# Melting Characteristics of Some Steel and Aluminum Alloy Wires in GMA Welding†

Xie-Sheng FU *, Masao USHIO **, Fukuhisa MATSUDA ***

**Abstract**

*Wire melting characteristics of steel wire and aluminum alloy wire are examined in electrode positive polarity. In steel wires such as mild steel and stainless steel wire, the contribution of ohmic heating to melting rate of wire electrode takes about 50% in usual welding condition. But, in Al-alloy wire the dominant part of heat input for wire melting comes from anode heat input from arc and ohmic heating has little effect.*

*Shielding gas and arc length have little effect on melting of steel wire. For aluminum alloy wire, main mechanism of heat input is anode heat input. But, remarkable increase in melting rate in short arc length 'intrinsic self-regulating effect of arc length' cannot be attributable to the increase in anode heat input from arc. It must be related to the decrease in heat content of droplet.*

*The decrease in heat content of droplet in rather short arc length in Al-alloy wire welding is associated with climbing up of arc roots in wire electrode. The effect is more intense in Al-5183 wire than in Al-4043 wire. The climbing up of arc roots may increase in effectiveness of uniform heating of wire electrode. This might be caused by intense evaporation at the anode spot due to the existence of volatile element magnesium in the wire.*

**KEY WORDS:** (GMA Welding) (Melting Rate of Wire) (Aluminum Welding) (Intrinsic Self-Regulation) (Shielding Gas)

## 1. Introduction

Recently, E. Halmøy showed the very conventional expression on melting rate of MIG welding based on the analytic consideration of relationship among the welding current, wire extension length and wire melting rate as follows[1],

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

where $V_W$: wire melting rate (mm/sec), j: current density of wire (A/mm$^2$), L: wire extension length (mm), $H_0$ : heat content of molten droplet (J/mm$^3$), $\Phi$: equivalent voltage of melting due to arc heat input (V), a: constant ($\Omega$ mm) and b: constant (J/mm$^3$). The first term in the righthand of the equation represents the contribution of arc heating and the second the one of ohmic heating. The applicability of the relationship was examined for some iron steels in MIG welding.

The above relationship gave the physical concept on the experimental expression on wire melting showed by A. Lesnewich[2], but the precise structure of arc heating part $\Phi$ and particularly the relation with the phenomenon known as "intrinsic self-regulating effect of arc length" has not been clear.

The melting rate of low resistance wire like aluminum alloy wire is considered to be much influenced by arc heating than that by ohmic heating. The $\Phi$ value, which is related to arc heating, will be varied by the change in working gas, because it is mainly to be consisted of the work function of wire material and the electrode drop of working gas.

The phenomenon "intrinsic self-regulating effect of arc length" means the specific melting rate increase with decrease in arc length without shortcircuiting[3,4]. The phenomenon can be observed typically in MIG welding of aluminum alloy wire, in which the meso-spray arc defined by a medium arc length between those of long spray arc and shortcircuiting arc has been understood to be attributable to the phenomenon. However the cause of the phenomenon has not yet been clear. The above relationship will give some prospects to the mechanism of the phenomenon. It is considered to be necessary to study the phenomenon from the point of view coming from the above analytical theory.

† Received on Oct. 31, 1983.
* Lecturer of Gansu University of Technology, Lanzhou, Gansu, CHINA
** Associate Professor
*** Professor

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The purpose of the work described here is to show the effect of shielding gas composition and alloying element of wire on melting rate and to make clear the relation to the intrinsic self-regulating effect of arc length.

## 2. Experimental Procedures

Schematic illustration of experimental setup is shown in **Fig. 1**. A transistorized welding power source is used with mainly constant current characteristic and electrode positive polarity (DCEP). Wire feed rate can be set independently of the welding current and voltage.

High speed cine camera, HYCOM is used to observe the wire extension length and metal transfer phenomenon. High speed motion pictures of 3000 frames/sec are taken by using a xenon lamp as a backing light.

Chemical compositions of materials used for wires are listed in **Table 1**. As aluminum alloy wires, Al-4043

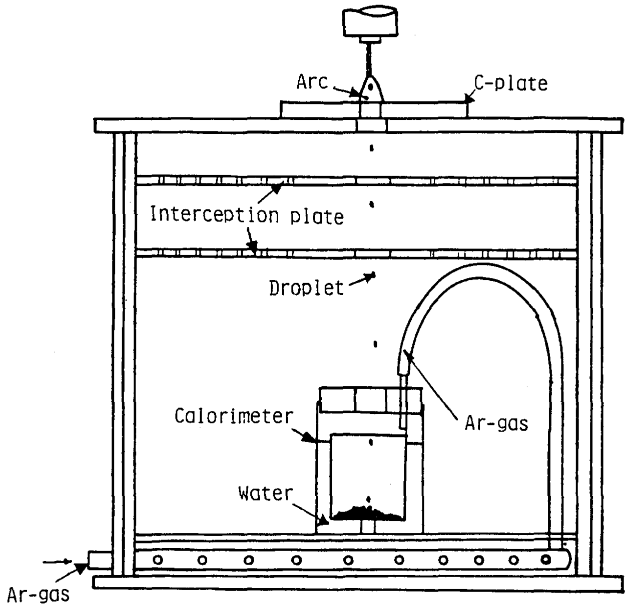


**Fig. 2** Schematic illustration of calorimeter used for measurement of heat content of molten droplet.

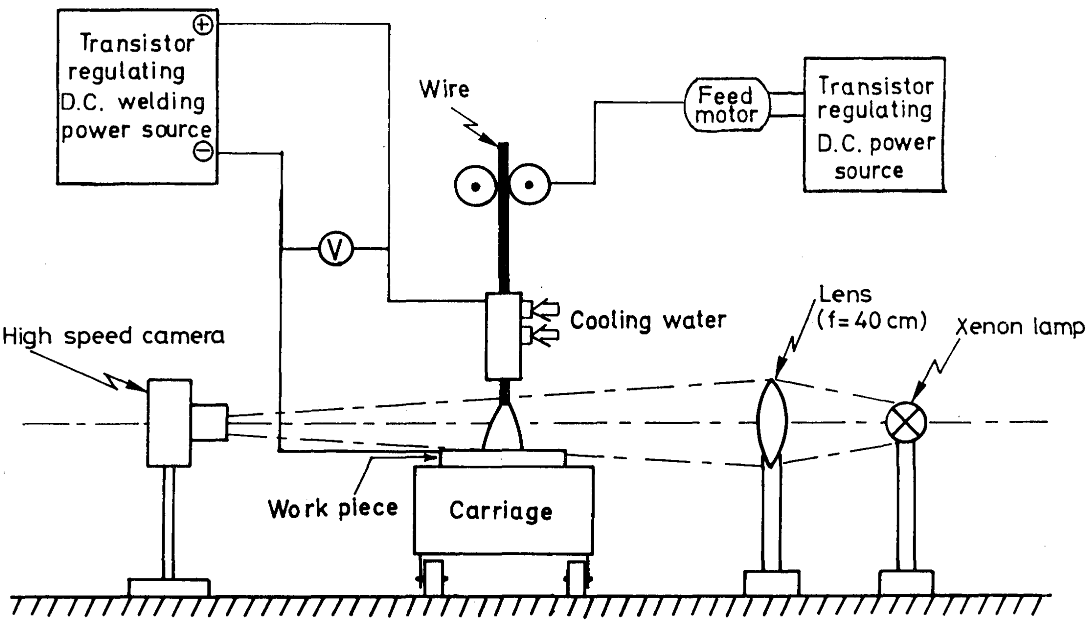


**Fig. 1** Schematic illustration of experimental setup.

**Table 1** Chemical composition of materials used.

| Materials | Chemical compositions (wt%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Cu | Si | Fe | Mn | Mg | Cr | Zn | Ti | Al |
| A5183 | < 0.1 | < 0.04 | < 0.04 | 0.5-1.0 | 4.3-5.2 | 0.05-0.25 | < 0.25 | 0.05-0.20 | bal. |
| A5083 | < 0.1 | < 0.04 | < 0.04 | 0.4-1.0 | 4.0-4.9 | 0.05-0.25 | < 0.25 | 0.15 | bal. |
| A4043 | < 0.3 | 0.45-0.60 | < 0.8 | 0.05 | 0.05 | | < 0.1 | < 0.2 | bal. |
| A1070 | < 0.04 | < 0.20 | < 0.25 | < 0.30 | 0.03 | | < 0.04 | < 0.03 | > 99.7 |
| Materials | C | Si | Mn | P | S | Ni | Cr | Fe | |
| Mild Steel | 0.097 | 0.61 | 1.28 | 0.016 | 0.017 | | | bal. | |
| SUS 309 | 0.12 | 0.6 | 1.0-2.5 | 0.03 | 0.03 | 12.0-14.0 | 23.0-25.0 | bal. | |

(Al-Si) and Al-5183 (Al-Mg) are used. Additionally a mild steel and a stainless steel wires are applied.

**Figure 2** shows a box which is used for the measurement of heat content of molten droplet. It is the calorimeter shielded by argon gas to prevent the droplet from being oxidized during transferring a space between the wire tip and the calorimeter.

## 3. Effect of Shielding Gas Composition on Melting Rate for Steel Wires

Melting rate of mild steel and stainless steel wires was examined in variable cases of shielding gas composition, which is shown in **Fig. 3**. Pure argon, 80%Ar+20%$CO_2$ and 60%He+40%Ar were used as shielding gases. Wire melting rate is plotted as a function of extension length of wire in the cases of 200 A and 250 A of welding current.

In the figure the effect of shielding gas on the melting rate has little significance with the gases used. The values of a and b appeared in Eq. (1) were experimentally determined for these materials through the same procedure as that in Halmφy's paper and listed in **Table 2**. By using the values and Eq. (1), the Φ and $H_0$ were calculated

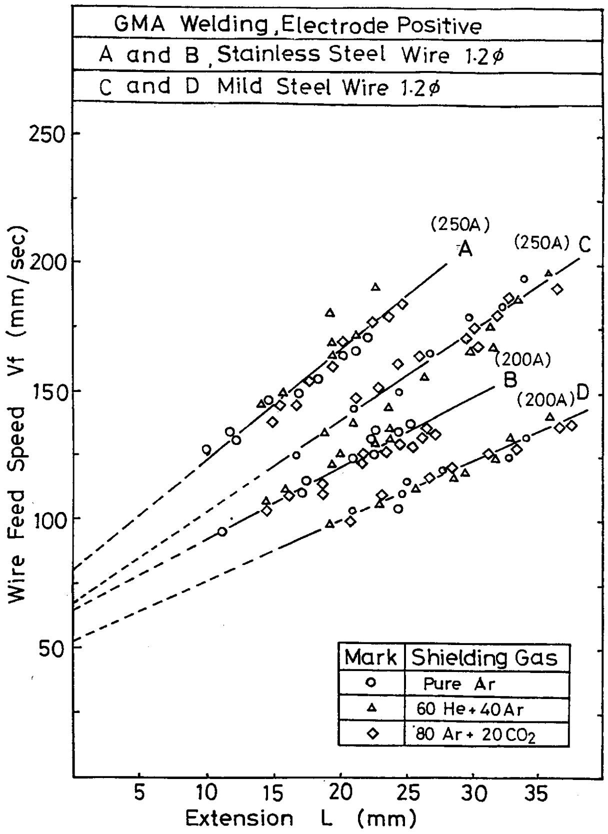


**Fig. 3** Relation between wire melting rate and extension length.

**Table 2** Measured constants a and b, and contribution of ohmic heating to wire melting.

| Materials | a($\times 10^{-5}$ Ωmm) | b(J/mm$^3$) | $H_0$(J/mm$^3$) | $V_l$/Vw(%) | Φ (V) |
|---|---|---|---|---|---|
| A5183 | 7.5 | 0.03 | 5.28 | 3.6 | 5.5 |
| A4043 | 3.6 | 0.01 | 6.12 | 1.96 | 4.64 |
| A1070 | 3.5 | 0.04 | 6.4 | 1.87 | |
| Mild steel | 130 | 5.0 | 12.36 | 45.0 | 5.20 |
| SUS309 | 135 | 1.0 | 14.23 | 55.0 | 5.69 |

**Table 3** Temperature and heat content of molten droplet of Al-alloy.

| Arc length | 10-15 (mm) | | 2-5 (mm) | |
|---|---|---|---|---|
| Materials | T(C°) | $H_0$(J/mm$^3$) | T(C°) | $H_0$(J/mm$^3$) |
| A5183 | 1200-1500 | 4.43-5.28 | 1100-1300 | 3.87-4.71 |
| A4043 | 1700-2100 | 5.84-6.97 | 1500-1800 | 5.28-6.12 |

**Table 4** Φ values of Al-alloy.

| Materials | A5183 | | A4043 | |
|---|---|---|---|---|
| Diameter (mm) | 1.6 | 1.2 | 1.6 | 1.2 |
| m (mg/A·sec) | 2.69 | 2.92 | 2.18 | 1.98 |
| Φ (V) | 5.29 | 5.7 | 4.78 | 4.5 |

from experimental plots in Fig. 3, and its averaged values are also shown in Table 2. In the calculation the values Φ and $H_0$ had little differences respectively with the change in shielding gas or welding current. From these results it can be derived the following conclusion, that is, the shielding gas has little effect on melting rate of steel wire under the experimental condition.

## 4. Effect of Ohmic Heating on Melting Rate of Wire

**Figure 4** shows the relation between arc length and wire extension under the condition of constant current and constant feeding rate of wire. For the mild steel wire, even if the arc length varies with the change in distance between the wire tip and plate, the extension length is kept constant. On the otherhand for aluminum alloy 5183 wire, arc length is kept constant with the change in the distance between wire tip and plate. This is shown in **Fig. 5**. These results mean the contribution of ohmic heating to wire melting is large for steel wire, but is negligible for aluminum alloy wire.

**Figure 6** illustrates an example of melting characteristic curve of Al-5183 alloy wire. In the figure wire feed rate and arc length observed by taking picture of arc are also shown by numbers above and along the line, respectively.

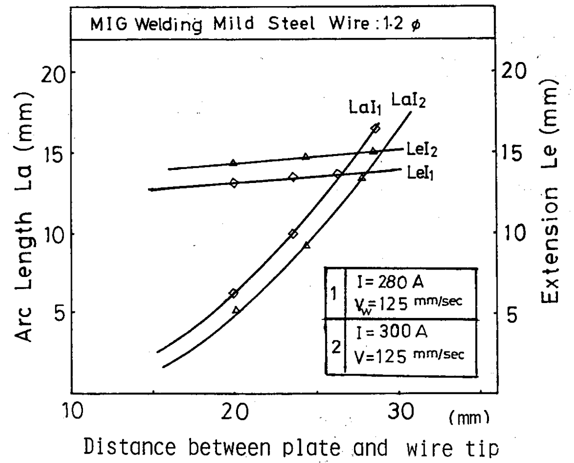


Fig. 4 Relation between arc length and wire extension with change in distance between wire tip and plate in case of mild steel welding.

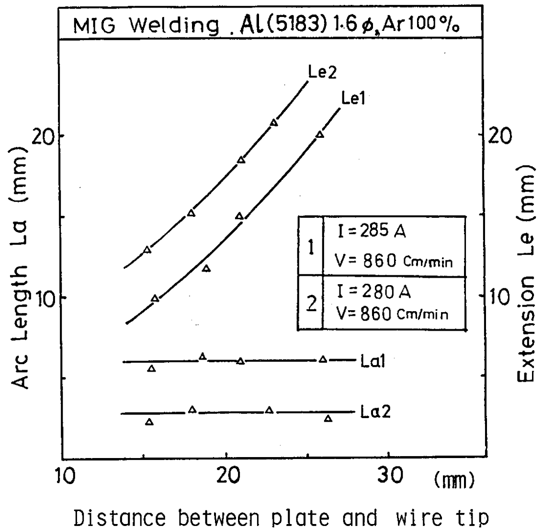


Fig. 5 Relation between arc length and wire extension with change in distance between wire tip and plate in case of aluminum alloy Al-5183 wire welding.

A dashed line shows the one in case that a carbon plate with a hole whose diameter is 16 mm is used as a cathode plate. The molten metal droplet passes through the hole and drops into the calorimeter without being oxidized as shown in Fig. 2. Measured temperature of droplet is shown in **Table 3**. By using the values, the ratio of the contribution of ohmic heating to the total melting rate is calculated as follows,

$$\frac{V_1}{V_W} = \frac{aLj^2/(H_0+b)}{V_W} \qquad (2)$$

The results shown in Table 2 are under the condition of 20 mm in extension length. Ohmic heating has only negligible influence on wire melting of aluminum alloy wire. However, it has the contribution of about 50% or more for the steel wire melting.

Droplet temperature has dependence on the arc length. The temperature in case of short arc length is lower than that in long arc length. Moreover the droplet temperature of Al-4043 wire is higher than that of Al-5183 wire.

Occurence of explosion of melted droplet was sometimes observed in the high speed cine film in the case of long arc length for Al-5183 alloy wire. It may be related to boiling of magnesium in the droplet. Estimation of boiling point of Al-5183 alloy wire based on the thermochemistry leads to 1527°C.* This value seems to back up the measured results of droplet temperature.

The droplet temperature of Al-5183 alloy wire is nearly equal to boiling point of wire material, so that the intense vaporization occurs particularly from the area of arc root at the wire end. The vapor transferred with the molten droplet lies on the top of plate. The X-ray analysis

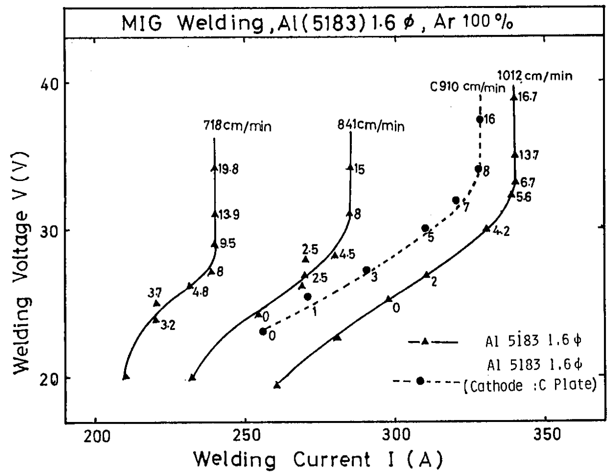


Fig. 6 Melting characteristic curve of aluminum alloy Al-5183 wire of 1.6 mm in diameter under the condition of 25 mm in distance between wire tip and plate.

of the material made clear the compositions of evapolated materials are consisted of Aluminum and Magnesium as shown in **Fig. 7**. These results mean a part of anode heat input must be dissipated in evapolating the wire material, and its amount may be considered to be depend on arc length.

* According to thermochemistry, the relation between saturated vapor pressure and boiling point of pure magnesium are represented as follows[5],

$$\log(P_{pure}) = \frac{-7550}{T_{boil}} - 1.41\log(T_{boil}) + 12.79$$

where $P_{pure}$ represents the saturated vapor pressure and $T_{boil}$ is the boiling point of magnesium. By replacing the $P_{pure}$ value by the partial pressure of magnesium, the boiling point of magnesium included in aluminum alloy is roughly estimated.

$T_{boil} = 1527°C$

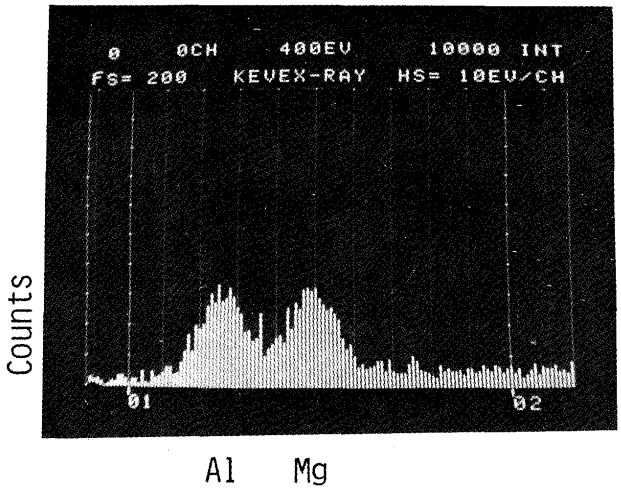


**Fig. 7** EDX result of vapor material piled up on top of plate surface in case of Al-5183 alloy wire welding.

## 5. On Anode Electrode Drop

Wire melting of Aluminum alloy wire is dominated by arc heating so that we may assume that the heat content of molten droplet is supplied by only anode electrode heating. Usually the following equation can be expressed as a balance of energy,

$$m \cdot H = 0.24\phi, \qquad (3)$$

where m: specific melting rate (mg/sec A), H: heat needed for raising up the temperature of droplet (cal/mg), $\phi$: equivalent voltage of wire melting (V).

Above expression has substantially same meaning as Eq. (1), if $\phi$ is replaced by $\Phi$. After averaging the $H_0$ values tabulated in Table 2, $\Phi$ values are calculated by the use of above equation as shown in **Table 4**. The difference between $\Phi$ value of Al-4043 and that of Al-5183 is nearly

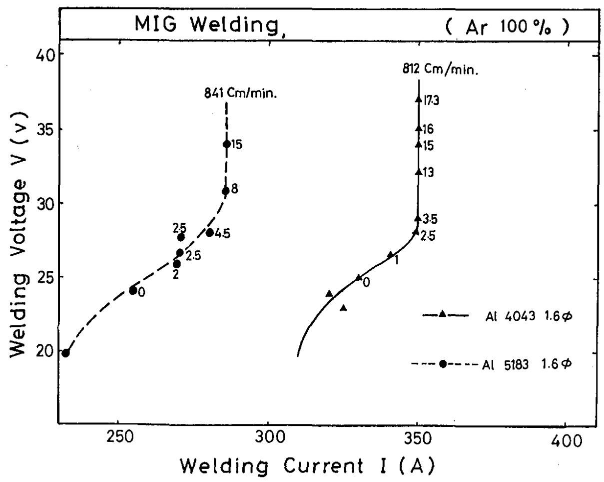


**Fig. 8** Comparison between the melting rate of Al-5183 wire and that of Al-4043 alloy wire.

1 V. By using the TIG welding with these materials plate, the difference of anode electrode drop was measured and nearly same voltage drop difference was obtained.

**Figure 8** is the illustration showing the difference in melting rates of Al-4043 wire and Al-5183 wire. These two curves are drawn under the similar feeding rates of wire. The differences in heat content $H_0$ and electrode drop between Al-4043 wire and Al-5183 one can be regarded as the cause of large difference in welding current under the condition of nearly same melting rates.

As is evidently seen in Fig. 8, the melting characteristic curve for Al-5183 wire has a bend at about 8 mm in apparent arc length and inspite of the decrease in welding current the same melting rate is kept in the region of short arc length without electrical shortcircuiting. This phenomenon is rather intense in Al-5183 wire than that in Al-4043 wire. This effective melting is the result from intrinsic self-regulating effect of arc length and is discussed in the following section.

## 6. Intrinsic Self-regulating Effect of Arc Length

In mild steel wire, the effect of resistance heating on wire melting is so high that the wire extension is stably kept constant under the constant current of welding. On the otherhand, in melting of aluminum alloy wire in argon shielding, the melting rate of wire increases with decrease in arc length in spite of constant current and constant extension. This phenomenon is known as the intrinsic self-regulating effect of arc length. This phenomenon must be caused by not wire resistance heating but the variation of $\Phi$ or/and $H_0$. In the previous section, it is shown the heat content of droplet decreases with decrease in arc length. In fact, the increase in melting rate in the case of short arc length can be ascribed to not the increase in $\Phi$ but the decrease in $H_0$ as shown in Table 4. The phenomenon is rather effective in Al-5183 wire than that in Al-4043 wire as appeared in Fig. 8.

High speed cine-camera was used to observe the arc behavior around the wire end particularly in Al-5183 wire. In the case of short arc length the climbing up of arc roots was observed. A picture of wire end taken by Scanning Electron Microscope showed the existence of many traces representing the climbing up of arc roots, as shown in **Fig. 9**. These traces may be made by evaporation of wire element, associating with the rooting of arc. In the case of Al-4043 wire, these traces could not be seen clearly. The climbing up of arc roots may cause the dispersion of heat input by occupation of comparatively wide area as anode, and consequently the increase in effectiveness of uniform heating of wire electrode. This rather moderate heating may decrease the concentrated local heating and therefore

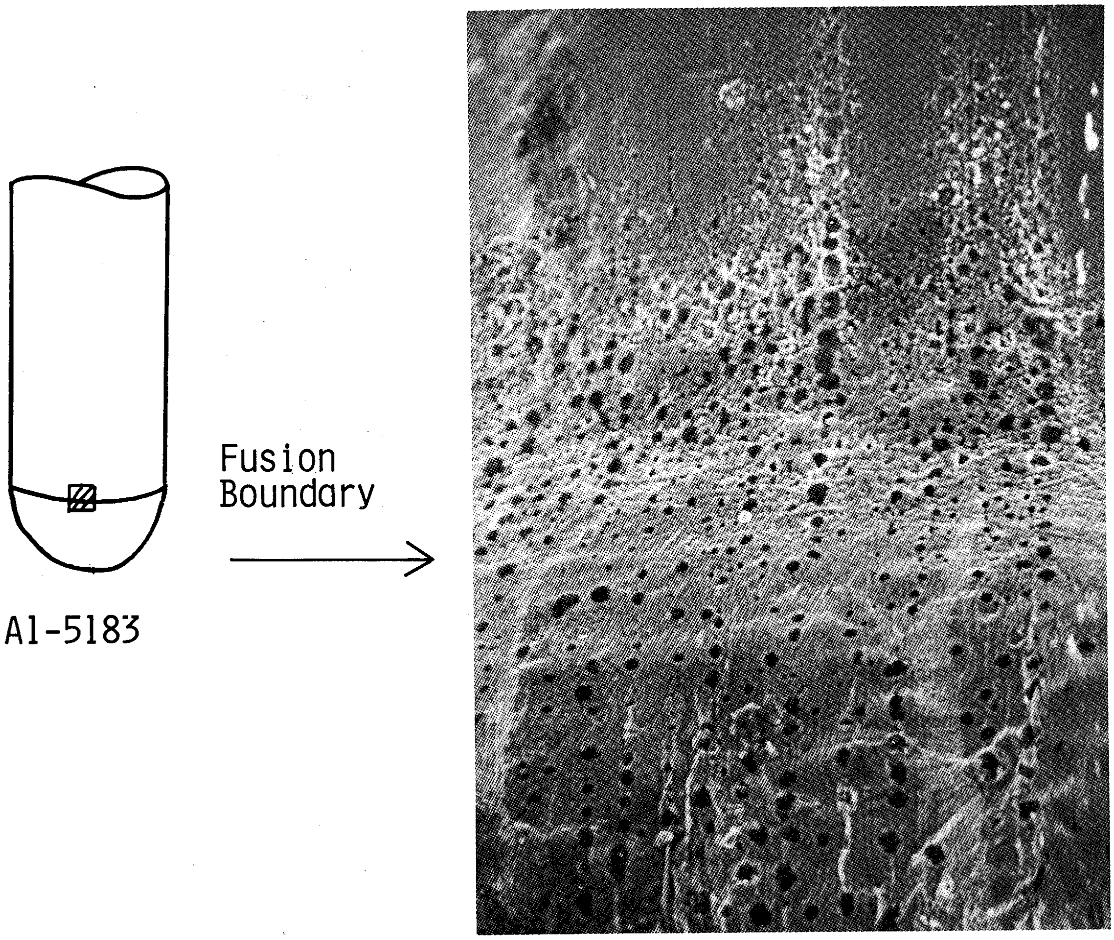


Fig. 9 Traces representing evaporation of wire materials due to climbing up of arc roots. (x 400)

it can reduce the occurrence of intense evaporation except that occurred at climbed anode spot. These may be resulted in the effective melting and decrease in heat content of molten droplet.

Roughly speaking the degree of climbing up of arc roots might be related to the difference between the electric field intensity of arc column and that in the droplet at wire end as illustrated in **Fig. 10**. It is necessary for climbing up of anode spots to satisfy the following equation,

$$\frac{U}{l_1 - l_2} \geq E \qquad (4)$$

where E: electric field intensity of arc column, U: potential drop in melted wire, $l_1$, $l_2$ : the minimum path of current between the arc roots and the cathode spots usually localized at the edge of cleaning area. The intrinsic self-regulating effect of arc length can not be seen in the case of helium shielding even in Al-5183 wire. This fact in helium shielding may support the above consideration. However, it cannot explain the difference in intensity of the effect between the Al-5183 wire and Al-4043 wire.

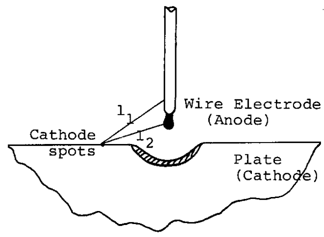


**Fig. 10** Schematic illustration of arc configuration of GMA welding.

In the case of Al-5183 wire, the existence of volatile material, magnesium, might be responsible to this phenomenon. Very intense vaporization of wire materials occurs at the anode spots. Its vaporization might push aside the spots to the solid part of the wire and it may seems the climbing up of arc roots.

## 7. Conclusions

Melting characteristics of steel wire and aluminum alloy wire are examined in the electrode positive polarity.

1) In steel wires such as mild steel and stainless steel wire, the contribution of ohmic heating to melting rate of wire electrode takes about 50% in usual welding condition. On the otherhand, in aluminum alloy wire, the dominant part of heat input for wire melting comes from anode heat input from arc and ohmic heating has little effect on melting.
2) Shielding gas and arc length have little effect on melting rate of steel wire. In these cases Eq. (1) is very useful.
3) For aluminum alloy wire, main factor of arc heat input is anode heat input. But, the remarkable increase in melting rate in short arc length, intrinsic self-regulating of arc length, cannot be attributable to the increase in anode heat input from arc. It must be related to the decrease in heat content of droplet.
4) The decrease in heat content of droplet in rather short arc length is associated with the climbing up of arc roots in anode electrode. It may increase in effectiveness of uniform heating of wire electrode. This effect is more intense in Al-5183 wire than in Al-4043 wire. This might be caused by intense evaporation at the anode spots due to the existence of volatile material in the wire.

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