Met. Mater. Int., Vol. 15, No. 3 (2009), pp. 471~477
doi: 10.1007/s12540-009-0471-3 Published 26 June 2009

Effects of Flux Composition on the Element Transfer and Mechanical Properties of Weld Metal in Submerged Arc Welding

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(received date: 21 March 2008 / accepted date: 7 November 2008)

Submerged arc welding was performed using metal-cored wires and fluxes with different compositions. The effects of wire/flux combination on the chemical composition, tensile strength, and impact toughness of the weld metal were investigated and interpreted in terms of element transfer between the slag and the weld metal, *i.e.*, △ quantity. Both carbon and manganese show negative △ quantity in most combinations, indicating the transfer of the elements from the weld metal to the slag during welding. The amount of transfer, however, is different depending on the flux composition. More basic fluxes yield less negative △ C and △ Mn through the reduction of oxygen content in the weld metal and presumably higher Mn activity in the slag, respectively. The transfer of silicon, however, is influenced by Al_2O_3, TiO_2 and ZrO_2 contents in the flux. △ Si becomes less negative and reaches a positive value of 0.044 as the oxides contents increase. This is because Al, Ti, and Zr could replace Si in the SiO_2 network, leaving more Si free to transfer from the slag to the weld metal. Accordingly, the Pcm index of weld metals calculated from chemical compositions varies from 0.153 to 0.196 depending on the wire/flux combination, and it almost has a linear relationship with the tensile strength of the weld metal.

Keywords: submerged arc welding, metal-cored wire, flux, element transfer, weld metal mechanical properties

1. INTRODUCTION

In general, submerged arc welding (SAW) produces a coalescence of metals by heating them with an arc between a bare metal wire (electrode) and the metal. The arc and molten metal are "submerged" in a blanket of fusible flux. In addition to bare metal wires, cored wires, also known as composite wires, are used in the process as well. Cored wire is a tubular filler metal wire consisting of a metal sheath and a core of various powdered materials. The wires represent the least expensive means of producing a weld metal of complex composition compared to solid wires, which may be unavailable, highly expensive, or impossible to produce; hardsurfacing wires are typical examples. However, the most common advantage of welding with cored wires is productivity. Due to their tubular design, cored wires differ from solid wires in that at any given welding current for the same diameter, the melting rate, or the burn off rate is significantly increased with a corresponding increase in the weld metal deposition rate. It is reported that the deposition rate can be up to 30 % greater than that of a solid wire of equivalent size and similar amperage [1]. Because of this high deposition rate, attempts have been made recently to apply cored wires to the fabrication of ships or offshore structures [1,2]. Farrow and Studholme [1] reported an application of the wires in offshore fabrications and Yoon *et al*. [2] in shipbuilding.

To apply cored wires to the fabrication of welded structures, it is important to be able to estimate weld metal composition from the wire/flux combination used. In this work SAW was performed using cored wires and fluxes with different compositions. The effects of flux composition on the chemical composition, tensile strength, and impact toughness of weld metal were investigated. As the slag/metal reaction seems to play a major role in the determination of the weld metal composition in SAW [3-8], the results were interpreted in terms of element transfer between the slag and the weld metal.

2. EXPERIMENTAL PROCEDURES

SAW was carried out using two 4mm diameter AWS A5.23

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Table 1. Chemical composition of cored wires and base plate used

	Chemical composition (wt.%)										
	C	Si	Mn	P	S	Ni	Al	Nb	Mo	Ti	B
Wire A	0.034	0.60	1.95	0.015	0.012	0.92	-	-	-	0.22	0.0066
Wire B	0.053	0.61	1.95	0.015	0.012	-	-	-	0.22	0.23	0.0074
Base Plate	0.076	0.30	1.52	0.007	<0.002	0.024	0.046	0.021	-	0.011	<0.0002

Table 2. Chemical composition of fluxes used

	Chemical composition (wt.%)												
	SiO_2	TiO_2	Al_2O_3	FeO	MnO	CaO	MgO	Na_2O	K_2O	ZrO_2	B_2O_3	CaF_2	BI*
Flux 1	15.02	6.96	47.26	4.14	3.46	1.69	9.40	0.49	0.48	0.15	0.20	10.50	0.62
Flux 2	18.18	2.35	21.98	4.53	3.22	6.13	29.93	0.26	1.45	0.05	0.15	13.75	1.82
Flux 3	16.66	7.96	19.31	2.70	0.53	11.30	37.29	0.30	0.20	0.09	0.52	6.80	1.90

*Basicity index = $\{CaO + MgO + CaF_2 + Na_2O + K_2O + 1/2(MnO + FeO)\}/\{SiO_2 + 1/2(Al_2O_3 + TiO_2 + ZrO_2)\}$

EC-G metal-cored wires. To determine the chemical composition of the cored wires, the wires were dissolved in acid solution and analyzed using inductively-coupled plasma emission spectrometry following KS D 1673. Table 1 shows the results. Compared to chemical composition of conventional solid wire, an increase of silicon and reduction of carbon are observed. Nickel is added in Wire A and molybdenum in Wire B. For each wire, three welds were made using three different bonded-type fluxes. Table 2 shows the chemical composition of the fluxes. The composition is the calculated value for the assumed compounds from the results of elemental analyses performed following KS E ISO 11535. According to IIW classification scheme [9], Flux 1 is classified as aluminate rutile ($Al_2O_3 + TiO_2 > 45$ %) and Fluxes 2 and 3 as aluminate basic ($Al_2O_3 + CaO + MgO > 45$ %, $Al_2O_3 > 20$ %). The basicity indexes of the fluxes are also contained in the table.

For each wire/flux combination, two sets of welds were made: single and multi pass welds. Single pass welds were made to study the element transfer between the slag and the weld metal. Bead-in-groove welds were made on 300 × 500 × 34 mm plates with welding parameters of 850 A-46 V-25 cm/min. The groove design is shown in Fig. 1(a). After welding, chemical and metallographic analyses of weld metal were conducted using the transverse section of weldments. Chemical analyses were performed using an emission spectrometer. Weld metal oxygen and nitrogen contents were determined using the inert gas fusion technique. To study the tensile strength and impact toughness of weld metals, multi pass welds were made. Single-V-groove welds were made

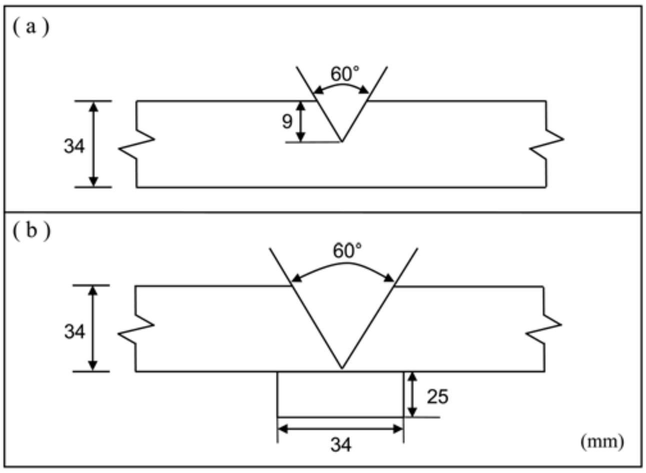

Fig. 1. Schematic diagram showing a joint design for (a) single pass and (b) multi pass welding.

using the same welding parameters as those used in single pass welding. The joint design is shown in Fig. 1(b). After welding, tensile specimens with 24 mm gage length and 6 mm diameter were obtained from the center of the weld metal and tested at room temperature. For impact toughness testing, full sized Charpy V-notch specimens were machined and notched on the weld centerline and tested at –20 °C. The Charpy test specimens were taken from both the upper and lower portions of the weld metal. The depth of the specimens was 3.5 mm below the top and bottom surfaces, respectively. The plate used for both single and multi pass welding is AB

EH36 grade steel with 34 mm thickness, and its chemical composition is also shown in Table 1.

3. RESULTS AND DISCUSSION

The results of the chemical composition analysis, tensile, and Charpy V-notch impact tests are summarized in Tables 3 and 4. As described in the experimental procedures, specimens for the tensile and impact tests were machined from multi pass weld metals, whereas specimens for chemical composition analysis were obtained from single pass weld metal in order to minimize the effect of dilution caused by multi pass welding. To compare the chemical compositions of the weld metals, the Pcm index of each weld metal was calculated using the formula shown in Table 3. The Pcm index is widely used as a weld cracking parameter because it represents the hardenability of the weld metal or heat-affected zones. Weld metal with high Pcm index has high hardness, and, thus, it is more susceptible to weld cracking. As shown in Table 3, weld metal Pcm indexes vary from 0.153 to 0.196 depending on the wire/flux combination. Figure 2 shows a relationship between the Pcm index and the tensile strength of weld metal. With an increase of the index, the tensile strength of the weld metal increases almost linearly, indicating the Pcm

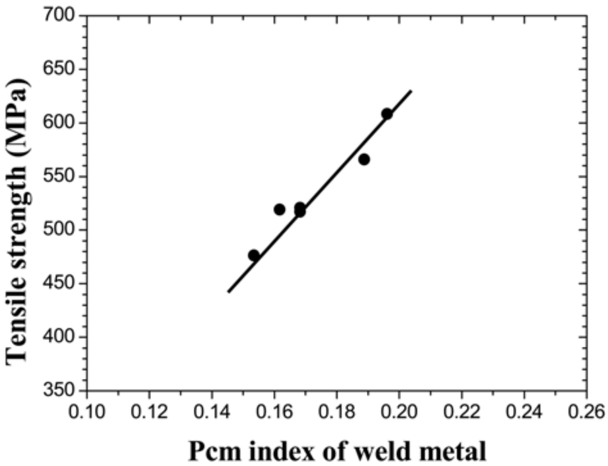

Fig. 2. Variation of weld metal tensile strength as a function of the Pcm index.

Table 3. Chemical composition of weld metals

	Chemical composition (wt.%)												
	C	Si	Mn	P	S	Ni	Mo	Al	Ti	B	O	N	Pcm*
Wire A / Flux 1	0.058	0.45	1.47	0.016	0.004	0.31	-	0.03	0.018	0.0020	0.053	0.0037	0.162
Wire A / Flux 2	0.056	0.40	1.70	0.017	0.003	0.35	-	0.016	0.0016	0.0016	0.042	0.0039	0.168
Wire A / Flux 3	0.055	0.143	1.61	0.015	0.002	0.34	-	0.03	0.028	0.0055	0.037	0.0043	0.189
Wire B / Flux 1	0.055	0.40	1.42	0.014	0.005	0.02	0.07	0.03	0.020	0.0018	0.059	0.0033	0.153
Wire B / Flux 2	0.062	0.34	1.64	0.016	0.004	0.02	0.08	0.02	0.010	0.0015	0.034	0.0034	0.168
Wire B / Flux 3	0.070	0.40	1.56	0.014	0.004	0.02	0.08	0.03	0.022	0.0058	0.033	0.0033	0.196

*Pcm = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B

Table 4. Tensile properties and impact absorbed energy of weld metals at –20 °C

	Tensile properties			Impact absorbed energy at -20℃ (J)	
	TS (MPa)	YS (MPa)	El (%)	Upper portion	Lower portion
Wire A / Flux 1	519.3	432.8	34.3	16.4, 28.1, 26.2	22.3, 23.1, 27.0
Wire A / Flux 2	521.0	407.8	31.4	72.1, 85.0, 92.8	105.3, 67.8, 49.9 102.0
Wire A / Flux 3	565.9	387.6	31.5	49.0, 64.7, 44.5	76.5, 109.4, 72.6, 56.2, 49.0
Wire B / Flux 1	476.3	362.3	37.2	12.7, 11.6, 12.4	10.9, 7.7, 10.2
Wire B / Flux 2	517.1	433.8	29.2	81.4, 68.6, 102.0	30.5, 17.5, 24.3, 37.6, 19.0
Wire B / Flux 3	608.4	433.8	29.2	69.5, 82.4, 45.7, 84.6	32.0, 28.9, 21.6, 32.4, 38.4

metal tensile strength. This result implies that the selection of wire/flux combinations is very important for weld metal to have an adequate Pcm index or chemical composition and, thus, target strength.

The delta (△) quantity of the elements present in the weld metal was calculated and used to interpret the effect of the wire/flux combination on the chemical composition of the weld metal. The △ quantity is simply the difference between the analyzed and expected compositions in the weld metal and has been used to study slag/metal reactions in several works [6,10-12]. The formula used for calculation is given as follows:

$$\triangle \text{ quantity} = \text{analyzed comp.} - \text{expected comp.} \quad (1)$$

If it is positive, the element is considered to transfer from the flux (slag) to the weld metal, and, if it is negative, the element is considered to transfer from the weld metal to the slag. The expected composition can be calculated on the compositions of wire and plate used and the percentage of dilution through the following formula:

$$\text{expected comp.} = \frac{\text{dilution}}{100} \times \text{base metal comp.} + \frac{100-\text{dilution}}{100} \times \text{wire comp.} \quad (2)$$

The percentage of dilution was determined geometrically from the transverse section of the weldments. As carbon, manganese, and silicon are major alloying elements in weld metal, the △ quantity of each element was determined. Figure 3 illustrates the variation of △C depending on the wire/flux combination. Except the Wire B/Flux 3 combination, all combinations yield negative △C, indicating a transfer of carbon from the weld metal to the slag. As Wire B has higher carbon content, 0.053 %, than Wire A, 0.034 %, it yields larger transfer. It has been reported [13] that the transfer of carbon from the weld metal to the slag is influenced by the oxygen content in the weld metal through the following reaction:

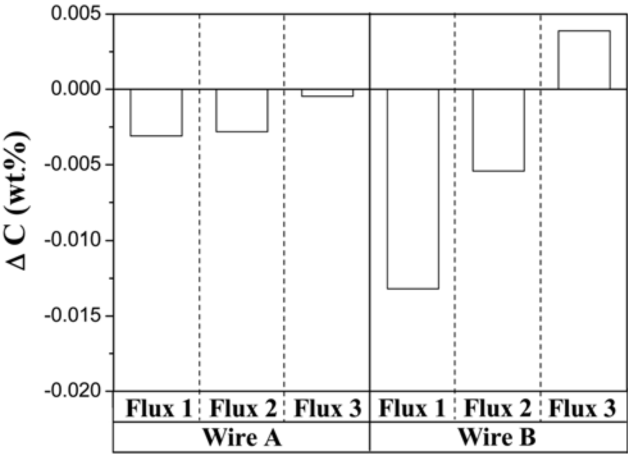

Fig. 3. Changes in △ C depending on the wire/flux combination.

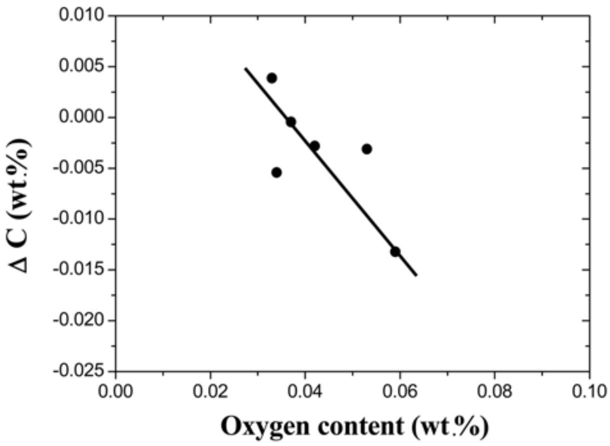

Fig. 4. Variation of △ C as a function of the oxygen content in the weld metal.

$$[C] + [O] = CO \quad (3)$$

Figure 4 shows the variation of △C as a function of oxygen content in the weld metal. As expected from the reaction, △C becomes less negative as the oxygen content decreases and becomes positive, 0.004, when the oxygen content is reduced to 0.033%. It is obtained in the Wire B/Flux 3 combination and is the lowest oxygen content in the present experiment. On the contrary, the highest oxygen content, 0.059 %, is obtained in the Wire B/Flux 1 combination and accordingly gives the largest negative △C, -0.013. It is reported [14-16] that the oxygen content in weld metal is highly dependent on flux basicity and it decreases with an increase of the basicity. As indicated in Table 2, Flux 1 has the lowest basicity, 0.62, while Flux 3 has the highest, 1.90. Accordingly, the weld metals used in Flux 1 have relatively high oxygen contents, 0.053 % to 0.059 %, while the weld metals used in Flux 3 have low oxygen content, 0.033 % to 0.037 %. These results indicate that it is necessary to use fluxes with high basicity for lower oxygen content in weld metal and, thus, for less negative or even positive △C.

Figure 5 illustrates the variation of △Mn depending on the wire/flux combination. Except the Wire A/Flux 2 combination, which shows a positive value, 0.004, all other combinations show negative values from -0.040 to -0.246. Hence, like carbon, manganese is also transferred from the weld metal to the slag in most combinations. However, the amount of transfer is different depending on the flux used. It is -0.246 to -0.203 in Flux 1, and -0.144 to 0.004 in Fluxes 2 and 3, showing larger transfer in Flux 1. As Flux 1 has almost the same or even larger MnO content than Fluxes 2 and 3, the observed larger transfer from the weld metal to the slag in Flux 1 is not caused by the MnO content difference. Previous reports stated [13,17] that the Mn balance between the slag and the molten metal was strongly influenced by the alkaline earth cation concentration in the slag. Davis and

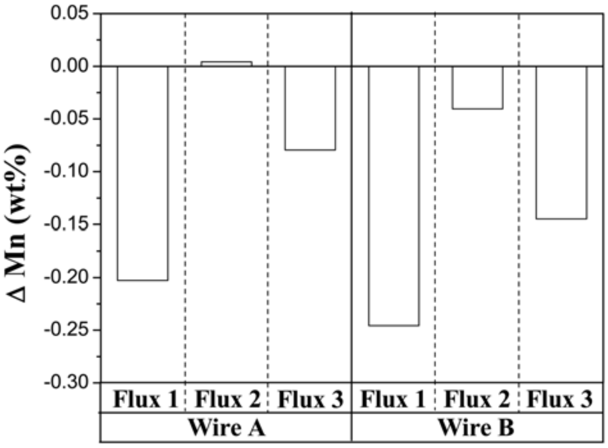

Fig. 5. Changes in △ Mn depending on the wire/flux combination.

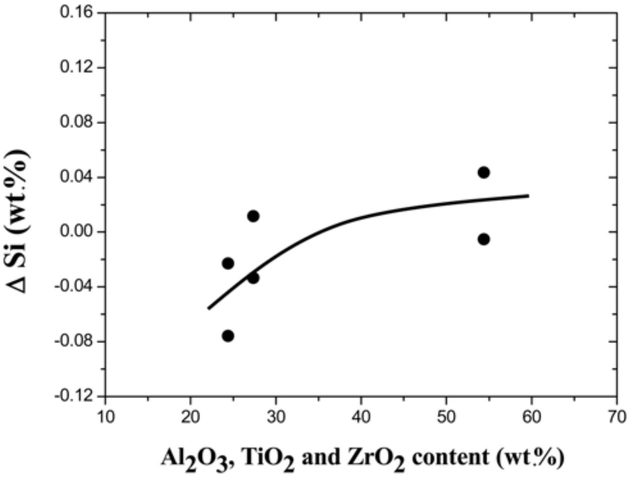

Fig. 7. Variation of △ Si as a function of the Al_2O_3, TiO_2 and ZrO_2 contents in the flux.

Bailey [13] claimed that Ca and Mg contents in the slag do affect the transfer of Mn because Ca and Mg cations increase the activity of Mn in the slag. As indicated in Table 2, Flux 1 has the smallest CaO and MgO contents and, thus, likely has lower Mn activity in the slag, resulting in larger manganese transfer from the weld metal to the slag. Therefore, it is necessary to use fluxes with higher CaO and MgO contents, *i.e.*, fluxes with high basicity, in order to obtain lower manganese transfer from the weld metal to the slag or less negative △Mn. When a comparison is made between Fluxes 2 and 3, Flux 2 shows less manganese transfer than Flux 3, even if Flux 2 has less CaO and MgO contents. This is because theh MnO content differs between the two fluxes. While it is 3.22 % in Flux 2, it is only 0.53 % in Flux 3. Therefore, less transfer is expected in Flux 2.

Figure 6 illustrates the variation of △Si depending on the wire/flux combination. When Wire A is used with Fluxes 1 and 3, △Si shows positive values, 0.044 and 0.012, respectively. Except these combinations, all other combinations show negative values from -0.005 to -0.076. This difference is not caused by the SiO_2 content difference because the content is almost the same as 15 % to 18 % in three fluxes. According to Davis and Bailey [13], an increase in Al, Ti, and Zr could replace Si in the SiO_2 network, leaving more Si free to transfer from the slag to the weld metal because Al, Ti, and Zr oxides are also network-formers like SiO_2. Figure 7 shows the variation of △Si as a function of Al_2O_3, TiO_2, and ZrO_2 content in the flux. As the content increases, △Si becomes less negative and reaches a positive value, 0.044, when Wire A is used with Flux 1, which has the largest Al_2O_3, TiO_2, and ZrO_2 content. This result indicates that, in contrast to carbon and manganese transfer, silicon transfer is promoted in fluxes with high basicity because the oxides decrease the flux basicity. Finally, variations of △B depending on the wire/flux combination are also studied because boron has a powerful effect on the Pcm index as well, even though it accounts for a very small amount of the weld metal. As shown in Fig. 8, both wires show positive values when used with Flux 3 and negative values with Fluxes 1

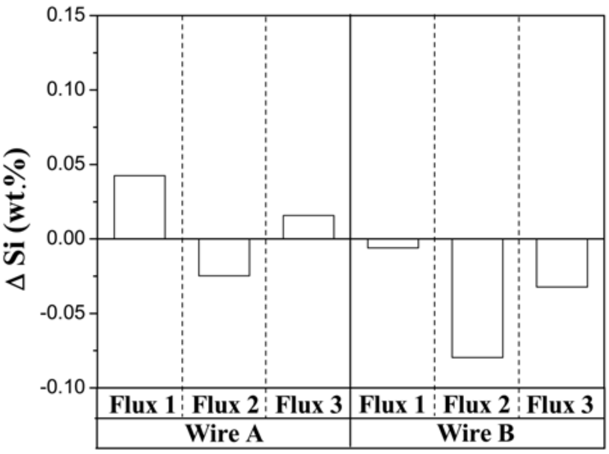

Fig. 6. Changes in △ Si depending on the wire/flux combination.

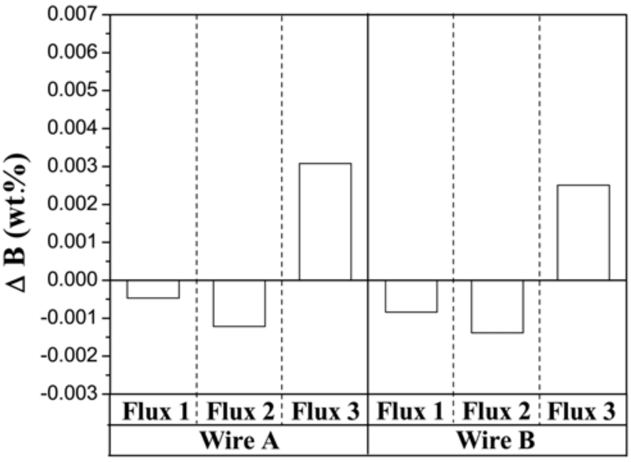

Fig. 8. Changes in △ B depending on the wire/flux combination.

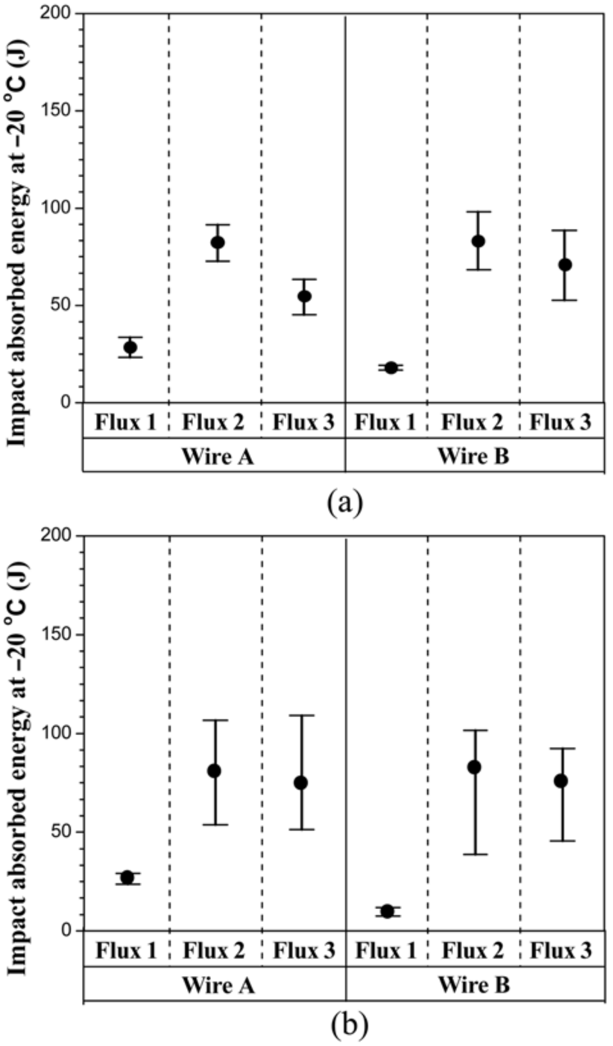

Fig. 9. Impact absorbed energy of the weld metal at −20 °C: (a) upper and (b) lower portions.

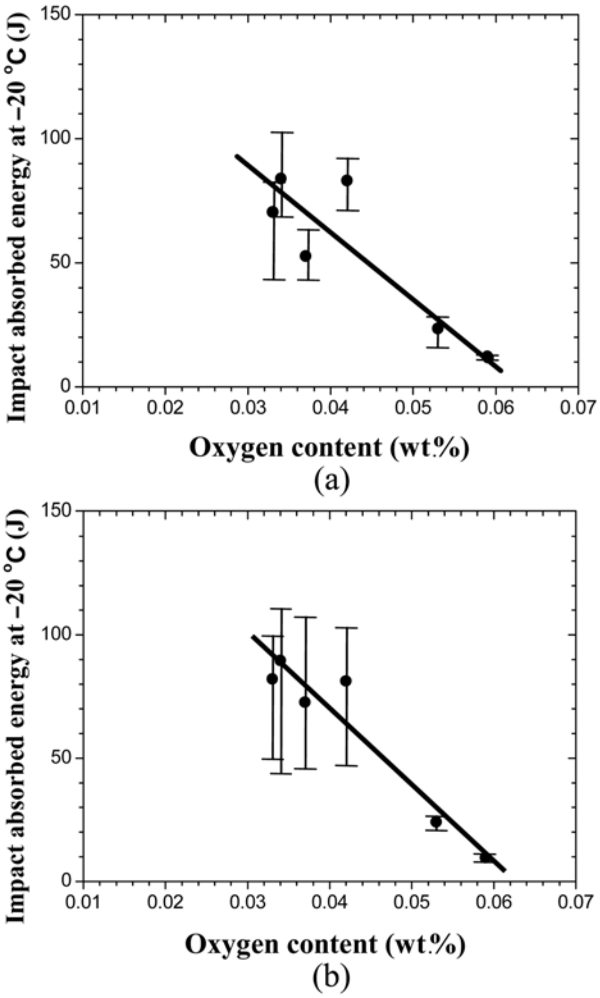

Fig. 10. Variation of impact absorbed energy of the weld metal at −20 °C as a function of oxygen content: (a) upper and (b) lower portions.

and 2. As Flux 3 has higher B_2O_3 content than Fluxes 1 and 2, more boron is expected to transfer from the slag to the weld metal. As shown in Table 2, the B_2O_3 contents in Fluxes 1, 2, and 3 are 0.20 %, 0.15 %, and 0.52 %, respectively.

Meanwhile, a variation of the Charpy V-notch impact absorbed energy of the weld metal is shown in Fig. 9. Regardless of the specimen location, Fluxes 2 and 3 show 40 J to 50 J higher energies than Flux 1 in both wires. The variation of the energy was plotted as a function of oxygen content in weld metal in Fig. 10. It increases continuously as oxygen decreases from 0.059 % to 0.033 % in both specimen locations. Therefore, it is essential to select a wire/flux combination that yields lower oxygen content for high impact toughness. According to Table 3, the oxygen content in the weld metal is very highly dependent on the flux used, and Flux 3 yields the lowest oxygen content: 0.037 % when used with Wire 1, and 0.033 % with Wire 2. As mentioned earlier, as the oxygen content in weld metal decreases with an increase of flux basicity, the observed low oxygen content in Flux 3 is attributed to its high basicity, 1.90. Therefore, in terms of the impact toughness of the weld metal, it is desirable to use the highest basic flux, Flux 3.

4. CONCLUSIONS

Submerged arc welding was performed using metal-cored wires and fluxes with different compositions. The effects of the wire/flux combination on the tensile strength and impact toughness of weld metal were investigated and interpreted in terms of the element transfer, △ quantity, between the slag and the weld metal. The important results that were obtained are as follows:

1. Depending on the wire/flux combination, different △ quantity and, thus, different chemical composition of weld metals are obtained. The Pcm index calculated from the chemical composition of weld metals, accordingly, varies

from 0.153 to 0.196 depending on the combination. The tensile strength of weld metal increases almost linearly with an increase in the Pcm index.

2. Both carbon and manganese show negative △ quantity in most combinations, indicating transfer from the weld metal to the slag. The amount of transfer, however, is different depending on the flux composition. More basic fluxes give less negative △C and △Mn through the reduction of oxygen content in the weld metal and presumably higher Mn activity in the slag.

3. △Si becomes less negative and reaches a positive value, 0.044, as the Al_2O_3, TiO_2, and ZrO_2 contents in the flux increase. This is because Al, Ti, and Zr could replace Si in the SiO_2 network, leaving more Si free to transfer from the slag to the weld metal.

4. The impact toughness of the weld metal increases with an increase of flux basicity through a reduction of the oxygen content in the weld metal. Fluxes with a basicity of 1.82 to 1.90 show 40 J to 50 J higher impact absorbed energies than flux with a basicity of 0.62.

ACKNOWLEDGMENTS

The authors are grateful to Chul-gyu Park and Sun-il Lee of KISWEL for supplying the metal-cored wires used in this experiment.

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