Metal Transfer Characteristics in Pulsed GMA Welding†

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Abstract

Metal transfer characteristics of pulsed current GMA welding of mild steel are investigated by using constant current power source with electrode positive polarity. It is shown that stable zone of welding condition in lower current region is widened by using pulse welding. Melting rate of wire is much increased in the pulse welding and its value is calculated in the same manner used for stationary D.C. current welding.

Welding condition under that one droplet is formed in higher current phase and detached in the lower current phase is explored and the welding parameter to realize it is systematically determined. It is shown that the duration and amplitude of peak current together with wire feed rate mainly determine the condition and therefore the drop size. Effects of the change in the duration and amplitude in peak current on the condition of one droplet transfer are also investgated. Increase in duration of peak current phase require increase of wire feed rate. The maximum and the minimum sizes of droplet are almost same respectively in the range of peak current of 300 – 450 A.

In pulsed MIG welding the detaching of droplet is not so sharp compared with that in pulsed MAG welding. In this case the fluctuation of arc length is so wide that the stable zone of one droplet transfer could not be found in the higher feed rate of wire.

KEY WORDS: (GMA Welding) (MAG Welding) (MIG Welding) (Pulse Welding) (Pulsed GMA Welding) (Metal Transfer)

1. Introduction

For successful open arc operation, the GMA welding process has two basic requirement, those are, the wire feed rate must be balanced with the burn-off rate to maintain a constant arc length, and there is a stable transfer of metals from the electrode wire to the weld puddle.[1,2] For pulsed GMA welding, the things are same. However, arc phenomena and metal transfer characteristics of pulsed GMA welding are very complicated because of many parameters of current pulsation, pulse repeat frequency, wave form, amplitude and duration of higher and lower levels of current, and so on. The correlation between metal transfer characteristics and the current pulsating condition is very important particularly with respect to the stability of welding.

Essentially pulsed current welding occurs when the welding current has two levels, a high level to produce the penetration and a low level to permit pulses of high current. In the higher current phase, melting rate of the wire electrode is also high. If the two or many droplets transfered to the weld puddle in this high current phase, pulsed GMA welding is only the stationary high current D.C. welding with pulsive rest time of metal transfer, because in the lower current phase the wire does not melt sufficiently to produce the molten metal droplet.

The major premise for controlling the metal transfer in pulsed GMA welding is the transfering one droplet in one cycle of current. One droplet transfer only in high current phase is not necessarily better choice of welding condition, because in high current phase the spray transfer comprising the continuous projection of a series of small droplets may occurs in MIG and MAG welding and the adjustment of one droplet transfer only in the high current phase may be difficult to accomplish in practice. If the synchronization of the transfer phenomera with current pulse can be obtained in the form that a droplet is formed in the higher current phase and detached in the lower current phase, it is an optimum condition particularly from the view point of stable control of weld puddle and low heat input of welding.

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The purpose of this paper is to describe the investigated results concerning to the metal transfer characteristics related to the current pulsating condition in GMA welding of mild steel.

In this paper, MIG welding means the GMA welding in argon shielding and that in mixed gas shielding of argon (80%) and carbon dioxide (20%) is called MAG welding.

2. Experimental Procedures

Schematic illustration of experimental setup is shown in **Fig. 1**. A transistorized welding power source is used with constant current characteristics and electrode positive polarity (D.C.E.P.). Wire feed rate can be set independently from the welding current and voltage. Distance between the contact tip and the plate is 30 mm, which is a little longer than usual case so that the wire feeding rate may be changeable on a large scale.

High speed cine camera, HYCOM is used to observe the metal droplets transfer phenomena and arc behavior. High speed motion pictures of 3000 frames/sec are taken by using a Xenon lamp as a backing light.

As shielding gas, mainly 80% Argon + 20% CO_2 (25 liter/min) is used and for the comparison with it, 100% Argon is also used. Chemical compositions of mild steel wire (1.2 mmϕ) and test plate are shown in **Table 1**.

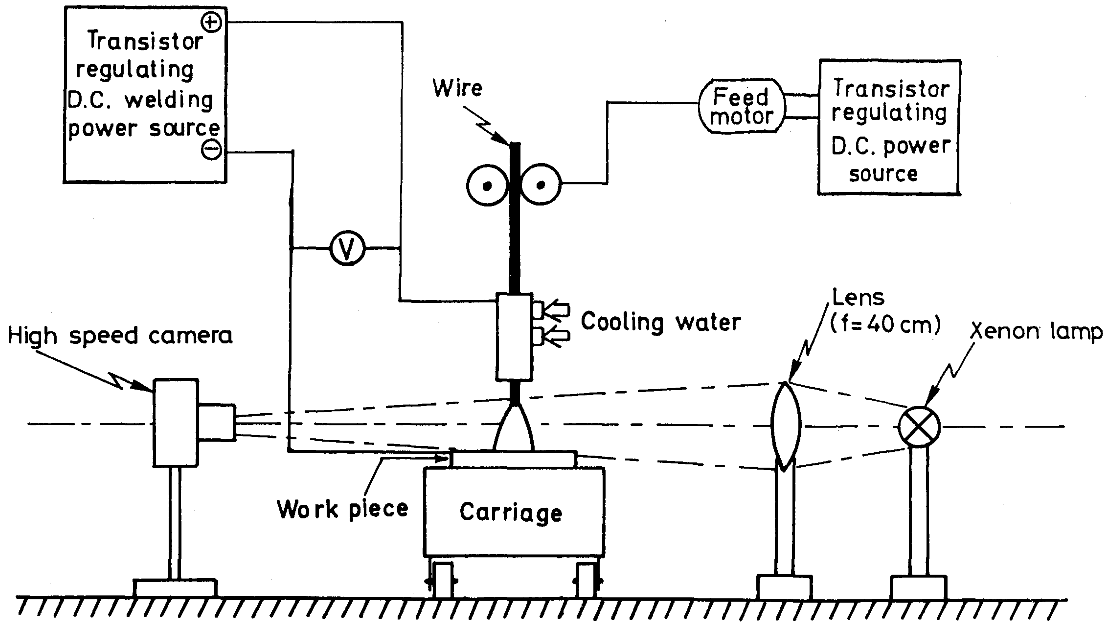


Fig. 1 Schematic illustration of experimental setup of GMA welding.

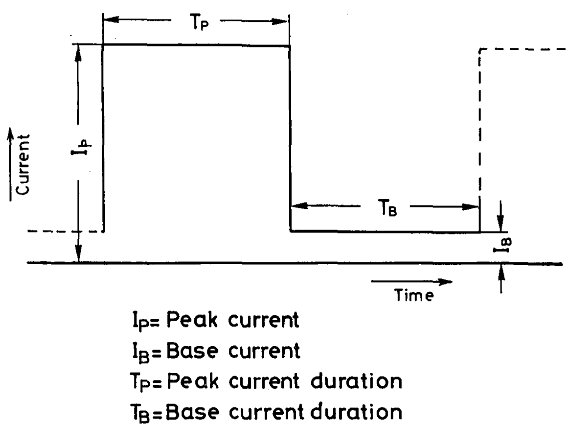


Fig. 2 Terminology and symbols of unit pulse of current.

Table 1 Chemical compositions of materials used.

	C	Si	Mn	P	S	Al	Ti
Base metal (SM41A)	0.23	-	2.5 C	0.040	0.040	-	-
Mild steel wire (MG50T)	0.08	0.38	0.38	0.014	0.015	-	-
Mild steel wire (Mix50)	0.097	0.61	1.28	0.016	0.017	0.040	0.007

MG-50T is used in Chap. 3 and MIX-50 is used in Chap. 4.

Terminology of pulsed current is shown in **Fig. 2**. In every case the lower current level I_B is kept to be constant value, 50 A, in which the arc can be maintained stably.

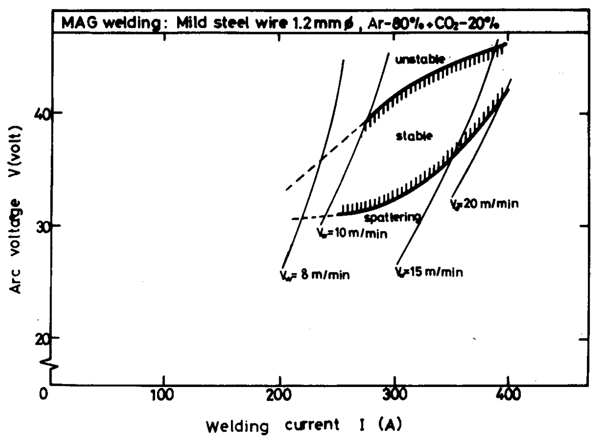
All experiments in this study are carried out under the condition of bead on plate welding with constant current characteristics of power source.

3. Stationary Current and Pulsed Current GMA Weldings

3.1 Effect of current pulsation on arc stability

Figure 3 shows the comparison of stable zone of the arc for D.C. MAG and pulsed current MAG welding. In the low current level, the condition under which arc does not root stably on the base metal and the arc rotation or irregular movement becomes remarkable, resulting in difficult detachment of droplet, is regarded as "unstable".

By the current pulsation, stable zone of the arc voltage became wide and the arc is stabilized in the low current level in averaged value.



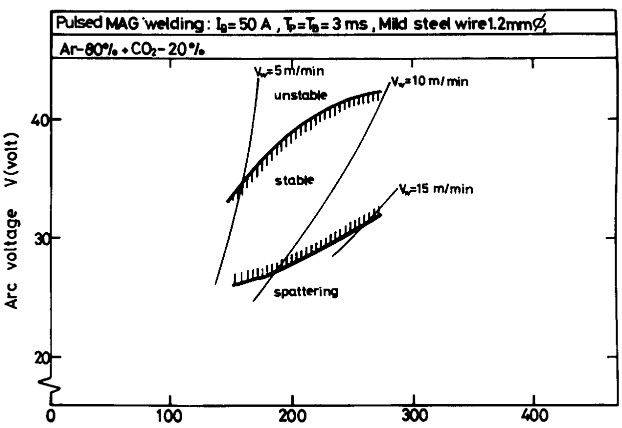


Fig. 3 Comparison of stable zone of welding condition in cases of stationary D.C. MAG welding and pulsed current MAG welding.

3.2 Wire melting rate for pulsed GMA welding

Halmøy[1)] showed the universal relationship among the welding current, wire extension and wire feeding rate in GMA welding as follows,

$$v_W = \frac{1}{H_0 - b}(\Phi j + a E_X j^2), \quad (1)$$

where,

v_W : wire feeding rate (mm/sec),
j : welding current density (A/mm²),
E_X : wire extension (mm),
H_0 : heat content of melted droplet (J/mm³),
Φ : equivalent voltage on melting due to arc heat (V),
a, b : constant values, a : (Ω mm), b : (J/mm³).

The first term of Eq.(1) represents the part by the arc heating and the second the part by the Joule heating.

The values of a, b, H_0 and Φ for the used mild steel wire (MG-50T, 1.2 mmφ) are experimentally determined as follows,

$a = 1.13 \times 10^{-3}$ (Ω mm),
$b = -3.79$ (J/mm³),
$H_0 = 11.3$ (J/mm³),
and $\Phi = 4.5$ (V).

By using these values, Eq.(1) is represented as

$$v_W = 0.264\, I + (5{,}86 \times 10^{-5}) E_X I^2, \quad (2)$$

where, I shows the total welding current.

In case of pulsed current GMA welding, Eq.(2) is converted as

$$v_W = 0.264\, I_{av} + (5.86 \times 10^{-5}) E_X I_{eff}^2$$
$$= 0.264 \frac{I_P T_P + I_B T_B}{T_P + T_B} + (5.86 \times 10^{-5}) E_X \frac{I_P^2 T_P + I_B^2 T_B}{T_P + T_B}. \quad (3)$$

When the same current (in the case of pulse welding, averaged current is used) and the same wire extension are used in Eqs.(2) and (3), the part of the arc heating in the case of stationary D.C. current is equal to that in the pulsed current. But the term of the Joule heating in the stationary D.C. current is different from that in the pulsed current.

$$\left(\begin{matrix}\text{Joule heating term}\\ \text{in D.C. current}\end{matrix}\right) / \left(\begin{matrix}\text{Joule heating term}\\ \text{in pulsed current}\end{matrix}\right)$$
$$= \left(\frac{I_P T_P + I_B T_B}{T_P + T_B}\right)^2 / \left(\frac{I_P^2 T_P + I_B^2 T_B}{T_P + T_B}\right)$$
$$= (I_P T_P + I_B T_B)^2 / [(I_P T_P + I_B T_B) + (I_P - I_B)^2 T_P T_B]. \quad (4)$$

Above ratio shows that the generation of Joule heat for the pulsed current is more than that for stationary D.C. current. Therefore, in the pulsed welding the effect of this Joule heating is utilized and then wire burn-off rate or wire feed rate increases.

In **Fig. 4** the allowable ranges in the wire feed rate are shown in related with averaged currents of stationary D.C. and pulsed welding. In the case of the pulsed current, the conditions of $T_p = T_B = 1$ msec under which the wire extension is considered constant is adopted. The minimum values of feed rate $v_{w_{min}}$ are obtained from the none of effect of Joule heating. This is corresponding to the situation that the wire extension equals to zero. We can see the calculated values coincide with the experimented ones.

The relation between the wire feed rate and the wire extension under the conditions of $I_p = 350$ A is shown in **Fig. 5**. For the same value of wire extension, the wire melting rate in pulsed current welding is higher than that in D.C. welding.

The effect of the peak current value on the wire melting rate is shown in **Fig. 6**.

These results means that for the longer extension pulsed current welding require the higher feeding rate and its tendency increases with the increase in peak current due to the effectiveness of Joule Heating. Consequently the allowable range of the wire feed rate for welding becomes wide. In other words, when the wire feed rate is varied, the change in wire extension is small for the higher value of peak current I_p. But too high value of peak current is not practical because of requirement of long duration of base current phase.

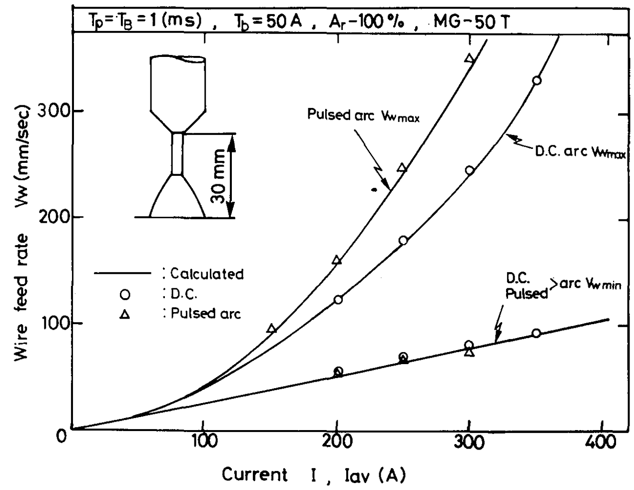


Fig. 4 Difference in maximum and minimum feed rate of wire applicable to stationary and pulsed GMA welding.

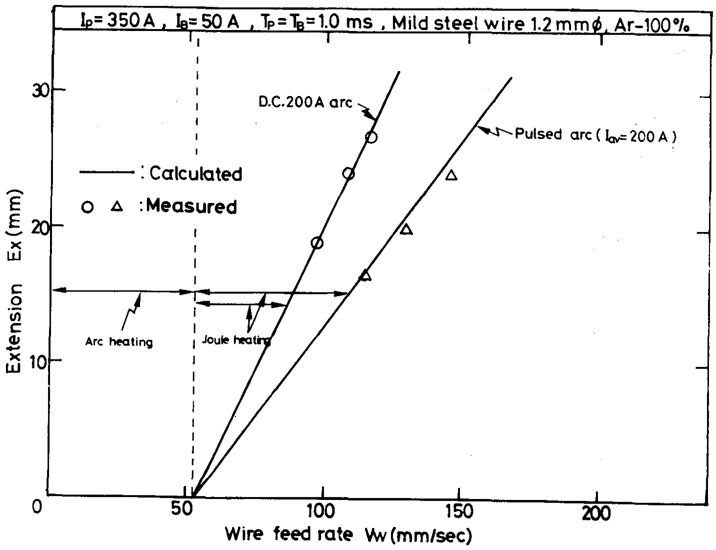


Fig. 5 Difference in wire melting rate as a function of wire extension in cases of D.C. 200 A and pulsed (I_p : 350 A, I_B : 50 A and I_{av} : 200 A) arcs.

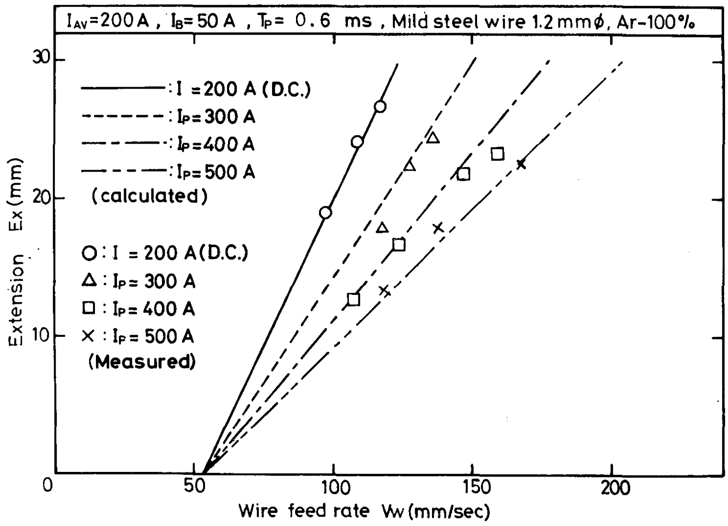


Fig. 6 Effect of peak current I_p on wire melting rate (I_{av} : 200 A).

4. Effect of Pulse Condition on Metal Transfer Characteristics

4.1 Preliminary consideration

As already described, there is a combined relation between the wire feed rate and the relevant pulsating parameters. The pulse parameters are the duration and amplitudes of higher and lower currents. The approach to study this relationship was based on the two criteria, namely, the balance between the wire feed rate and melting rate to maintain a constant arc length, and the control of metal transfer by regularly repeated application of a current pulse. The former fundamentally examined in preceding chapter.

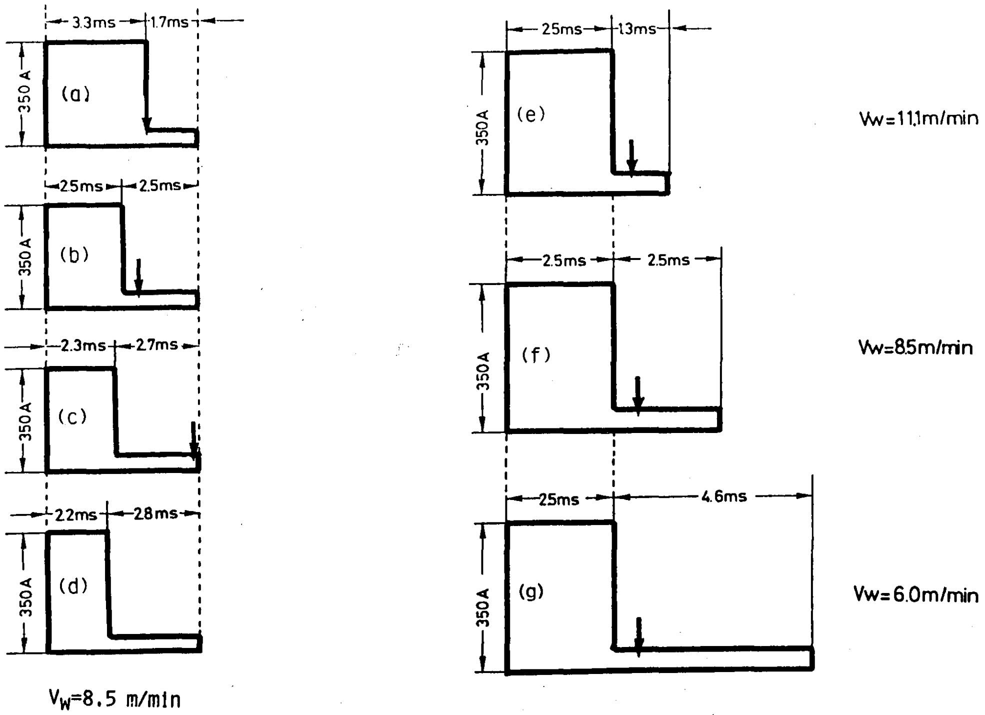


Fig. 7 Schematic illustration showing effect of peak current duration on time of droplet detachment under the same repeat frequency of pulse and same wire feed rate (8.5 m/min) ---Left side---
The case of adjusted wire feed rate is shown in right side. Under the condition of same amplitude and duration of peak current, wire feed rate is adjusted so that the melting rate in one pulse duration ($T_P + T_B$) is equal in each case. The arrow shows the instant of detachment of droplet.

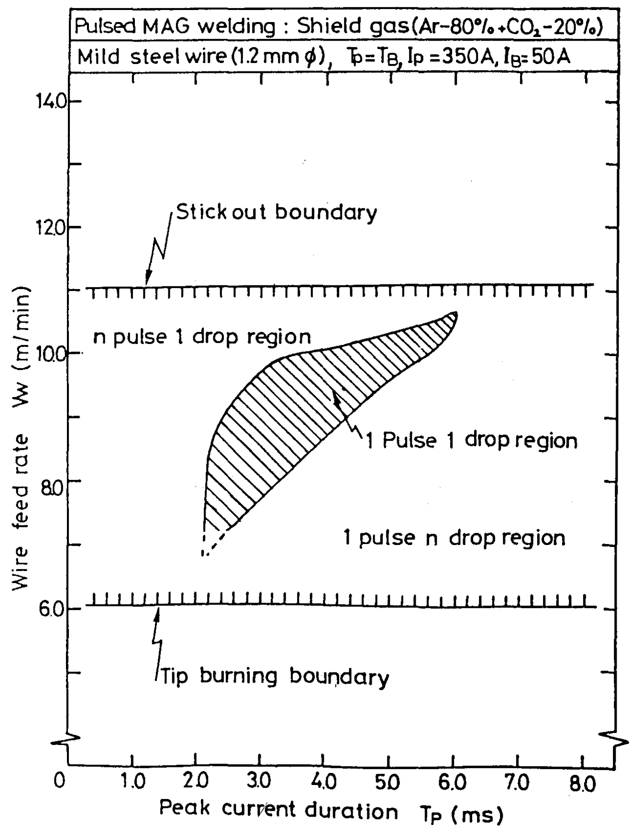


Fig. 8 Stable zone of transfer condition of one droplet in one pulse and variation of transfer characteristics related to those of wire feed rate and peak current duration.

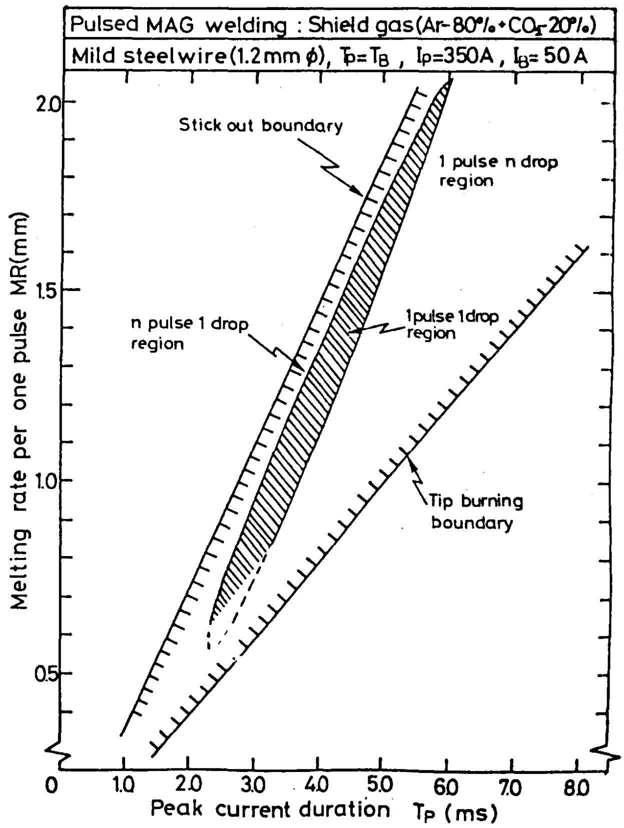
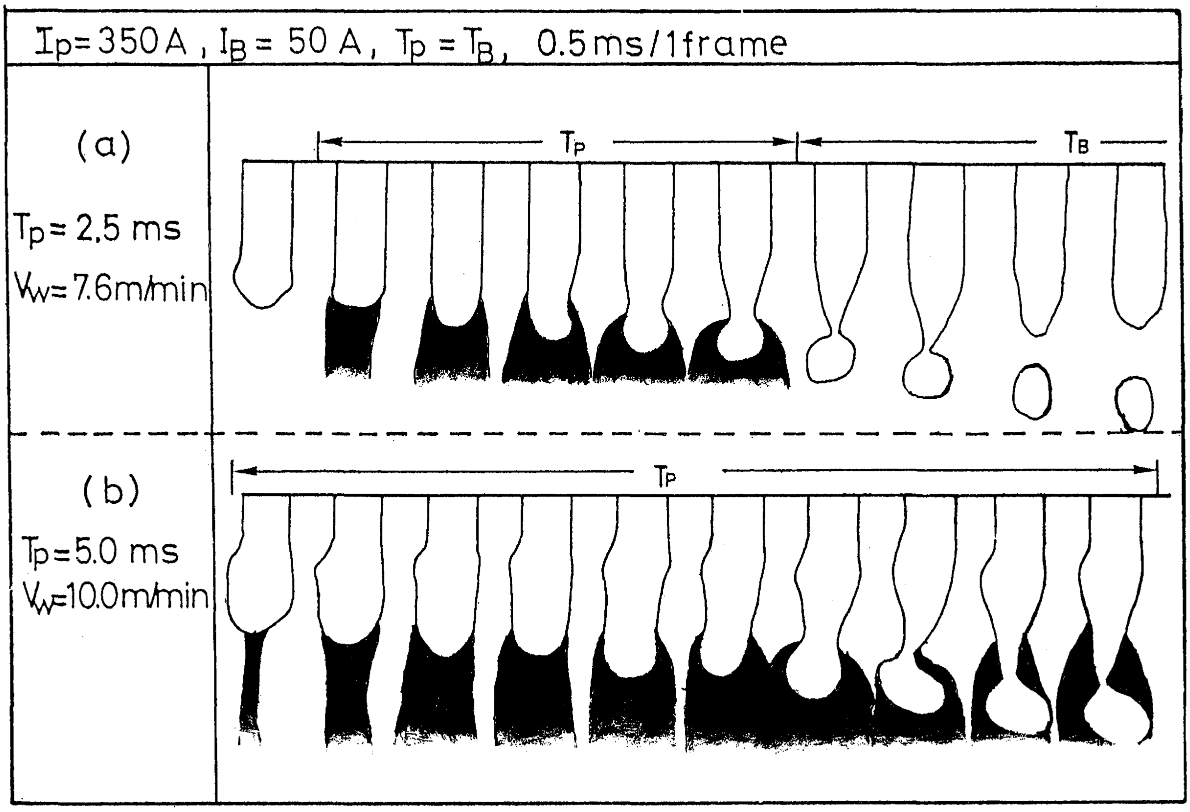
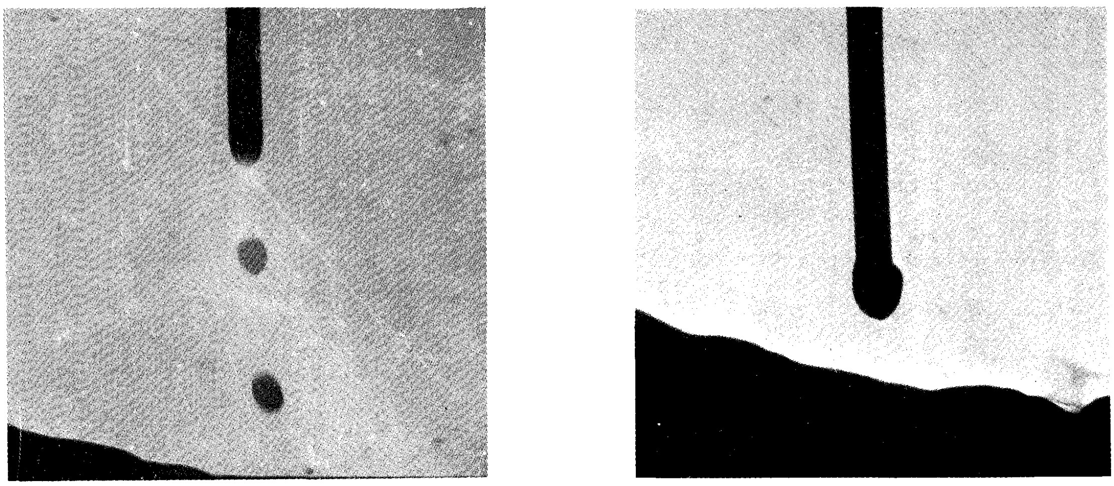


Fig. 9 Stable zone of transfer of one droplet in one pulse related with melting rate per one pulse and peak current duration.





(a) T_p=2.5 ms V_W=7.6 m/min

(b) T_p=5.0 ms V_W=10.0 m/min

Fig. 10 Difference in time-variations of arc and wire tip configurations under following conditions,
(a) short wire extension, slow wire feed rate, T_p : 2.5 msec, v_W : 7.6 m/min,
(b) long wire extension, high wire feed rate, T_p : 5.0 msec, v_W : 10.0 m/min.
And photographs of wire tip at end of base current duration.

For a given feed rate which is balanced with the melting rate, the pulse duration must be adjusted so that one droplet is transfered in one cycle of the pulse. **Figure 7** illustrates the some results of preliminary experiment. (a), (b), (c) and (d) in the figure show the effect of pulse duration on the time of detachment of droplet under the condition that the peak current and wire feed rate are kept constant. The arrow in the figure indicates the time of detachment of droplet. When the duration of T_p became short, the time of detachment was delayed in the lower current phase, and one droplet for one pulse could not be realized under the condition of $T_p <$ 2.2 msec.

Next the duration and amplitude of peak current are hold to be constant and base current duration is changed. The feed rate of wire are balanced with the calculated melting rate so that the same melting rate is obtained in one cycle of pulsed current. The results are shown in (e), (f) and (g) in the same figure. As a result, the timings on detaching coincide under all conditions.

The experimental results means the melting rate of wire in one cycle of pulsed current is decided mainly from the amplitude and duration of peak current. And in order to adjust the melting rate to form a droplet having a relevant size, the proper duration must be placed.

In these experiments the droplet could be detached in the phase of base current. This feature of metal transfer is of most advantageous from the view point of preventing from explosive spattering, stabilizing the weld puddle fluid movement, and accomplishing the lower heat input welding. So, the operating condition of one droplet for one pulse, which mean the above mentioned characteristics of metal transfer, is explored under the condition of $T_p = T_B$.

4.2 Operating condition of one droplet in one pulse

Figure 8 shows the stable zone of operating condition of one droplet in one pulse for MAG welding under the condition of $I_p = 350$ A, $I_B = 50$ A and $T_p = T_B$. **Figure 9** was obtained from Fig. 8, by converting the wire feeding rate v_w (m/min) to the melting rate MR (mm). The figure indicates the difference between the maximum melting rate in one pulse and the minimum one is very large. It results in the difference of droplet size in volume ratio of 3.3. Change in droplet size in this case are tabulated in **Table 2**.

Figure 10 shows the difference in time-variation of arc and wire tip configuration and the photographs of the wire tip at the end of base current phase under the maximum and minimum droplet size conditions. Under the maximum droplet size condition, the volume of molten part of wire is comparatively large and considerable amount of excess molten metal is remained at the wire end. This represents excess melting due to the long T_p after the occurrence of constriction of molten metal to produce a droplet.

Table 2 Maximum and minimum of droplet size in variable durations of peak current under the condition of $I_p = 350$ A and $T_p = T_B$.

T_p (ms)	Droplet radious (mm)		Droplet volume (mm^3)	
	Maximum	Minimum	Maximum	Minimum
2.5	0.58	0.54	0.82	0.66
3.0	0.64	0.58	1.10	0.82
4.0	0.71	0.67	1.50	1.26
5.0	0.78	0.75	2.00	1.77
5.5	0.80	0.79	2.15	2.01

Figure 11 illustrates a diagram interpretting the configuration of the stable zone of one droplet in one pulse, in relation to wire feed rate and peak current duration. At the mid-point A the droplet is detached in the middle of the duration of base current. With increase of T_p or decrease of v_w from the condition of point A, the timing of detachment becomes short, on the otherhand, decrease of T_p or increase of v_w requires the long time for the onset of the detachment. These tolerances permit the practicably wide zone for stable transfer of one droplet in one pulse.

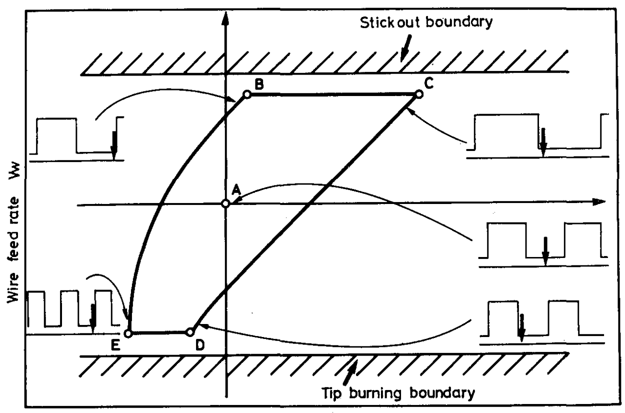


Fig. 11 Diagram representing the contour of transfer zone of one droplet in one pulse.

4.3 Effect of peak current on one droplet in one pulse condition

Figure 12 shows the effect of peak current value on the variation of stable zone of one droplet transfer in one

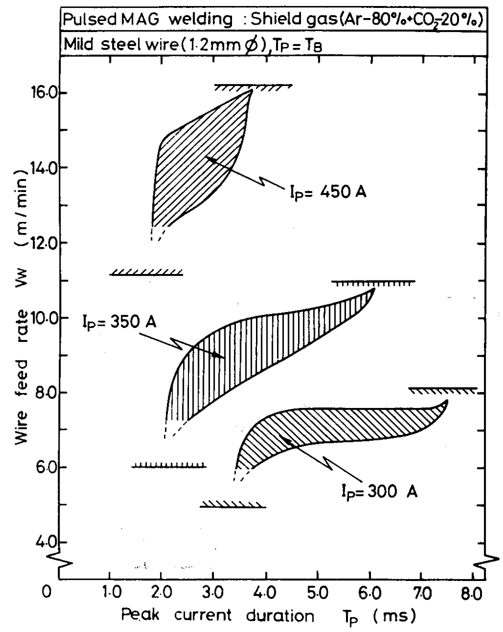


Fig. 12 Effect of peak current value on the variation of stable zone of one droplet transfer in one pulse.

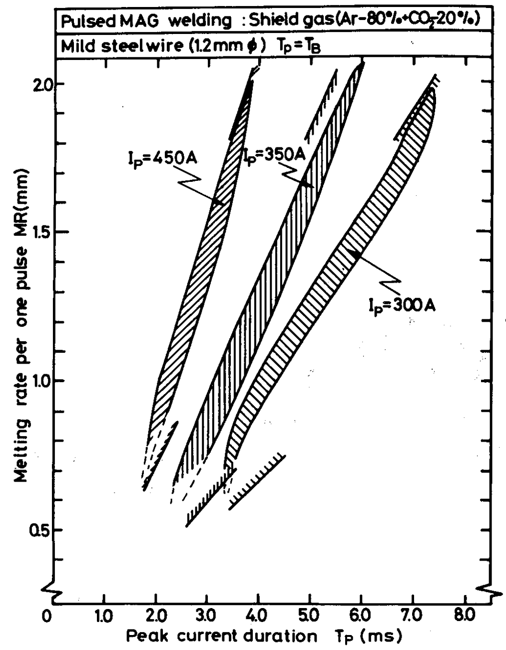


Fig. 13 One droplet transfer in one pulse zone with various peak current in relating with melting rate per one pulse and peak current duration.

pulse. The preferable value of v_w and its allowable range became large with increase of peak current, but with respect to the value of T_p and its allowable range, it provides opposite effect. The increase of peak current shorten the time required for the formation of droplet due to increase of pinch force. This reduces the necessary time interval T_p and make narrower the applicable range for T_p.

Figure 13 was obtained by rewriting of Fig. 12, in the same manner already mentioned. It indicates the maximum and minimum droplet size are almost the same respectively among three typical cases of peak current.

Figure 14 illustrates the applicable range of wire feed

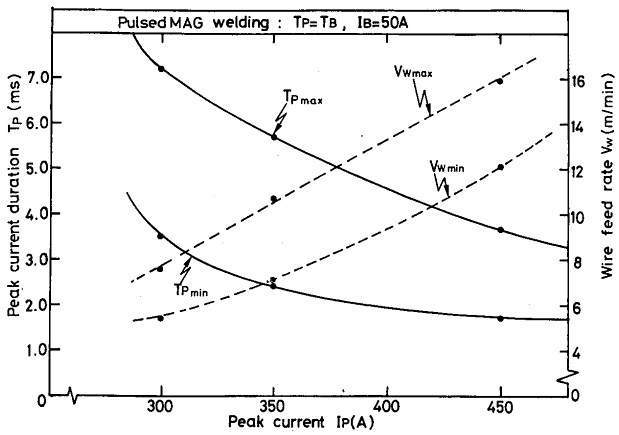


Fig. 14 Applicable range of wire feed rate and peak current duration for the condition of one droplet transfer in one pulse.

rate and peak current duration for the condition of one droplet in one pulse. Wire feed rate must be increased with increase of peak current I_p, but T_p has to be small and allowable tolerance for T_p also becomes narrower.

4.4 Effect of shielding gas composition on the condition of one droplet in one pulse

In order to examine the effect of shielding gas composition, the transfer zone of one droplet in one pulse in MIG welding is compared with that of MAG welding as shown in **Fig. 15**. **Figure 16** shows the time-variation of arc and droplet configurations at wire tip in both cases under the same conditions of pulse parameters and wire feed rate. In pulsed MAG welding we can see two droplets are transfered in one pulse while one droplet is detached in one cycle of pulsed current in MIG welding. The difference is due to the effectiveness of pinch force on detaching the droplet from wire end. In MIG welding the arc roots on the wire climb up so higher than that in MAG welding. This branch-out of the wire current far above the costricted area does lower the pinch force acting inside and downward to assist the detaching of droplet.

Furthermore in MIG welding, the long and fine string of wire metal is formed at the end of tapered electrode. After detaching the droplet this long string of molten metal is drawn up due to the surface tension. But this wide fluctuation of extension of wire metal causes the

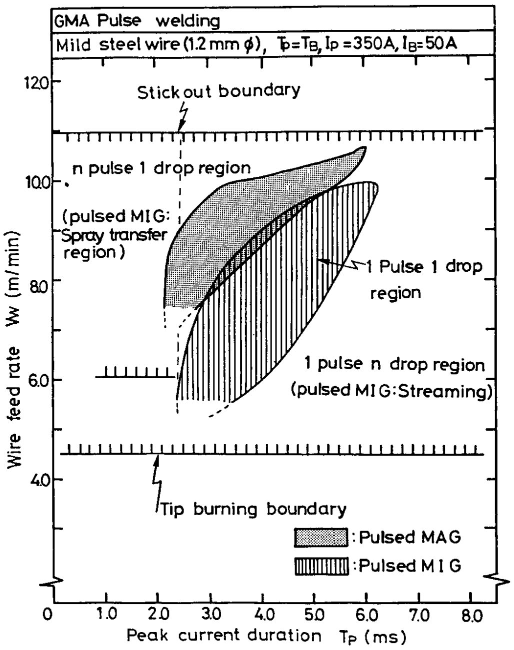


Fig. 15 Comparison between one droplet transfer zone of MIG welding and that of MAG welding.

short-circuitting frequently, especially in the case of short arc length. This is the reason why the stable transfer zone for one droplet in one pulse in MIG welding is placed in the lower region of wire feed rate, compared with that of MAG welding.

5. Conclusions

The welding parameters of pulsed current GMA welding were investigated. And following conclusions were obtained.

(1) The limitation imposed by unstable arc due to the Globular metal transfer in stationary D.C. current GMA welding can be removed by using the pulsed current GMA welding. Stable zone of welding condition in lower current region is widened by using this technique.

(2) The melting rate of wire is much increased in the pulsed current GMA welding compared with that in stationary D.C. GMA welding of the same current (averaged value).
This is due to increase of Joule heat in the wire.

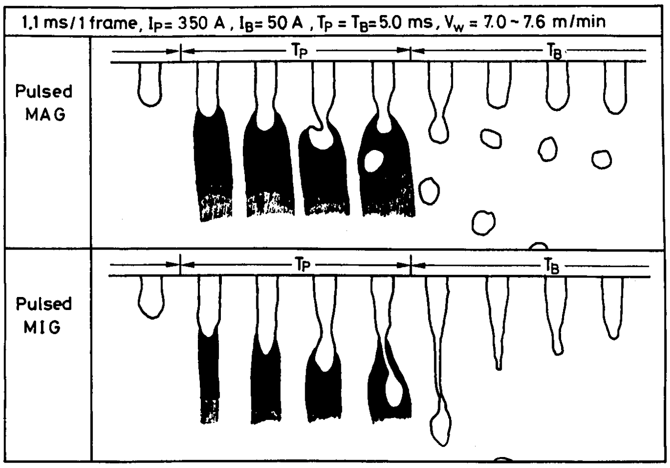


Fig. 16 Difference in time-variation of wire tip configuration and droplet transfer due to change in shielding gas.

(3) Welding condition under that one droplet is formed in the higher current phase and detached in the lower current phase is considered and the welding parameters to realize the metal transfer characteristics were determined. The most important parameters of pulse current are the amplitude and duration of peak current. These two parameters together with wire feeding rate mainly determine the condition and therefore the droplet size.

(4) The increase in duration of higher current phase require the increase in wire feed rate.

(5) The maximum sizes of droplets were almost same in the range of peak current of 300-450 A. The minimum ones were also constant in the above range of current.

(6) In pulsed MIG welding the detaching of droplet is not so sharp compared with that in pulsed MAG welding. In this case the fluctuation of arc length is so wide that the stable zone of one droplet transfer could not be found in the higher feed rate region of wire.

References

1) E. Halmϕy; "Wire melting rate, droplet temperature and effective anode melting potential", Proc. of Int. Con. on Arc Physics and Weld Pool Behavior, TWI, London (1979).

2) M. Amin; "Synergic pulse MIG welding", Metal Construction, vol.13, No.6 (1981).