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Marangoni Convection and Welding Penetration in A-TIG Welding†

LU Shanping *, **FUJII Hidetoshi** **, **Sugiyama Hiroyuki*****, **TANAKA Manabu** **
and NOGI Kiyoshi ****

Abstract

The activated flux TIG (A-TIG) welding process is now considered as a feasible alternative to increase the process productivity using a thin layer of an active flux that results in a significant increase in weld penetration. The mechanisms by which five single oxide fluxes, Cu_2O, NiO, SiO_2, CaO and Al_2O_3, exert their effects on depth / width ratios in SUS304 stainless steel are studied. The oxygen dissolved in the weld plays an important role in altering the liquid pool surface tension gradient, the Marangoni convection mode and hence the weld penetration. The effective range of oxygen in the weld is between 70-300 ppm. Too high or too low oxygen content in the weld pool does not increase the depth / width ratio. The change in the surface tension of the molten pool is considered to be the principal mechanism for increased penetration. The decomposition of the flux significantly depends on the flux stability.

KEY WORDS: (Marangoni Convection) (Oxide Flux) (Weld Penetration) (Gas Tungsten Arc Welding)

1. Introduction

Activated fluxes that increase the penetration of tungsten inert gas welds (A-TIG) offer a means of significantly increasing the productivity of the welding process. A-TIG was first invented in the 1960s by researchers at the Paton Electric Welding Institute in Ukraine [1]. Limited published information regarding the use and composition of the flux attracted many researchers' attention in 1990s, such as the Edison Welding Institute (EWI) and United Kingdom Welding Institute (TWI) [2]. Many investigations on the mechanism and the application technology of the A-TIG process have been made and the two representative theories are the arc contraction [3-8] and reversal of the Marangoni convection in the welding pool [9-11]. However, there is still no common agreement about the A-TIG mechanism.

In this study, five different kinds of oxide fluxes were used to systematically study the effects of the single flux quantity and stability on the welding penetration in order to accumulate some flux optimization data for application in industry. Based on these results, the mechanism for A-TIG was discussed based on the oxygen content analysis of the weld metal after welding.

2. Experimental Procedures

A SUS304 stainless steel substrate machined into rectangular plates, 100×50×10mm^3, was used with the average composition of 0.06%C, 0.45%Si, 0.96%Mn, 8.19%Ni, 18.22%Cr, 0.027%P, 0.0015%S, 0.0016%O and the remainder of Fe. Before welding, one 100mm×5mm×0.1mm 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. As the acetone was volatilized, bead-on-plate welding was carried out.

GTA welding was performed using a DCEN power supply with a mechanized system in which the test piece was moved at a constant speed of 2mm/s under the torch. A 1.6-mm diameter thoriated tungsten electrode (2%Th) was used, and the electrode gap was maintained constant

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† Received on January 31, 2003
* Foreign Research Fellow
** Associate Professor
*** Graduate Student
**** Professor

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at 3 mm. The shielding gas was argon flowing at 10L/min. The welding current was 160A.

After welding, the cross-section of the bead etched by HCL+Cu_2SO_4 solution was photographed using an optical microscope (Olympus HC300 Z/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).

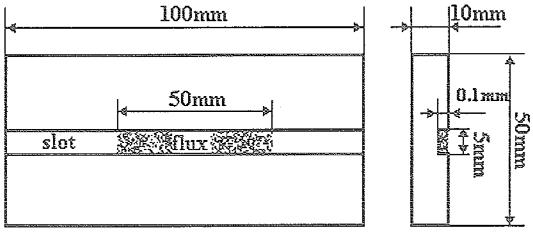

Fig.1 Schematic of SUS304 plate used in A-TIG

3. Results and Discussion

3.1 Flux quantity effect on the weld pool shape

Different quantities of flux in terms of [O] content in the oxide from 1.0×10^{-5} mol to 480×10^{-5} mol were used to study the effect of the flux quantity on the penetration. The cross-section shapes of the beads are shown in **Fig. 2**. Except for the Al_2O_3 flux, all the other four fluxes, Cu_2O, NiO, SiO_2 and CaO, significantly increase the penetration over a certain range of flux quantity compared with the fusion zone shape without flux. The penetration depth first increased, followed by a decrease with an increase in the oxide quantity for the Cu_2O, NiO and SiO_2 fluxes. However, the penetration depth is still deep with the CaO flux even at the high quantity of 480×10^{-5}mol. For the Al_2O_3 flux, there is no effect on the welding pool shape in the quantity range used in this study.

The depth / width ratio (D/W) and oxygen content in the weld after welding are plotted versus the oxygen quantity in the covered flux before welding in **Fig.3** and **Fig.4**, respectively. It is clear that the 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 CaO flux, the D/W ratio gradually increases and remains high even for the large quantity of 480×10^{-5} mol. The Al_2O_3 has no effect on the penetration and the D/W ratio remains constant around 0.25. The oxygen content in the weld metal after welding increases with flux quantity for the Cu_2O, NiO and SiO_2 fluxes, while the oxygen content in the weld metal with the CaO flux increases first and then remains around 140ppm. There is no large change in the oxygen content of about 30ppm in the weld for the Al_2O_3 flux. Irrespective of the flux category, when the oxygen content in the weld metal is in the range of 70-300 ppm, the D/W ratio is high.

Based on the results above, the oxygen content in the weld from the decomposition of the oxide flux plays an important role in changing the weld penetration. The surface tension gradient on the welding pool surface is one of the principal variables changing the convection mode. Heiple, Roper and Olsen [9-11] proposed that surface active elements such as O, S, Se and Te can change the

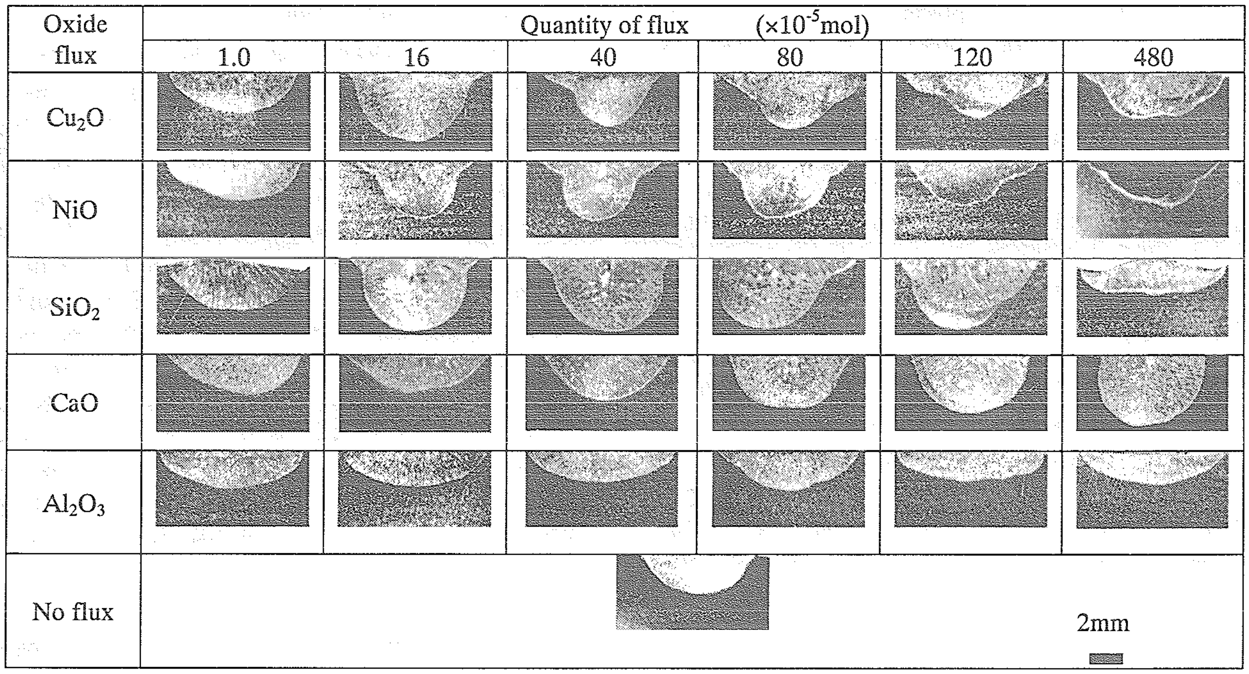

Fig.2 Effect of flux quantity on weld pool shape

temperature coefficient of the surface tension for iron alloys from negative to positive, $\partial\sigma/\partial T>0$, and also change the direction of the fluid flow in the weld pool from outward to inward. In that case, a relatively deeper and narrow weld is produced. The conclusion by Taimatsu and Nogi[12)] showed that oxygen was an active element in pure liquid iron in the range of 150~350 ppm. In this range, the temperature coefficient of the surface tension of the Fe-O alloy is positive, while outside this range, the temperature coefficient of the surface tension becomes zero or even negative. It can be assumed that the oxygen in the stainless steel weld pool has the same effect. However, the effective oxygen range in stainless steel for a positive $\partial\sigma/\partial T$ is 70~300 ppm. For that reason, the D/W ratio for the Cu_2O, NiO and SiO_2 fluxes initially increases, followed by a decrease with the oxygen in the weld metal as shown in **Fig. 3**.

3.2 Flux stability and weld penetration

Figure 4 shows that the oxygen content in the weld decreases in the order of Cu_2O, NiO, SiO_2, CaO and Al_2O_3. The stability of the five oxides increases in the order of Cu_2O, NiO, SiO_2, Al_2O_3 and CaO. The more stable the oxide, the more difficult the decomposition of the oxide. For stationary GTA welding on thick stainless steel, the peak surface temperature under the center of the arc can reach 2200-3000 K. At such a high temperature, the relative stability of Al_2O_3 and CaO will invert as shown in **Table 1**. It is assumed here that the ΔG^o calculation equations can be used over this temperature range. At the high temperature on the surface center under the arc, the stability of Al_2O_3 is nearly the same or slightly higher than that of CaO, so that a small portion of CaO can be decomposed in the center position of the slot under the arc and the oxygen content in the weld can reach 150 ppm, while the Al_2O_3 is not decomposed under the arc. Since the effective range for the oxygen content in the weld for deep penetration is limited to 70~300 ppm, the oxygen dissolving in the weld from the decomposition of the unsteady oxide is easily over 300 ppm for the relatively the lower quantity of flux used.

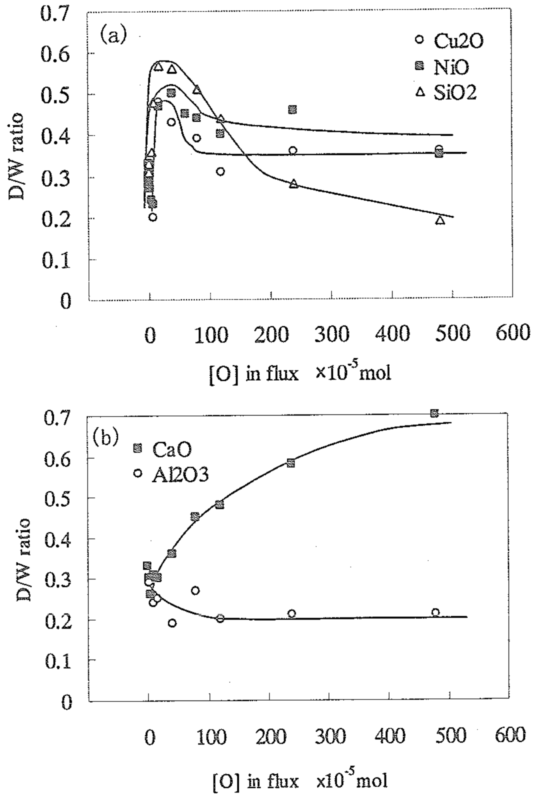

Fig.3 D/W ratio and oxygen content in weld vs. flux quantity
(a) Cu_2O, NiO and SiO_2 (b) CaO and Al_2O_3

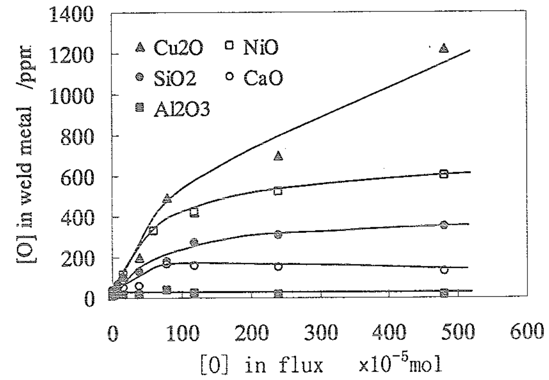

Fig.4 Dependence of oxygen content in weld on the flux quantity for different oxides

Table 1 Standard Gibbs free energy of Al_2O_3 and CaO

Reaction	$\Delta G^o/J=A+BT\log T+CT$			Temperature range /K	ΔG^o /J		
	A	B	C		2400K	2700K	3000K
$4/3Al+O_2=2/3Al_2O_3$	-1345574		300.4	2330~2500	-624614	-534494	-444374
$2CaO+O_2=2CaO$	-1590757		390.12	1760~2500	-654469	-537433	-420397

4. Conclusions

(1) In A-TIG welding, there is a different range of flux quantity to enhance the weld penetration for different fluxes, which depends on the stability of the flux.

(2) The oxygen content in the weld pool plays an important role in increasing the weld penetration through the reverse of the surface tension gradient on the weld pool from negative to positive over the specific range of 70-300 ppm for SUS304 stainless steel.

(3) The reversal of the Marangoni convection in the pool is essential for the A-TIG phenomenon.

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