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Fused Metal Temperature in Arc Spraying*

—Study on Arc Spraying (Report 3)—

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Abstract

A flight process of fused metal in arc spraying is divided into four Stages, i.e., 1) fusion from wire, 2) flying in arc plasma, 3) flying in the air, and 4) adhesion on substrate. The fused metal temperature is estimated at two points of the flight process. One of them, (Tc), is estimated at the adhesion stage with a silicone oil calorimeter, and the other, (Ti), at the fusion stage by the calculation of heat input.

The following results are obtained from the estimations,

(1) *(Tc) and (Ti) depend on a wire feed speed parameter* $v_+/(v_+ + v_-)$, *and the (Tc) versus* $v_+/(v_+ + v_-)$ *curves shows a similar shape to the (Ti) curve, where* (v_+) *is the positive electrode side and* (v_-) *the negative.*

(2) *The temperature (Tc) at the adhesion stage is higher than the temperature (Ti) at the fusion stage for all the experimental values of* $v_+/(v_+ + v_-)$.

(3) *The heating effect of the fused metal in the arc plasma is thought to be greater than the cooling effect of the fused metal in the air. This accounts for the higher temperature attained at adhesion stage than the temperature at the fusion stage.*

1. Introduction

Arc spraying is a spraying method in which an electric arc is employed as the heat source to fuse the metal wire and to spray it onto the steel plate, or other surfaces to form a coating. It is believed that the temperature of the fused metal will largely influence the coating performance. Up to date, only the temperature of fused particles of other spraying methods such as plasma spraying has been measured,[1),2)] but, the temperature of fused metal in arc spraying method has not been determined.

In the previous report,[3)] the authors divided the process into four stages fiom the fusion of wire to the adhesion of fused particles in the arc spraying as shown in Figure 1 (namely, Stage I ; wire fusion process, Stage II ; fused metal flying process in the arc, Stage III ; fused metal flying process in the air, Stage IV; fused metal adhesion process). The authors also believed that temperature of fused metal varies in each stage.

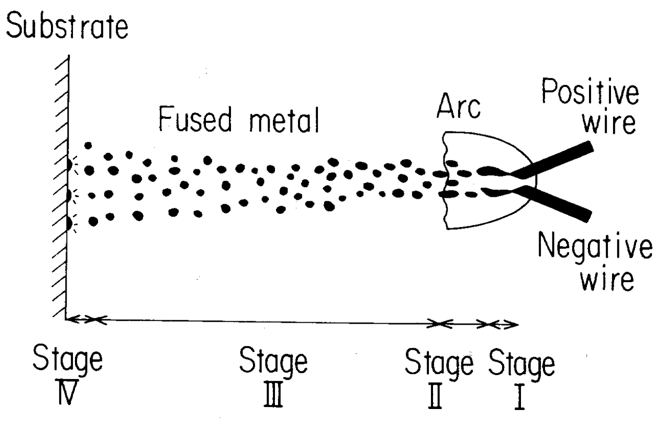

Fig. 1 Arc spraying process.

In the first report[4)] of this series, the authors reported that both the sprayed coating adhesive strength and the arc stability are largely influenced by the feeding speed condition of positive and negative wires.

In the current study, the temperature of fused metal when the wire feed speed is changed is examined, employing aluminium wire and stainless steel wire as the spraying materials. The estimation of the fused metal temperature was made at two points; namely, at a point just before the adhesion of the fused metal onto the steel plate (namely, Stage IV) and at a point just after wire fusion (namely, Stage I). The temperature in the former case (hereinafter referred to as "Tc") was measured by a special calorimeter employing silicone oil as the heat absorbing material. The temperature in the latter case (hereinafter referred to as "Ti") was estimated from the heat input conditions. These two temperatures were compared, and it was confirmed that the temperature varies from the moment just after fusion of wire to the moment just before adhesion.

2. Spraying Materials, Spraying Equipment and Spraying Conditions

Table 1 shows the spraying materials used for the experiment. For each material, a wire with a diameter of 1.6 mm was used.

Table 1 Spraying materials.

Material	Composition
Aluminium (Al)	Pure Al (over 99.7%)
Stainless steel (SUS308)	10~12%Ni, 19~21%Cr

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The arc spraying equipment used for the experiments included a constant voltage characteristic DC power source, and two electric motors for the separate feeding of positive and negative wires.

The arc current and arc voltage were measured by the pen-writing oscillograph; each average value was taken as average arc current (Iav) and average arc voltage (Vav).

Table 2 shows the arc spraying conditions. Employing aluminium and stainless steel (SUS 308) as the spraying materials, the negative wire feed speed (v_-) was varied, keeping the average arc voltage (Vav) and positive wire feed speed (v_+) constant.

Table 2 Arc spraying condition.

Spraying material	Al	SUS 308
Vav (V)	30	30
v_+ (m/min)	8	6
v_- (m/min)	3,6,8,12,16	4,6,8,10

3. Estimation Method of Fused Metal Temperature (Tc) just before Adhesion onto Steel Plate

The temperature increase in the calorimeter caused by the heat quantity of fused metal just before the adhesion was measured, and (Tc) was estimated from the measured value. Generally water is used as the heat absorbing material for the calorimeter.[5),6)] However, in the current study, silicone oil was used because of adoption of the measurement method described below.

(1) Calorimeter

Figure 2 shows a schematic diagram of the calorimeter for used the estimation of the fused metal temperature (Tc). The main unit of the calorimeter consists of a cylindrical container (outer diameter: 140 mm, height: 120 mm) made of vinyl chloride and a copper inner case (wall thickness: 1 mm, diameter: 94 mm, height: 80 mm) installed with a thermal insulating material. For the cap, a cork with a wall thickness of 20 mm was used. In this cap, an opening (diameter: about 40 mm) was made. 350 g of silicone oil was poured into this container as the heat absorbing material. A copper cylindrical container, (thickness: 1 mm, diameter: 40 mm, height: 70 mm) was dipped into the silicone oil to catch the fused metal by hanging it through an opening in the cap. In addition, in the silicone oil, an agitator and a copper-constantan thermocouple (A) for liquid temperature measurement were installed. Between the above-mentioned container and the spray gun, a water-cooled conical copper shelter (diameter of top-opening: 20 mm) and a shelter made of mild steel (diameter of opening: 30 mm) were provided. Between the copper shelter and the mild steel shelter, a copper-constantan thermocouple (B), to measure the temperature of compressed air flow heated by the arc, (hereinafter referred to as the "hot air") was installed in a position where no fused metal can come into contact with it.

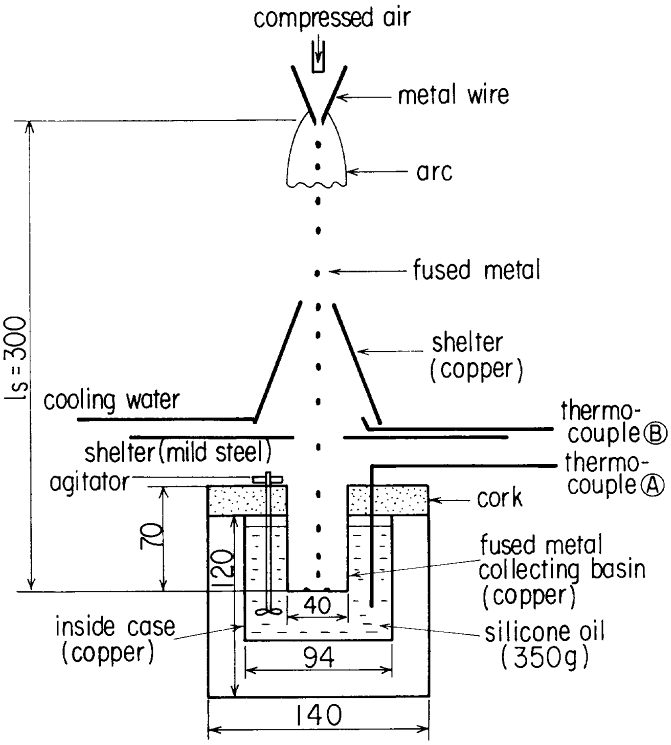

Fig. 2 Schematic diagram of calorimeter.

Above the calorimeter, spraying was done for 5 seconds, with a spraying distance (ls) of 300 mm. The fused particles passing through the two shelters were collected in the cylindrical copper container. The heat conveyed by fused metal and the hot air was transmitted to the silicone oil through the copper container. While sufficiently agitating the silicone oil, the change in silicone oil temperature (To) was measured against the time and the increase in silicone oil temperature (ΔT) was determined.

(2) Fused metal temperature

When the spraying is done for a certain period of time with the equipment shown in Fig. 2, the total transmitted amount of heat (Ht) can be obtained from the following equation.

$$Ht = Hc + H_f, \quad \cdots\cdots (1)$$

where (Hc) is the heat transmitted by fused metal and (H_f) is the heat transmitted by the hot air.

If (Hc) can be determined separately, the fused metal temperature (Tc) can be obtained. However, in arc spraying, both (Hc) and (H_f) cannot be measured separately. Therefore, the authors proposed to lower (H_f) value to zero in order to obtain (Hc). Now, in the case of aluminium spraying, the fused metal temperature is higher than the melting point (660°C), and the hot air temperature (T_f) is considered to be relatively low due to the use of a large amount of compressed air, thus

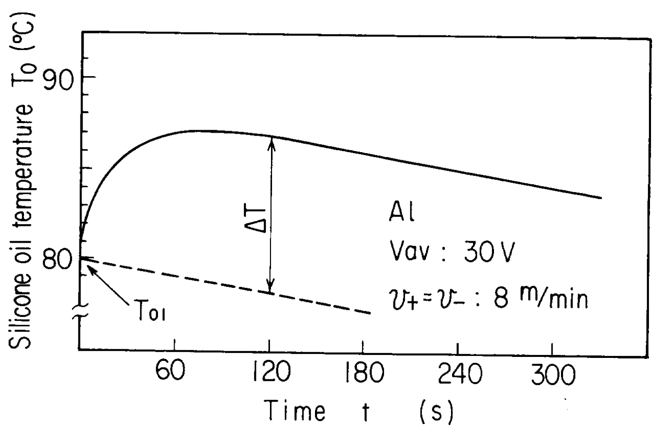

Fig. 3 Cooling-rate of calorimeter after arc spraying.

$Tc > T_f$

is believed to hold. An experiment was conducted by changing the silicone oil temperature in the calorimeter from (To_1) to (T_f) in several steps before spraying. This was done so that as the silicone oil temperature approaches (T_f), (H_f) would become nearly zero. Hence, in equation (1), (Ht) comes close to (Hc) if (H_f) becomes nearly zero. The experimental procedure and data are shown as follows.

Figure 3 illustrates the change in temperature of silicone oil against time measured after spraying aluminium for 5 seconds into the calorimeter, with the temperature of silicone oil (To_1) in the calorimeter kept at 80°C, the average arc voltage (Vav) at 30 V and the feeding speed of positive and negative wires (v_+) and (v_-) respectively at 8 m/min. In Fig. 3, the solid line represents the actual change of (To), and thus, the increase in silicone oil temperature (ΔT) can be obtained by drawing an auxiliary line parallel to the linear part of solid line shown here by a broken line. Hence, (Ht) is obtained from (ΔT) by the following equation.

$$Ht = J \cdot \Delta T, \qquad \cdots\cdots (2)$$

where, J: Amount of heat necessary to increase the silicone oil temperature in the calorimeter by 1°C (J/°C).

In the next step, (Ht) is obtained when (To_1) is varied to approach (T_f) with constant spraying conditions.

Figure 4 shows the relationship between (To_1) and (Ht) as obtained by the above-mentioned method.

When initial temperature of silicone oil (To_1) is raised from room temperature to (T_f), the measured (Ht) decreases. It is also mentioned above that as (To_1) approaches (T_f), the value of (H_f) approaches zero. Hence, when (To_1) is (T_f), the value of (Ht) will be equal to (Hc). In the experiment, (T_f) was measured by the thermocouple illustrated in Fig. 2, and therefore (Tc) can be obtained by the following equation.

$$Tc = Tm + \{Hc/M - C_1 \cdot (Tm - T_f) - Qm\}/C_2, \qquad \cdots\cdots (3)$$

where, Tm: Melting point of spraying material (°C),
M: Weight of fused metal collected (g),

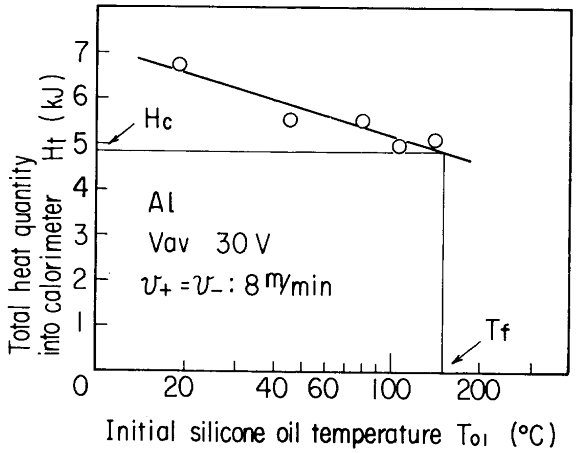

Fig. 4 Relation between initial silicone oil temperature and total heat quantity (Al).

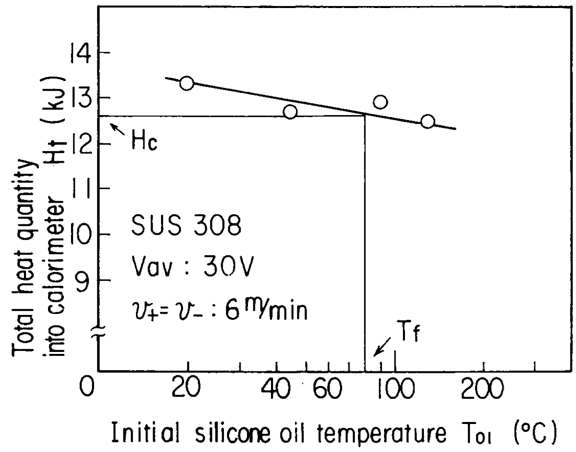

Fig. 5 Relation between initial silicone oil temperature and total heat quantity (SUS 308).

C_1: Average specific heat of spraying material under the melting point (J/g·°C),
C_2: Average specific heat of spraying material above the melting point (J/g·°C)
and Qm: latent heat of fusion of spraying material (J/g).

By the above-mentioned method, the temperature of fused metal (Tc) of aluminium spraying was estimated.

Figure 5 illustrates an example of the relationship between (To_1) and (Ht) of stainless steel (SUS 308) spraying. Since this shows the same trend as with aluminium, (Tc) is estimated by this method as well as for stainless steel (SUS 308) spraying.

In this experiment, the effect of arc radiation is considered to be small and hence negligible.[6]

4. Estimation Method of Fused Metal Temperature (Ti) just after Wire Fusion

Since the fused metal temperature just after wire fusion cannot be measured, the estimation was done from the heat input conditions.

Figure 6 illustrates the wire fusing status at the top end of the spray gun.[3] The total heat input (Qi) per unit weight supplied around points (B) and (C) to fuse the positive and negative wires is given by the

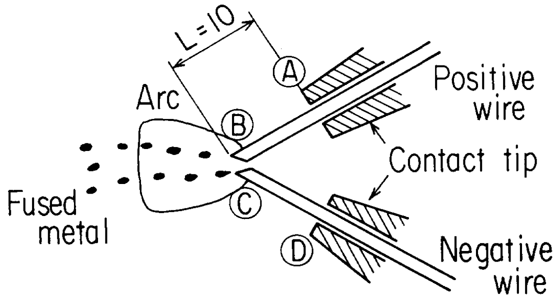

Fig. 6 Schematic illustration of arc spraying.

following equation:

$$Qi = Q_1 + Q_2 + Q_3 , \quad \cdots\cdots (4)$$

where, Q_1: Amount of heat generated by anode and cathode (J/g),
Q_2: Heat generation by electric resistance between (A) and (B), and (C) and (D) (J/g) (Joule heating) and
Q_3: Amount of heat transmitted from arc (J/g).

When the wire feed speed is much faster than the heat transmitting speed from the arc as was the case in this experiment, (Q_3) can be neglected.[7] Therefore, equation (4) becomes

$$Qi = Q_1 + Q_2 = Vm \cdot Iav/Mw + 2R \cdot Iav^2/Mw , \quad \cdots\cdots (5)$$

where, Vm: Equivalent voltage for fusion (V),
Mw: Amount of wire fed (g/s) and
R: Electric resistance due to wire extension (Ω).

The fused metal temperature (Ti) can be obtained by the following equation.

$$Ti = Tm + \{Qi - C_1(Tm - Tr) - Qm\}/C_2 , \quad \cdots\cdots (6)$$

where, Tr: Wire temperature before spraying (°C).

In the following, the estimation method to obtain (Ti) is explained in both aluminium and stainless steel (SUS 308) spraying. Table 3 shows the physical properties of the spraying materials used for the calculation.

Table 3 Physical properties of spraying materials.

Spraying material	Al	SUS 308
$Vm^{*1)}$ (V)	11.0	17.25
$R^{*1)}$ (Ω)	1.3×10^{-4}	5.5×10^{-3}
Tm (°C)	660	1400
Qm (J/g)	398	272
Tr (°C)	20	20
C_1 (J/g·deg)	1.05	0.63
C_2 (J/g·deg)	1.13	0.63
ρ (g/cm³)	2.7	8.0

*1) Estimation was done by the method shown in APPENDIX.

(1) With aluminium spraying

Since with aluminium spraying, the Joule heat generation in the wire extension is very small as can be seen from the physical properties shown in Table 3, equation (5) becomes

$$Qi \fallingdotseq 122\, Iav/(v_+ + v_-) .$$

Hence, by measuring the average arc current (Iav) under given positive wire feed speed (v_+), and negative wire feed speed (v_-), (Qi) under that spraying condition can be determined, and (Ti) can be obtained from equation (6).

(2) With stainless steel (SUS 308) spraying

In stainless steel spraying, the generation of Joule heat at the wire extension has to be taken into consideration. Thus, from the physical properties as shown in Table 3, equation (5) becomes

$$Qi = (63.9\, Iav + 0.04\, Iav^2)/(v_+ + v_-) .$$

Therefore, as in the case of stainless steel spraying, (Qi) and (Ti) can be obtained from (v_+), (v_-) and (Iav).

5. Comparison of (Tc) and (Ti)

Comparison is made as follows between the fused metal temperature (Tc) in Stage Ⅳ, as estimated in section 3, and the fused metal temperature (Ti) in Stage Ⅰ, as estimated in section 4.

(1) Aluminium spraying

Figure 7 shows the fused metal temperature (Tc) (solid line) just before adhesion onto the steel plate, and the fused metal temperature (Ti) (broken line) just after the wire fusion, with wire feed speed conditions $v_+/(v_+ + v_-)$ as the abscissa. As can be seen,

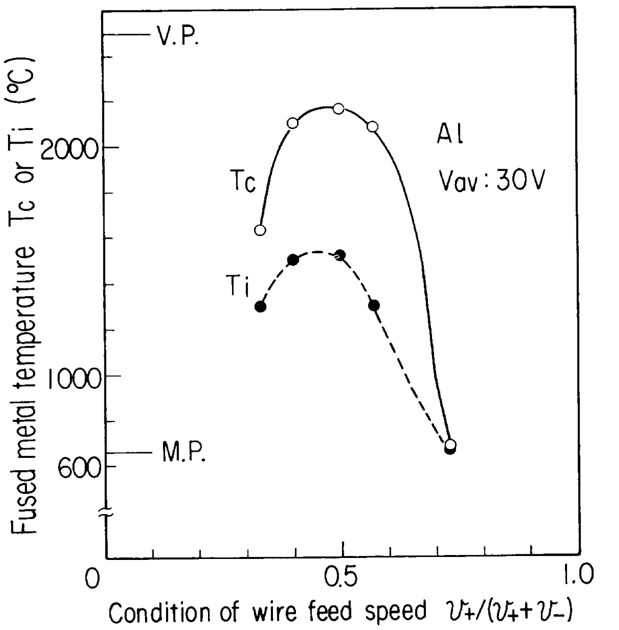

Fig. 7 Relation between condition of wire feed speed and fused metal temperature (Al).

(Tc) and (Ti) vary between the melting point (M.P.) (660°C) and vapourisation point (V.P.) (2,500°C) depending on the wire feed speed conditions. (Tc) becomes generally higher than (Ti), and both (Tc) and (Ti) are maximum when $v_+/(v_+ + v_-) = 0.4 \sim 0.5$.

From the above, the thermal change mechanism of fused metal during flying is considered as follow. The fused metal temperature is influenced by the wire feed speed condition, just after wire fusion, namely, in Stage Ⅰ. It is considered that the influence remains unchanged, even when the fused metal is heated by an arc in Stage Ⅱ or cooled by air in Stage Ⅲ. In Stage Ⅱ, the fused metal flies in the high temperature arc with a relatively low speed,[3] and later flies in the low temperature air at a high speed.[8] It is believed that the increase in the fused metal temperature as a result of being heated in the arc is slightly greater compared with the temperature decrease through cooling in the air. As seen from Fig. 7, the temperature difference between (Tc) and (Ti) varies and depends on the wire feed speed conditions. This is thought to be due to the fact that when the wire feed speed conditions are varied, not only the fused metal temperature, but also the shape and speed of the fused metal vary.[3),4)] It is also thought that the amount of heat-absorption and amount of heat-radiation are also changed.[9]

(2) Stainless steel spraying (SUS 308)

Figure 8 illustrates the relationship between the wire feed speed conditions $v_+/(v_+ + v_-)$ and (Tc) and (Ti). (Tc) and (Ti) vary between the melting point (M.P.) (1,400°C) and vapourisation point (V.P.) (2,900°C) depending on the wire feed speed conditions. Generally (Tc) is higher than (Ti) and both (Tc) and (Ti) are maximum when $v_+/(v_+ + v_-) = 0.4$

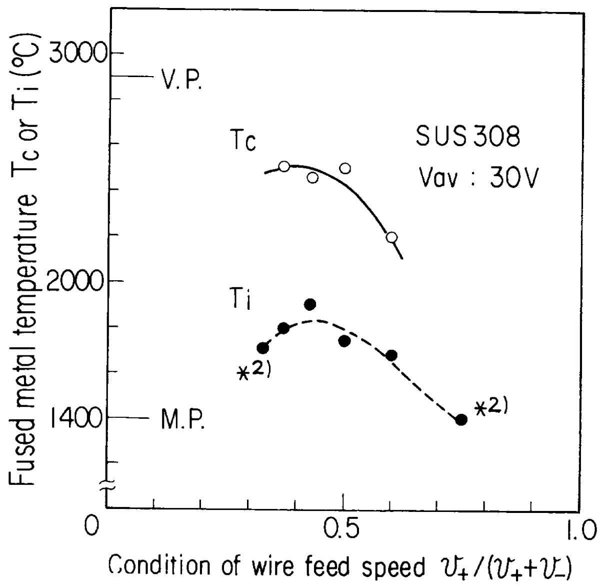

Fig. 8 Relation between condition of wire feed speed and fused metal temperature (SUS 308).

*2) In addition to the spraying conditions shown in Table 2, the experimental value under the conditions of $v_+ = 6$ m/min, $v_- = 2$ and 12 m/min were added.

approximately. This trend is just the same as in aluminium spraying. Therefore, it is believed that the changing mechanism of the fused metal temperature is the same as in aluminium spraying. Namely, it is considered that the changing mechanism of the fused metal temperature remains unchanged, even if the spraying material is varied.

Thus, as can be seen above, the fused metal temperature in two different stages was estimated by employing the calorimeter and calculating the heat input, and by comparing the two temperature values, the changing mechanism of the fused metal temperature during the period just after the wire fusion to adhesion onto the steel plate of the fused metal was estimated.

6. Conclusions

The fused metal temperature in aluminium and stainless steel arc spraying was estimated. The estimation of the fused metal temperature was made at two points, namely, just before the adhesion of fused metal onto the steel plate (Stage Ⅳ) and just after the fusion of wire (Stage Ⅰ). The temperature of former (Tc) was estimated by employing a special calorimeter, and the temperature of the latter (Ti) was estimated by calculating the heat input. The following was obtained by the comparison of these two temperature values.

(1) Tc and Ti are largely influenced by the feeding speed (v_+, v_-) of the positive and negative wires. The graphs of (Tc) and (Ti), when plotted against wire feed speed parameters $v_+/(v_+ + v_-)$, show similar trend.

(2) Considering the fact that (Tc) is generally higher than (Ti), it is likely that the fused metal temperature rises during the flying period from just after wire fusion to just before adhesion onto the steel plate of the fused metal.

From the above results, it is believed that the changing mechanism of the fused metal temperature during the period of flying from the fusion of wire to the adhesion onto the steel plate of fused metal in the arc spraying is as follows.

Just after the fusion of wire, the fused metal temperature is influenced by the wire feed speed conditions. That influence remains virtually unchanged while the fused metal is cooled by low temperature air, after being heated by the arc. Since the increase in the fused metal temperature by heating in the arc is large compared with the temperature decrease by the cooling in the air, the fused metal temperature becomes higher just before the adhesion onto the steel plate than just after wire fusion.

APPENDIX

(1) Estimation of resistance (R) and equivalent voltage for fusion (Vm) in aluminium spraying

(a) Estimation of (R)

Taking the length and diameter of the wire extension as (L) and (D) respectively, the electrical resistance (R) in the wire extension can be expressed by the following equation.

$$R = \eta \cdot L/(\pi D^2/4)$$

η: Inherent resistance ($\Omega \cdot$cm)
When the aluminium wire with a diameter of 0.16 cm is sprayed: and $\eta = 2.6 \times 10^{-6}$ ($\Omega \cdot$cm), $L = 1.0$ (cm) (R) is given by the following.

$$R = \eta \cdot L/(\pi D^2/4) = 1.3 \times 10^{-4} .$$

(b) Estimation of (Vm)
Figure 9 shows an example of oscillograms of arc voltage (V) measured between the contact tips of positive and negative wires in arc spraying. (Vm) and (V) can be expressed respectively by the following equations:

$$Vm = V_+ + V_- \quad \text{and}$$
$$V = V_+ + V_- + Vp + 2IR = Vm + Vp + 2IR .$$

In the above equation, considering the minimum arc condition,[3] V shows the minimum value. From Fig. 9, the value of the minimum voltage is measured to be Vmin$=11$ (V). When taking the arc current as $I = 200$ (A)

$$V = Vm + Vp + 2IR$$
$$V\text{min} = Vm + 0 + 2 \times 200 \times 1.3 \times 10^{-4} = 11 \text{ (V)}$$
$$Vm = 11 \text{ (V)} .$$

Thus the equivalent voltage was estimated at 11 V.

(2) Estimation of resistance (R) and equivalent voltage for fusion (Vm) in stainless steel (SUS 308) spraying

(a) Estimation of (R)
As with aluminium, (R) is expressed by the following equation.

$$R = \eta \cdot L/(\pi D^2/4) .$$

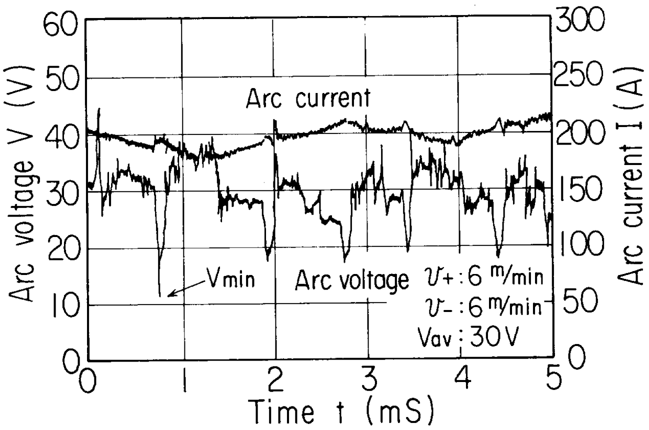

Fig. 9 Oscillograms of arc current and arc voltage (Al).

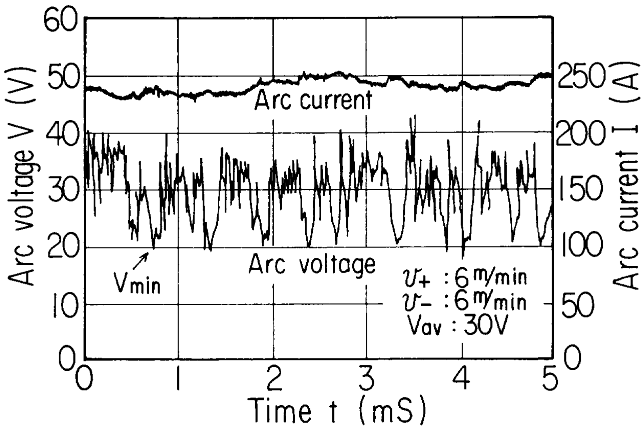

Fig. 10 Oscillograms of arc current and arc voltage (SUS 308).

When stainless steel (SUS 308) wire with a diameter of 0.16 cm is employed, and (η) and (L) are given ar follows.

$$\eta = 1.1 \times 10^{-4} \ (\Omega \cdot \text{cm}), \ L = 1.0 \ (\text{cm}) ,$$

(R) is given as follows.

$$R = \eta \cdot L/(\pi D^2/4) = 5.5 \times 10^{-3} .$$

(b) Estimation of (Vm)
An oscillogram of arc voltage (V) is shown in Figure 10. (Vm) and (V) are expressed by the following equations.

$$Vm = V_+ + V_- \quad \text{and}$$
$$V = V_+ + V_- + Vp + 2IR = Vm + Vp + 2IR .$$

Considering that (L) becomes (Vmin) when $Vp \fallingdotseq 0$ (V) as with aluminium, Vmin$=20$ (V) is obtained from Fig 10. When taking the arc current $I \doteqdot 250$ (A),

$$V = Vm + Vp + 2IR ,$$
$$V\text{min} = Vm + 0 + 2 \times 250 \times 5.5 \times 10^{-3} = 20 \ (V),$$

and

$$Vm = 20 - 2.75 = 17.25 \ (V) .$$

Thus the equivalent voltage (Vm) was estimated at 17.25 V.

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