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Arc voltage behavior in GMAW-P under different drop transfer modes

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Methodology of research

ABSTRACT

Purpose: Experimental measurements have been made to investigate meaning of the change in voltage for the pulse gas metal arc welding (GMAW-P) process operating under different drop transfer modes.
Design/methodology/approach: Welding experiments with different values of pulsing parameter and simultaneous recording of high speed camera pictures and welding signals (such as current and voltage) were used to identify different drop transfer modes in GMAW-P. The investigation is based on the synchronization of welding signals and high speed camera to study the behaviour of voltage signal under different drop transfer modes.
Findings: The results reveal that the welding arc is significantly affected by the molten droplet detachment. In fact, results indicate that sudden increase and drop in voltage just before and after the drop detachment can be used to characterize the voltage behaviour of different drop transfer mode in GMAW-P.
Research limitations/implications: The results show that voltage signal carry rich information about different drop transfer occurring in GMAW-P. Hence it's possible to detect different drop transfer modes. Future work should concentrate on development of filters for detection of different drop transfer modes.
Originality/value: Determination of drop transfer mode with GMAW-P is crucial for the appropriate selection of pulse welding parameters. As change in drop transfer mode results in poor weld quality in GMAW-P, so in order to estimate the working parameters and ensure stable GMAW-P understanding the voltage behaviour of different drop transfer modes in GMAW-P will be useful. However, in case of GMAW-P hardly any attempt is made to analyse the behaviour of voltage signal for different drop transfer modes. This paper analyses the voltage signal behaviour of different drop transfer modes for GMAW-P.
Keywords: Welding; Arc voltage; Drop transfer modes

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1. Introduction

Among the aluminum welding processes, automated GMAW-P has been recognized as an efficient alternative for minimizing defects [6, 10, 11, 13, 15]. In GMAW-P, droplets are regularly detached at a fixed frequency and directionally transferred to the workpiece under influence of current waveform (Fig. 1). Influence of the metal transfer mode on the weld quality is well known for the GMAW-P process. This makes attractive looking

GMAW-P sensitive to operating parameters. Shape of the current waveform dictates the type of metal transfer mode in GMAW-P. The basic waveform parameters for GMAW-P current include the background current I_b, peak current I_p, background time T_b, and peak time T_p.

Several sensors have been developed to detect metal transfer in GMAW. The most popular method to identify the metal transfer and instant at which it occurs is through arc sensing [24, 26,]. This system relies on detecting fluctuations in current and voltage and correlating it with metal transfer mode. The advantage of this method is the cheap cost [27]. High-speed cinematography employing back-lighting shadowgraph is also a common technique to observe dynamic metal transfer process [24]. Other sensors based on acoustic emission, arc light etc. have also been developed and investigated for its relationship with metal transfer mode [3, 21]. The problem with these type is corruption of signal due to background noise.

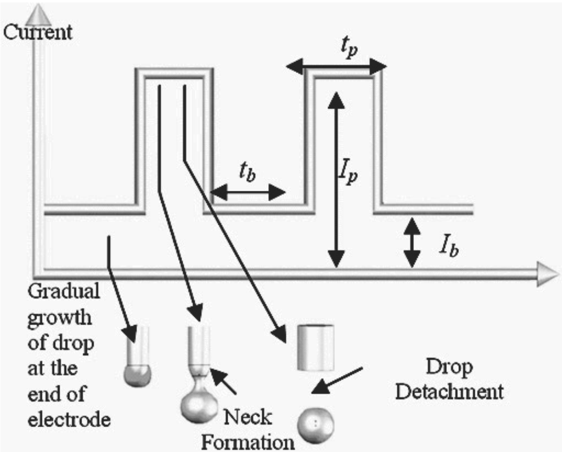


Fig. 1. Parameters of pulsed current waveform

Understanding influence of pulsing parameters dictating the current waveform on the metal transfer modes has been one of the major objects of several researches for a long time and a great number of works has been carried out with an objective of identifying and explaining the metal transfer mechanisms [25]. Most of the previous research in GMAW-P has used the experimentation technique to characterise, establish region of stable metal transfer and developed several static droplet detachment metal transfer mode [1, 2, 4, 8, 9, 12, 15, 19, 22, 27]. These models employ certain simplifications which result in discrepancies between the predicted and experimental results. Hence there is still gap in our knowledge preventing us from fully understanding the droplet dynamics especially for the newer materials like Aluminum [29].

Identification of the prevalent metal transfer modes in real time becomes important when the target is optimization and control of the GMAW-P process. Generally for automated system most robust and cheapest method for monitoring the metal transfer phenomena is through arc sensing. But success of this monitoring algorithm depends upon the knowledge of interaction between the drop transfer and voltage signal and understanding of the physical basis for the dynamics of droplet transfer.

This paper reports an experimental study to investigate the metal transfer process in GMAW-P and the subsequent assessment to understand the overall impact of droplet dynamics on the current and voltage signals with a reasonable accuracy. This was achieved by correlating precisely the welding arc electrical signals (arc current and voltage) with the droplet images recorded simultaneously in real time.

2. Experiments

2.1 Experimental setup

The experimental set-up used in this study is shown in Figure 2. Through-the-arc sensing of the welding current, arc voltage and high speed imaging of the droplet transfer are assembled in conjunction with each other to study the influence of the pulse current waveform on the metal transfer process during GMAW-P. The experimental setup consisted of a pulsed type inverter controlled GMAW power source with constant current characteristics, automated welding system with 3-axis servo motors and controllers, sensors for measuring actual welding current and voltage signals, A/D converter, high speed camera with 10000 frames/s performance and xenon lamp along with set of lenses and filters was used as light source to provide back light for high-speed filming.

Table 1.
Experimental design plan

Levels	1	2	3	4
Peak Current (A)	220	250	280	310
Base Current (A)	40	50	60	70
Peak Time (ms)	2	4	6	8
Base Time (ms)	10	16	22	28

Experiments were carried out using the principle of back-light high speed xenon lamp cinematography which was synchronized with data acquisition system. A high-speed video camera was used to acquire the images of the droplets. The images acquired by the high-speed video camera were transferred in the form of video signal to the computer for analysis. The backlight was projected by the xenon lamp after passing through a set of lenses and filters towards the droplet/wire system. Light blocked by the droplet/wire will not reach the lens. So 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. The advantage of xenon lamp over laser light is lower cost and its larger light spot makes it possible to capture the images of both droplet/wire system and arc. Also diffused xenon lamp illumination needs to be focussed over a small region by passing it directly through a mild steel sheet cylinder. The arc voltage was measured between the contact tip of the welding gun and the fixture. This allowed voltage measurements as close to the arc as possible to most accurately measure the arc voltage. The welding current was measured with a Hall sensor, which was attached to the earth cable. A data acquisition card in combination with a laptop personal computer was used to acquire voltage and current signals alsong with high speed camera pictures. The sampling rate was 10 kHz. The noise on the signals was removed by a digital low pass filter with a 200 Hz cut-off frequency.

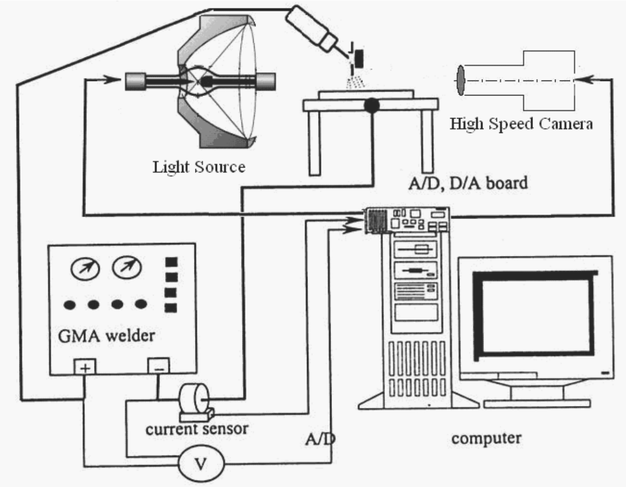


Fig. 2. Schematic diagram of experimental setup

The data acquisition system measurements were compared to a calibrated digital oscilloscope. Several measurements were taken and synchronised with both the oscilloscope and the data acquistion system, and subsequently compared. The waveform signals were collected during a 2 s period after 10 s elapsed from the start of welding.

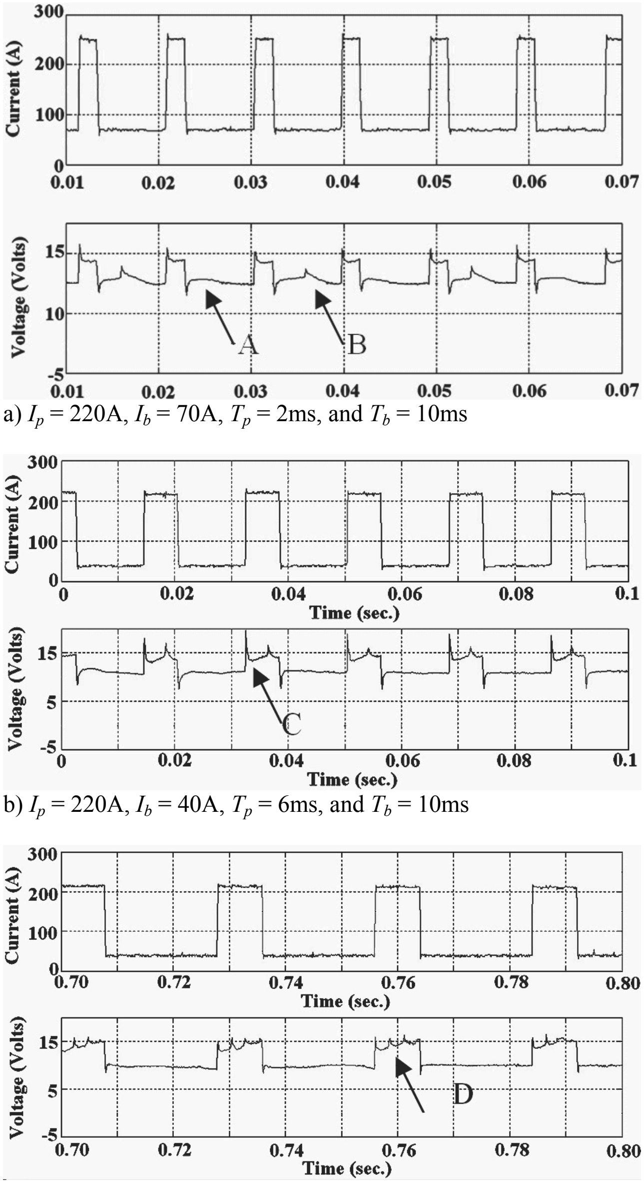
2.2. Welding conditions

Bead on plate welds were made in the flat position using an inverter controlled GMAW power source. Welds were made in the constant current mode. The filler material used was a 4047 aluminum alloy welding wire with a 1.2 mm diameter. The base material was 6061 aluminum alloy with a thickness of 6 mm. The shielding gas used throughout the experiments was pure argon with a gas flow rate of 20 L/min. Contact tip to workpiece distance (CTWD) and speed was kept constant through out the experiments. The values of CTWD and speed used for all the experiments were 20 mm and 4 mm/s. Table 1 shows the setting conditions of pulsing parameters used for the experimentation. Figure 3 shows typical waveforms of welding current and voltage for different metal transfer modes.

3. Results and discussions

The welding current and voltage as a function of time, corresponding to three different drop transfer modes namely one droplet per multiple pulses (ODMP), one drop per pulse (ODPP) and spray or multiple drops per pulse (MDPP) respectively are compared with each other in Figure 3. The measurements were made using 4047 aluminum alloy welding wire with 1.2 mm diameter at wire feed rate of 4 m/min under different pulsing conditions.

Based on Figure 3 it can be concluded that both current and voltage signals have a repetitive fluctuating pulsing format and appears to be noisy in general. They also appear to mimic different metal transfer modes by varying in a very distinct manner for different drop transfer modes. At first instance, it seems difficult to understand the exact behaviour of the different characteristics signals in conjunction with metal transfer modes observed. But careful investigation by correlating the welding signals and high speed camera reveal ample information that can be used to classify different types of drop transfer modes occurring in GMAW-P system based on the voltage and current signals.



a) I_p = 220A, I_b = 70A, T_p = 2ms, and T_b = 10ms

b) I_p = 220A, I_b = 40A, T_p = 6ms, and T_b = 10ms

c) I_p = 220A, I_b = 40A, T_p = 8ms, and T_b = 22ms

Fig. 3. Typical welding current (top) and voltage (bottom) as functions of time for different drop transfer modes, namely (a) ODMP, (b) ODPP, and (c) MDPP

One drop per multiple pulses (ODMP) waveform is characterized by two regions namely A, and B which occur successively one after the other throughout the voltage waveform and each region has frequency less than frequency of the pulse waveform. These regions are shown in Figure 3(a). Region A is characterized by almost constant voltage except for one instance where sudden increase in voltage is observed where as Region B is characterized by almost constant voltage except for two instances where sudden increase in voltage is observed.

One drop per pulse (ODPP) waveform is characterized by one region namely C, which occur periodically with every pulse and has same frequency as the pulse waveform and droplet transfer frequency. This is a key characteristic of the ODPP metal transfer mode. This region is shown in Figure 3(b). The regularity of the fluctuations suggests that the size and the process of each individual droplet transferred in this mode are relatively steady. Region C is characterized by almost constant voltage except for two instances where sudden increase in voltage is observed.

Multiple drops per pulse (MPPP) waveform is characterized by one region namely D (as shown in Figure 3(c)) which occur periodically with every pulse and has same frequency as the pulse waveform. This corresponds to a high frequency but smaller sized multiple drops with a more or less constant arc length. Region D is characterized by almost constant voltage except for multiple instances where sudden increase in voltage is observed.

For all the drop transfer modes, arc length variation was observed just before and after the droplet detachment. Also current waveform appears to have very low frequency components. The possible reason for this behavior is that the inductance of the power supply has limited and smoothed the change in the current as the welding power source is operating in the constant current mode.

3.1. Drop transfer characteristics in ODPP Online Signal

Lower peak time generally results in ODPP drop transfer mode and as a result droplet detachment is generally observed at the end of the peak time as seen in the Figure 3(b). Hence it is difficult to explain the influence of droplet travel on welding arc. So ODPP droplet detachment during the base current (see Figure 4) has been specifically selected to explain the influence of droplet detachment and travel on the voltage signal in region C. Figure 4 gives a generalised picture of ODPP phenomenon in GMAW-P process using the synchronized images of the high speed camera pictures with voltage and current waveform during ODPP mode and region C. Based on the evidence of electrical signals for unit period of fluctuation together with high speed camera pictures as shown in Figure 4, one can conclude that one droplet detach every pulse. Also as Region C repeats itself through out the pulse structure suggests that the droplets are all transferred in a very similar fashion which is ODPP. Figure 4 also reveals rich information about the influence of droplet formation, necking, detachment and travel on the welding arc.

During the starting phase of the base time or droplet growth, only a small amount of the liquid metal melts and assumes hemispherical shape at the tip of the electrode wire. As a result surface tension acting on the liquid metal is much higher compared to electromagnetic force due to small current densities. The droplet at the end of the electrode steadily grows during this phase as seen in the high speed camera pictures of the region C marked in Figure 4. As droplet reaches sufficient size, the current is changed to higher peak value which corresponds to the start of the region C. First sudden increase in voltage is observed in the starting of region C (or starting of the peak phase of the pulse) and corresponds to the power supply dynamics which occurs due to need for faster response in the form of overshooting of actual programmed values which are current and voltage [20].

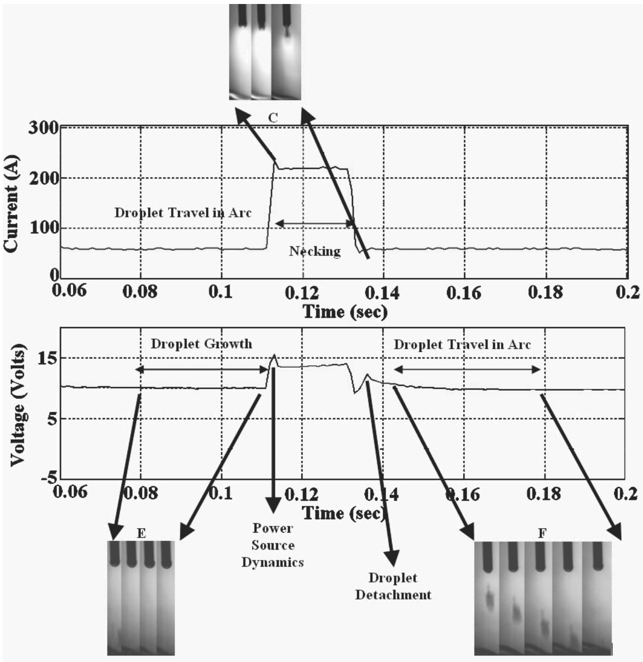


Fig. 4. Synchronized images of high speed camera pictures with arc current and voltage waveform for ODPP [17]

As seen clearly in the high speed camera pictures of region C in Figure 4, this sudden increase in voltage does not result in any detachment and from this point onwards necking of the droplet begins because of higher current in the welding system.

It is well known that a current-carrying conductor establishes a magnetic field around the conductor. Hence, by pulsing the welding current, magnetic forces may be used to detach drops from the electrode. In the liquid drop at the tip of the electrode with moderate and high welding current, the longitudinal component of electromagnetic force (commonly referred to as Lorentz force) acts as a detaching force which removes liquid metal away from the neck region of the droplet promoting droplet detachment [7].

Second sudden increase in voltage occurs just before the droplet detachment due to necking at the solid-liquid interface. It is observed as a small rise in the arc voltage, probably due to the increased electrical resistance of the droplet neck just before separation [14] and sudden reduction in arc length due to elongation of the droplet.

Droplet detachment event can be seen on voltage curve by sudden drop in voltage as shown in Figure 4. Droplet detachment event is characterized by drop in voltage due to sudden increase in arc length just after the droplet detachment and simple recovery from the necking effect. However sometimes droplet dynamics at the end of the electrode just after the droplet detachment may cause the voltage drop during droplet detachment to exceed the voltage rise due to necking in the opposite direction. The reason for this behaviour is that sometime just after the droplet has detached, small amount of liquid metal still remains at the tip of the wire, and unbalanced surface tension force causes the remaining liquid to recoil and oscillate on the wire tip causing small additional voltage drop [23].

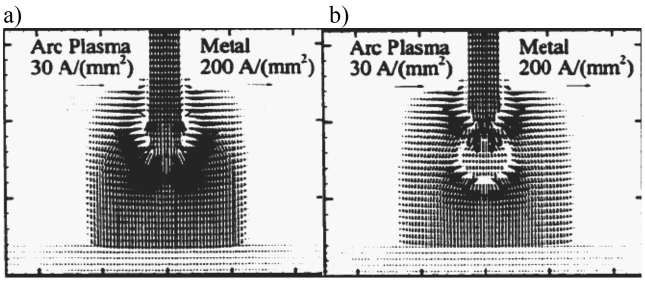


Fig. 5. Current density distribution in the welding arc: (a) Start of the melting process, and (b) Just after droplet detachment (or at the start of the droplet travel) [28]

Droplet travel in the welding arc is characterized by almost constant voltage. General distribution of the current density in the welding arc is uniform, originates from the electrode tip following a fan like distribution and converges in the form of a circle on the base metal as shown in the Figure 5(a). Since the droplet size is close to electrode diameter, as a result the size of the droplet is expected to have some influence on the arc. Especially the distortion is most serious when the droplet is near the electrode as shown in the Figure 5(b). In presence of droplet in the welding arc, the current flow pattern is first in to the droplet and then from droplet in to the base metal in the form of fan distribution again as shown in Figure 5(b). Based on the comparison of current distributions in Figure 5(a) and (b) during droplet formation and travel, one can conclude that though the arc plasma are very different but the outer shapes of the arc plasma are identical [28]. Also there is always a minimum in the electric potential in different cathode sport curves which corresponds to the lowest energy consumption by the system as the optimum value [5]. Hence droplet travel in the welding arc is characterized by almost constant voltage.

3.2. Drop transfer characteristics in MDPP Online Signal

As discussed above, MDPP mode has certain characteristics features in the region D, and this region has same frequency as the pulse waveform. Synchronized images of high speed camera pictures with voltage and current waveform during MDPP mode and region D represented in Figure 3(c) is shown in Figure 6.

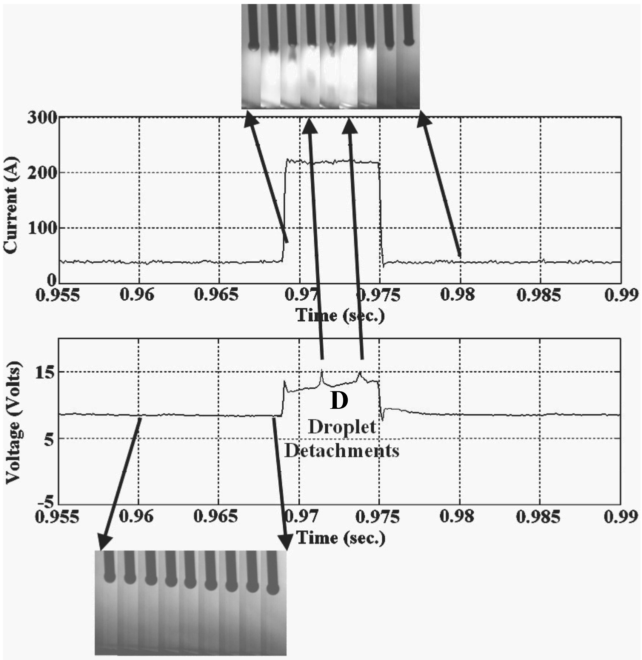


Fig. 6. Synchronized images of high speed camera pictures with arc current and voltage waveform for MDPP

Carefully correlating the welding arc signals (arc current and voltage) with high speed camera pictures reveal that multiple droplets detach in region D which has same frequency as pulse waveform. The regular occurrence of Region D through out the pulse suggests that the droplets are all transferred in a very similar fashion. The influence of droplet formation, necking, detachment and travel on the welding arc are similar to ODPP which has been explained earlier in section 3.1. Droplet detachment instances of droplets have been marked in Figure 6 showing synchronized droplet images together with arc voltage and current signal at corresponding times. The images selected give a generalised picture of the MDPP phenomenon in GMAW-P. Based on the evidence of high speed camera in Figure 6, we can conclude that multiple drop detaches during MDPP after passing of single pulse, but have a regular fashion corresponding to number of droplet detachments. In MDPP mode, frequency of detachments (which are recorded as sudden increase in the voltage signal) always exceed the frequency of the waveform pulses.

3.3. Drop transfer characteristics in ODMP Online Signal

As discussed above, ODMP mode has certain characteristics features in the region A and B, and this region has less frequency than that of the pulse waveform. Synchronized images of high speed camera pictures with voltage and current waveform during ODMP mode and regions A and B are represented in Figure 3(b) is shown in Figure 7. Carefully correlating the welding arc signals (arc current and voltage) with high speed camera pictures reveal that one droplet detaches for every two pulses in region B which has lesser frequency compared to frequency of pulse waveform. The regular occurrence of Region B through out the pulse suggests that the droplets are all transferred in a very similar fashion. The influence of droplet formation, necking, detachment and travel on the welding arc are very similar to ODPP which has been explained earlier in section 3.1. Droplet detachment instance have been marked in Figure 7 showing synchronized droplet images together with arc voltage signal at corresponding times. The images selected give a generalised picture of the ODMP phenomenon in GMAW-P. Based on the evidence of high speed camera in Figure 7, we can conclude that one droplet detach during ODMP after passing of two pulses, but have a regular fashion corresponding to number of droplet detachments. In MDPP mode, frequency of detachments (which are recorded as sudden increase in the voltage signal) will always be less than the frequency of the waveform pulses.

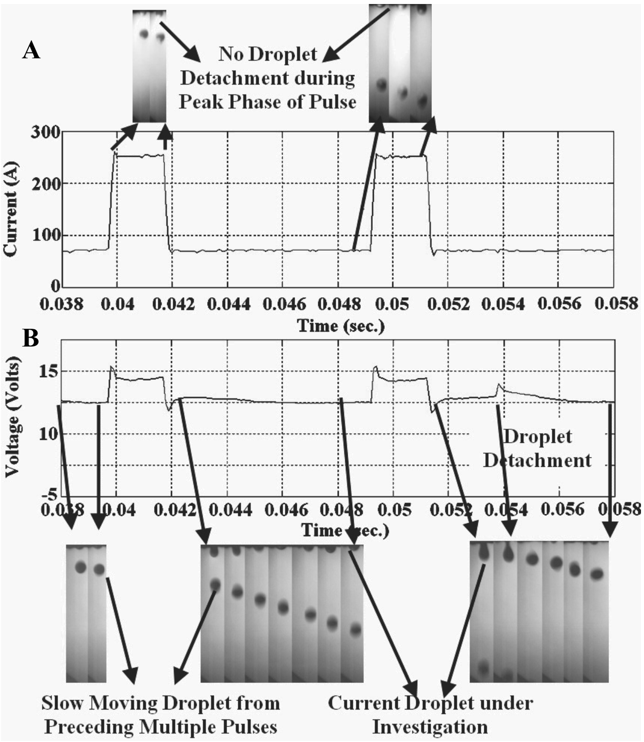


Fig. 7. Synchronized images of high speed camera pictures with arc current and voltage waveform for MDPP

4. Summary and conclusions

In this work, online signals for different metal transfer modes in GMAW-P have been reported. Attempt has been made to correlate the drop dynamics and electrical characteristics for understanding the behaviour of the welding electrical signals during the several phases of the metal transfer. Based on the investigation reported in this work, it can be concluded that detectable differences were found in the welding voltage for detecting droplet detachment and different metal transfer modes.

Results suggest that different stages of metal transfer in GMAW-P influence voltage signal in different ways. The welding arc is regular and short term variations in the voltage signal occurs regularly corresponding to the droplet detachment as a result of sudden change in the arc length just before and after droplet detachment. Frequency of the pulse waveform was found to have a fixed relation with the number of droplet detachments or number of instances of sudden rise in the voltage. Frequency of the pulse waveform was found to be smaller, equal and exceed the frequency of droplet detachment for ODMP, ODPP and MDPP.

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