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Influence of welding current on metal transfer modes in Pulsed Gas MAG welding*

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Carbon dioxide gas-shielded arc welding, which is widely used in industry, generates a large amount of spatter in the medium and high current range. To solve this problem, we developed a new welding process with low spatter and low gas cost that we call “Pulsed Gas MAG” (PGMAG) welding. In PGMAG welding, the metal transfer is controlled by the suitable addition of Ar gas, but the effect of the welding current has not been clarified. Therefore, we investigated metal transfer in the 235- to 325-A range and found that the pulse frequency of Ar gas must be adjusted between 35 and 65 Hz to match the welding current (i.e., wire feed rate) to control metal transfer. A wide area where metal transfer is controllable is obtained by adjusting the Ar addition frequency for a current of 235-325 A. It was considered that there is a suitable volume for the droplet to be released and that the growth speed depends on the wire feed rate.

Key Words: CO_2 arc welding, MAG welding, control of droplet transfer, spatter

1. Introduction

Carbon dioxide gas-shielded arc welding, in which 100% CO_2 is used as the shielding gas and the electrode melts as it generates the arc to form the weld metal, making highly efficient welding possible and whose many other advantages include the formation of a deep, smoothly curved penetration and gas cost reduction, is widely used in the industrial world. It also has the disadvantage of producing a large quantity of spatter and the development of low-spatter processes through improvements in welding machines and welding materials is widespread and ongoing.

MAG welding using a mixture of Ar and CO_2 (Ar 80% – CO_2 20%) as shielding gas has been considered to be a gas-shielded arc welding method with reduced spatter[1)]. Welding with greatly reduced spatter can also be performed by using a low-spatter process involving metal transfer control by pulsed current waveforms[2-7)]. There have been reports of carbon dioxide gas-shielded arc welding with reduced spatter involving a metal transfer control method in which a specific pulsed waveform is used[5] and a method of welding by DCEN using a special wire containing REM elements[8)]. Since, however, these methods require comparatively high-cost welding power sources and other equipment and special welding materials, their introduction faces considerable difficulties. The gas cost for MAG welding is very high, approximately 3-fold that of CO_2 (based on gas cylinders) and the tendency for a large number of blowholes to occur is another disadvantage[9)]. Accordingly there is a need for a novel gas-shielded arc welding method which is capable of both holding down equipment cost and gas cost and also reducing spatter.

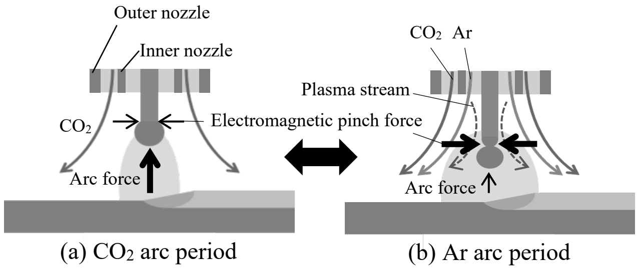

Fig. 1 Schematic illustrations of metal transfer and gas flow

To solve this problem, we developed a new welding process with low spatter and low gas cost, which we named “Pulsed Gas MAG” (PGMAG) welding[10-14)]. It was confirmed that this process could produce the same or lower amount of spatter and good penetration shape with less than 1/4 the amount of Ar compared to ordinary MAG welding using Ar-20%CO_2 mixed shielding gas.

The PGMAG process uses a double nozzle composed of an outer nozzle emitting CO_2 at a constant flow rate and an inner nozzle emitting pulsed Ar at a constant frequency. As shown in Fig. 1, the gas atmosphere around the droplet changes periodically from CO_2 to an Ar-rich gas. This gas compositional change leads to a large decrease in the repelling force and thus, a molten droplet

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formed at the wire tip during the CO_2 period is released before it grows excessively. In this manner, the PGMAG welding process can provide smooth drop transfer synchronized with each Ar gas injection pulse instead of a repelled transfer, and can reduce spatter significantly. Note that even though the welding power source used was an ordinary DC constant-voltage power source, a pulsed current and voltage waveform is obtained due to the sudden change in gas composition of the arc[12].

The range of Ar addition conditions at which low spatter can be achieved with this process has been reported by Fujiwara et al.[12,13] However, their experiment was carried out under limited welding current conditions, and the optimum Ar addition conditions might be affected by the welding current. Therefore, the present study investigated the influence of welding current on metal transfer modes in PGMAG welding.

2. Experimental procedure

Fig. 2 shows the experimental setup, and Table 1 shows the gas and welding conditions. The shielding gases were CO_2 in the outer nozzle (inner diameter 19 mm) and pure Ar in the inner nozzle (inner diameter 7 mm). CO_2 was supplied at a constant flow rate of 25 L/min, and Ar was supplied intermittently with a solenoid valve at an average flow rate of 1 to 8 L/min. The Ar supply path from the solenoid valve outlet to the nozzle outlet had a length of 300 mm. The Ar addition frequency was varied from 20 to 90 Hz. The valve opening time (one solenoid valve pulse) was 2-10 ms. The Ar flow rate may be expressed as the "peak flow rate," which is calculated using equation (1), where Qave [L/min] is the average flow rate, f [Hz] is the Ar addition frequency, and t [ms] is the valve opening time[12].

$$Q\mathrm{p} = \frac{Q\mathrm{ave.}}{f} \times \frac{1}{t}. \qquad (1)$$

The welding power source was digitally controlled and operated in DC constant-voltage mode. The welding current was 235, 280, or 325 A, and the corresponding wire feed speeds were 9, 11.9, or 14.5 m/min, respectively. The arc voltage was varied between 31 and 40 V to maintain an arc length of approximately 3 mm. The welding speed was set to 30 cm/min. The welding wire used was JIS Z 3312 YGW11 with a diameter of 1.2 mm. The contact tip to work distance (CTWD) was 25 mm. Bead-on-plate welding was performed in a flat position, and a high-speed camera (1000 fps) was used to observe the metal transfer.

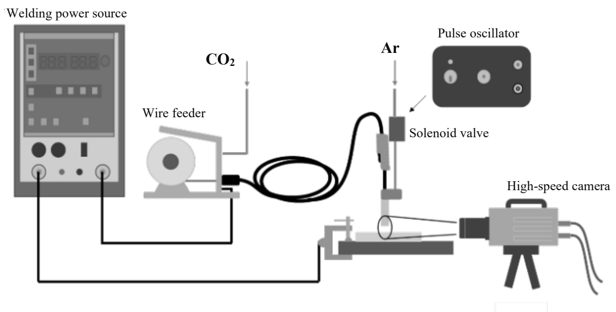

Fig. 2　Experimental setup

Table 1　Gas and welding conditions

Ar	Frequency f		20-90 Hz
	Flow rate (average) Qave		1-8 L/min
	Valve opening time t		2-10 ms
CO_2	Flow rate		25 L/min
Wire	JIS Z3312 YGW11 Ø1.2 mm		
Base metal	SS400		
Welding current	235 A	280 A	325 A
Wire feed speed	9 m/min	11.9 m/min	14.5 m/min
Arc voltage	31 V	36 V	40 V
Welding speed	30 cm/min		
CTWD	25 mm		

3. Result and discussion

The metal transfer modes were classified into four types: "asynchronous" (✕), "semi-synchronous" (■), "synchronous" (○), and "excess drops" (▲). The evaluation criteria were as follows: asynchronous means that droplets were transferred without being synchronized with Ar additions, semi-synchronous means that a droplet was transferred once every 1-3 Ar additions, synchronous means that each droplet transfer was synchronized with each Ar addition, and excess drops means that several smaller droplets similar to spray transfer followed after the first large drop in each Ar addition pulse.

Figs. 3(a)-(c) show the relationship between the pulsed Ar gas conditions and metal transfer modes for different welding currents [(a) 235 A, (b) 280 A, and (c) 325 A] when the Ar addition frequency was kept constant at 50 Hz. As shown in Fig. 3 (b), a wide synchronous range (i.e., controllable range of metal transfer) is confirmed at 280 A. The metal transfer mode becomes asynchronous or semi-synchronous when the peak flow rate is too low or the valve opening time is too short. The excess-drop range appears under conditions with relatively high peak flow rates and long valve opening times. These results show that the metal

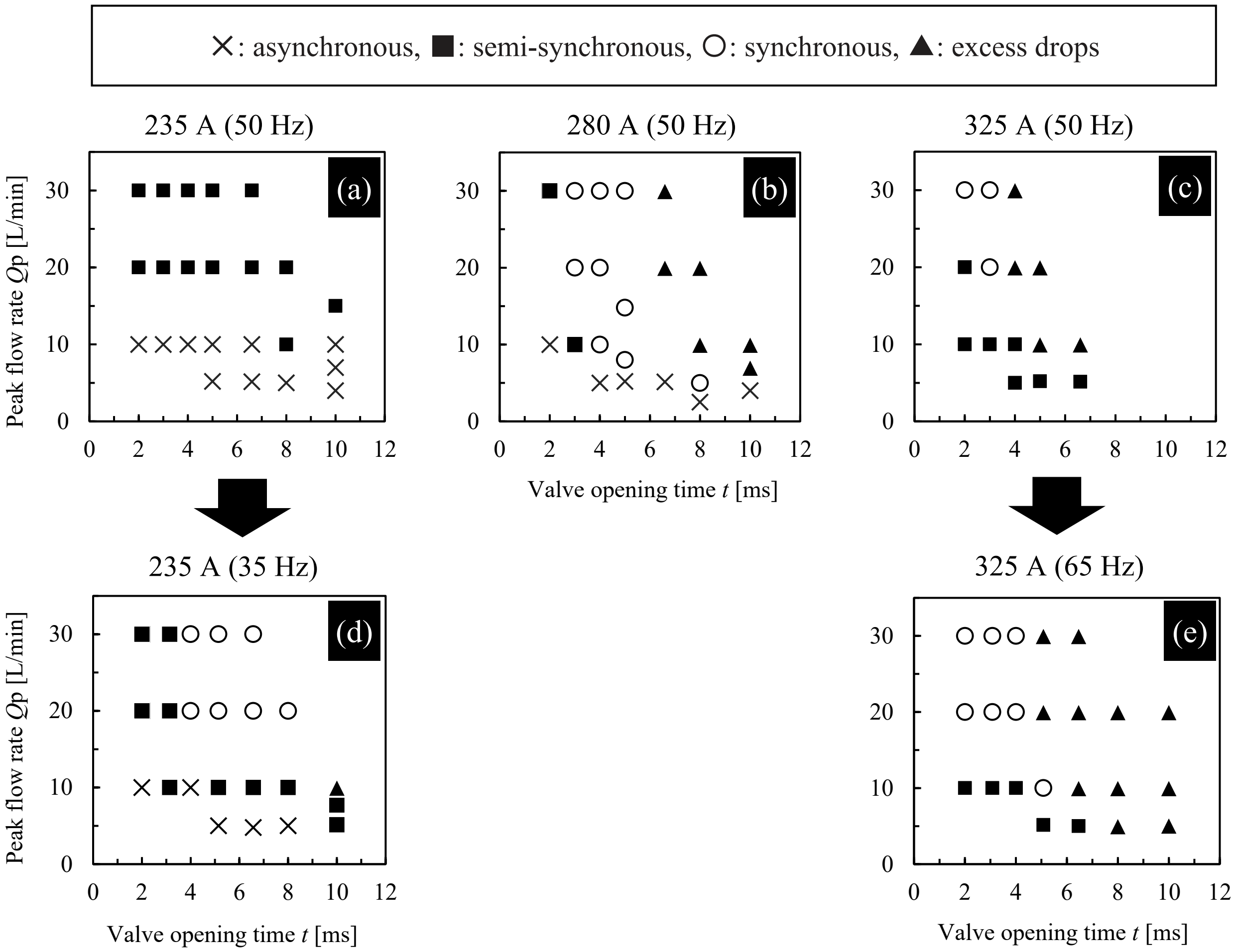

Fig. 3 Relationship between pulsed Ar gas conditions and metal transfer modes at each current level. (a) 235 A at 50 Hz, (b) 280 A at 50 Hz, (c) 325 A at 50 Hz, (d) 235 A at 35 Hz, and (e) 325 A at 50 Hz.

transfer mode is determined by the Ar peak flow rate and valve opening time settings even under the same conditions of welding current and Ar addition frequency. From these results, it is clear that it is necessary to increase and maintain the Ar concentration around the arc in order to detach the droplet grown during the CO_2 period[14]. From this point of view, under semi-synchronous or asynchronous conditions, the Ar flow rate and addition time were low, so the Ar concentration and retention time were insufficient for droplet release. In contrast, under excess-drop conditions, the Ar retention time was too long and caused spray transfer.

Compared with Fig. 3 (b), the synchronous area shrinks and is replaced by the semi-synchronous and excess-drop conditions at currents of 235 A and 325 A [Figs. 3 (a) and (c)], respectively, even though the same Ar addition conditions were applied. The difference between them is the welding current used, namely the wire feed rate. At a low welding current of 235 A, droplet growth at the wire tip is slower than at 280 A and, hence, the size of the droplet may not become large enough to be released when the gas composition changes. In fact, it was often observed in high-speed video that, at 235 A, drop transfer occurred at every two gas pulses instead of one pulse. It is assumed that the Ar addition frequency of 50 Hz is too high for droplet growth at a welding current of 235 A. At a welding current of 325 A, just the opposite occurred and a higher Ar addition frequency is assumed to be required.

To achieve synchronous metal transfer, molten metal droplets formed at the wire tip must grow large enough to be released when the main gas composition around the arc changes from CO_2 to Ar. From this point of view, the results in Figs. 3 (a)-(c) can be interpreted as follows: the droplet did not grow enough to detach at 235 A (a slower wire feed speed) and grew too much at 325 A (a faster wire feed speed) compared with the size at 280 A. These results suggest that there might be an optimum Ar addition frequency for different welding currents (i.e., wire feed speeds).

Based on the above results and discussion, we considered that there might be an optimum droplet size (volume) for drop transfer. If the droplet volume obtained at 280 A and 50 Hz [Fig. 3 (b)], in

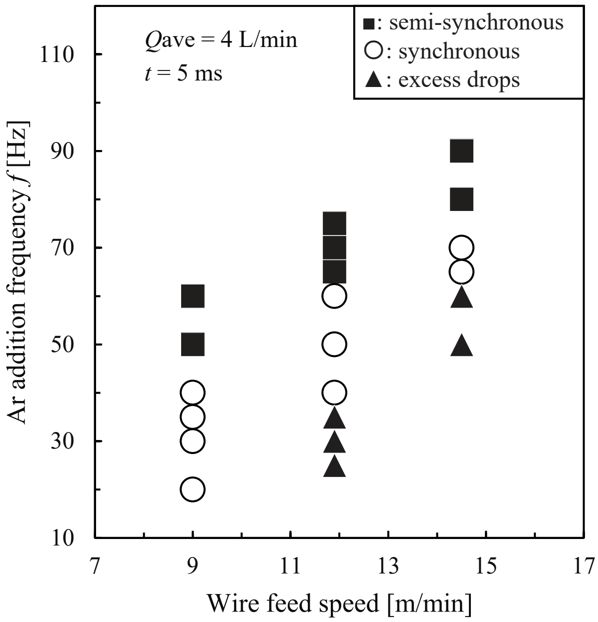

Fig. 4 Ar addition frequencies that can be synchronized at different wire feed speeds

which the synchronous state has a wide range, is assumed to be the correct size for transfer, the suitable droplet volume is calculated to be 4.49 mm^3. In the literature, a similar value of 4.4 mm^3 was also reported as the droplet volume under almost the same welding conditions (280 A, 12 m/min) when low spatter welding was achieved in CO_2 gas-shielded arc welding by regulated globular transfer with pulsed waveforms[5)]. The volume obtained here may not be optimal, but it is believed that this volume is, at least, the right condition for the droplet to be released by the gas compositional change.

If this is also true at 235 A and 325 A, the Ar addition frequencies for each case should be 37 Hz and 61 Hz, respectively. The results for 35 Hz at 235 A and 65 Hz at 325 A are shown in Figs. 3 (d) and (e). As expected, expansion of the synchronous metal transfer condition regions can be seen clearly for each welding condition. However, the distribution for each metal transfer mode is different for 235 A and 325 A. In the excess-drop state, a wide range of excess drops exists for valve opening times of 5 ms or at more at 325 A, although there is almost no plot of this kind at 235 A. Also, in the semi-synchronous or asynchronous states, for peak flow rates of 20 L/min or more, some of these plots exist at valve opening times of 3 ms or less at 235 A, but not at 325 A. This is because the increased current (i.e., electromagnetic pinch force) enhances droplet release and spray transfer does not occur because 235 A is not high enough for the critical current[15)].

Fig. 4 is an overview of the relationship between the wire feed speed (welding current) and applicable Ar gas frequency for an average Ar gas flow rate of 4 L/min and a valve opening time of 5 ms. It can be seen that reasonably wide synchronous ranges can be obtained if the Ar addition frequency is adjusted based on the wire feed speed.

As Fig. 4 shows, the Ar addition frequency should increase as the wire feed speed increases. The droplet growth rate is increased with increasing wire feed speed, and the Ar addition frequency must be selected based on the desired droplet growth rate. At 14.5 m/min, the synchronous range is narrower, and it is expected to be even narrower at higher wire feed speeds. One reason for this is that, as can be seen from equation (1), an increase in f while Qave and t are fixed causes a decrease in Qp. A decrease in Qp leads to a lower amount of Ar in a single pulse and a narrower synchronous range at high frequencies because the reduced Ar gas supply causes a lower Ar concentration in the arc atmosphere and reduces the arc force reduction. Another reason is that, as noted above, an increase in wire feed speed leads to an increase in current, and then spray transfer leading to excess drops is more likely to occur. However, equation (1) shows that the peak flow rate can be increased by decreasing the valve opening time, so that the synchronous range is expected to be extended by decreasing the valve opening time to about 3 ~ 4 ms at high frequencies and high currents.

4. Conclusions

This study showed that the Ar addition conditions need to be set appropriately in PGMAG welding to obtain synchronous droplet transfer, that is, one droplet transfer per one pulse. This is because the Ar concentration around the arc must be increase and maintain up to the levels where the metal droplet grown during the CO_2 period can be smoothly detached in the manner of drop transfer but not repelled or spray transfer.

It was also found that the Ar addition frequency must be adjusted based on the wire feed speed when the welding current is changed. This indicates that the droplet volume during the CO_2 period must have the right size for it to be released by the gas compositional change. In the experimental conditions reported here, a wide synchronous range was obtained by setting conditions to form a droplet size of about 4.5 mm^3.

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