Effect of oxygen on distribution of wire feeding elements in laser-GMA hybrid welding
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1. Introduction

The hybrid welding has a lot of advantages compared with single laser welding and arc welding. It includes wider gap tolerance, higher welding speed, improving the weld metal microstructure using filler materials and so on. In improving the weld metal microstructure, it is essential to achieve the homogeneous distribution of the alloying elements in the weld metal. In this paper, the effect of the oxygen on the distribution of the wire feeding elements was investigated.

2. Experimental procedures

CO2 laser and pulsed GMA hybrid welding was used in this experiment. I-butt welding was carried out on 11mm thick JIS SM490A steel under the constant laser power of 8kW and welding speed of 1.0m/min. The metal transfer mode of one droplet per pulse was achieved by optimizing the GMA pulse waveform (9kW). He-38%Ar-O2 mixed gas was used as an arc shielding gas. To elucidate the effect of oxygen on the distribution of the wire feeding elements, the oxygen content in the shielding gas was varied from 0 to 10%. 70% Ni filler wire was used to examine the distribution of the wire feeding elements in the weld metal. After welding, the distribution of nickel was analyzed by EPMA in the longitudinal section of the weld metal. The homogeneity of the alloying elements must be affected by the molten metal flow. Then, the molten metal flow on the pool surface and inside the samples was observed by a high speed video camera and an in-situ X-ray transmission imaging system. The flow on the pool surface was visualized by a movement of Al2O3 particles, which was put on the sample surface prior to the welding. The inside flow was visualized by Pt, which was put on the top or bottom surface prior to the welding.

3. Results and discussion

Figure 1 shows the concentration profiles of nickel in the longitudinal section of the weld metal for various oxygen contents in the arc shielding gas. It can be seen that the nickel distribution is more homogeneous with increasing the oxygen content from 0 to 2%. Similar distribution as Fig.1(b) is also observed in 10% O2.

To understand the mechanism, the molten metal flow was observed. Figure 2 shows the molten metal flow on the pool surface for various oxygen contents. When the oxygen content is 0%, the alumina particles move from the keyhole to the middle of the weld pool and a lot of oxide films stay in the middle of the weld pool as shown in Fig.2(a). This means that the fluid flow between the keyhole and the middle of the weld pool direct backward. On the other hand, the oxide film is not observed on the pool surface and the alumina particles go towards the keyhole when the oxygen content is 2% as shown in Fig.2(b). This means that the molten metal flow in 2% O2 is opposite to that in 0% O2.

Figure 3 shows the inside flow observed by in-situ X-ray transmission imaging system. The platinum set on the top surface moves downward along the keyhole when the oxygen content is 2% as shown in Fig.3(b). In 0% O2, on the other hand, the platinum flows downward about 5mm behind the keyhole as shown in Fig.3(a).
It is well known that the direction of Marangoni flow changes dramatically by adding a small amount of surface active elements such as sulfur and oxygen. Generally, the surface tension decreases with increasing the temperature for a pure metal and many alloys. In the weld pool for such materials, the fluid flows to the rear pool end, which means the backward Marangoni flow. If some surface active element, such as oxygen or sulfur, is added into the weld pool, the temperature coefficient of the surface tension can be changed for iron alloys from negative to positive and further the direction of the fluid flow in the weld pool changes to the opposite direction. The molten metal flow is called as the forward Marangoni flow. Then, the oxygen content of the weld metal near the top surface was analyzed in the hybrid welds with different shielding gas. The results show 20 and 40 ppm for 0% and 2% O₂ shielding gas, respectively. For Fe-O system, the variation of the temperature coefficient of the surface tension with oxygen content is shown in Figure 4. When the oxygen content is 20ppm, the critical temperature where the temperature coefficient changes from positive to negative is about 1550°C from Fig.4. Then, the temperature coefficient in the area near the keyhole must be negative, resulting in the backward Marangoni flow. When the oxygen content is 40ppm, the critical temperature is about 1700°C from Fig.4. It may be possible that the forward Marangoni flow occurs near the keyhole. Fig.5 schematically shows the effect of the Marangoni flow force on the molten metal flow for various oxygen contents in the shielding gas. The direction of the molten metal flow is mainly determined by the balance between the Marangoni flow force and the arc plasma force. When the oxygen content is 0%, the backward Marangoni flow force is stronger than the arc plasma force near the keyhole, resulting in promoting backward flow as shown in Fig.5(a). When the oxygen content is 2%, on the other hand, both of the Marangoni flow force and plasma force direct to the keyhole as shown in Fig.5(b). As a result, the forward molten metal flow is promoted in 2% O₂. Compared with the backward flow, the alloying elements can more easily reach the bottom of the keyhole for the forward flow. Thus, the distribution of the alloying elements is more homogenous with increasing of the oxygen content in the shielding gas.

Fig.3 Inside molten metal flow observed by in-situ X-ray transmission imaging system (a) 0%O₂; (b)

Fig.4 Variation of temperature coefficient of surface tension with oxygen content

Fig.5 Schematic diagram of molten metal flow and driving force acting on the molten pool in different oxygen content of shielding gas (a) 0%O₂; (b) 2%O₂