Melting Characteristics of Flux Cored Wire †

Masao USHIO *, A RAJA ** and Fukuhisa MATSUDA ***

Abstract

Metal transfer phenomena and melting rate of flux cored wire were studied by using high speed cine technique and measurement of high temperature resistivity of wire. Factors influencing the melting rate are discussed and experimentally analyzed. In flux cored wire, the flux has little influence on the high temperature resistivity of wire but it certainly increases the heat capacity. The influence of ohmic heating on melting rate is suppressed due to the presence of flux at longer extension or lower wire feed speed. The arc heating is also observed to have reduced contribution on wire melting due to its dissipation for melting the core flux. Since the heat conducted into core flux from the melted sheath and the one from the arc also used to melt the core flux are not taken into account, it may be improbable to apply the usual procedure used in the solid wire welding for the flux cored wire melting.

KEY WORDS: (Flux cored wire), (FCA welding), (Wire melting), (Wire melting rate), (Metal transfer).

1. Introduction

In MIG/MAG welding, the melting rate of wire is determined by the ohmic heating of the electrode extension and the heat from the arc. The ohmic heat has considerable influence on the melting rate especially with high resistive electrode like steel. Therefore, it is of importance to estimate the heat contributed by ohmic heating. It is possible to calculate the heat generated by ohmic heating in the case of solid wire to a fair approximation.[1,2,5] However, in the case of flux cored wire the presence of flux make the situation more complex, and also it makes the measurements difficult. In this paper an attempt has been made to determine the high temperature resistivity of the flux cored wires and thereby to calculate the heat generated due to ohmic heating. This paper also deals with the melting characteristics of flux cored wire with different shapes, the influence of polarity on melting rate and metal transfer. The influence of flux on the resistivity and heat content was also studied.

2. Experimental Procedure

A transistorized welding power source is used with very low internal inductance condition. Flux cored wires in the experiment have all mild steel metal sheath and usually used for CO_2 shielding. The composition of flux is titania type. The wire diameters and cross sectional shape of these wires are shown in **Table 1**.

The measurements of wire resistivity were done along the Halmφy's experimental procedure. A constant current of 100 A is applied to the wire of 10 cm in length and measured the time variation of voltage across the entire length of wire.

Metal transfer phenomena were observed by high speed cine film technique. The procedure is shown in the following section.

Table 1 Wire cross section and diameter of flux cored wires used.

Name of wire	Cross section of wire	Dia. of wire(mm)	Area of metal (mm^2)	Ratio(%)
A		1.6	1.45	72
B		2.0	1.92	61
C		2.0	1.90	60
NA		2.0	1.95	62

3. The Melting Characteristics of Flux Cored Wire

The current and voltage characteristics at different wire feeding rates were plotted for four different wires with DCEP polarity. Since the current and voltage characteristics of these wires appear nearly similar, the melting characteristic of only one wire is shown here **(Fig. 1)**. The melting characteristic curve at lower wire feed rates appear rather vertical, compared to the curve at higher feed rate. This may be due to the influence of contribution of ohmic heating to the wire melting. At lower current, the ohmic heat generated is very low and is conducted away into the flux due to the reason that the time allowed for heat conduction is more, than the time allowed for heat

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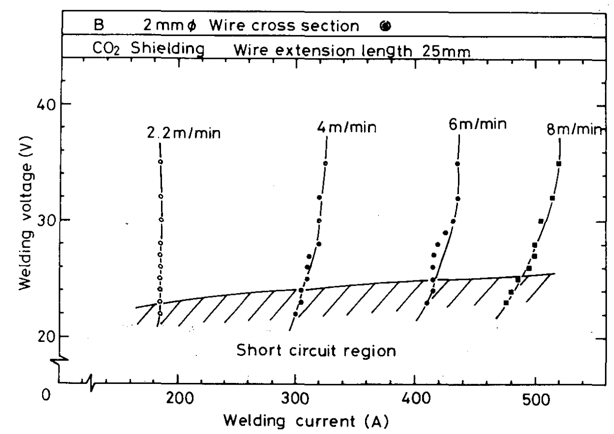

Fig. 1 Wire melting characteristic curve related to welding condition.

conduction at higher wire feed rates. Thereby the influence of ohmic heat on melting rate is reduced.

At higher wire feed rates the melting characteristic curve has a slope. This behavior is quite similar to that of solid wire melting characteristics. This is due to the influence of ohmic heat on the melting characteristic. At higher wire feed rates, due to larger current density and also due to less heat conduction time, the contribution of ohmic heat for the melting is enhanced. Therefore the influence of ohmic heat on melting rate is realized at higher wire feed rates.

4. Observation of Metal Transfer

The metal transfer characteristics of four different flux cored wires were investigated under DCEP and DCEN conditions. The shielding gas used was CO_2. The metal transfer characteristic of one self-shielded wire was also studied. High speed motion pictures of 3000 frames/sec were taken to observe the metal transfer phenomena by using a Xenon lamp as a backing light. Some photographs showing the formation of droplet are displayed in **Figs. 2** and **3**. The welding parameters were selected from the free flight transfer region for each wire[3,4]. The wire diameters and the cross sectional shape of these wires are shown in the Table 1. Except wire C, all other wires have circular cross section. Wire C has a complex cross sectional shape. Wire A, B and C are all CO_2 shielded wires for use. Wire NA is self-shielded type of wire.

4.1 Metal transfer under DCEP

With wire A, under DCEP condition, the metal transfer characteristic was studied. The welding parameter was 230 A and 30 V. In this case, the arc was emerging from the wire tip and was quite stable. The flux and metal sheath melts together and droplet is formed at the wire tip and transfers to the weld pool. The detachment frequency

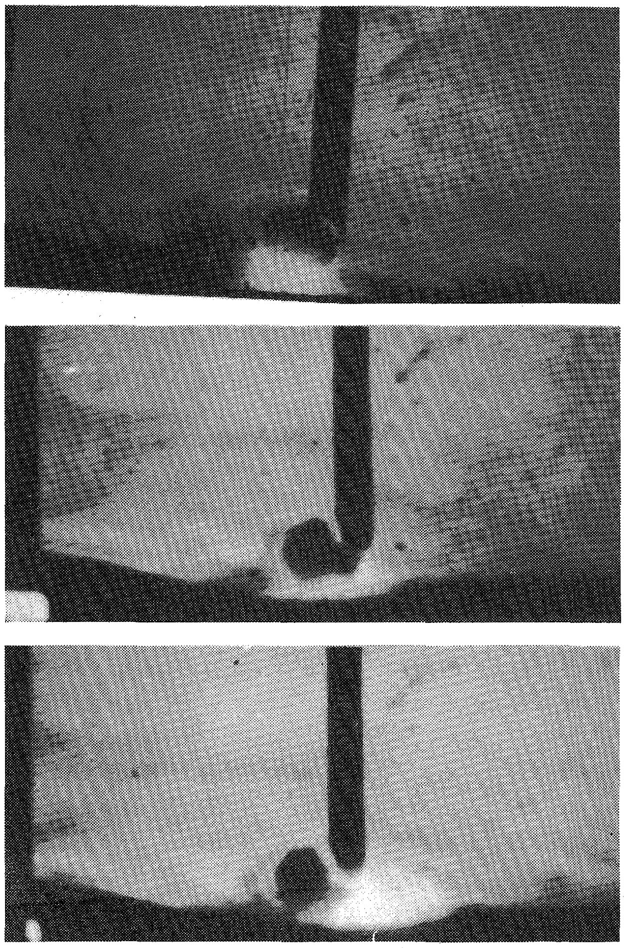

Fig. 2 Typical photographs showing the drop transfer in flux cored arc welding using wire A under DCEP condition.

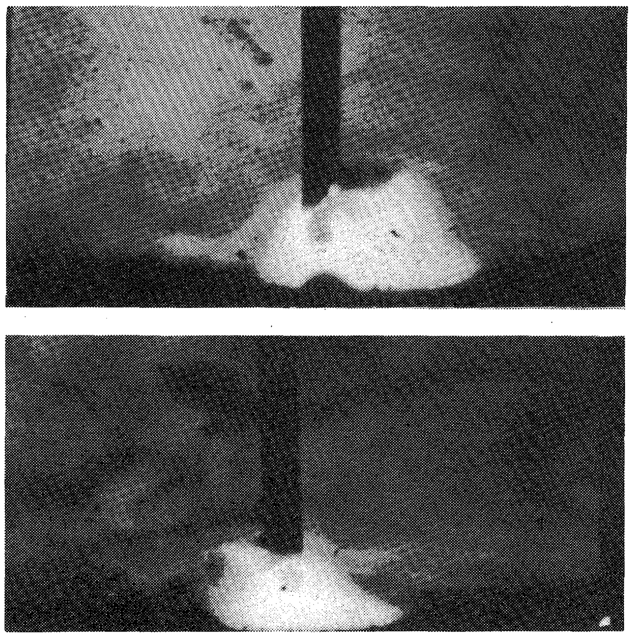

Fig. 3 Typical photographs showing the separation of meatl portion from cored flux in FCA welding under the condition of DCEN of wire A.

of droplet is very uniform. A slight difference in melting rate between the metal sheath and the flux was observed. Due to this difference, the flux is little protruding into the arc. But this molten flux is retracted back to the wire tip where it mixes with the molten metal and is transfered as a single droplet. The bead appearance in this case was good and spattering is very less.

The case that the current is rather high was observed by using the wire B. The welding parameter used was 380 A and 34 V. With wire B, it was observed that the arc is emerging from the circular metal portion. The melting rate of the metal sheath is faster than the flux core. Due to the difference in the melting rate, the molten flux is always bridging with the weld pool. The metal sheath melts faster and droplet is formed at one side of the wire tip. When the droplet becomes larger in size it is transfered non-axially. The formation of droplet at one side of the wire tip and non axial detachment disturbs the arc shape and stability.

The cross sectional shape of wire C is different from wires A and B. With wire C, the arc is originating from the metal portion of the wire cross section. With this wire, small size droplets are formed at one side of the wire tip and sometimes the detachment is accompanied by a minor explosion. This minor explosion may be due to the formation of gases within the droplet. In this case, the metal sheath and flux melt at the same rate. The droplet transfer is more closer to that of axial type of transfer.

4.2 Metal transfer with DCEN

With wire A, under DCEN condition it was observed that the melting rate of the metal sheath is much faster than the flux core. The droplet is formed at one side of the wire tip and it is transfered non-axially. Due to the difference in melting rate between the metal sheath and flux core, the flux core is extending or protruding in the arc column. And this protruding flux pole melts and transfers independently of the droplet. Therefore, the reaction between the molten metal and flux is very little at the droplet stage.

In the case of wire B, the arc is encompassing the periphery of the wire tip. In other words, the wire tip is protruding into the arc column. The melting rate of the metal sheath is much larger than the flux core. Therefore the flux pole is bridging with the weld pool. Large size droplets are formed at one side of the wire tip and it moves around the wire tip. When it reaches the opposite side, where it gets detaching, the droplet transfer is more non-axial.

With wire C, the arc shape is like as in the case of wire B. The melting rate of metal sheath is faster than the flux core. Therefore two flux poles are formed due to the geometry of the wire cross section and flux poles are melted and transfered in to the weld pool separately. The droplet is formed at one side of the wire and it is transfered non-axially.

5. Resistivity Measurement

In MIG welding, the melting rate of solid wire is generally represented as follows,[1)]

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

where, V_m: wire melting rate ($=V_f$: wire feed speed) (mm/sec),

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

L : extension length (mm),

Φ : equivalent voltage on melting due to arc heating (V),

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 right side of Eq. (1) represents the part by arc heating and the second the part by ohmic heating. The value H_0 equals to the heat content generated by ohmic heating and arc heating.

The electrode wire is heated up as it is fed through the extension length. If we consider a unit element of the wire extension, the temperature and heat content of this unit element progressively increases, as it travels from the contact tube to the arc root. Therefore the resistivity of the wire also changes along the extension length. To calculate the heat generated by the ohmic heating, it is essential to plot the resistivity as a function of the heat content of the unit element of the wire. In this study Dr. E. Halmφy's experimental procedure was used to measure the resistivity of the flux cored wires. The principle of Halmφy's experimental procedure is that when a constant current is applied to a fixed length S of an electrode wire, the entire wire will be heated up in the same manner as a small element moving along the stickout. The voltage $V(t)$ across the wire is proportional to dH/dt, when the current is constant,

$$dH/dt = (V(t)/S) \cdot J$$

where H is heat content of the wire element.

In this study the high temperature resistivity of flux cored wire A, B, C and NA, and two solid wires for use in CO_2 welding were measured. The H and $f(H)$ value were

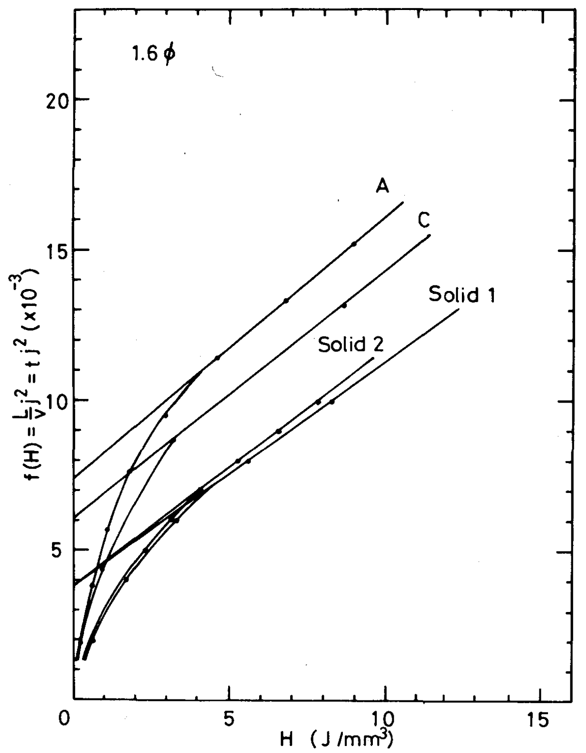

Fig. 4 H-f(H) relation for flux cored wires A and C. In the figure the ones of solid wires are also shown.

calculated and plotted as shown in the **Fig. 4**. The value of $f(H)$ represents tj^2, which corresponds to ((extension length)/(wire feed speed)) (current density)^2, namely (L/v_f) (j^2). H value is calculated using the following equation,

$$H = j \frac{1}{S} \int_o^t V(t)dt. \qquad (3)$$

The values of a and b could be obtained from the linear part of H-$f(H)$ plot by using the following relation,

$$H = a\,(Lj^2/V_f) - b.$$

The **Table 2** shows the $a(\Omega \text{ mm})$ and $b(\text{J/mm}^3)$ values for all the wire measured.

It is observed from Table 2 that the high temperature resistivity of the flux cored wire and solid wire are of the same order. But the values of b, for solid wire are much lower than those of flux cored wires. The higher b value in the case of flux cored wire is attributed to the higher heat capacity of the flux cored wires.

To find out the influence of flux on the resistivity, experiments were conducted on wires, with flux and without flux. To do the later experiment, flux was removed manually from the flux cored wires. The H vs $f(H)$ curves are shown in **Fig. 5** for wire B and wire NA. It is clear from these experiments that the influence of flux on the high temperature resistivity is negligible. But in both cases, the b value is higher for the wire with flux, this again proves that the heat capacity of flux cored wire is higher.

Table 2 Values of constants a and b derived from the high temperature resistivity measurement experiment.

Wire	a (Ω mm)	b (J/mm^3)
A	1.14×10^{-3}	8.3
B(with flux)	1.03×10^{-3}	11.34
(without flux)	1.01×10^{-3}	7.95
C	1.23×10^{-3}	7.66
NA(with flux)	1.32×10^{-3}	11.48
(without flux)	1.36×10^{-3}	10.3
Solid 1	1.30×10^{-3}	4.7
Solid 2	1.25×10^{-3}	4.5

It is considered that the H value calculated for flux cored wires along above procedure are not the H value experienced by wire element in the actual welding. When the current density in the stick-out portion is rather high and/or wire feed speed is also high, the heat conducted into the flux may be low, compared to the case of low current density and/or slow wire feed speed. Though the melting rate of solid wire could be represented simply by Eq.(1), the constant values may change to the variables dependent on the extension length, current density and wire feed speed in the flux cored wire welding. Namely, in Eq.(1) the heat conducted into the flux is not sufficiently taken into account. Also the heat generated in the flux core due to the ohmic heating is not taken into the consideration even if it was low. Halmøy's experimental procedure suffers on account of these two factors when it is applied for flux cored wire.

6. Discussion on Resistivity and Melting Rate

The Figure 5 shows the H vs $f(H)$ plots for wires B and NA with and without flux. In these two cases it is found that the heat content H is higher for the wire without flux than with flux for the same resistivity value. It is also observed from the experiments that the wire with flux takes more time than the one without flux to reach the same resistivity value shown in **Fig. 6**. This may be partly due to the conduction of heat into the flux core. Due to the heat conduction from the metal core into the flux, the heat content in the metal sheath is lowered and therefore the flux cored wire takes longer time to reach the same resistivity value as that of solid wire. For instance in the case of wire NA, the heat H generated during 1 sec, in the case of the wire without flux is about 3.8 J/mm^3, but in the case of wire with flux it is only 3.1 J/mm^3. Also, the time taken for melting off of the wire is less in the case of wire without flux than with flux. This is attributed to the higher heat capacity of the flux cored wire.

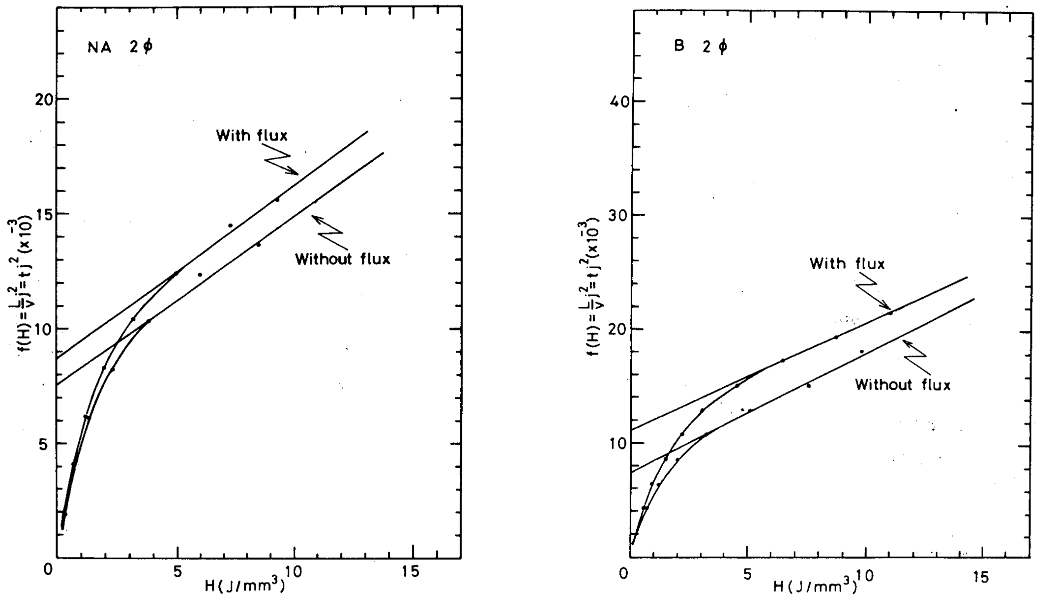

Fig. 5 H-f(H) curve of wire B in cases of with flux and without flux. H-f(H) curve of wire NA under similar conditions are also shown.

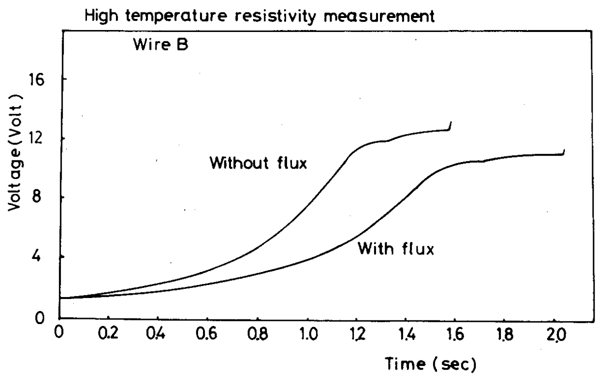

Fig. 6 Time variation of voltage across the wire from the applying the constant current (100A) in cases of with flux and without flux for wire B.

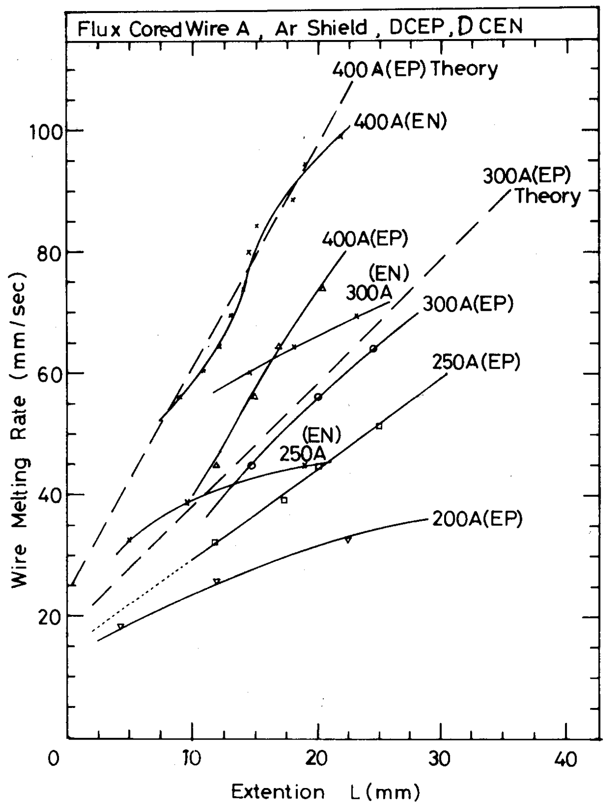

Fig. 7 Measured relation between extension and melting rate is some constant welding current, and theoretical prediction of the curve for 300 A and 400 A cases under DCEP condition. In the figure the measured results under DCEN condition are also displayed. These curve are drawn under argon shielding condition.

As shown in above section, the molten drop was formed at the wire end and stayed there for some time. In that case the heat capacity of the drop makes the understanding of the heat flow more difficult. To simplify the problem, the relationship between the melting rate and wire extension for some constant currents were experimentally obtained using the spray transfer mode with argon shielding. The results are shown in **Fig. 7**.

As increasing the current, the dependence of melting rate on extension length increases. To examine the availability of Eq.(1) for flux cored wire, the curve fitting technique was applied for the case of 250 A and DCEP condition using the a and b values listed in Table 2. The constant values obtained were $H_0 = 14.9$ J/mm^3 and $\Phi = 2$ V.

With these values the theoretical curves were drawn for the cases of 300 A and 400 A, which are shown by dashed lines in the same figure. The calculated one can be found in the left side of experimental one. In order to obtain the same melting rate, the extension length should be larger than the calculated one. The difference is more as increase in current or extension length. This is attributable to the heat conduction into the flux and the influence of heat capacitance of cored flux. Some portion of the ohmic and arc heats both generated in the metal part is used for melting the flux, and it becomes large if the current is increased. It is necessary to spend longer time to melt off the wire and flux than the expected one from the condition of lower current, and it consequently resulted in long extension under the same feed rate.

In the medium range of extension, the gradient of experimental curve has good agreement with the theoretical prediction curve. It suggests that the heat content of drop H_0 is nearly constant and has little dependence on the current. The value H_0 consists of the contribution from ohmic heating and the one from arc heating. As increase the current or wire feed speed, the portion of the ohmic heat conducted into the flux from the metal sheath becomes less. Thereby the rate of arc heat used for melting the flux in the total heat becomes high, and the portion of arc heat dissipated for melting the metal part is decreased. Consequently the experimental plots are placed under the theoretical curve.

In the same figure some plotts under the DCEN condition also displayed. In this case the droplet transfer is not so stable and situation of heat at the electrode also becomes very complex. From Eq.(1) point of view, none of meaningful results has obtained.

The quantity of heat conducted into the flux depends on the flux weight percentage, chemical composition of the flux and high temperature physical and electrical properies of the flux. Therefore, it is essential to understand the above mentioned properties of the flux, to make an accurate measurement of resistivity and heat content H in the case of flux cored wire.

In order to predict precisely the melting rate of flux cored wire, it is necessary to measure the individual constant term in Eq.(1) as dependent variables. Moreover to ensure the procedure, the metal transfer should be stabilize and make smooth to obtain the steady situation of heat flow.

7. Conclusions

The following are the conclusions drawn from the study.

(1) In flux cored wire, the flux has little influence on the high temperature resistivity of flux cored wire but it certainly increases the heat capacity.

(2) Since the heat conducted into the flux core from the melted sheath is not being taken into account, it may be improbable to use Dr. Halmφy's experimental procedure for flux cored wire resistivity measurement. In order to predict accurately the melting rate of flux cored wire, it is necessary to measure the individual constants in Eq.(1) as dependent variables.

(3) The influence of ohmic heating on melting rate is suppressed due to the presence of flux, at lower wire feed rates or longer extension length.

(4) The arc heating is also observed to have reduced contribution on wire melting due to its dissipation for melting the flux.

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