1. Introduction

In past decades, the effects of minor elements on the shape and penetration of GTA welds have long been investigated because the GTA welding process is widely used in modern industry. In order to increase weld production, the demand for the automatic and precision control of the weld with deep penetration is increasing with time. Furthermore, for the welds being made by automatic equipment, it is difficult to compensate for variability in the weld pool geometry once the welding parameters have been set. Understanding and precisely controlling the effect of minor elements on the weld shape are critical to generate a satisfactory weld joint.

The main minor elements are the groups VIB (fluorine, bromine and chlorine) and VIIB (oxygen, sulfur, selenium and bismuth), which may change the weld penetration in GTA welding. Minor elements can be added to the weld pool by adjusting the chemical composition to the base material,1–6) smearing fluxes (halides or oxides) on the plate surface7–19) or using active gaseous addition to the argon shielding gas.20–22) The intentional or unintentional addition of a small amount of minor elements to the base material is critical to generate a satisfactory weld joint.

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Adding a small amount of gas containing minor elements to the Ar shielding gas is a way to accomplish the transfer of the minor elements to the weld pool and is expected to increase the weld penetration. Compared to the A-TIG welding, the study on the effect of gaseous additions to the Ar shielding gas on the weld penetration is very limited. However, the mixed gas is easily controlled and applied by automatic GTA welding in the industry if the addition gas can increase the weld penetration efficiently. In the 1970s, Bad'yanov et al.20,21) found that adding some gaseous fluorides (BF3, WF6 and SF6) to the argon can increase the penetration. In the 1980s, Heiple and Burgardt22) studied the effect of SO2 shielding gas additions on the GTA weld shape and proposed that the maximum benefit from SO2 additions was achieved between 500 to 1400 ppm. However, both the gaseous fluorides and the sulfur dioxide are toxic, which limited their application in industry.

Oxygen is also an active minor element. The presence of oxygen in the weld pool has been reported to have positive effects on the penetration and the shape of the weld.12,25) In this study, oxygen was selected as the active gaseous addition to the Ar shielding gas on the GTA weld shape and proposed that the maximum benefit from O2 additions was achieved between 500 to 1400 ppm. However, both the gaseous fluorides and the sulfur oxide are toxic, which limited their application in industry.

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2. Experimental Procedure

Experiments were designed and performed to evaluate the effect of oxygen additions to the shielding gas on the weld shape for the tungsten arc welding of SUS304 stainless steel. The shielding gases were pure argon and argon with oxygen addition from 1,000 to 10,000 vol ppm. A constant current power source was used with direct current electrode negative (DCEN) polarity to make bead-on-plate welds with a mechanized system in which the test piece was moved at a constant speed under the torch.

The base material used was type SUS304 stainless steel machined into rectangular plates, 100 mm × 50 mm × 10 mm. The chemical composition of the plate is shown in Table 1. Before welding, the substrate surface was lightly ground using 80-grit flexible abrasive paper and then cleaned with acetone. Bead-on-plate welds were made at the set welding parameters listed in Table 2. The 2% thoriated tungsten electrode was ground and the electrode gap was measured for each new bead before welding to ensure the bead was made under the same conditions except for the shielding gas content and flow rate.

After welding, the weld specimens were sectioned and prepared according to standard metallographic techniques and etched by HCl/CuSO₄ solution to reveal the bead shape and size. The cross-sections of the beads were photographed using an optical microscope. The width, depth and depth/width ratio of the weld were measured. The oxide layer on the weld surface was also observed and photographed using the optical microscope. The oxygen content in the weld metal was analyzed using an Oxygen/Nitrogen Analyzer. Samples for the oxygen measurement were prepared as follows: first the oxide layer on the bead surface was moved by 400-grit abrasive paper grinding, and then the weld metal was directly cut out as the oxygen analysis specimen.

3. Results

3.1. Oxygen Added Shielding Gas Effect on Weld Shape

In the experiment, the oxygen content in the shielding gas was changed from 1,000 to 10,000 ppm at the flow rates of 10 and 20 L/min. Cross-sections of the welds made under the pure Ar and O₂–Ar mixed gases are shown in Fig. 1. The detailed values of the weld width and depth are given in Fig. 2 for both the 10 and 20 L/min flow rates. In Fig. 1, it is clear that the oxygen added shielding gas had a significant effect on the weld shape. For the low and high oxygen additions, the welds are wide and shallow. When the oxygen concentration is in the range of 3,000 to 5,000 ppm, the weld shape become deeper and narrower. Furthermore, it is interesting to find that the weld shape is quite different between the low oxygen addition content (<2,000 ppm) and high oxygen addition content (>6,000 ppm) though both of them are shallow and wide. A flat bottom weld shape is formed at a low oxygen addition content, while a concave bottom weld shape is generated at a high oxygen content in the argon gas. The weld pool convection mode has a significant effect on the weld shape. As shown in Fig. 2, three areas are designated based on the torch gas oxygen content illustrated by I (<2,000 ppm, shallow and wider flat shape), II (3,000 to 5,000 ppm, deep and narrow shape), and III (>6,000 ppm, shallow and wider concave shape).

3.2. Weld Depth/Width Ratio and Oxygen Content in Weld

In order to show the effect of oxygen in the shielding gas on the oxygen transfer to the weld pool, the weld was directly cut out for oxygen analysis using the Oxygen/Nitrogen Analyzer. The weld D/W ratios were calculated based on the cross-sectional pictures. The D/W ratio and oxygen content in weld after welding are plotted versus the torch gas oxygen content as shown in Fig. 3. There is a certain range of oxygen content from 3,000 to 5,000 ppm for...
which a large D/W ratio (around 0.5) is obtained for both the 10 and 20 L/min flow rates. When out of this range, the D/W ratio decreases to approximately 0.2. This relation between the D/W ratio and the oxygen content in the shielding gas is similar to the results obtained by Heiple. However, the efficient range of oxygen content for deep penetration is quite different from Heiple’s results. In Heiple’s experiment, the efficient range for a large D/W ratio is approximately between 200 to 1 000 ppm. The oxygen analysis of the weld shows that the oxygen in the weld is increasing with the oxygen addition content in the shielding gas up to 6 000 ppm, and then maintained a nearly constant value around 200 to 250 wt ppm. The D/W ratio and oxygen content in weld are not sensitive to the shielding gas flow rate.

3.3. Oxidation of the Weld Pool Surface and Electrode Tip

The argon and helium inert gases are the most widely applicable gases for GTA welding to protect the weld from atmospheric oxygen and nitrogen. In the experiments here, the oxygen addition to the argon shielding gas made the oxidation of the weld pool surface inevitable. The oxide layer on the weld pool surface plays an important role as a barrier for oxygen to transfer and become solute in weld pool, also it prevents the weld pool surface from moving freely. Observations of the surface oxide layer were taken by optical microscopy. The cross-sections of the weld beads being made under the pure argon and oxygen–argon mixed shielding gases were photographed as shown in Figs. 4, 5 and 6, respectively.

The oxide layer on the weld surface made under pure argon is about 5 μm thick as shown in Fig. 4. When the oxygen addition content is 1 000 to 5 000 ppm, the oxide layer thickness on the weld surface is around 15 μm (see Figs. 5(a), 5(b) and Figs. 6(a), 6(b)). The thickness of the oxide layer suddenly increases to 30 to 40 μm when the oxygen addition content is over 6 000 ppm (see Figs. 5(c), 5(d) and Figs. 6(c), 6(d)).

Oxygen addition to the argon shielding gas also makes the electrode tip oxidize inevitably. Photos of the electrode tip after welding are shown in Fig. 7 with different O₂ addition content. It is clearly shown that when the oxygen content is below 5 000 ppm for both the gas flow rate 10 L/min
and 20 L/min, the oxidation of the electrode tip surface is weak. While the oxygen content in the shielding gas is over 5 000 ppm for 10 L/min flow rate and reaches 5 000 ppm for 20 L/min flow rate, a thick ring of oxide layer formed on the upper area of the electrode tip. The oxidation of the electrode tip will shorten the electrode application life. In order to decrease the oxidation of the electrode tip, it is necessary to control the oxygen content in the shielding gas at low level, less than 5000 ppm.

4. Discussion

4.1. Marangoni Convection and Weld Shape

For the GTA welding, the weld shape depends to a large extent on the heat transfer in the welding pool by conduction and convection. The heat transfer by conduction is based on the weld plate thermal properties. Since the base materials in these experiments are the same, the heat transfer by conduction is nearly same in the pool and the heat transfer by convection becomes the main factor influencing the weld shape.

In the welding process here, there is no significant changes of the arc shape when the oxygen addition content in the shielding gas varies. Marangoni convection can affect the shape of the weld pool dramatically. Generally, the surface tension decreased with the increasing temperature, $\partial \sigma / \partial T < 0$, for a pure metal and many alloys. In the weld pool for such materials, the surface tension is higher in the relatively cooler part of the pool edge than that in the pool center under the arc, and hence, the fluid flows from the pool center to the edge. The heat flux is easily transferred to the edge and the weld shape is relatively wide and narrow.
as shown in Fig. 8(a). Heiple\textsuperscript{5,12)} proposed that minor elements, such as oxygen, sulfur, selenium and tellurium can change the temperature coefficient of the surface tension for iron alloys from negative to positive, \( \frac{\partial \sigma}{\partial T} \), and further change the direction of the fluid flow in the weld pool as illustrated in Fig. 8(b). In that case, a relatively deep and narrow weld is made.

From the results of the oxygen analysis of the weld as presented in Fig. 3, the oxygen in the weld transferring from the mixed shielding gas increases with the oxygen addition content in the shielding gas when the oxygen content is below 6 000 ppm. Former research shows that oxygen is an active element in pure iron and stainless steel in the range of 150–350 ppm\textsuperscript{24)} and 70–300 ppm, \textsuperscript{25)} respectively. In these ranges, the temperature coefficient of the surface tension of the welding pool is positive (inward convection in weld pool), while outside of this range, the temperature coefficient becomes negative or nearly zero. In the experiment here, as the oxygen content in weld is over 100 ppm, the Marangoni convection mode suddenly changed from outward to inward and the weld shape become narrow and deep as shown in Fig. 1.

The weld pool is oxidized under the \( \text{O}_2-\text{Ar} \) shielding gas as shown in Figs. 4, 5 and 6. One mode to illustrate the oxide layer on the weld pool surface and the oxygen conveyance under different oxygen additions is proposed here as shown in Fig. 9. Under pure Ar shielding, the welding pool is completely separated from the atmosphere and no oxide layer is theoretically generated as the weld pool in liquid station. One free pool surface forms as shown in Fig. 9(a). In the real situation, as the torch moves away, the solidified pool surface is at a high temperature and contacts the atmosphere, which may oxidize the weld surface and form a thin oxide layer as shown in Fig. 4. The oxide layer

\[ \frac{\partial \sigma}{\partial T} \]

\[ \frac{\partial \sigma}{\partial T} \]
is thin when the $O_2$ addition content in the shielding gas is between 1,000 to 6,000 ppm. Since the welding pool surface is not stationary and flows under the plasma shear force and Marangoni convection force, the thin oxide layer easily is destroyed and exposes the weld pool surface to the arc and shielding gas. Therefore, the oxygen is easily transferred and become a solute in the welding pool as shown in Fig. 9(b) named quasi-free surface. The oxide film on the weld surface becomes quite thick when the $O_2$ addition content is over 6,000 ppm in the shielding gas. The thicker oxide film will protect the liquid steel pool from direct contact with the shielding gas like a liquid blanket on the weld pool surface as shown in Fig. 9(c) named restricted surface. This thicker oxide layer becomes a barrier for oxygen transfer and become a solute in the weld pool. Therefore, the oxygen in the weld pool remains nearly constant when the $O_2$ addition content is over 6,000 ppm. However, the D/W ratio decreased again when the oxygen addition is over 6,000 ppm.

### 4.2. Oxide Layer Effects on Weld Pool Motion

As the oxygen addition content is over 6,000 ppm, the oxide layer on the weld surface is thicker than 30 $\mu$m as shown in Figs. 5 and 6. In that case, the thick oxide layer covered on the weld pool surface is like a liquid blank as shown in Fig. 9(c). It is like a layer of melted flux in submerged arc welding. This oxide layer will confine and prevent the liquid pool surface from moving freely, which makes the inward Marangoni convection in the weld pool become weaker and the weld shape become relatively wide and shallow again when the oxygen addition content is over 6,000 ppm in the argon shielding gas as shown in Fig. 2. However, the Marangoni convection mode is still inward because the oxygen content in the weld is around 200 ppm, and therefore, a concave weld shape forms. When the oxygen addition content is less than 3,000 ppm, the oxygen content in the weld is below 100 ppm and the Marangoni convection is in the outward mode. In that case, a shallow flat weld bottom forms.

When the oxygen addition is between 3,000 ppm and 5,000 ppm, the thin oxide film on the pool surface is easily destroyed and a quasi-free surface forms during the welding process as shown in Fig. 9(b). This quasi-free weld pool surface can move freely. In that case, the Marangoni convection is in the inward mode because the oxygen content in the weld is in the range of 100 to 250 ppm.

### 5. Conclusions

The effects of the addition of small concentrations of $O_2$ to the normal argon shielding gas on the weld shape and oxygen content in the weld were investigated on SUS304 stainless steel by GTA welding. Based on the obtained results, the following conclusions were achieved:

1. Oxygen-added argon shielding gas can dramatically improve the weld D/W ratio to 0.5 when the oxygen concentration is in the range of 3,000 to 5,000 ppm. Too higher or lower an oxygen addition content will decrease the D/W ratio to approximately 0.2. The weld shape is not sensitive to the investigated shielding gas flow rate.

2. Marangoni convection can affect the shape of the weld pool dramatically. Oxygen in the weld pool from the shielding gas plays an important role as an active element affecting the Marangoni convection direction on the weld pool surface. When the oxygen content in the weld pool is over 100 ppm, inward Marangoni convection occurs on the weld pool surface and the weld D/W ratio increases suddenly.

3. A thicker oxide layer on the weld surface is generated when the oxygen addition content is over 6,000 ppm. This heavy oxide layer protects the liquid pool from the shielding gas and plasma arc, and thus makes the oxygen in the weld remain nearly constant. Also, it prevents the welding pool from moving freely and weakens the Marangoni convection, and hence changes the weld pool shape.

4. In order to weaken the oxidation of the electrode tip in the welding process, it is necessary to keep the oxygen content in the shielding gas at a low level, less than 5,000 ppm.

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