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Oxide Flux Quantity and Size Effects on the Penetration Depth in A-TIG Welding†

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Abstract

Four single oxide fluxes, Cu_2O, NiO, SiO_2 and TiO_2, were used to investigate the effect of active flux on the depth / width ratio in SUS304 stainless steel. Flux quantity, and particle size effects on the weld pool shape and oxygen content in the weld after welding were studied systematically. The results showed that the depth/width ratio of the weld pool was closely related to the oxygen content in the pool. The oxygen content in the weld metal increases with the quantity of fluxes for Cu_2O, NiO and SiO_2. However, for the TiO_2 oxide flux, the highest oxygen content in the weld metal is below 200 ppm. As the oxygen content in the weld metal is in a certain range, the depth/width ratio increases to 1.5 to 2.0 times. Too low or too high oxygen content in the pool does not increase the depth/width ratio. The oxygen from the decomposition of the flux in the welding pool alters the surface tension gradients on the weld pool surface, and hence, changes the Marangoni convection direction and the weld pool penetration depth. The decomposition of the flux strongly depends on the flux particle size. TiO_2 flux and SiO_2 flux with small particle size (0.8μm or 4μm) is a highly recommended active flux for deep penetration for real GTAW applications.

KEY WORDS: (Oxide flux) (Depth / Width Ratio) (Weld Penetration) (Gas Tungsten Arc Welding)

1. Introduction

Improvements in weld penetration have long been sought in gas tungsten arc welding (TIG welding) because although the TIG welding has a good weld appearance, high quantity, it has relatively shallow penetration especially in the single pass welding process for stainless steel and titanium alloys. There are two main methods to improve the TIG welding penetration and production. One is changing the raw material composition by adding some minor elements to the stainless steel, such as O, S, Se and Bi [1,2], which is of particular interest to steel-makers who supply the raw materials. The other method is from welding engineers using activating fluxes in TIG welding (ATIG or FBTIG)[3-6].

ATIG was first invented in the 1960s by researchers at the Paton Electric Welding Institute in Ukraine[7]. Limited published information regarding the use and composition of the flux attracted many researchers' attention in the 1990s, such as the Edison Welding Institute (EWI) and United Kingdom Welding Institute (TWI)[3]. Many investigations of the mechanism and the application technology of the ATIG process have been made and the two representative theories are arc contraction[8-16] and reversal of the Marangoni convection in the welding pool[11, 17-20]. However, there is still no common agreement about the ATIG mechanism. Even for the arc contraction, different researchers have different explanations[8]. Heiple and Roper had done many research studies on the minor elements' effect on the Marangoni convection in the welding pool[17, 18, 20]. Their results showed that the active elements, such as O, S and Se, in the welding pool changed the temperature coefficient of the surface tension, $\partial\gamma/\partial T$, from negative to positive, and hence reversed the Marangoni convection direction

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from outward to inward. As the convection was inward, the penetration was increased dramatically.

In this study, four different kinds of oxide fluxes were used to examine the effect of the single flux quantity on the welding penetration of the stainless steel systematically. Furthermore, the flux particle size effect on the weld penetration was investigated to accumulate some flux optimization data for application in industry. Based on these results, the mechanism for ATIG was discussed through the oxygen content of the weld metal after welding.

2. Experimental Procedure

A bead-on-plate weld was made on a SUS304 stainless steel substrate machined into rectangular plates, 100×50×10 mm, with the average composition of 0.06%C, 0.44%Si, 0.96%Mn, 8.19%Ni, 18.22%Cr, 0.027%P, 0.001%S, 0.0016%O and the rest of Fe. The oxide fluxes used in the experiment were Cu_2O, NiO, SiO_2 and TiO_2 powders with the particle sizes shown in **Table 1**. For the SiO_2 flux, three kinds of particle sizes were selected to investigate their effect on the weld penetration. Before welding, the substrate surface was ground using 80# abrasive paper and one 100×5×0.1 mm slot was planed on the surface center of the substrate as shown in **Fig.1**. The flux was manually pre-placed in the slot over a 50 mm length and uniformly dispersed with acetone.

Welding was carried using a DCEN power supply with a mechanized system in which the test piece was moved at a constant speed under the torch. **Table 2** shows the welding parameters used in the trial. The tungsten electrode was ground and the arc length was measured for each new bead before welding to ensure the bead was made under the same conditions.

Table 1. Particle size of the oxide flux

Oxide	Size /μm
Cu_2O	3.0
NiO	0.9
SiO_2	0.8, 4.0, 25.0
TiO_2	1.0

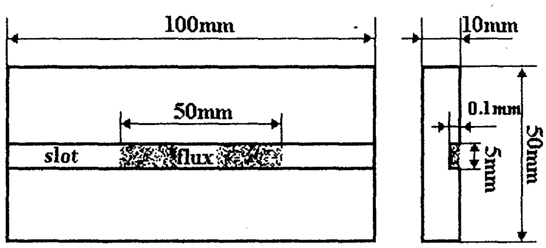


Fig.1 Schematic of the SUS304 plate used in GTAW

Table 2. Welding parameters

Parameters	Value
Electrode type	DCEN, W-2%ThO_2
Diameter of electrode	1.6 mm
Vertex angle of electrode	60°
Shield gas and flow rate	Ar, 10 l/min
Arc length	3 mm
Bead length	50 mm
Spot time	3 s
Welding current	160 A
Welding speed	2 mm/s

After welding, the cross-section of the bead etched by $HCl+Cu_2SO_4$ solution was photographed using an optical microscope (Olympus HC300Z/OL). The depth/width ratio of the weld (D/W) was measured. The oxygen content in the weld metal was analyzed using an oxygen/nitrogen analyzer (Horiba, EMGA-520). Samples for the oxygen measurement were prepared as follows: first the slag on the bead surface was removed by 400-grit abrasive paper grinding, and then the weld metal was cut out directly for the oxygen analysis specimens.

3. Results

3.1 Weld cross-sections

Cross-sections of the welding beads made using different oxide fluxes of different quantities were photographed. The fusion zone shapes with a different single component flux are shown in **Fig.2**. All the four oxide fluxes, Cu_2O, NiO, SiO_2 and TiO_2, increased the penetration significantly in a certain range of flux quantity. For a selected single flux, **Figure 2** illustrates the large variation in penetration as a result of different quantities of flux used. Except for TiO_2 flux, the penetration depth with the other oxides in the experiment increased first, followed by a decrease with the increasing oxide quantity. However, the penetration depth was still deep with the TiO_2 flux even at the high quantity.

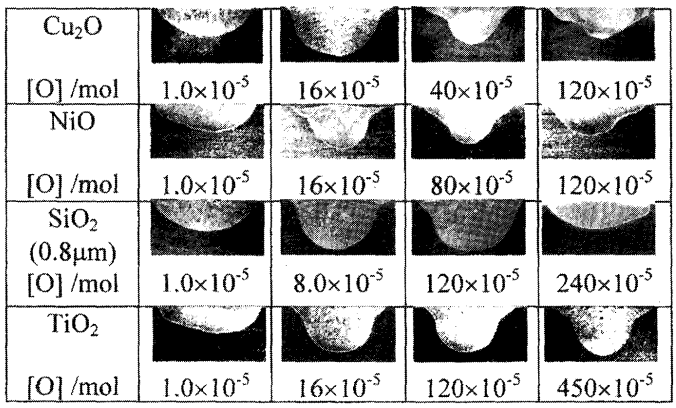


Fig. 2 Weld cross-sections with different oxides 2mm

3.2 Weld D/W ratio and oxygen analysis

The depth/width ratio and oxygen content in the weld after welding are plotted versus the oxygen quantity in the covered flux before welding in **Fig.3**. It is clear that the weld D/W ratio initially increases sharply, followed by a decrease as the flux quantity increases for the Cu_2O, NiO and SiO_2 fluxes. For the TiO_2 flux, the weld D/W ratio increases first and then remains nearly constant with the quantity of flux. The measured oxygen value in the weld after welding increases with the oxide flux quantity covered before welding for Cu_2O, NiO and SiO_2 fluxes, while for the TiO_2 oxide, the oxygen content in weld first increases then remains approximately constant at 120 ppm.

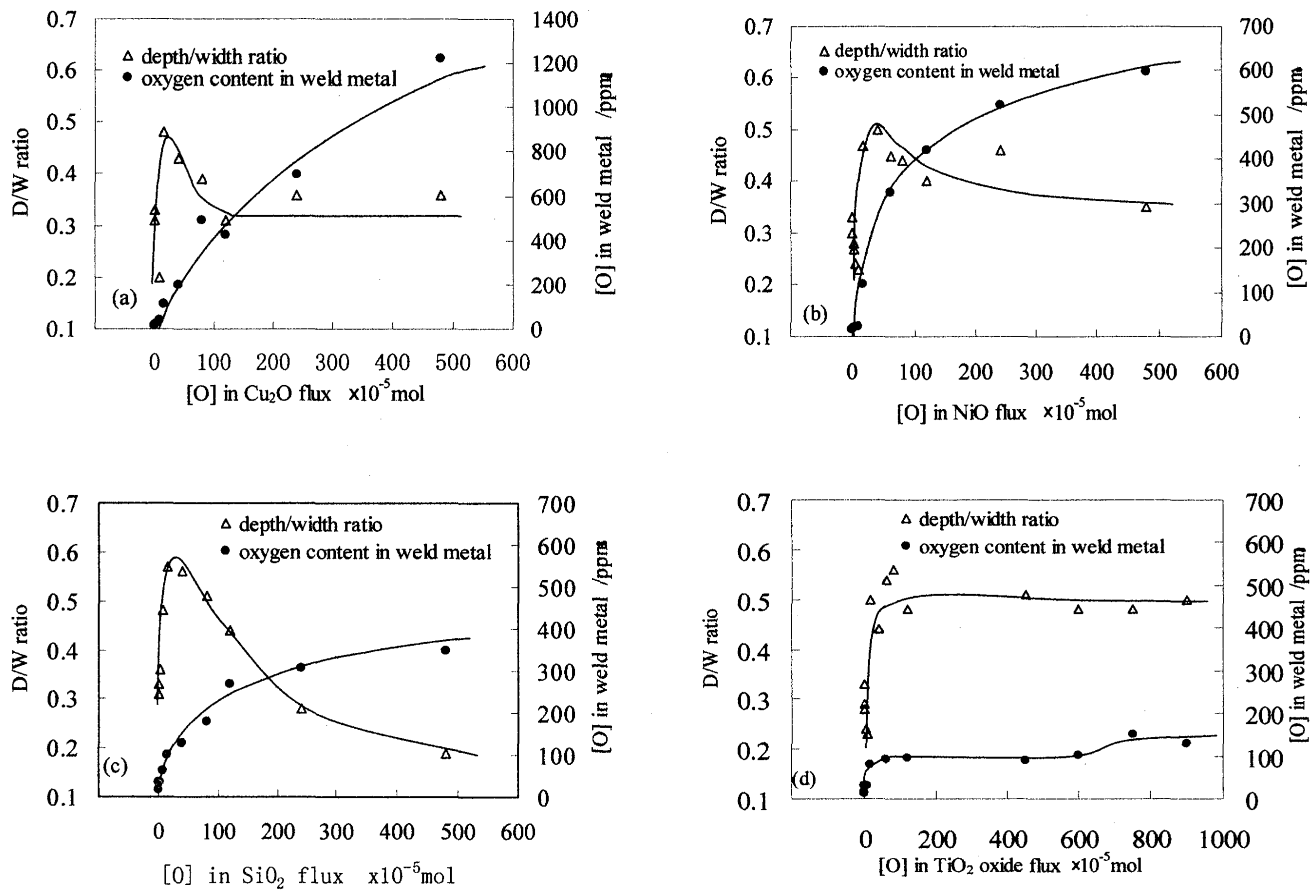


Fig.3 D/W ratio and [O] in weld vs. flux quantity
(a) Cu_2O (b) NiO (c) SiO_2 (0.8μm) (d) TiO_2

3.3 Effect of SiO_2 particle size on the penetration

Three kinds of SiO_2 fluxes with particle size of 0.8 μm, 4μm and 25μm are selected to show the effect of flux size on the weld penetration in the ATIG process. The specific areas of the particles are measured and listed in **Table 3**. The smaller the flux particle, the larger is the specific surface area. The cross-sections, D/W ratios and oxygen contents in the welds are illustrated in **Fig.4, Fig. 3(c) and Fig.5**. It is clear that the small particles (0.8μm, 4μm) have a good effect in enhancing the penetration, while the large particle size (25μm) has no effect. The oxygen content in the weld for the SiO_2 (25μm) flux is very low, less than 50 ppm. This implies that the decomposition of large SiO_2 particles is very weak. For the small particle size SiO_2, the oxygen content increases with the flux quantity. Since the decomposition of the oxide depends on the reaction rate, which increases with the specific area, the small particle is easily decomposed.

Table 3. Specific surface area of SiO_2 flux

Particle size (μm)	0.8	4.0	25.0
Specific surface area ($\times 10^3$ m^2/L)	7.5	1.8	0.3

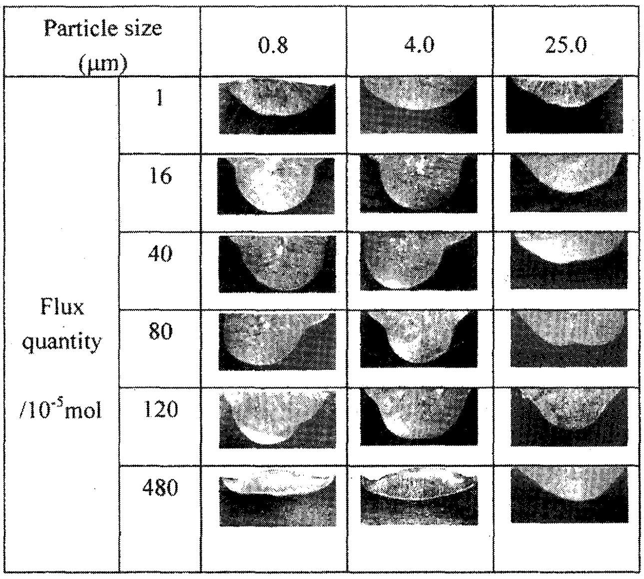


Fig. 4 Effects of SiO_2 flux size and quantity on the weld pool shape 2mm

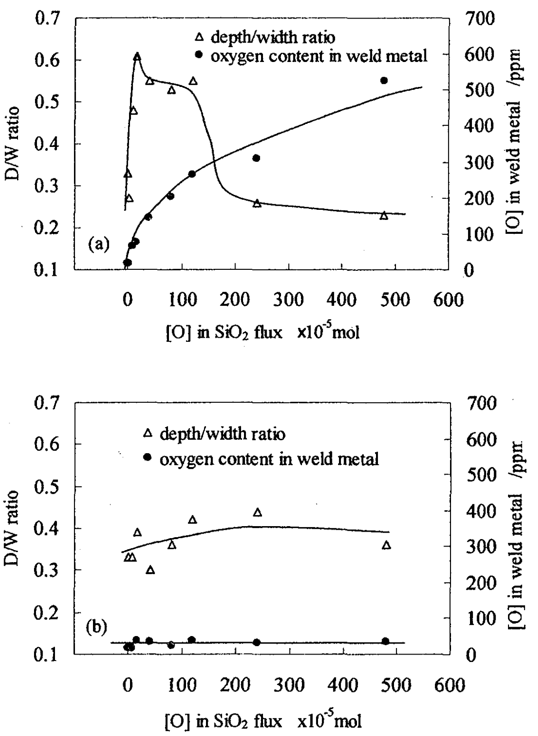
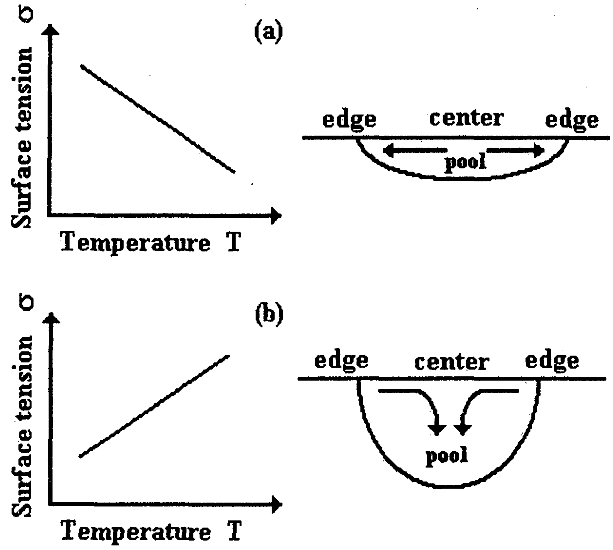


Fig. 5 D/W ratio and oxygen content in weld vs. SiO_2 flux quantity (a) 4μm (b) 25μm

4. Discussion

Weld penetration in GTAW was determined by the fluid flow mode in the weld pool. The surface tension gradient on the welding pool surface is a principle variable that changes the convection mode. Generally, the surface tension decreases with the increasing temperature, $\partial\gamma/\partial T<0$, for 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 pool shape is relatively wide and narrow as shown in **Fig.6(a)**. Heiple and Roper [18, 20] proposed that surface active elements such as oxygen, sulfur and selenium can change the temperature coefficient of surface tension for iron alloys from negative to positive, $\partial\gamma/\partial T>0$, and further more, change the direction of fluid flow in the weld pool as illustrated in **Fig.6(b)**. In such a case, a relatively deep and narrow weld will be produced.



(a) $\dfrac{\partial\sigma}{\partial T}<0$; (b) $\dfrac{\partial\sigma}{\partial T}>0$

Fig.6 Marangoni convection mode by surface tension gradient

In our experiments, the oxygen in the weld from the decomposition of the oxide flux played the important role as an active element and changed the Marangoni convection mode of the liquid weld pool. The research conclusion by H.Taimatsu and K.Nogi [21] showed that oxygen was an active element in pure liquid iron in the range of 150 ppm~350 ppm. In this range, the temperature coefficient of the surface tension of the Fe-O alloy is positive as shown in **Fig.7**, while out of the range, the coefficient of surface tension to temperature changed to negative or nearly zero. It can be assumed that the oxygen in the stainless steel weld pool has the same effect. As the oxygen content in the weld increased with the oxide flux quantity, the Marangoni convection mode changed from outward to inward first, and then the inward convection became weaker or changed to the outward direction as the oxygen content was high in the weld. For that reason, the D/W ratio increased initially, followed by a decrease with the oxygen in the weld metal as shown in **Fig.3**. In our experiments, it was found when the oxygen content in weld was in the range of 70-300 ppm, the penetration of the weld pool was deep as shown in **Fig.8**.

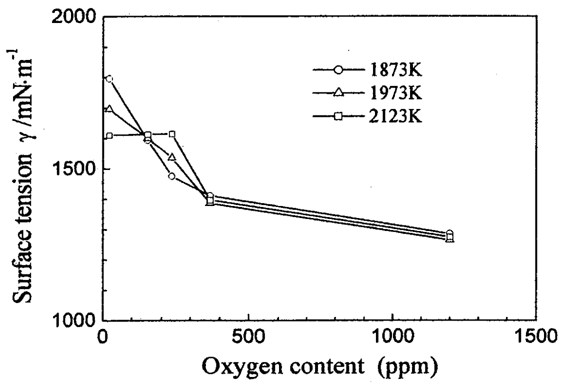


Fig.7 Effect of oxygen content on surface tension of liquid iron

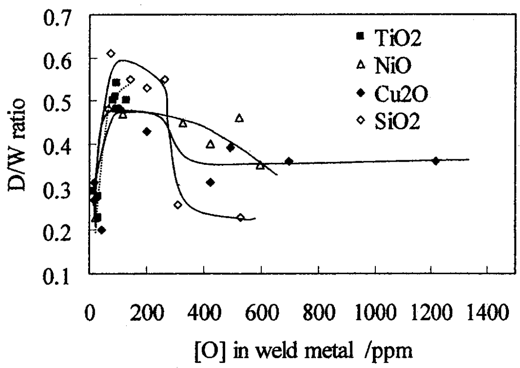
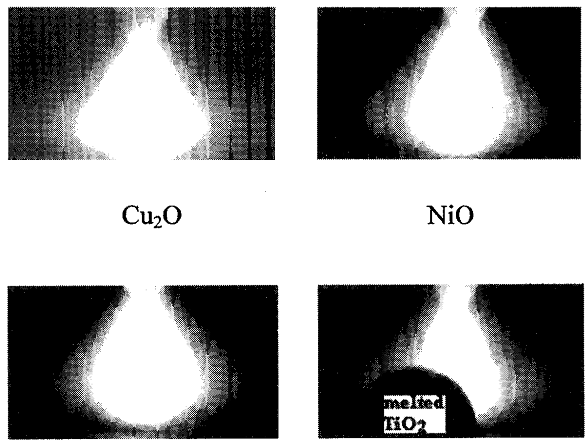


Fig.8 D/W ratio vs. [O] in weld metal

Comparing the results of the Cu_2O flux with that of the TiO_2 flux in Fig.3, it was found that there was a narrow range of Cu_2O quantity for which the D/W ratio was higher than 0.4, while there was a substantial range of the TiO_2 quantity ([O] in $TiO_2 > 100\times10^{-5}$mol,) for which the D/W ratio is independent of flux quantity. This significant difference is related to the physico-chemical properties of the oxide. From the Ellingham diagram (ΔG^o-T), the Cu_2O oxide is unstable and easily decomposed under the arc. The decomposed oxygen would dissolve in the welding pool and quickly increases the oxygen content in the weld. If the oxygen content is too high, the inward Marangoni convection becomes weak or changes to the outward direction and the weld pool penetration decreases again. However, if the oxide is stable and not easily decomposed completely under the arc, and causes the oxygen content in the weld pool to be relatively low, the Marangoni convection mode is maintained in the inward direction.

Through the observation of the arc shape, as the TiO_2 oxide quantity in the 5×0.1×50 mm slot was over 120×10^{-5} mol, the majority of the TiO_2 flux was melted into a liquid ball just in front of the arc and moved forward together with the arc as shown in **Fig.9**. The size of the liquid flux ball increased gradually as the new flux melted. At the end, the liquid ball would be broken under the arc and leave a pit on the bead. Because of this, the majority of TiO_2 has no function in increasing the oxygen in the weld. This phenomenon does not exist for the other oxides used in these experiments.



Cu_2O NiO

SiO_2 TiO_2

Fig.9 Arc images in welding with different flux

5. Conclusions

(1) In GTA welding, the quantity of the oxide flux has a significant effect on the weld penetration. The weld depth/width ratio initially increased, followed by a decrease with the increasing flux quantity for the Cu_2O, NiO and SiO_2.

(2) The oxygen in weld pool from the decomposition of the flux alters the surface tension gradient on the weld pool surface and hence changes the Marangoni convection direction and the weld pool penetration. The reversal of the Manrangoni convection in the welding pool is essential for the ATIG phemonena. When the oxygen content in the weld is in the range of 70-300 ppm, the weld depth/width ratio increased by 1.5 to 2 times. Too low or too high oxygen

content in the weld does not increase the depth/width ratio.

(3) The decomposition of the flux under the arc is strongly dependent on the particle size. The smaller the particles of the oxide, the easier is the decomposition.

(4) The weld depth/width ratio was not sensitive to the TiO_2 quantity. Therefore TiO_2 is a highly recommended active flux for real GTAW applications for deep penetration.

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