Evaporation phenomena of magnesium during pulsed-MIG arc welding of aluminum alloy†

WANG Jing-Bo*, NISHIMURA Hitoshi*, KATAYAMA Seiji** and MIZUTANI Masami**

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1. Introduction

Welding fumes are frequently formed during pulsed-MIG arc welding of aluminum alloy using a 5xxx aluminum alloy welding wire because of the evaporation of magnesium which is present at several percents for the prevention of welding cracks [1]. There are two methods to evaluate the evaporation phenomena during arc welding. The one is to collect the total welding fumes formed during a constant welding period to quantitatively calculate the evaporation rate. The other one is to directly observe the droplet behavior with a high-speed video imaging system. By both methods, unfortunately, it is impossible to evaluate the evaporation phenomena during peak or background periods separately.

This paper presents a novel method for calculating the evaporation rate and flux of magnesium in peak period during pulsed-MIG arc welding.

2. Method to visualize droplet behavior

A high-speed video imaging system was used to observe the arc morphology and the behavior of droplet formation. A diode laser with a center wavelength of 930 nm was used for illumination in order to visualize the formation of particulate fumes from the droplet surface.

3. Method to calculate evaporation rate and flux

The calculation of the evaporation rate and flux is conducted by the following three steps.

(1) An automated robot welding system is used to produce a series of droplets by shutting-down the peak current and stopping the wire feeding at different droplet growth times in one peak period.

(2) The magnesium contents of the above produced droplets are analyzed by EDX analyzer. At the same time, the droplet volumes of these droplets are measured, and the droplet surface areas are measured from a series of high-speed video images.

(3) From the relationship between the magnesium content, droplet volume, droplet surface area and the droplet growth time, the evaporation rate and flux of magnesium during peak period are calculated.

Welding conditions and the chemical compositions of materials used are shown in **Table 1** and **Table 2**.

Table 1 Materials used and welding conditions.

Material	Plate	A5052 (^{t} 9 mm)
	Wire	A5356 (ϕ 1.2 mm)
MIG	Torch angle	Perpendicular to work
	Tip-to-work distance	18 mm
	Shielding gas (Ar)	20 L/min
	Average current	150 A
	Average voltage	20 V
	Peak current	335 A
	Background current	80 A
	Frequency	180 Hz
Welding speed		8.33 mm/s
Welding position		Bead on plate

4. Experimental results and discussions

In order to characterize the behavior of the droplet formation and the evaporation phenomena a series of high-speed video images are examined. One example showing the droplet transfer is shown in **Fig. 1**. Attention, especially, should be taken to the time for forming a neck near the droplet-wire boundary which is about 1 ms from the beginning of a peak period and is nearly coinciding with the time for the formation of particulate fumes.

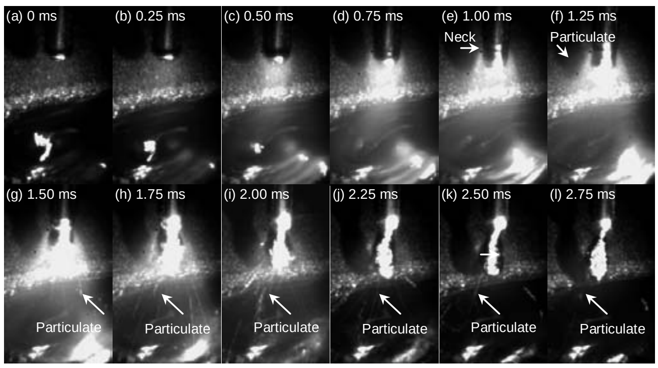

Figure 1 A series of high-speed video images showing the droplets formed at the welding wire tip (peak: (b)-(g); background: (a), (j)-(l); transition from peak to background: (h)-(j)).

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* Panasonic Welding Systems Co., Ltd., Osaka, Japan
** JWRI, Osaka University, Osaka, Japan

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Table 2 Chemical compositions of materials used.

Materials	Chemical compositions (mass %)								
	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Al
Plate (A5052)	0.170	0.010	0.270	2.650	0.000	0.080	0.000	0.000	Bal.
Wire (A5356)	0.058	0.001	0.167	4.952	0.055	0.128	0.072	0.002	Bal.

Droplet volume and droplet surface area are measured, and the magnesium content in the droplet is analyzed. The obtained results of droplet volume V_{drop}, droplet surface area S_{drop}, and magnesium content C_{Mg}, are shown in **Fig. 2**. About the droplet growth behavior, when the droplet growth time TS is under 0.5 ms, both the droplet volume and droplet surface area increase slightly. From the high-speed video images, the arc root is seen to spread from the droplet bottom to climb toward the wire boundary and the droplet itself deforms. Before the arc root spreads up to a solid part of the welding wire, the droplet volume increased only a little. When TS is over 0.5 ms to 1.6 ms, both the droplet volume and the droplet surface area increase abruptly. About the magnesium evaporation behavior, when TS is 0 ms, that is, at the end of the background period or the beginning of the peak period, the magnesium content in droplet is 4.63 mass %. With increasing the droplet growth time TS up to 1.0 ms, the magnesium content decreased to 4.2 mass %. After that, the magnesium content decreased very slowly to reach about 4.0 mass % at the end of the peak period of about 1.6 ms. The decrease in magnesium content with increasing TS is considered to be caused by the evaporation of magnesium from the droplet surfaces whose temperatures are reported to nearly reach their boiling point [2]. From Fig. 2, empirical relationships between the droplet volume V_{drop} (mm^3), droplet surface area S_{drop} (mm^2), magnesium content C_{Mg} (mass %) and TS (ms) are obtained as Equation (1) to (3).

$$V_{drop}=0.844+8TS^2/(TS^2+18) \quad (1)$$
$$S_{drop}=3.405+8TS^2/(TS^2+3.2) \quad (2)$$
$$C_{Mg}=3.9+0.73e^{(-TS/0.85)} \quad (3)$$

From equation (1) to (3), the evaporation rate and flux of magnesium during peak period can be calculated as follows. Firstly, one peak period is divided by a time interval $\triangle TS$ (=0.01 ms) into $TS_{(i)}$ (i=0, 1, 2, ･･･, n). $V_{drop(i)}$ and $C_{Mg(i)}$ (i=0, 1, 2, ･･･, n) are calculated from Equation (1) and (2) by inputting TS=ix$\triangle$TS. Secondly, the evaporation rate and flux are calculated as follows by putting i=1, 2, ･･･, n.

(1) Calculating the mass of magnesium $W_{dMg(i-1)}$ and $W_{dMg(i)}$ at $TS_{(i-1)}$ and $TS_{(i)}$, respectively.
(2) Calculating the mass of magnesium W_{wMg} in the welding wire melted during $\triangle$TS.
(3) Calculating the evaporation rate of magnesium $V_{vap(i)}$ [$=(W_{dMg(i-1)}+W_{WMg}-W_{dMg(i)})/\triangle TS$].
(4) Calculating the evaporation flux by dividing $V_{vap(i)}$ by Equation (2).

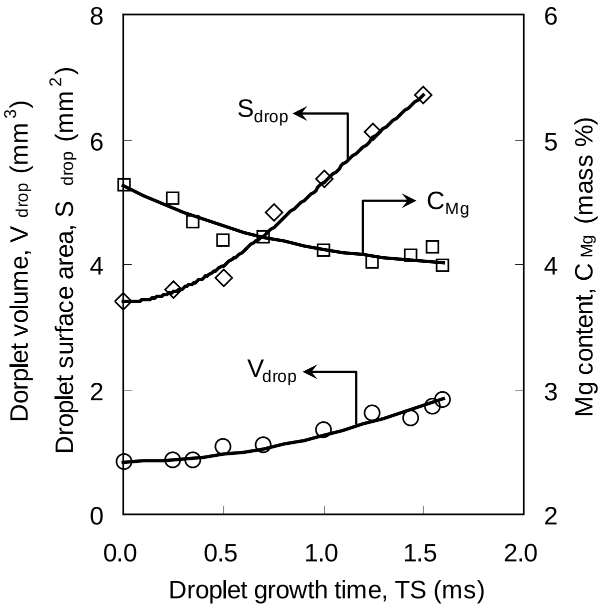

Figure 2 Droplet volume, droplet surface area and magnesium content at different droplet growth times.

After the above calculation, the evaporation rates $V_{vap(i)}$ (i=1, 2,･･,･n) and evaporation flux are plotted accounting for TS. The calculated results are shown in **Fig. 3**. It is seen that in region I (TS=0-0.2 ms) slight decreases both in the evaporation rate and flux are confirmed. This is attributed mainly to the evaporation from the anode root area. In region II, the evaporation rate increases very fast with increasing TS up to 1.2 ms and the evaporation flux increases slightly and finally reaches a saturated value. When TS increases into region III, the increase of the evaporation rate with increasing TS slows down a little and the evaporation flux decreases slightly. The change from region II to region III is considered to correspond with the formation of particulate fumes as shown in Figure 1. In region III the slow-down of the evaporation rate or the decrease of evaporation flux with increasing TS is thought to be caused by the evaporation of aluminum accompanied with magnesium which is supposed to be included in particulate fumes.

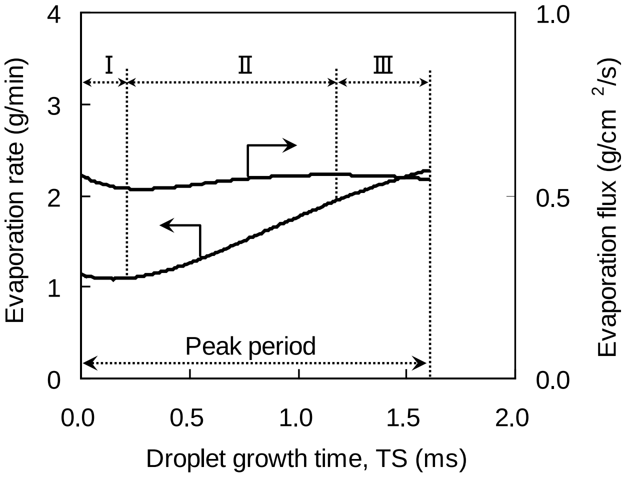

Figure 3 Calculated evaporation rate and evaporation flux of magnesium from the droplet surface.

5. Conclusions

This study is summarized as follows.

(1) According to the evaporation behavior of magnesium, the peak period is divided into three regions. That is, the region I is from TS=0-0.2 ms, the region II from TS=0.2-1.2 ms and the region III from TS>1.2 ms.

(2) In region I, both the evaporation rate and flux decrease slightly, and the evaporation is considered to be dominated by the evaporation of magnesium from the anode root area on the droplet surface.

(3) In region II and III the evaporations are considered to be dominated by the evaporation from the whole droplet surface. The region III corresponds to the formation of particulate fumes which is considered to accompany with a small amount of aluminum.

References

[1] J. H. Dudas and F. R. Collins, Welding J., 45 (1966), pp.241s-249s.
[2] R. A. Woods, Welding J., 60 (1980), pp.59s-66s.