Droplet Transfer in Pulsed Gas Metal Arc Welding of Aluminum

Droplet transfer modes in pulsed GMAW of aluminum are identified and a method for characterizing one droplet per pulse is described

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ABSTRACT. The droplet transfer mode is a critical element in the arc welding process. Multiple transfer modes have been identified, and the conditions under which they occur have been characterized. In the pulsed gas metal arc welding (GMAW-P) process, droplet transfer mode is affected not only by welding voltage and current, but also by the pulsing parameters. In this work, experimental techniques were used to investigate the transitions from pulsed globular to pulsed spray to pulsed streaming transfer in GMAW-P of 1.2-mm 4047 aluminum welding wire. A new method for characterizing one-droplet-per-pulse (ODPP) operating conditions is described and the transition from pulsed globular to pulsed spray transfer is characterized. The roles of pulse frequency and duty cycle on droplet transfer are explained.

Introduction

The nature of liquid metal transfer from the consumable electrode to the workpiece has an important practical effect in welding because it affects the ability to weld in various positions, the degree of penetration, the stability of the weld pool and the amount of spatter loss. Control of metal transfer may be one means of extending the range of plate thickness for which a given welding process can be used.

In GMAW-P, the objective is usually to establish a set of pulse parameters that will provide spray transfer (Ref. 1). It also is generally believed that one droplet should be detached in every pulse, a condition referred to as *one droplet per pulse* (ODPP) (Refs. 2, 3). Ideally, the droplet diameter should be approximately equal to that of the wire, which will give a controlled form of metal transfer and produce a stable process. As reported in the literature (Ref. 4), this type of transfer produces welds with minimal defects and spatter.

Obtaining this transfer mode is a function of setting the correct pulse parameters — peak current, background current, peak time and background time — as seen in Fig. 1. The peak and background times also define the pulse frequency (pulsing cycles per second) and duty cycle (percent of time at peak). In addition, the wire feed rate must be set correctly to match the burnoff rate that corresponds to the pulsing parameters. Determining which parameters will provide ODPP with a droplet diameter approximately equal to the wire diameter can be very time consuming and complicated. This is generally due to the complex nature of the interactions between the parameters and the use of trial and error in developing welding procedures. This work attempts to establish a systematic methodology for identifying the stable ODPP region for GMAW-P of aluminum. In this paper, metal transfer in 1.2-mm 4047 aluminum wire is analyzed and a method is presented for mapping the ODPP transfer region. Different transfer mechanisms will be discussed. An empirical model for obtaining one-drop-per-pulse conditions is presented.

KEY WORDS

Aluminum
Argon
Electrode
GMAW-P
Pulsed Current
Pulsed Globular
Pulsed Spray

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Background

Weld metal transfer from the electrode tip to the plate has been the subject of research for more than half a century. Lancaster (Ref. 5) as well as several other researchers have extensively reviewed gas metal arc welding (GMAW) metal transfer studies.

The "static force balance theory" and the "pinch instability theory" (Refs. 5–7) have formed the primary foundation of the modeling and analysis of metal transfer, although other theories have been presented (Ref. 6). The static force balance theory assumes that a droplet detaches when the net downward force exceeds the retaining forces. The pinch instability theory is based on the perturbation of a cylindrical liquid column. Neither approach fully explains experimental observations of metal transfer phenomena (Refs. 6–8).

Most of the previous work on metal transfer in GMAW-P has employed experimentation to establish when conditions of ODPP prevail. The main techniques used have been high-speed filming and analysis of current and voltage signals. Matsuda (Ref. 9) suggested that droplet detachment during the background current phase is optimal for arc stability and low heat input. Matsuda, *et al.* (Ref. 2), established the ODPP region for steel with several shielding gases. Allum, Amin and Rajasekharan (Refs. 10–12) have developed power law relations of the type $I_p^a T_p = C$ to characterize the ODPP region, where I_p is peak current, T_p is time at peak current, and a and c are experimentally determined constants. Jacobsen (Ref. 13) studied drop detachment in GMAW-P using a pendant drop. He found evidence for the existence of a recoil force of evaporating metal and established relations for minimum detachment time as a function of peak current for mild steel as

$$T_{dmin} I_p^{1.67} = 43 \quad \text{below 350 A} \qquad (1)$$

$$T_{dmin} I_p^{1.18} = 2.4 \quad \text{above 350 A} \qquad (2)$$

where T_{dmin} is the minimum detachment time.

Kim (Refs. 7, 14) studied GMAW-P of aluminum and steel and established the ODPP condition for steel. However, he did not establish the ODPP condition for aluminum. He found that the droplet size predicted by static force balance theory was closest to the experimentally determined values. Allum (Ref. 15) developed a power law model for GMAW-P using the instability approach and a 1.2-mm aluminum wire as

$$T_p I_p^{1.556} \cong 32\delta^{2.722} \qquad (3)$$

where δ is the factor accounting for tip geometry ≅ 0.8 (small drop).

He determined the effect of background current conditions and background time for a limited range of conditions, presenting an equation for droplet detachment during background phase as follows:

$$T_b \geq \frac{1.3\times10^{12} R_w^{3.278}}{I_b^{1.556}} \quad \text{for aluminum} \qquad (4)$$

where

I_b = background current
T_b = background time
R_w = radius of wire

To summarize, most of the previous work in GMAW-P has been on steel. Power law relations that do not account for the effect of background conditions have generally been used to characterize the ODPP region. While this omission is probably due to the desire to minimize background current and overall heat input, the effect of background current may be significant and should not be ignored. In this work, a model for ODPP transfer in 4047 aluminum was generated, taking into account the background conditions, which proved to be significant. The effect of pulse frequency and duty cycle on droplet transfer mode was also considered.

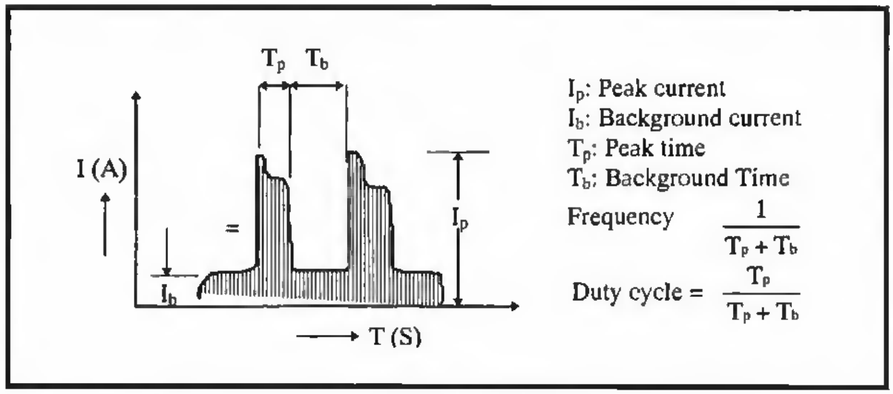

Fig. 1 — Pulsing parameters and calculation of area under current curve.

Table 1 — Pulse Parameter Range for Experiments

	Level 1	Level 2	Level 3
Peak current	250 A	325 A	400 A
Background current	50 A	100 A	150 A
Duty cycle	10%	25%	40%
Pulsing frequency	50 Hz	225 Hz	400 Hz

Table 2 — Design Matrix for Metal Transfer Experiments

Exp. No.	I_p (A)	I_b (A)	D (%)	F (Hz)	W (in./min)	Transfer
MT1	400	150	10	50	262	>ODPP
MT2	400	150	40	400	416	ODPP
MT3	325	50	10	225	130	<ODPP
MT4	325	150	10	50	252	>ODPP
MT5	400	50	25	400	240	<ODPP
MT6	250	100	10	50	198	>ODPP
MT7	400	50	10	50	155	>ODPP
MT8	400	50	40	400	315	>ODPP
MT9	325	50	25	50	205	>ODPP
MT10	400	100	10	400	198	>ODPP
MT11	400	100	40	50	345	>ODPP
MT12	250	150	10	400	255	<ODPP
MT13	250	50	10	400	135	<ODPP
MT14	250	150	40	50	328	>ODPP
MT15	250	100	40	400	295	ODPP
MT16	250	150	25	225	304	ODPP
MT17	250	50	40	50	220	>ODPP
MT18	320	55	20	150	190	ODPP
MT19	400	70	25	400	265	ODPP

where I_p = peak current, I_b = background current, D = duty cycle (% of time at peak), F = pulsing frequency, W = wire feed rate.

Experiments

A 4047 aluminum alloy welding wire with a 1.2-mm diameter was used in the experiments. High-speed filming at 2000 frames/s was used to characterize the metal transfer behavior. Experiments were carried out using a laser shadowgraph system. In this method, as described in detail in Ref. 16, a He-Ne laser acts as a backlight and is passed through a set of lenses and filters. In the process, almost all of the arc light is eliminated and a shadow of the drop and wire is captured by a high-speed camera. In order to study process behavior over the widest possible range with a minimum number of experiments, a statistical design of experiments (DOE) was done using D-Optimal design (Ref. 17). The range of parameters studied is shown in Table 1.

These four parameters at three levels resulted in 17 experimental runs, which are presented in Table 2. Screening experiments were performed initially to establish limits for the DOE. Data collected during these screening experiments were also used for analysis (MT18

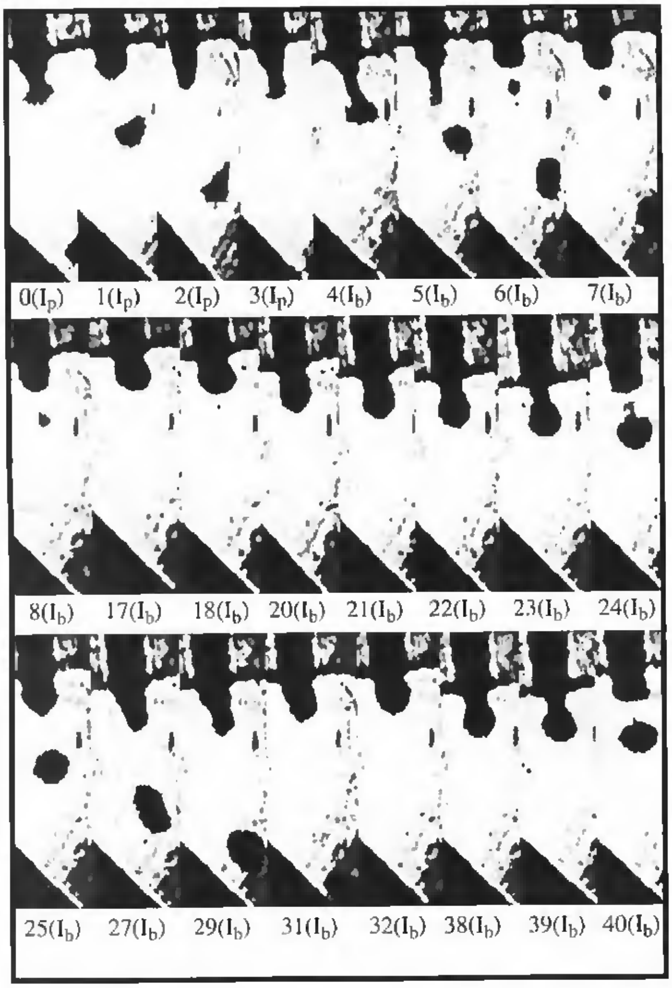

Fig. 2 — Experimental run MT1 showing multiple droplet detachments in one pulse cycle. 0.4 ms between frames. I_p: 400 A, I_b: 150 A, D: 10%, F: 50 Hz, W: 262 in./min.

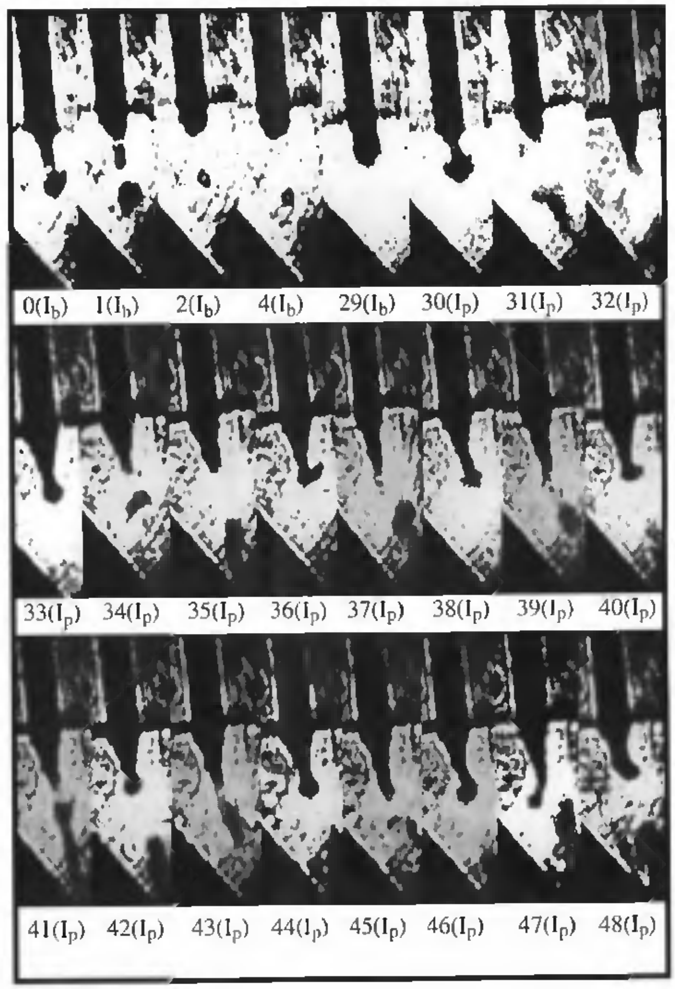

Fig. 3 — Experimental run MT11 showing multiple detachments in the peak phase. 0.4 ms between frames. I_p: 400 A, I_b: 100 A, D: 40%, F: 50 Hz, W: 345 in./min.

and MT19 in Table 2). All experiments were carried out with a tip-to-work distance of 15 mm, using pure argon as shielding gas at a flow rate of 30 ft^3/h. Preliminary wire feed rate was computed using earlier wire feed rate models (Refs. 5, 10, 18), which were then fine-tuned for each run to get stable transfer, without any short circuiting or meltback. This was established by looking for any short circuiting in the voltage signal, and verified by high-speed filming.

A series of images from the 16-mm film, corresponding to one pulse cycle for each experimental run, were digitized for measurement and analysis. Current and voltage signals were simultaneously recorded and synchronized with the camera for analysis. To make accurate calculations, the data were recorded at a 50-kHz sampling rate, and actual values of peak and background current every 20 μs during the pulse cycle were used for analysis.

The instantaneous values I_pT_p and I_bT_b were calculated from the area under the current curve, as given by Equations 5 and 6 and shown in Fig. 1.

$$I_pT_p = \int I_p(t)dt \quad (5)$$

$$I_bT_b = \int I_b(t)dt \quad (6)$$

$I_p(t)$ and $I_b(t)$ are the instantaneous values of current in the time interval, dt. The time interval in this case is the time between consecutive sampling points (0.02 ms).

Computing the I_pT_p and I_bT_b values in this way accounts for the effects of power supply behavior (*e.g.*, rise time, overshoot) minimizing the power-supply dependence of these results.

Results

Droplet Detachment Mechanisms

When considering droplet transfer in GMAW-P we can easily define three categories of metal transfer behavior:

1) More than one droplet per pulse.
2) Multiple pulses required for detachment.
3) One droplet per pulse (ODPP).

Each of these is considered below.

Multiple-Droplet Detachments Per Pulse

Several test conditions produced multiple-droplet detachments per pulse. These are denoted in Table 2 with ">ODPP" in the transfer column (e.g., MT1, MT4, MT9). Multiple-droplet detachments were observed in cases when the peak time was too long or when the background current was high and background time was long. Figure 2 shows images of experiment MT1. Under these conditions, drop detachment occurs in frame 1 (peak detachment), frame 5 (beginning of background), frame 24 (background detachment) and frame 40 (background detachment) with peak and background times of 2 ms and 18 ms. The high peak (400 A) and background currents (150 A), as well as long background time, result in multiple-drop detachments.

The acceleration of drops detached during the peak-current phase is very high, since the axial Lorentz force imparts considerable acceleration to the droplet (frames 0–2). In contrast, the drops detached in the background (frames 24 and 40) have a much lower acceleration, as should be expected. When the drop transfers to the weld pool, it imparts kinetic energy to a region local to the surface; this kinetic energy may be used in generating a cavity (Refs. 5, 19). The high-velocity droplets impact the weld pool with considerable momentum, which can result in greater penetration. The velocity of the droplets can influence the arc force, which is due to inertia of the droplets, the gas jet impinging on the weld pool surface, or both (Ref. 5). The droplet velocity also influences weld pool convective flow and penetration. Although background detachment is often recommended to minimize spatter (Ref. 9), peak detachment could be useful in heavier-section welds where higher penetration may be needed.

If the peak current is high and duration is long, streaming transfer will result as observed in Fig. 3. In this case, the pulsing frequency is low at 50 Hz. As a result, the peak time is 8 ms. At such high peak current levels (400 A), there is considerable tapering of the electrode and a streaming form of transfer results. This has also been reported by other researchers (Refs. 7, 14). Since streaming transfer can result in extensive spatter, these conditions are generally undesirable.

Figure 4 shows another case of streaming transfer that illustrates the role of the pinch instability theory in this transfer mechanism. The first drop is detached in frame 1, which is about the middle of the peak phase. In frames 2 and 3, the current is still in the peak phase and a new droplet begins to form. The tapering evident in frame 3 is similar to that seen during droplet formation in Fig. 3. In frame 4, the current drops to the background level of 50 A.

At the lower current level, the forming drop does not detach. Instead, the lateral displacement of the taper observed in frame 3 ceases. Jacobsen (Ref. 13) has postulated the existence of an evaporative recoil force that is much greater at high currents than at low, which may be the cause of the lateral displacement observed in this frame. In frames 4 and 5, a long pendant, liquid cylinder is clearly visible. In frames 6 and 7, the breakup of the liquid cylinder into multiple drops is observed. This classic example of Rayleigh instability behavior — when a thin liquid column is perturbed resulting in droplet detachment — illustrates why this mechanism does not completely explain ODPP spray transfer (Ref. 7), in which no liquid column forms.

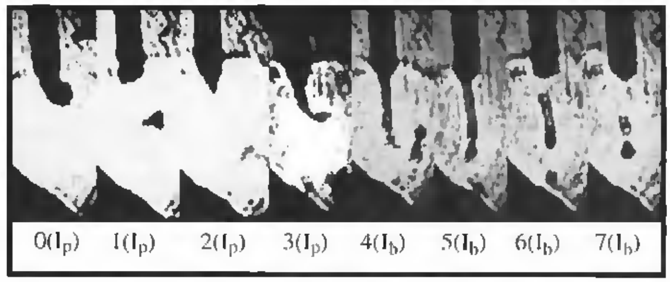

Fig. 4 — Metal transfer in MT7 showing instability and breakup of the liquid column due to transient current conditions. 0.4 ms between frames. I_p: 400 A, I_b: 50 A, D: 10%, F: 50 Hz, W: 155 in./min.

Multiple Pulses Required for Detachment

Under certain pulsing conditions, a globular form of transfer can be obtained, which occurred in experiments MT3 and MT13. The pulse parameters used for these runs are shown in Table 3.

This transfer mode will be referred to as *pulsed globular*. This type of transfer results when pulsing takes place at high frequencies and low background currents. In this case, the pulse duration is very small and there is not sufficient energy to detach a drop in each pulse. The drop keeps growing during each pulse cycle and the surface tension is the predominant force preventing transfer. Finally, a large globule detaches (primarily due to its own weight) as shown in Fig. 5, which illustrates a case of static force balance controlled metal transfer. This example also shows that the peak time must reach some minimum value to detach one drop every pulse. In these experiments, the minimum peak time that detached ODPP was 0.6 ms.

One Drop Per Pulse (ODPP)

As discussed earlier, it is desirable in GMAW-P to establish pulse parameters that provide ODPP transfer. Several empirical relations of the form $I_p^a T_p = C$ have been established by previous researchers, but the work was done at low background currents under the assumption that no melting occurs during the background-current phase. In this work, a wider range of pulse parameters was used, which might be found in a high-volume, thin-section welding application where high travel speeds and deposition rates are required. Because this can result in more melting during the background phase, simple power law models are not sufficient to define the ODPP condition. The welding parameters used in the five cases from the DOE and screening experiments that resulted in ODPP are given in Table 4.

Figure 6 shows the droplet transfer for condition MT16 (ODPP4). The transfer mode is pulsed spray, with the droplet approximately equal in diameter to the wire and with little or no tapering of the electrode observed.

Table 3 — Pulse Parameters Resulting in Pulsed Globular Transfer

	I_p (A)	I_b (A)	D (%)	F (Hz)	W (in./min)	T_p (ms)	T_b (ms)
MT3	325	50	10	225	130	0.4	4
MT13	250	50	10	400	135	0.25	2.25

Table 4 — Pulse Parameters Giving ODPP with Programmed and Measured Values

	I_p (A)	I_b (A)	T_p (ms)	T_b (ms)	I_pT_p (Programmed)	I_bT_b (Programmed)	I_pT_p (Actual)	I_bT_b (Actual)
ODPP1 (MT18)	320	55	1.3	5.3	416	291	410	277
ODPP2 (MT19)	400	70	0.6	1.9	240	133	276	100
ODPP3 (MT15)	250	100	1	1.5	250	150	337	120
ODPP4 (MT16)	250	150	1.1	3.3	275	495	397	459
ODPP5 (MT2)	400	150	1	1.5	400	225	470	175

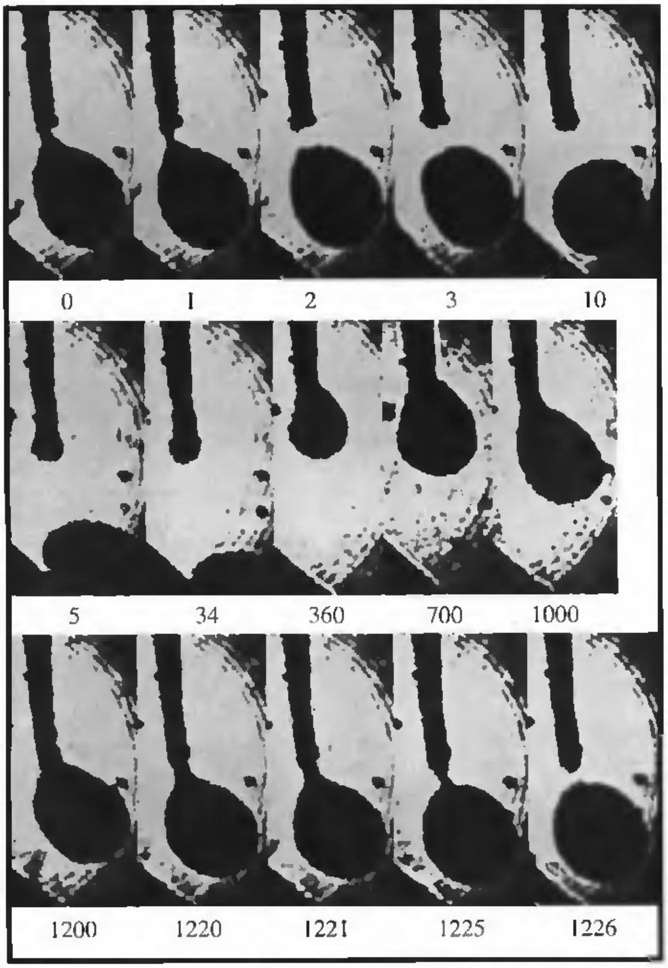

Fig. 5 — Droplet detachment in experiment MT13 showing globular droplet. 0.4 ms between frames. I_p: 250 A, I_b: 50, D: 10, F: 400, W: 135 in./min.

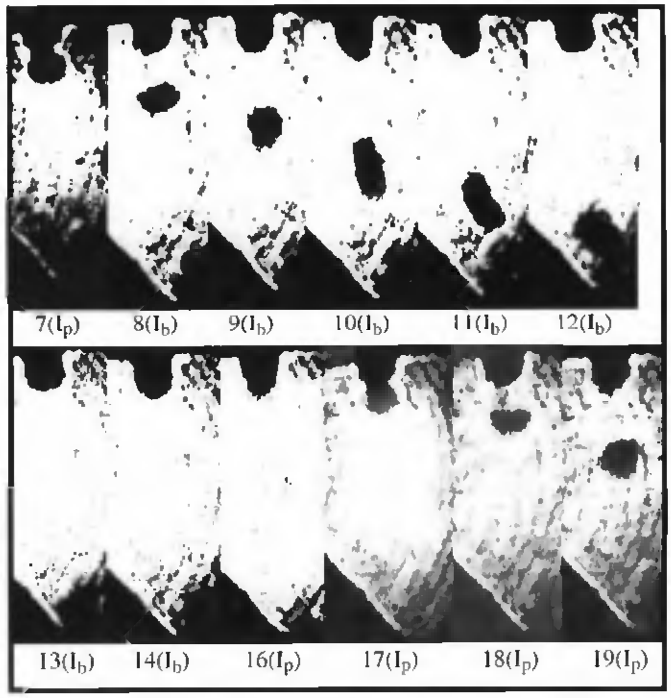

Fig. 6 — Droplet detachment for MT16 showing ODPP condition. 0.4 ms between frames. I_p: 250 A, I_b: 150 A, D: 25%, F: 225 Hz, W: 304 in./min.

Figure 7 plots the measured values of I_pT_p against I_bT_b and shows the operating region and the relationship between the pulse parameters that should be maintained to obtain ODPP transfer. In order to have a general equation that can conveniently describe the ODPP conditions, a combination of exponential and Lorentzian functions was fitted to the curve in Fig. 7. This function fit the data very well, as given by Equation 7:

$$I_pT_p = 496.1 * \left(1 - e^{-0.003 * I_bT_b}\right) + \frac{270.1}{\frac{(I_bT_b - 182.2)^2}{8423.5}} \quad (7)$$

Although it too is empirical in nature, this model differs from those used by previous authors in incorporating the effect of background conditions. Allum, Amin and Rajasekharan (Refs. 10–12, 15) present power law models that consider only the effect of peak energy, while Kim and Eagar (Ref. 14) consider drops/pulse as a function of pulse frequency and peak current, without reference to background conditions. The background current is usually kept low (below 50 A). Droplet transfer and melting rate can be significantly affected by the magnitude and duration of background current (Ref. 18). Our results show that background current and duration also play an important role in establishing ODPP conditions over a wide range of pulsing parameters — essential when it is necessary to obtain high melting rates. To achieve high droplet transfer frequency and still maintain ODPP, the background current must be increased. This is seen in experimental run MT2, which has a high background current (150 A) and resulted in the highest deposition rate. Figure 7 also shows the droplet diameters measured at the point of detachment for these conditions, with the droplet diameter increasing along the X-axis. Although both peak and background conditions are important over a wide range of parameters, the background conditions play an important role in controlling the droplet size, as noted in other works (Refs. 10, 15).

Two process regimes are observed in Fig. 7. The first three points on the graph are at a pulsing frequency of 400 Hz and at conditions $I_pT_p > I_bT_b$, which show that for high-droplet frequencies, the peak conditions predominate. The fourth and fifth points are at lower frequencies and the background conditions seen here are more significant, with the value of I_pT_p much closer to that of I_bT_b. Over the range of parameters studied in this work, when the pulsing conditions correspond to a point outside this curve, it results in more than one droplet per pulse or multiple pulses for detachment — Fig. 7. The limited nature of the statistically designed experiments makes it impossible to isolate the effects of frequency (of particular importance if time at peak current is short).

As noted previously that the minimum peak time to detach a droplet in these experiments was observed to be 0.6 ms. However, this equation defines the minimum peak time required for detachment as a function of the ratio of background conditions to I_p.

Transition from Pulsed Globular to Pulsed Spray Transfer

The transition from globular to spray transfer has been a widely researched topic in conventional arc welding (Refs. 7, 20, 21). This is of interest in GMAW-P as well, because it illustrates the role of pulsing frequency in metal transfer.

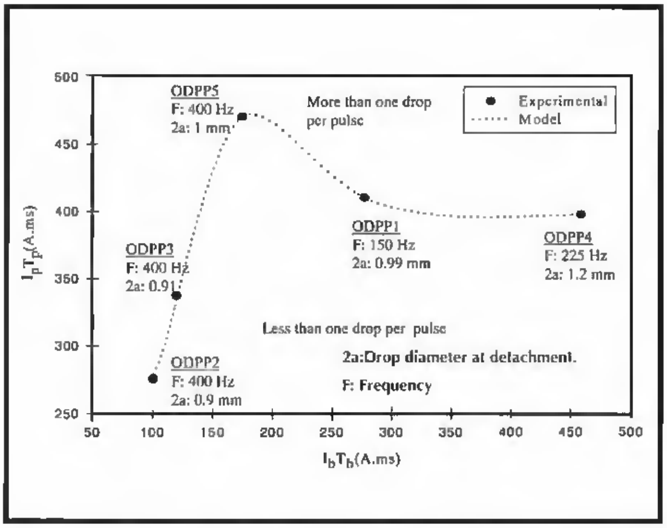

Fig. 7 — Operating region for one droplet per pulse.

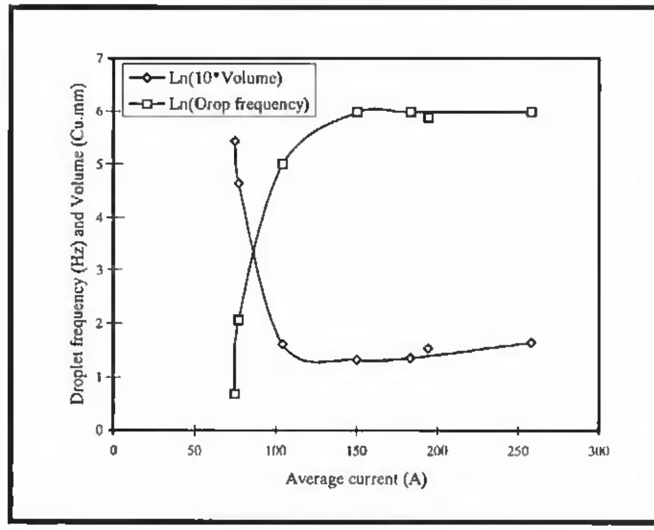

Fig. 8 — Relation between pulse parameters, droplet frequency and volume.

Figure 8 shows the pulsed-globular-to-pulsed-spray transition using droplet frequency and volume as indicators.

The average current shown in Fig. 8 is computed using Equation 8:

$$I_{av} = \left(I_pT_p + I_bT_b\right) / \left(T_p + T_b\right) \qquad (8)$$

The first two points are the pulsed-globular conditions and the remaining five points are conditions resulting in spray transfer with ODPP.

If T_p is less than T_{pmin} (the minimum time required to detach a droplet) due to high pulsing frequency, large droplets result — Fig. 5. However, when T_{pmin} is reached, a rapid transition to pulsed spray results, with droplet frequency equal to pulse frequency. This plot is analogous to the plot of Lesnewich (Ref. 20), which shows the transition current from globular to spray transfer for constant power GMAW in steel. Recently, several researchers (Refs. 7, 21) have indicated that the transition from globular to spray transfer may be more gradual than reported by Lesnewich (Ref. 20) and others. In our measurements, a relatively abrupt change between the pulsed globular and ODPP transfer modes is observed. The globular form of transfer, which is produced when a high pulsing frequency and small duty cycle are combined (as illustrated in Fig. 5), requires very specific conditions. When these conditions do not exist, a rapid transition to spray transfer at a high current occurs. The abruptness of the transition can be affected, to some extent, by selection of pulsing parameters.

Transition from Spray to Streaming Transfer

In general, this transition occurs in GMAW-P in a manner similar to that observed in nonpulsed GMAW. At high currents, electrode tapering begins, followed by elongation of the taper and a transition to formation of a stream of droplets (Ref. 22). Assuming the necessary peak current to produce the transition from spray to streaming exists, the primary effect of pulsing is the role of time at peak current, as controlled by pulse frequency and duty cycle. This is exemplified by Fig. 4 in which the transition from peak to background current — after formation of a taper but prior to detachment of a stream of droplets — led to the formation of a long pendant liquid column. This column broke up into a number of droplets, essentially suppressing the streaming transition. Had peak current been maintained for a longer period of time, continuous streaming would have occurred — Fig. 3.

Conclusions

These results show that by independently changing the pulse parameters, droplet formation and detachment in GMAW-P can be controlled. The pulse parameters can be adjusted to control the droplet transfer mode, heat input, droplet size or droplet velocities for different welding situations. This type of flexibility for process control is not possible with conventional GMAW.

ODPP conditions cannot be modeled comprehensively over a wide range of pulse parameters by simple power relations that consider only the peak conditions. An experimental approach is demonstrated, allowing the incorporation of peak and background conditions to achieve a broader model for obtaining ODPP.

The transition from pulsed-globular to pulsed-spray transfer has been characterized and found to be abrupt. Globular transfer during GMAW-P at peak currents of industrial significance (*i.e.*, peak current above spray transition at constant power) requires a very short time at peak current. When the minimum time at peak for spray transfer is increased, a sharp transition from pulsed-globular to pulsed-spray transfer occurs.

The role of frequency and duty cycle in GMAW-P of aluminum is primarily in controlling the droplet transfer mode, because time at peak current is critical.

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