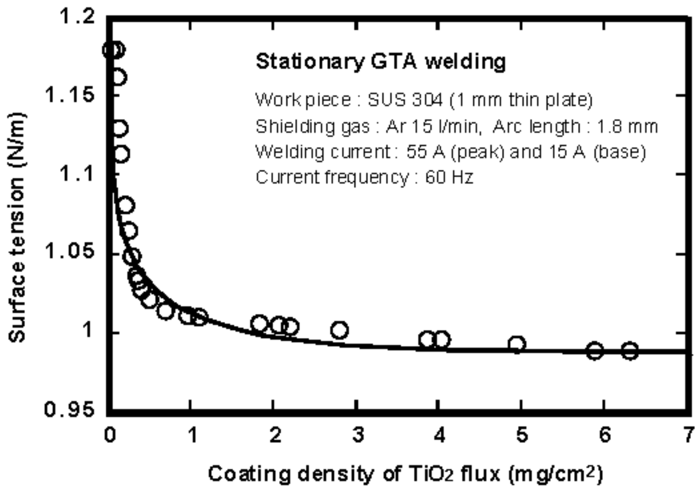

Fig. 5 Relationship between surface tension and coating density of flux.

these results, it should be considered that the surface tension is an important element for the mechanism of increase in the penetration depth as shown by Heiple [8] and David [10].

4. A Mechanism

It is well known that there are four driving forces of fluid flow in the weld pool [23]. These are the drag force of the cathode jet on the liquid surface, the buoyancy force, the electromagnetic force due to the self-magnetic field of the welding current, and the surface tension gradient force of the weld pool. Figure 7 shows distributions of temperature and fluid flow velocity of the weld for the individual driving forces. These predictions were made

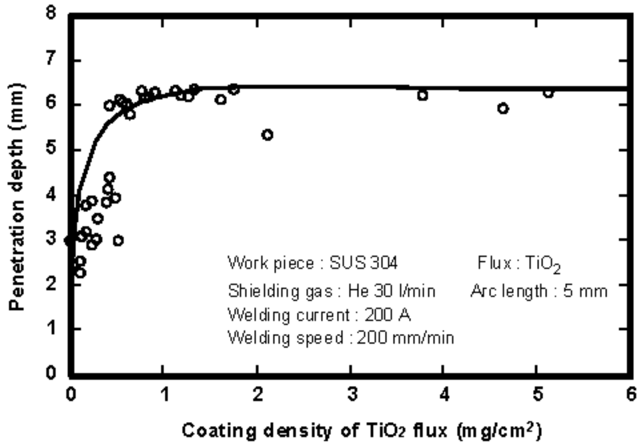

Fig. 6 Relationship between penetration depth and coating density of flux.

by the steady state calculations of stationary argon GTA welding process from a unified arc-electrodes model [24]. Each maximum velocity for drag, buoyancy, electromagnetic and surface tension gradient (Marangoni) force is 47 cm s^{-1}, 1.4 cm s^{-1}, 4.9 cm s^{-1} and 18 cm s^{-1}, respectively. Figure 7 suggests that the calculated convective flow in the weld pool is dominated by the drag force of the cathode jet and the Marangoni force as compared with other two driving forces. It also suggests that a balance between the drag force and the Marangoni force should dominate the direction of re-circulatory flow in the weld pool.

From above experimental results and discussion, a mechanism for the effect of the flux on GTA welding process should be proposed, as follows.

In the case of GTA welding without flux, since a normal negative temperature coefficient of surface tension [8, 10] causes outward fluid flow in the weld pool by the Marangoni force together with the drag force of the cathode jet, the heat input from the arc should transfer from center to edge on the weld pool surface. This heat transfer leads the gentle gradient of surface temperature of the weld pool, which also leads the metal plasma distribution expanded widely on the whole weld pool surface due to much lower ionization potential of the metal compared with that of helium. As a result, the diffuse anode root is formed.

In the case with flux, the temperature coefficient of surface tension changes from negative to positive due to the surface active elements such as oxygen contained by the flux [8, 10]. The positive temperature coefficient of surface tension causes inward fluid flow contrary by the Marangoni force. This Marangoni force would be larger than the drag force of the cathode jet. According to this inward flow, the heat input from the arc should transfer from surface to depth in the weld pool. This heat transfer leads the great gradient of surface temperature of the weld pool, which also leads the metal plasma distribution localized at center on the weld pool surface. As a result, the constricted anode root is formed, which should make the anode spot obviously at the center of the weld pool surface. Furthermore, the constricted anode root should lead higher current density at the anode, which should encourage the inward re-circulatory flow driven by the electromagnetic force (the Lorentz force). Consequently, the multiplication effect between the Marangoni force and the Lorentz force seems to make a strong inward re-circulatory flow in the weld pool.

The difference in flow direction in the weld pool changes the geometry or depth/width ratio of weld bead penetration. In our opinion, the effect of the surface active impurities in the base metal seems to be the same mechanism for the flux.

5. Conclusion

It was suggested that a balance between the Marangoni force and the drag force of the cathode jet should dominate the direction of re-circulatory flow in the weld pool. The electromagnetic force encourages the inward re-circulatory flow due to the constricted anode root in the case with flux. The difference in flow direction in the weld pool changes the geometry or depth/width ratio of weld bead penetration.

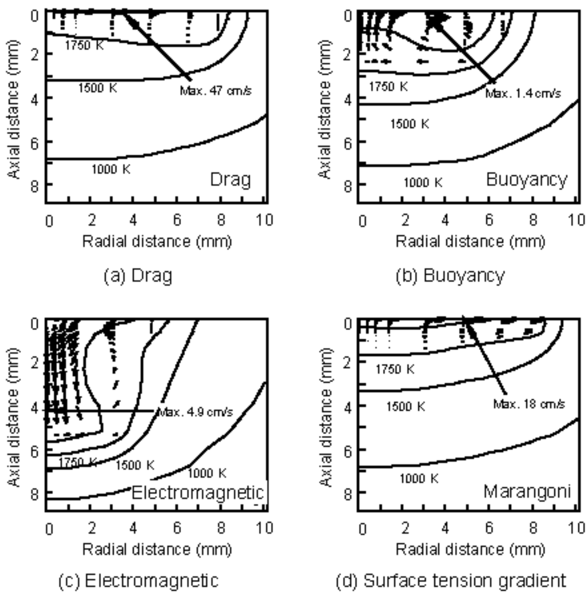

Fig. 7 Temperatures and fluid flow velocities in the welds for individual driving forces, which were made by the steady state calculations of stationary argon GTA welding process from a unified arc-electrodes model [24].

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