Melting Phenomena of Flux Cored Wire†

Masao USHIO*, Ding FAN**, Yoshiaki MURATA***and Fukuhisa MATSUDA****

Abstract

Melting characteristics of flux cored wire is studied by the use of measuring techniques on high temperature resistivity, wire melting rate and heat content of droplet, as well as the high speed cine film technique. Factors influencing the melting phenomena, characteristics and polarity of power source, shielding gas, existence of flux or not, high temperature resistivity, are experimentally analyzed and precisely discussed.

The simple equation indicating the melting rate of solid wire is applied to the case of flux cored wire and fairly good agreement is obtained between experimental melting rate and theoretical one. With constant potential power source the dependence of melting rate on the extension is strong compared with the one with constant current power source because of the difference in metal transfer mode. The melting rate in DCEN polarity is much higher than that in DCEP polarity due to the change in arc heat inputs to the metal sheath and flux pole. The effect of flux are also studied and it is made clear in comparison with the solid wire melting, the flux increases the heat content of wire and thereby decreases the melting rate of metal sheath, and the flux increases the equivalent voltage of melting by arc heating especially in DCEN polarity.

KEY WORDS: (Flux Cored Wire) (FCA Welding) (Wire Melting) (Wire Melting Rate) (Metal Transfer)

1. Introduction

Flux cored wire welding is progressively and widely used in industrial production nowadays for its fine operation property and very good quantity of weld joint. In order to realize the all-position automatic welding process with flux cored wire it is necessary to make clear the relationship between the melting rate of flux cored wire and welding conditions.

In the case of solid wire GMA welding, Lesnewich[1] and Halmφy[2] have already put forward a very conventional expression on the calculating of wire melting rate and it has proved a rather fair agreement with experimental results[3]. In the case of flux cored wire, however, there is not yet an appropriate expression and it is not clear whether the equation for solid wire can be used to flux cored wire or not, even though some investigations have already been made, as a consistent conclusion can not been obtained from these limited studies[4,5].

In the previous paper the author pointed out the difference between the theoretical expression and experimental one on the melting rate of flux cored wire in the region of rather higher current condition and studied on its cause[4]. It had to be necessary to carry out furthermore the study more precisely and carefully on the melting rate of flux cored wire.

In this paper, the melting characteristics of flux cored wire has been studied on the wires with and without flux with different characteristics and polarity of power source and welding conditions, measured the high temperature resistivity, as well as the heat content of droplet during welding. The metal transfer phenomena has also been shown related with melting phenomena.

2. Experimental Procedures

A transistorized welding power source was applied for the welding process under both constant current (C.C.) and constant potential (C.P.) characteristics with electrode positive polarity (DCEP) and negative polarity (DCEN). Wire feed rate were accurately measured as the melting rate each time when welding was conducted and it could be set independently of the welding current and voltage which were recorded by means of data recorder. CO_2 and Ar80%-CO_2 20% gases were used as the shielding gas.

Flux cored wire used in the experiment was only one

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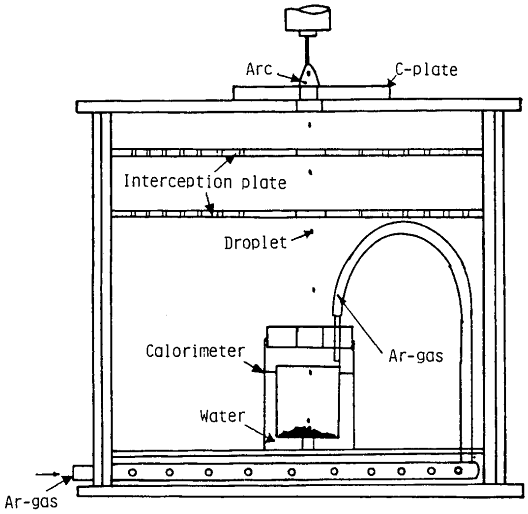

Fig. 1 Schematic illustration of install for measuring heat content of molten droplet.

type, made up with a mild steel sheath of 2 mm in diameter and flux of titania type. The metal cross section is a circular ring with a seam and its area is 1.92 mm^2.

Wire without flux (only metal sheath) of 2 mm in outer diameter and 2.63 mm^2 in area was also used as a comparison with flux cored wire.

The measurements of wire resistivity were done along Halmφy's experimental procedure at different currents.

Metal transfer phenomena were observed by high speed cine-photography[3]. The procedure is shown in the later section.

Heat content of molten droplet was measured with a install schematically illustrated in **Fig. 1**. Arc is started between flux cored wire and carbon plate with a hole in its center. Molten droplets fall down into the calorimeter shielded by Argon gas to prevent the drop from oxidization.

3. Experimental Results

3.1 Melting rate measurement

3.1.1 Melting rate with constant potential power source

In the welding with CO_2 gas as shielding gas and constant potential power source, the metal transfer mode is the shortcircuiting transfer mode. In the case the maximum extension length is equal to the distance between contact tip and workpiece. And the melting rate of wire is balanced with the feed rate of the wire in the stationary state of welding.

Figure 2 shows the measured result of melting rate of flux cored wire as a function of extension length and welding current under the condition, constant potential characteristics of power source, electrode positive polarity (DCEP) and CO_2 gas shielding. The case of electrode

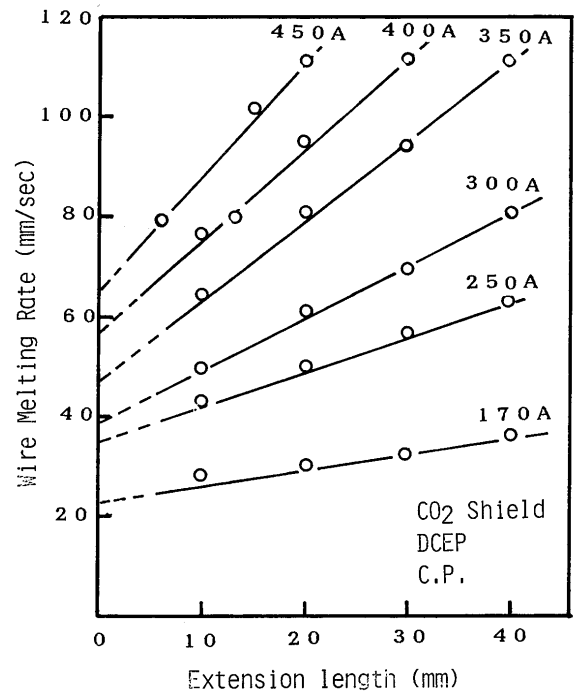

Fig. 2 Wire melting rate as a function of extension length and current (DCEP, C.P., CO_2 shielding).

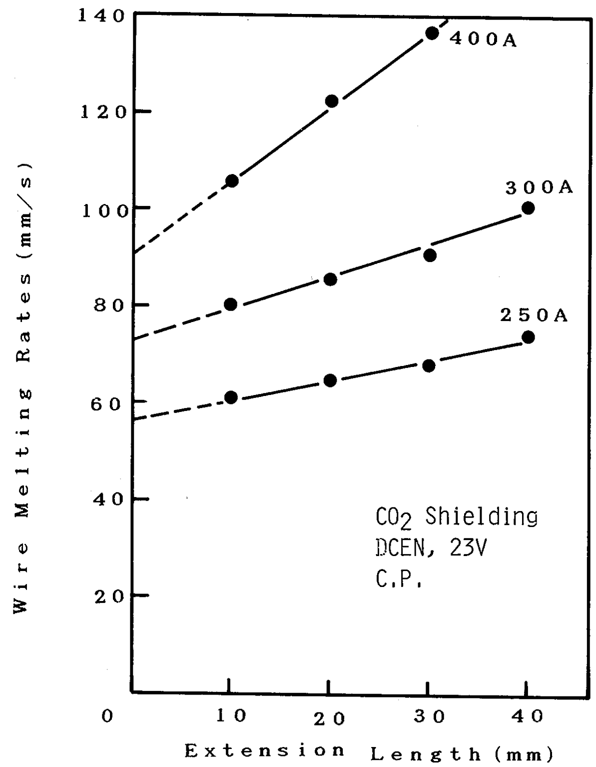

Fig. 3 Wire melting rate as a function of extension length and current (DCEN, C.P., CO_2 shielding).

negative polarity is shown in **Fig. 3**. In both cases the welding voltages are set to be 23 volts.

Figure 4 shows the case with Ar80%-$CO_2$20% as shielding gas.

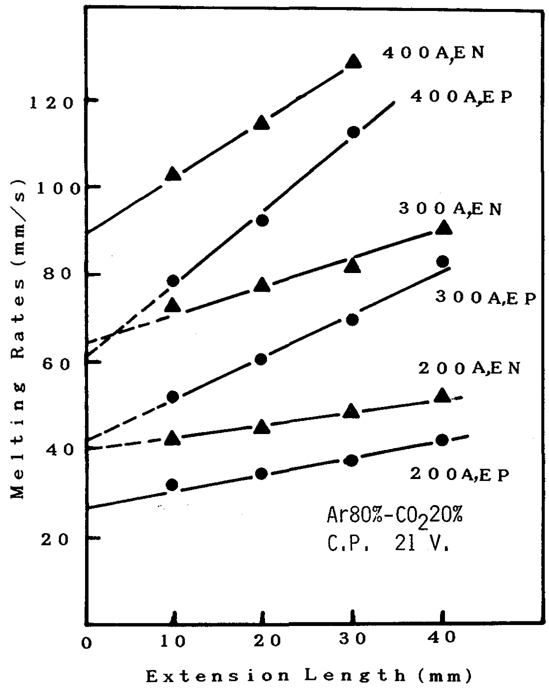

Fig. 4 Wire melting rate as a function of extension length, current and polarity (C.P., Ar80%-CO_2 20%).

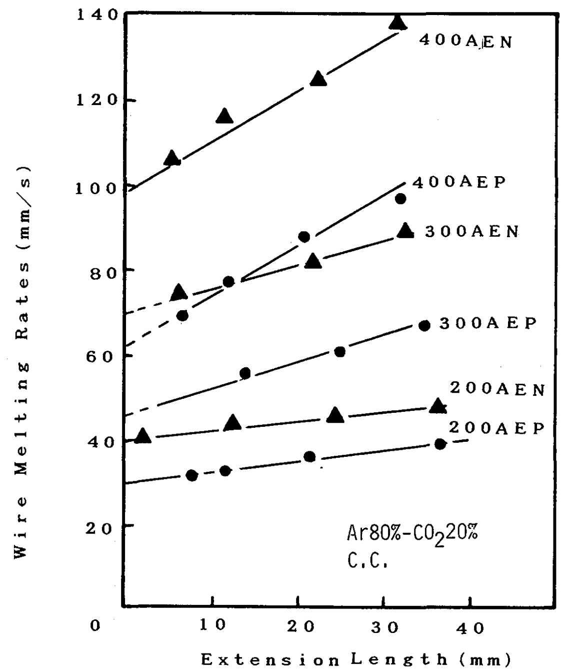

Fig. 5 Wire melting rate as a function of extension length and current (C.C., Ar80%-CO_2 20%).

It can be seen clearly from these figures that the wire melting rate increase linearly with wire extension at every current, which is similar to those of solid wire. The melting rates with DCEN polarity are much higher than that with DCEP polarity but the curve slope of the former is lower than that of the latter. This complies with the general concept that the heat used for melting comes from the ohmic heat in extension and the arc heat at the end of wire. Moreover, it is clear that the great extent of melting rate is decided by the welding current, extension length and electrode polarity, while the effect of shielding gas is not so obvious.

3.1.2 Melting rate with constant current power source

In this case the shielding gas of Ar80%-CO_2 20% is used. Since the arc is in open arc situation with this working gas, the extension length is measured by the use of high speed photograph. **Figure 5** shows the dependence of melting rate of flux cored wire on the welding current and polarity with constant current power source. It appears that the relationship among the melting rate, extension length, welding current and polarity is nearly the same to that with the constant potential power source, except that the curve slope in the region of rather higher current in the DCEP polarity. This means the contribution of ohmic heating to wire melting is greater in the DCEP polarity with C.P. power source.

3.1.3 Melting rate of wire without flux (only metal sheath)

In order to obtain a further understanding about the effects of flux on wire melting characteristics the melting

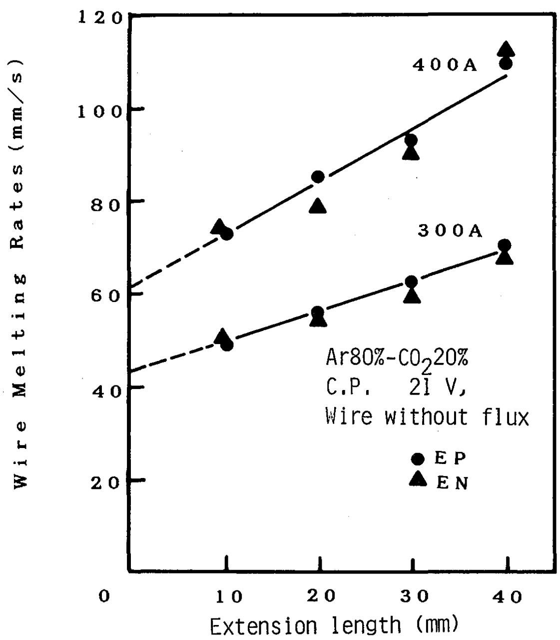

Fig. 6 Melting rate of wire without flux.

rate of wire without flux (only metal sheath) was measured with constant potential power source using Ar80%-CO_2 20% shielding gas. The result is displayed in **Fig. 6**. The melting rate of metal sheath wire is higher than that of wire with flux. And the difference between the melting rate with DCEP polarity and that with DCEN polarity was not so large.

3.2 Metal transfer characteristics

The metal transfer and arc phenomena of flux cored wire welding were studied by taking the high speed motion pictures in 3000 frames/s by the use of Xenon lamp as a backing light[3].

3.2.1 Metal transfer with constant current power source

The typical photographs showing the metal transfer and arc phenomena with C.C. power source with DCEP polarity are displayed in **Photo 1**. The welding parameter are 300 A, 32 V and Ar80%-$CO_2$20% as shielding gas. In the case, the arc is emerging from the circular metal portion covering the "flux pole" existed in the bottom of wire because of the difference in melting rate between the metal sheath and flux. The molten metal flows down along the flux pole. Droplet is formed at the tip of flux pole and is transfered axially into weld pool always together with flux. Spatter is quite small and usually appears with explosion of gas escaped from the flux. The average size of droplet and transfer speed towards to weld pool were measured by means of high speed cine film analyzer to be about 1.5 mm in diameter and 1.26 m/s in speed.

With DCEN polarity, the arc is emerging from the root of wire sheath and not stable. Due to the difference in melting rate between metal sheath and core flux, there are always a long flux pole protruding into the arc column. The droplet is formed at a point of metal sheath and it is transfered non-axially and independently with the flux pole, which is thought due to the effect of strong arc force in the cathode region and its non-uniformity. The droplet size is a little larger than that with DCEP polarity, while transfering speed is only about 0.4 m/sec, much lower compared to the case with DCEP polarity.

3.2.2 Metal transfer with C.P. power source

High speed photograph were taken with DCEP and DCEN polarity. Typical ones are shown in **Photo 3**. With this power source characteristics, metal droplet is transfered in the shortcircuitting transfer mode. When the molten metal bridge is broken in the final stage of shortcircuitting, the explosion always occurs and it is followed with the transfer of flux which generally forms a pole within the arc and contacts with weld pool.

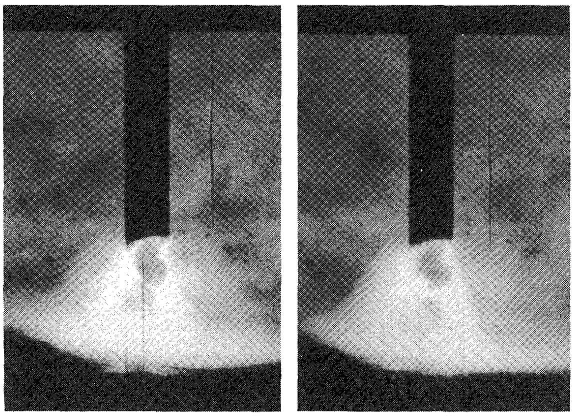

Photo 1 Photographs showing droplet axially transfered, (DCEP, C.C., 300 A, Ar80%-CO_2 20%).

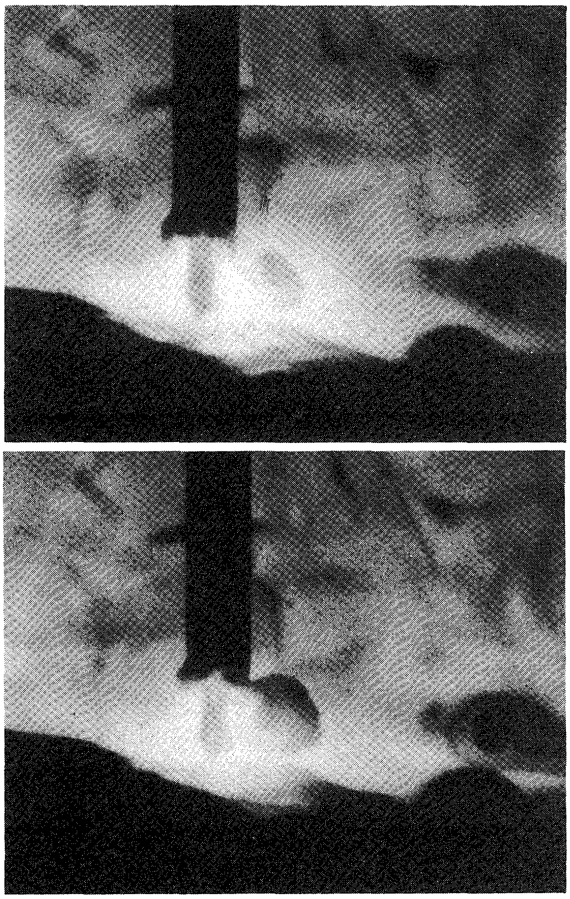

Photo 2 Photographs showing droplet transfered non-axially, (DCEN, C.C., 300 A, Ar80%-CO_2 20%).

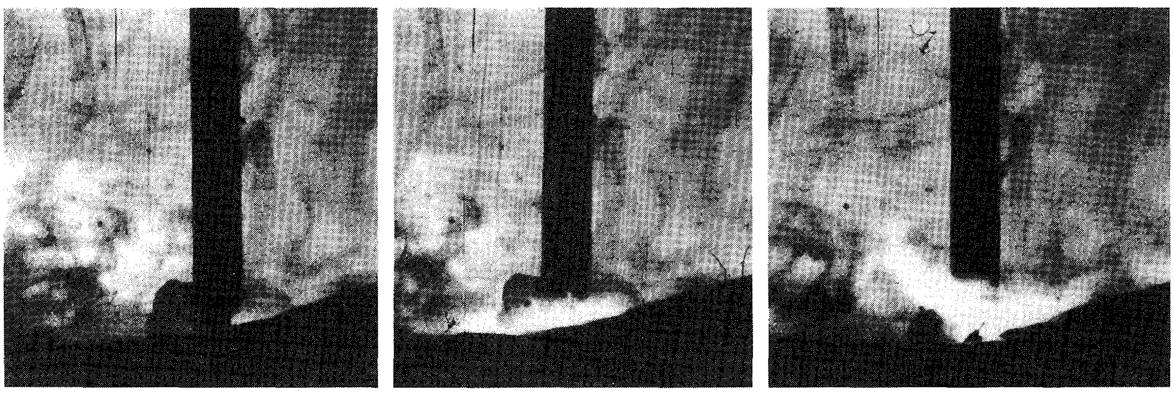

Photo 3 Photographs showing the shortcircuiting transfer, (DCEP, C.P., 300 A, Ar80%-CO_2 20%).

There is a difference between shortcircuitting phenomena with CO_2 shielding gas and that with Ar80%-CO_2 20% shielding gas, namely, with mixture gas the visible arc length is obviously longer than that with CO_2 gas even though the same arc voltage. Shortcircuit duration with mixture gas is about 1 ms, while the one with CO_2 gas is about 3 ms.

3.3 High temperature resistivity measurement

In solid wire GMA welding, the melting rate of wire is represented as follows by Halmøy,

$$U_m = \frac{1}{H_0 + b}(\Phi j + aLj^2) \qquad (1)$$

where,

U_m: wire melting rate (=wire feed speed in steady state) (mm/sec).

j: current density (A/mm^2)

L: extension length of wire (mm),

a: constant equals to high temperature resistivity of wire (Ω mm),

b: constant dependent on heat content at room temperature (J/mm^3),

H_0: heat content of molten droplet at detaching from wire end (J/mm^3).

The first term in the rightside of Eq.(1) represents the contribution by arc heating and the second the part by ohmic heating.

In order to determine the heat produced by ohmic heating in the case of flux cored wire, the high temperature resistivity of wire with and without flux were measured at different current along the procedure shown by Halmøy. The results are as follows,

for wire with flux, $a = 0.82 \times 10^{-3}$ (Ω mm), $b = 9.86$ (J/mm^3),

for wire without flux, $a = 0.85 \times 10^{-3}$ (Ω mm), $b = 7.8$ (J/mm^3).

It is found that the constant a and b are certainly independent of the current for both wires.

3.4 Heat content of flux cored wire

In order to obtain a further understanding about the melting characteristics of flux cored wire, the heat content of the droplet was measured with C.C. power source at different current with DCEP and DCEN polarity using Ar80%-CO_2 20% shielding gas. The result is shown in **Table 1**. The value of H represents the sum of heat content of metal and flux transfered, i.e.

$$H = \frac{Q_m + Q_F}{V_m} = H_m + H_F \frac{A_F}{A_m}, \qquad (2)$$

where,

Q_F, Q_m: heat quantity of flux and metal in the droplet, respectively,

H_F, H_m: heat content of flux and metal in the droplet, respectively,

A_F, A_m: Cross section area of flux and metal sheath,

V_m: volume of metal in the droplet.

It was found that the value of heat content H for DCEN polarity is higher than that for DCEP polarity. And with increasing the welding current the heat content increases. Further experiments showed that the influence of arc length and welding time on the measurement could be

Table 1 Some constant values deduced from Eqs.11 and 12

Constants	Φ (V)		H (J/mm^3)		K_1		$K_2 \times 10^5$	
Welding Condition \ Polarity	EP	EN	EP	EN	EP	EN	EP	EN
C.P., CO_2 Shielding, 170 ~ 450A, 23V	5.5	12.2	10.6	17.6	0.27	0.44	4.0	3.0
C.P., Ar80%-CO_2 20%, 200 ~ 400A, 21V	5.8	12.1	11.2	19.8	0.28	0.41	3.9	2.8
C.C., Ar80%-CO_2 20%, 200 ~ 400A, 30V	9.1	14.9	21.9	24.5	0.29	0.43	2.6	2.4
C.P., Ar80%-CO_2 20% Fluxless wire, 300 ~ 400A, 21V	8.1	~8.1	9.4	~9.4	0.39	~0.39	5.0	~5.0

Table 2 Measured values of heat content of droplet

Current	400A		300A		200A	
Polarity	EP	EN	EP	EN	EP	EN
H (J/mm^2)	22 ~ 26.9	24.6 ~ 28.7	20.1 ~ 24.2	—	13.4 ~ 15.8	14.2 ~ 19.1
C.C., Ar80%-CO_2 20%, ~ 35V						

neglected. The heat loss of droplet during falling down from wire tip to calorimeter was considered to be negligibly small. The estimation of this error was made using following equations[6],

$$\Delta H_P = \frac{3k}{2R_P^2} \cdot N_{Nu} \cdot (T_p - T_b) \cdot t_s \ , \quad (3)$$

$$N_{Nu} = \frac{h\, d_p}{k} = 2 + 0.60 \cdot N_{Re}^{0.5} \cdot N_{Pr}^{0.33} \ , \quad (4)$$

$$t_s = \frac{1}{g}\left[\sqrt{u_0^2 + 2gL} - u_0\right] \ , \quad (5)$$

$$N_{Re} = \frac{u\, d_p}{\nu} \ , \quad (6)$$

$$N_{Pr} = C_p \frac{\mu}{k} \ , \quad (7)$$

where,

ΔH_p: lossed heat content (J/mm^3),

where,

ΔH_p: lossed heat content (J/mm^3), about 0.37 J/mm^3 in this experiment,

k: thermal conductivity of air (2.59×10^{-5} J/mm°C),

R_P: radius of droplet (0.8 mm),

T_P: droplet temperature (2000°C),

T_b: environmental gas temperature (20°C),

t_s: *flight time of droplet during falling down in air (0.21 sec),*

N_{Nu}: Nusselt number,

N_{Pr}: Prandtl number,

h: heat transfer coefficient,

C_P: specific heat of air (1.005 kJ/kg°C),

N_{Re}: Reynoldz number,

μ: viscosity of air (1.81×10^{-6} pa.s),

ν: kinetic viscosity

u_0: initial speed of falling droplet (1.26 m/s),

L: distance between wire tip and calorimeter,

g: gravitational acceleration.

4. Discussions

4.1 Formula for calculating flux cored wire melting rate

According to the previous works and energy conservation law, following simple equations can be deduced for flux cored wire,

$$U_m\,(H_m + b_m) = \Phi_m j + aLj^2 - q_c/A_m \ , \quad (8)$$

$$U_F\,(H_F + b_F)\,A_F = q_c + q_a \ , \quad (9)$$

where,

U_m, U_F: melting rates of metal sheath and flux, respectively (mm/s),

H_m, H_F: heat contents of melten droplet of metal and flux, respectively (J/mm^3),

b_m, b_F: constants dependent on heat content of metal and flux at room temperature, respectively (J/mm^3),

A_m, A_F: cross sections of metal sheath and flux core, respectively, (mm^2),

Φ_m: equivalent voltage of melting of metal sheath due to arc heating (V),

L: extension length (mm),

a: constant equals to high temperature resistivity of wire (Ω mm),

q_c: heat quantity conducted out from metal sheath and used for melting flux, which is originally provided to the metal sheath (J/s),

j: current density (A/mm^2),

q_a: heat quantity thermally conducted to flux from arc column (J/s).

It must be noted that the thermal energy for melting flux comes mainly from two parts. The first one, q_c represents the part contributed by arc and ohmic heatings which is originally provided to the metal sheath and flow in to the flux by thermal conduction. The second one, q_a is heat flow transfered from the arc column to the flux which is always forms a "flux pole" protruding into the arc space.

In steady state of melting, the melting rate of flux, U_F, should be equal to the one of metal sheath, U_m, i.e. $U_m = U_F$, and by substitution this to Eqs.(8) and (9), we can obtain,

$$U_m = \frac{1}{H_m + H_F\dfrac{A_F}{A_m} + b_m + b_F\dfrac{A_F}{A_m}}\left[\Phi_m j + aLj^2 + \frac{q_a}{A_m}\right] \quad (10)$$

q_a must be related with current density and length of flux pole. When it could be simply assumed that q_a is directly proportional to welding current, Eq.(6) can be written as,

$$U_m = \frac{1}{H + b}\left[\Phi j + aLj^2\right] \ , \quad (11)$$

$$\text{or } U_m = K_1 j + K_2 j^2 \ , \quad (12)$$

where,

$$H = H_m + H_F\frac{A_F}{A_m} \ ,$$

$$b = b_m + b_F\frac{A_F}{A_m} \ ,$$

$$\Phi = \Phi_m + q_a/(A_m j) \ .$$

Above expression has just the same form like that for solid wire indicated by E. Halmφy.

H value can be directly measured by means of experiments described in previous section (3.4) or deduced from Eq.(11) through extrapolating extension length to zero.

b can be obtained experimentally as indicated in section 3.3. represents the equivalent voltage of melting due to arc heating but is affected by the length of flux pole, and its value can also be obtained experimentally and from Eq.(11). **Figures 10** and **11** show the relationship between the experimental melting rate and calculated one by Eqs. (11) and (12). There are rather good agreement between them.

4.2 Effect of external characteristics of welding power source on flux cored wire melting

As mentioned in section 3 and more clearly in Table 1, there are some differences in the curve slopes of melting rate related with extension length, K_2. Namely, K_2 with C.P. power source is greater than that with C.C. power source, which means with the C.P. power source the ohmic heating has more contribution than that with C.C. power source. Considering the fact that with C.P. source the metal transfer is in the shortcircuiting transfer mode, while in the latter case the transfer is carried out in the droplet or spray mode. In the shortcircuiting mode, the current is not always steadily constant, and during the period of shortcircuit the arc is extinguished and only ohmic heating has the effect. Furthermore, the heat content in the case of C.P. power source is lower than that with C.C. power source as displayed in Table 1.

From the Table 1, we can also find out that the equivalent voltage of melting, Φ, with C.C. power source is greater than that with C.P. power source. This is because in the former case the length of flux pole protruding into the arc space is longer and therby q_a is greater than the latter case.

4.3 Effect of polarity on flux cored wire melting

It has been pointed out in Section 3 that the melting rate of flux cored wire in DCEN polarity is much higher than that in DCEP polarity, but the dependence of melting rate on extension length in the former case is not so strong as that in the latter case. From Table 1 it can be seen that this is because the equivalent voltage, Φ, in DCEN is much higher than that in DCEP, since Φ_m, corresponding to cathode drop voltage, and heat flow transfered from arc column, q_a, are both greater than those in the case of DCEP. Moreover, the heat content of droplet in DCEN is higher than that in DCEP, which is confirmed by the direct measurement of heat content of droplet shown in **Table 2**. This may be the another reason.

4.4 Effect of flux core on wire melting

By comparing Fig. 6 with Fig. 4 it is found that the melting rate and its curve slope for wire without flux is higher than with flux under the same welding condition, and furthermore, in the case of wire with flux the melting rate has the dependence on the polarity of power source. In the fluxless wire the polarity has no effect on the melting rate, because of dominant effect of joule heating than the arc heating due to the shortcircuitting transfer mode by the use of C.P. power source. In addition, from **Figs. 7** and **8** the calculated melting rate is slightly high compared with the experimental one in the left side of the figure. All these difference should be attributable to the effect of the flux on wire melting characteristics. The effect of flux is briefly summarized as follows.

(1) The flux increase the heat content of wire since some heat is required to melt the flux, therefore, decreases the melting rate.

(2) The flux increases the equivalent voltage of melting particularly in DCEN polarity. This is due to the increase in the cathode drop voltage, which will have some variation due to the change in the chemical elements including in the flux such as fluoride and

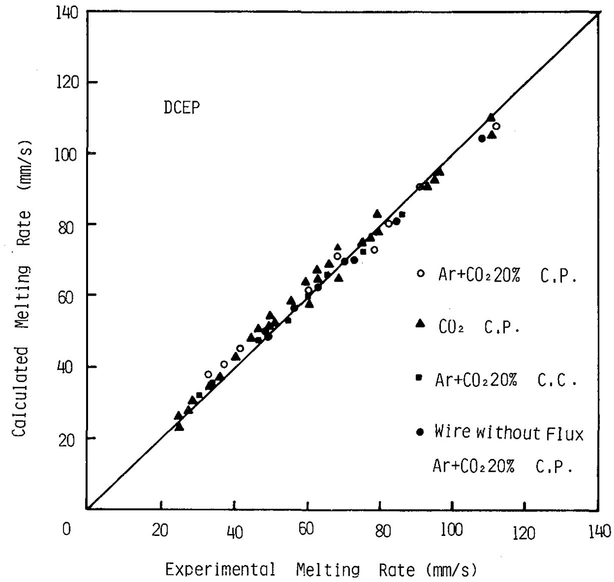

Fig. 7 Comparison between experimental wire melting rate and calculated one with DCEP polarity.

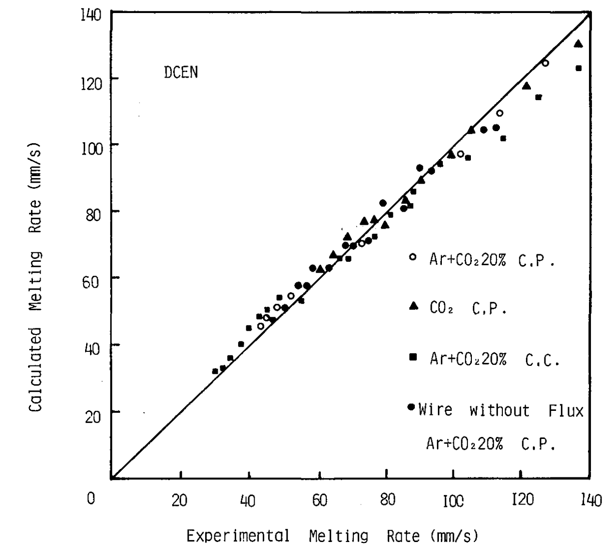

Fig. 8 Comparison between experimental wire melting rate and calculated one with DCEN polarity.

silica.

(3) The heat conduction to the flux from metal sheath along the extension. When the thermal conductivity is very low and the time duration in which the heat conduction occurs is rather short like this case, the effect is not so remarkable.

5. Conclusion

(1) The simple equation indicating the melting rate of solid wire is applied to the case of flux cored wire. The factor influencing the melting rate of flux cored wire is experimentally and analytically studied by the use of the equation. Fairly good agreement between the calculated melting rate and the experimental one was obtained.

(2) Welding power source has some influence on the melting rate of flux cored wire due to the change in transfer mode. With C.P. power source, the contribution of ohmic heating to the melting rate becomes higher than that with C.C. power source, because of shortcircuiting transfer. Therefore the dependence on extension length with C.P. power source is stronger as compared with that with C.C. power source. With C.C. power source, the metal transfer mode takes the droplet or spray transfer mode, so the arc burns continuously and droplet can be heated more.

(3) Electrode polarity has a great effect on the melting characteristics of flux cored wire. Because the equivalent voltage of melting by the arc heating is increased greatly with DCEN polarity, the length of flux pole becomes large, thereby, the heat input from arc column to the flux increases. Consequently the melting rate in DCEN is much higher than that in DCEP polarity. However, since the heat content of droplet is also increased in DCEN polarity, which has confirmed by the direct measurement of heat content of droplet, the dependence of melting rate on the wire extension is not so high as the case with DCEP polarity.

(4) The main effects of flux on wire melting is studied by comparing the melting phenomena of the wire with and without flux. And it was made clear that the flux make increase the heat content of wire and therefore decrease the melting rate of metal sheath, and the flux increases the equivalent voltage of melting by arc heating especially in DCEN polarity.

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