Active Metal Transfer Control by Monitoring Excited Droplet Oscillation

Downward momentum of the oscillated droplet is employed to enhance droplet detachment and detachment controllability.

BY Y. M. ZHANG, LIGUO E AND R. KOVACEVIC

ABSTRACT. Controlled metal transfer implies controllable heat and mass inputs and improved weld quality. Success of previous methods has been hindered by uncertainty in droplet detachment. In the proposed approach, an oscillation of the droplet is excited by switching the current from a peak level to a base level to initiate an active detachment period. The droplet oscillation is then monitored. When the droplet moves downward, the current is switched back to the peak level, which creates an ejection action and concludes the active detachment period. The droplet is detached by downward momentum and the increased current-induced electromagnetic force. Growth period of the succeeding cycle begins. The utilization of downward momentum eliminates the need for a very high current to detach the droplet, which is conventionally used in pulsed gas metal arc welding (GMAW-P). This elimination guarantees that no unexpected detachment occurs during the growth period. Also, reliable high-frame rate vision monitoring of the oscillating droplet guarantees that downward momentum will correspond with the ejection action. Hence, the metal transfer process can be precisely controlled. Experimentation has been conducted to demonstrate the effectiveness of the proposed approach in achieving the desired metal transfer process.

Introduction

Gas metal arc welding (GMAW) is the most widely used arc welding process. In comparison with gas tungsten arc welding (GTAW), GMAW has a much higher productivity. This higher productivity is attributed to its consumable electrode. As the electrode melts, a droplet develops at the end of the electrode until detaching and transferring to the weld pool. This process — referred to as metal transfer process — plays a significant role in determining the arc stability and weld quality. The control of this process historically has been an active research area in welding (Refs. 1–4).

Droplets transfer to the weld pool in three major distinct modes: short-circuiting, globular and spray (Ref. 5). Spray transfer can be further classified as drop (projected) spray and streaming spray based on drop size. (The diameter of the drop is approximately equal to the diameter of the electrode in drop spray or much smaller in streaming spray.) When welding current is small and/or arc length is short, the droplet may not be detached until it contacts the pool, resulting in short-circuiting transfer. If the current increases but is not large enough to generate sufficient electromagnetic force to detach the droplet, the droplet may surpass the electrode wire and be detached mainly by gravity. The resultant transfer is globular. When the current further increases to the level higher than the so-called transition current (Ref. 6), transfer will become drop or streaming spray.

Streaming spray is characterized by its directional transfer of droplets. Because droplets are very small in size and transfer frequency is very high, arc length does not change significantly during welding. The resultant welding process is very stable. However, high-speed impact of droplets may produce finger-shaped penetration, which is associated with poor mechanical properties (Ref. 7). In globular transfer, instability, spatters and a broad weld pool can always be expected. Hence, its application in production is rare. On the other hand, drop spray is generally characterized by uniform droplet size, regular detachment, directional droplet transfer and insignificant spatters; thus, it is often the preferred process (Refs. 4–8). However, the current range for generating drop spray is very narrow and varies with many welding conditions, *i.e.*, electrode material, electrode diameter, shielding gas and electrode extension (Refs. 9–10). The narrow range generates two problems:

1) The current and heat input associated with drop spray are too high to apply to thin-sectioned or heat-sensitive materials.

2) Because the narrow range is dependent upon welding conditions, drop spray may not be guaranteed by using pre-selected welding parameters.

Previous Efforts and Their Analyses

Pulsed GMAW

In an effort to solve the above two problems, pulsed current has been used (Refs. 3, 8–13). In GMAW-P, a low base current is used to keep the arc on and a higher peak current is used to melt the electrode and detach the droplet. Hence,

KEY WORDS
Beneficial Amplitude
Detachment
Droplet Oscillation
Ejection Level
GMAW-P
High-Frame Rate Vision Monitoring
Metal Transfer Process

Y. M. ZHANG and LIGUO E are with the Welding Research and Development Laboratory, Center for Robotics and Manufacturing Systems, University of Kentucky, and R. KOVACEVIC is with Southern Methodist University.

average current and heat input can be lowered so that the high-heat input problem can be resolved. However, the second problem is much more difficult. A solution to this problem in GMAW-P is to produce one and only one drop per pulse, called one-drop-per-pulse (ODPP) (Refs. 11–13), by properly selecting the duration of the peak current. To guarantee the detachment, *i.e.*, to avoid one-droplet-multiple-pulses (ODMP), the peak current must be larger than the transition current (Ref. 13). At such a high current, droplets can form and transfer very quickly. The range of the peak current duration for generating ODPP is therefore narrow. If the duration of the peak-current period is longer, multiple drops may be detached in a single pulse (Ref. 14), resulting in a streaming spray transfer. Or, if the duration is shorter, ODMP may occur (Ref. 11). Optimal peak-current duration depends upon welding parameters and conditions. To determine the optimal peak-current duration, studies have been conducted to experimentally correlate wire feed speed, peak-current level, peak-current duration, base-current level and base-current duration for given electrode material, electrode wire diameter and composition of shielding gas (Refs. 11–13). However, because of the narrowness of the optimal range and its dependence upon welding conditions, such an open-loop selection of the duration is often not robust with respect to welding parameters and conditions.

The above intuitive observation can be supported by a more detailed analysis. In fact, in GMAW-P, a droplet keeps growing as the electrode is melted during peak-current period. The change in droplet volume and gravity cause both geometry and mechanics of the droplet to change gradually. Before the droplet detaches, detaching force and retaining force are balanced. For given material and diameter of the electrode, maximum surface tension, the major retaining force generated at the interface between the solid wire and the melted droplet, is fixed. When the surface tension required to balance the increasing detaching force exceeds this maximum, the droplet detaches. Hence, the detachment of the droplet in conventional GMAW-P is a natural result of progressive development of force balance. Also, both detaching and retaining forces are dependent upon many welding parameters and conditions difficult to accurately control during welding. Hence, the progressive nature of force balance in GMAW-P causes the detachment instant to vary with welding parameters and conditions.

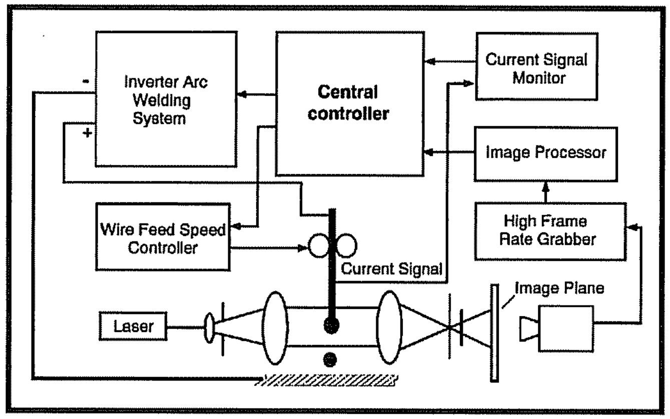

Fig. 1 — Experimental setup.

The detachment instant of an individual droplet influences the development of droplets in succeeding cycles. Such influence is accumulated. If welding parameters and conditions vary so that the volume of the detached droplet is smaller than the volume melted in a cycle, the detachment instant will shift toward the front edge of the peak current pulse. Accumulated effect will finally result in two droplets detached in some single-peak duration. Otherwise, if the volume of the detached droplet is larger than the volume melted in a cycle, some cycles may have no drops at all.

Detachment Detection

If the detachment instant can be detected, welding current may be switched to the base current after detachment to prevent multiple drops in a single pulse. Based on this idea, arc voltage and welding current have been sensed to detect the detachment instant (Refs. 15–18). Audio emissions caused by the arc jump from the tip to the root of the droplet have also been used (Ref. 16). To acquire a more reliable signal, Wang and Li (Ref. 19) welded mild steel using a mixed shielding gas (85%Ar and 15%CO_2) and aluminum using pure argon. It was found that the arc root on the pendent droplet forms a metal vapor source emitting arc light. When the neck breaks, the arc root covering the pendent droplet extinguishes instantaneously and promptly "jumps" onto the new tip of the electrode wire. This change decreases the arc emission flux significantly. After the detachment of the droplet, arc root spreads on the electrode tip and arc light flux in-

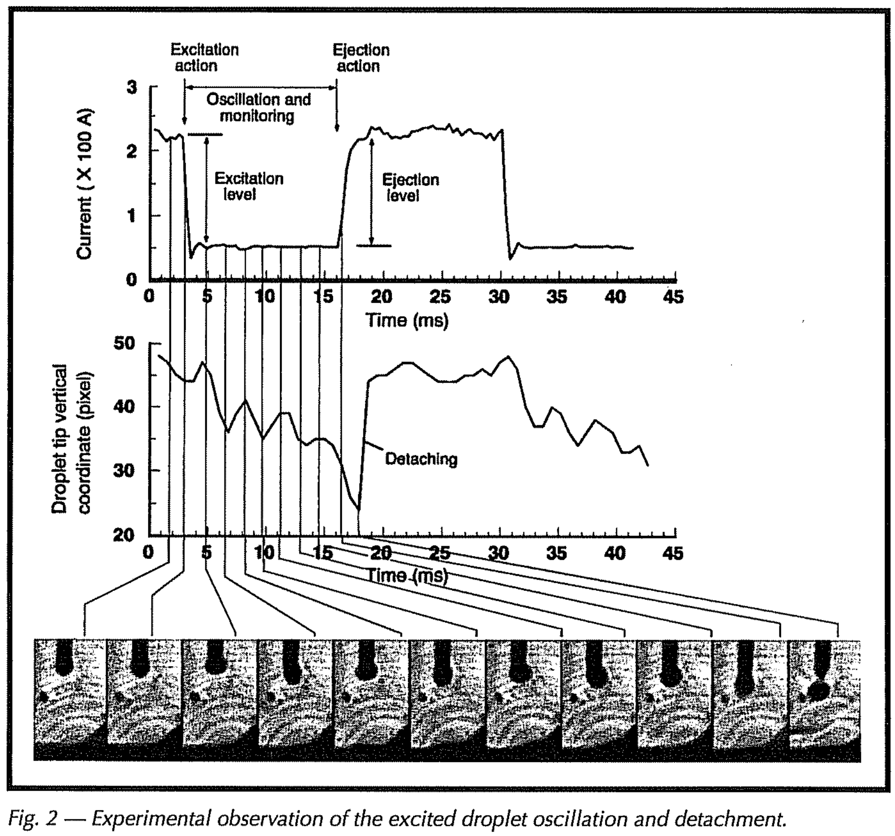

Fig. 2 — Experimental observation of the excited droplet oscillation and detachment.

creases. Based on this phenomenon, arc light flux variation has been used as a signal to detect the detachment.

Although these methods can obtain ODPP, detachment instant and droplet size are variable. In the present work, an approach will be proposed to achieve ODPP with controlled detachment instant and droplet size.

Experimental Setup and Conditions

The experimental setup is shown in Fig. 1. The power supply is an inverter arc power source. This power supply can be used for either constant current (CC) or constant voltage (CV) mode. In this work, CC mode is used.

Mild steel electrode wire is used. The diameter is 1.2 mm (0.045 in). Pure argon and 95%Ar + 5%CO_2 have been used as shielding gas. The arc voltage levels are 25 V for pure argon and 30.5 V for 95%Ar + 5%CO_2. Peak current is about 220 A, lower than the transition current, and base current is about 50 A.

The high-frame rate imaging system shown in Fig. 1 will be used to monitor the motion of the droplet during experiments. (High-speed photo cameras have been used to film the metal transfer process [Refs. 20–22] for off-line analysis.) Resolution of the high-frame rate camera used is 128 × 128, but 800 frames of images are outputted from the camera in a second as video signal for on-line computer analysis. The laser is projected by the left lens to travel toward the droplet/wire and then the image plane (Fig. 1) as a set of parallel lights. Lights blocked by the droplet/wire will not reach the right lens and the image plane. The rest of the laser lights will illuminate the image plane and be viewed by the camera. It is known that the intensity of arc light quickly decays as the travel distance increases. If the distance from the arc to the right lens is sufficient, the arc light will be weaker than the parallel laser lights on the image plane. Consequently, the camera can image the geometry of the droplet and wire. This method is referred to as *laser back-lighting technique* (Ref. 21). An image-processing algorithm has been developed to analyze the image in real time (Refs. 23, 24).

Proposed Approach

Principle

When the welding current is suddenly changed, an oscillation will be excited on the droplet at the electrode tip. This oscillation is referred to as *excited oscillation of droplet:* In Fig. 2, the current is about 220 A before it is switched to 50 A. Recorded vertical coordinates of the droplet tip given in the figure are obtained by the high-frame rate imaging system. Before the current is switched, no significant oscillation is observed. After the current is switched, oscillation occurs.

In the proposed approach, a pulse cycle is divided into two periods: growth period and detachment period. In the growth period, a current waveform, which is designed based on the desired average current and is below the transition current, is used. When the growth period ends, current is switched to the base level and the process enters the detachment period (at t = 3 ms in Fig. 2). As shown by the vertical coordinates of droplet tip (Fig. 2), the sudden change in welding current causes the droplet to oscillate vertically. When the droplet moves down, the current is changed back to a normal level (at t = 16 ms in Fig. 2). The increased electromagnetic force and downward momentum detach the droplet. Hence, the proposed approach utilizes the mechanical momentum to reduce the level of electromagnetic force required for droplet detachment so that high current can be avoided.

The elimination of the use of high current not only reduces superheating-related fumes and material property damage, large drop initial speed caused high-speed impacts and resultant spatters, and burning-through of thin-sectioned materials; it also resolves the problem of detachment irregularity associated with previous methods. In fact, in conventional GMAW-P, peak current must be larger than the transition current to guarantee that droplets be naturally detached with a size similar to the diameter of electrode. However, in the proposed approach, detachment of the droplet is not a natural transition. The droplet is detached by an active control action. Hence, the current can be lower than the transition current. Under this current, a natural detachment can occur only when the droplet is significantly larger than the diameter of the electrode. In our case, the increase of the droplet is controlled by the used current level and growth duration. Hence, no unexpected detachment could occur.

Note that mechanical oscillation has been used to control metal transfer (Ref 4). In that case, oscillation is generated by a mechanical approach. The droplet is detached during the oscillation. The periodical detachment is a result of a forced periodical oscillation. In the proposed approach, oscillation is generated electrically. Also, detachment is caused by an electrical action and is a result of mechanical momentum and electromagnetic force combined.

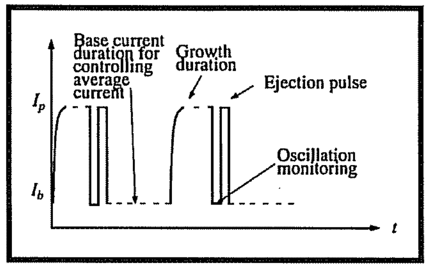

Fig. 3 — Heat input control.

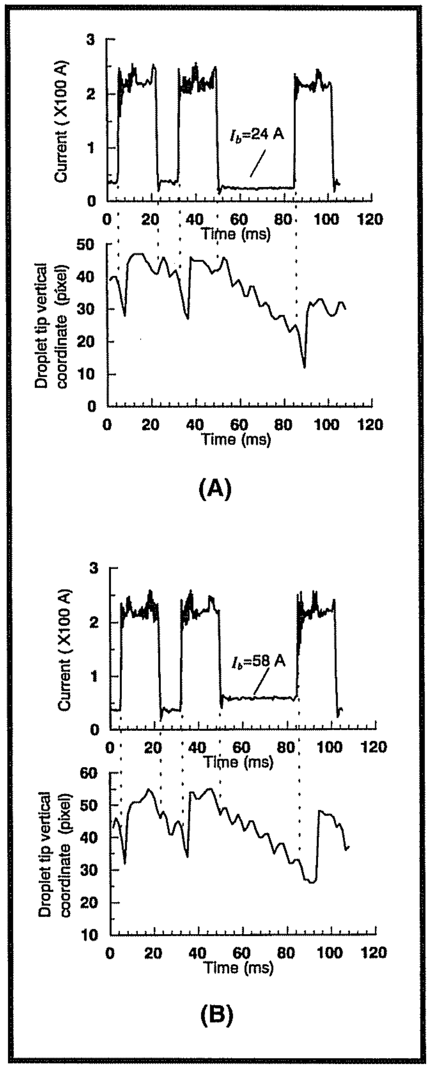

Fig. 4 — Independence of droplet oscillation frequency on the excitation level. A — With higher excitation level, about 180 A; B — with one lower excitation level, about 150 A.

Current Control

The proposed approach must be able to be implemented at different current, or heat input, levels to meet the requirement from a wide spectrum of applications. To this end, a specific waveform of the current as shown in Fig. 3 (*i.e.*, inserting a duration of base level current after detachment) can be used to control the average current. The insertion of base level current will divide the peak current duration into two periods: the ejection pulse and the succeeding growth period. To avoid a sudden increase in the detaching force, transition of the current from the inserted period to the succeeding growth period can be smoothed using a pre-set waveform — Fig. 3.

The current waveform in Fig. 3 will be used to achieve ODPP transfer in control experiments.

Monitoring of Excited Oscillation

To synchronize the ejection pulse and oscillation phase, the excited oscillation of the droplet must be precisely monitored in real time. The high-frame rate camera system has been used to monitor the droplet oscillation with a 15 mm^2 field of view. The corresponding resolution is 0.12 mm. It can be seen from the images given in this work that the resolution of the camera is sufficient to extract the geometrical parameters of the droplet.

Note that for a practical application of the proposed approach in GMAW, a simpler sensor should be developed to monitor the droplet oscillation. The research team is currently working on the development of a low-cost, non-image sensor.

Oscillation and Detachment

In principle, the proposed approach takes advantage of the momentum of excited oscillation to reduce the current level required for droplet detachment. However, in order to guarantee the detachment, certain conditions need to be satisfied. Discussion of these conditions requires an analysis of excited oscillation of the droplet.

Oscillation Frequency

Based on previous theoretical work about droplet oscillation (Refs. 25–28), oscillation frequency is mainly determined by the mass of the droplet. The oscillation amplitude, on the other hand, is dependent upon the amplitude of the current decrease used to excite the oscillation. This amplitude of current decrease is referred to as *excitation level* (Fig. 2). If the current waveform in Fig. 3 is used, the excitation level will equal $I_p - I_b$.

Figures 4 and 5 demonstrate two sets of excited oscillations. In the two oscillations shown in Fig. 4A and 4B, masses of droplets are roughly the same, but the excitation levels are different. It is found that the oscillation frequencies are both about 160 Hz, despite the difference in the excitation level. In Fig. 5, the second droplet in Fig. 5B has greater mass than the second droplet in Fig. 5A due to larger I_p. As can be seen in the figure, the span from the first to fifth peak in resultant oscillations is 25 ms and 28 ms for these two cases. Their oscillation frequencies are 160 and 143 Hz, respectively. The droplet with greater mass in Fig. 5B results in a slower oscillation.

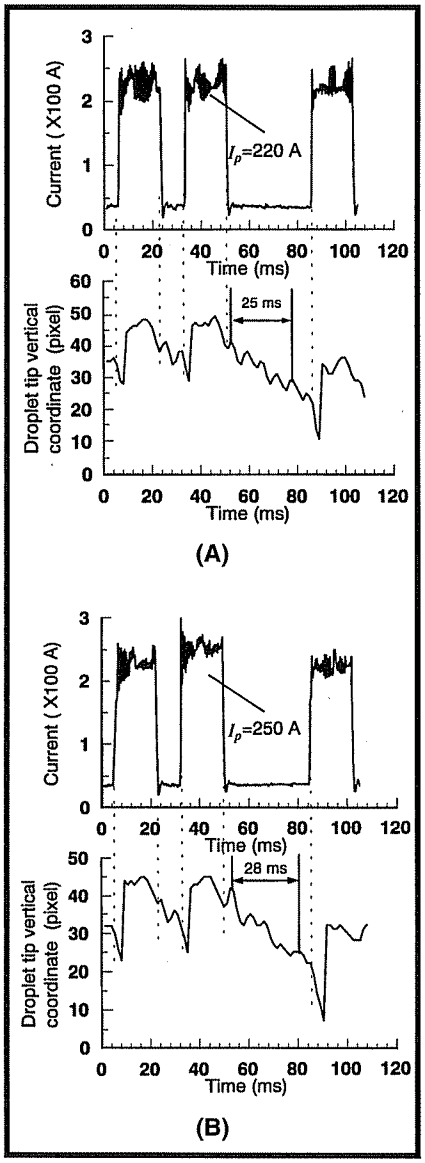

Fig. 5 — Dependence of droplet oscillation frequency on the mass of the droplet. A — With smaller droplet; B — With one larger droplet.

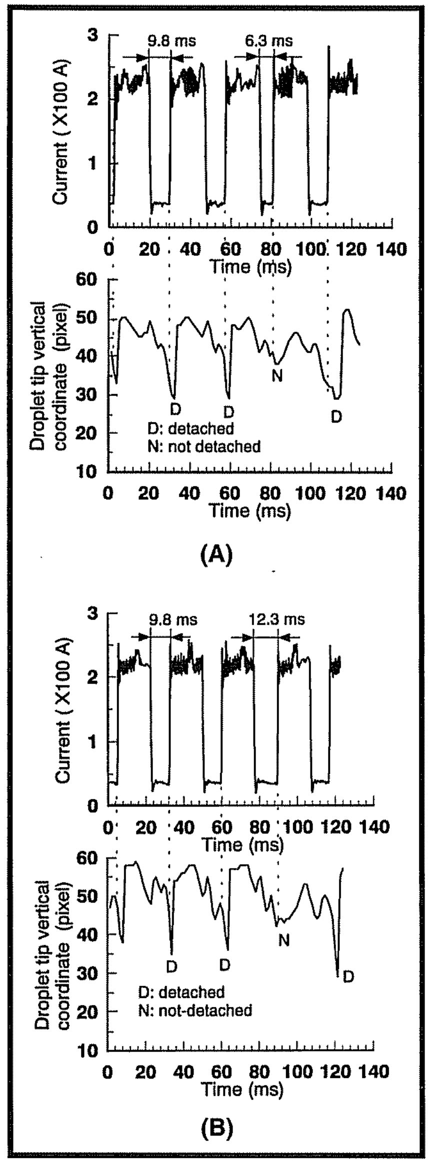

Fig. 6 — Experimental observation of the phase match. A — Experiment 1; B — Experiment 2.

Phase Match and Beneficial Amplitude

Examine the experiments shown in Fig. 6. In these experiments, the peak current I_p is 220 A and the base-level current I_b is 43 A. The excitation level is about 180 A. The duration of I_p is 17.5 ms and the duration of I_b is changed to examine its influence on detachment.

As shown in Fig. 6A, when the duration of I_b is 9.8 ms, the droplet is detached. However, if a shorter duration (*i.e.*, 6.3 ms) is used, the droplet is not detached. This is quite understandable. In fact, for the duration of 6.3 ms, the droplet is moving upward when the current is switched to the peak level. To detach the droplet, the downward momentum of the droplet must be combined with the step increase in the detaching electromagnetic force. This combination is referred to as *phase match*.

The role of phase match in detaching the droplet is also demonstrated in Fig. 6B. When the duration of I_b is 9.8 ms, the droplet is detached because of the phase match. However, when the duration is increased to 12.3 ms so that the phase match condition is not satisfied, the droplet is not detached. In this case, the droplet can only be detached when it grows to a sufficient size and transfer occurs in globular mode. Therefore, phase match is a necessary condition for the proposed approach.

The excited oscillation is a damped process. Its amplitude decays in each succeeding oscillation cycle. If the duration of I_b is too long so that the oscillation amplitude significantly decays, the maximum downward momentum of the droplet may become insufficient to detach the droplet together with ejection pulse. The oscillation amplitude measures the maximum momentum of the droplet available to enhance the detachment. Hence, the oscillation amplitude in the cycle when the ejection action is applied is referred to as *beneficial amplitude*. It is apparent that the beneficial amplitude depends upon excitation level, droplet mass, decaying time, electrode material, etc. To maximally take advantage of the downward momentum, the ejection action should be applied as soon as the downward motion of the droplet is detected (based on analysis of vertical coordinates of the electrode tip after the oscillation is excited).

Ejection Level and Detachment

Another important parameter in detaching the droplet is the level of current difference when the current is switched back from the lower level to the higher level. This difference is referred to as the *ejection level* — Fig. 2. (If the current waveform in Fig. 3 is used, the ejection level will be $I_p - I_b$ and be equal to the excitation level. However, different current levels may be used for growth period and ejection pulse so that the ejection level differs from the excitation level.) Phase match is the condition that ensures the momentum of excited oscillation can be used to enhance the detachment. The beneficial amplitude measures how much the excited oscillation can help for detachment. Because droplet detachment is a result of ejection action and droplet downward momentum, the ejection level also plays a critical role in detaching the droplet. Figure 7 shows that when the ejection level is 170 A, the detachment is achieved. However, when the ejection level reduces to 100 A, the droplet is not detached. It is evident that when the beneficial amplitude decreases, the required ejection level increases.

In addition to phase match, beneficial amplitude and ejection level, detachment is also dependent upon mass, electrode diameter, electrode material, etc. In fact, the detaching force increases as the mass increases because of gravity. The surface tension varies with the electrode diameter and material. When the current is switched from the base level to the high level, the amplitude of oscillation, which was initiated by applying a nonzero excitation level, increases because of an increase in the detaching electromagnetic force. In this case, the "spring force" is provided by the surface tension. When the droplet moves downward too far, the liquid-solid interface may not be able to provide sufficient surface tension. As a result, the "spring" is broken. The droplet is detached. Hence, the influence of the mass, electrode diameter and electrode material on the detachment is quite understandable.

For a specific application, the electrode diameter and material are given. The given diameter of the electrode determines a rough range of the droplet size. Under such a condition, the possible range of the desired size of the droplet for generating the drop spray is narrowed. Hence, the mass of the droplet can be regarded as roughly fixed when analyzing the detachment. Also, the maximum possible surface tension that can be provided by the electrode is certain for the given diameter and material of the electrode. In the proposed approach, the ejection action will be applied as soon as the phase-match condition is satisfied. Under these assumptions, the required excitation and ejection levels are roughly fixed. Therefore, if the oscillation of the droplet can be monitored so that the phase-match condition is satisfied, the detachment control of the droplet can be guaranteed.

Control Experiments

In conventional GMAW-P, pulse parameters must be carefully determined through trials prior to welding in order to achieve ODPP. When welding parameters and conditions change, optimal pulse parameters for obtaining ODPP will generally alter and need to be redetermined by experiments.

For the proposed approach, the droplet is detached by an active ejection action. Because of the elimination of high current, the droplet does not detach without the active ejection action. Hence, metal transfer can be controlled to achieve ODPP independent of welding parameters and conditions with current waveform as shown in Fig. 3.

In the following control experiments, duration of the ejection pulse is 2 ms. Desired transfer rate and average current are specified as input parameters. Based on these input parameters, duration of the growth period and the inserted base current period can be automatically determined.

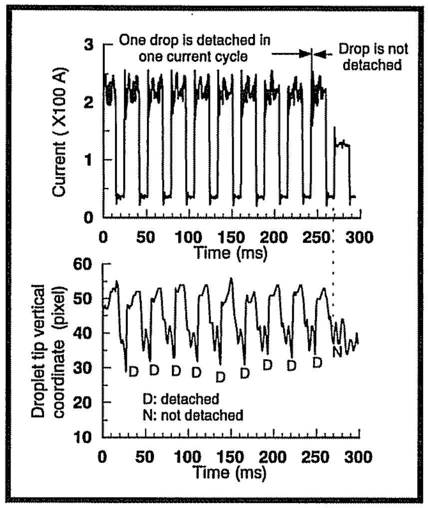

Fig. 7 — Detachment and ejection level.

Average Current Level

In Fig. 8, the shielding gas is 95%Ar + 5%CO_2 and its flow rate is 17 L/min. The desired average current is changed from 100 A to 165 A. The transfer rate setting is 30 Hz for 100 A and 65 Hz for 165 A. The rest pulse parameters are determined accordingly. The resultant current waveform is given in Fig. 8B.

Figure 8D shows that despite the change in average current and transfer rate (Fig. 8C), ODPP is not affected. The transfer processes are shown in Fig. 8A and 8B.

Shielding Gas

In conventional GMAW-P, detachment occurs when the detaching force is too large to be balanced with the maximum surface tension, which could possibly be provided by the interface of the solid electrode and liquid droplet. The change in shielding gas alters the maximum surface tension. Hence, optimal pulse parameters in conventional GMAW-P are influenced by shielding gas.

For the proposed active metal transfer control, surface tension required to balance the detaching force is much less than the maximum possible surface tension that can be provided by the interface between solid electrode and liquid droplet during growth period. This is because the elimination of high current reduces the detaching force. Hence, the droplet does not detach during the growth period when the shield gas is changed. Similarly, the combination of downward momentum and ejection action produces a very powerful detaching force. To balance this detaching force, surface tension must be very large. The ejection level has been designed so that

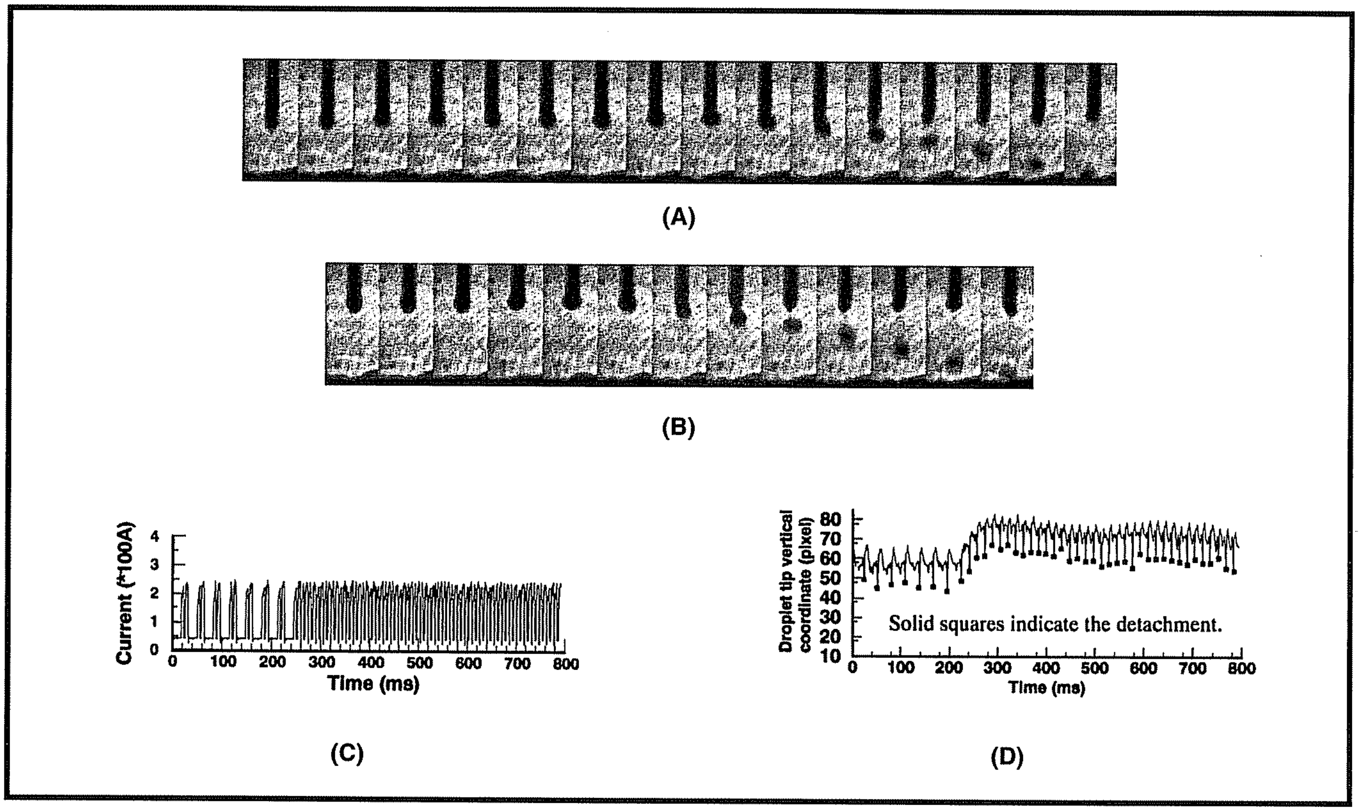

Fig. 8 — On-line adjustment of the average current using the active control of metal transfer. A — Metal transfer process with 100 A of average current; B — metal transfer process with 165 A of average current; C — welding current; D — droplet tip coordinate.

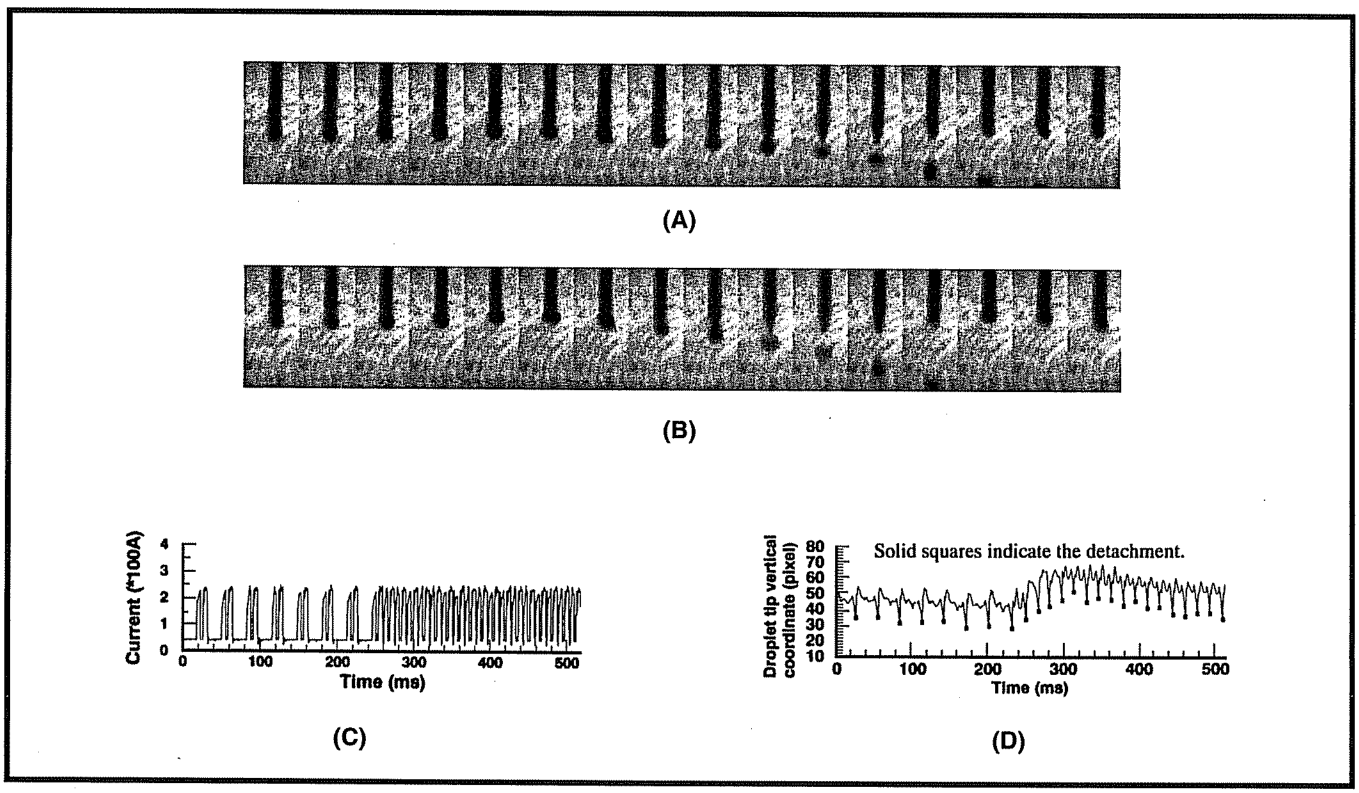

Fig. 9 — Active metal transfer control experiment using pure argon. A — Metal transfer process with 100 A of average current; B — metal transfer process with 165 A of average current; C — welding current; D — droplet tip coordinate.

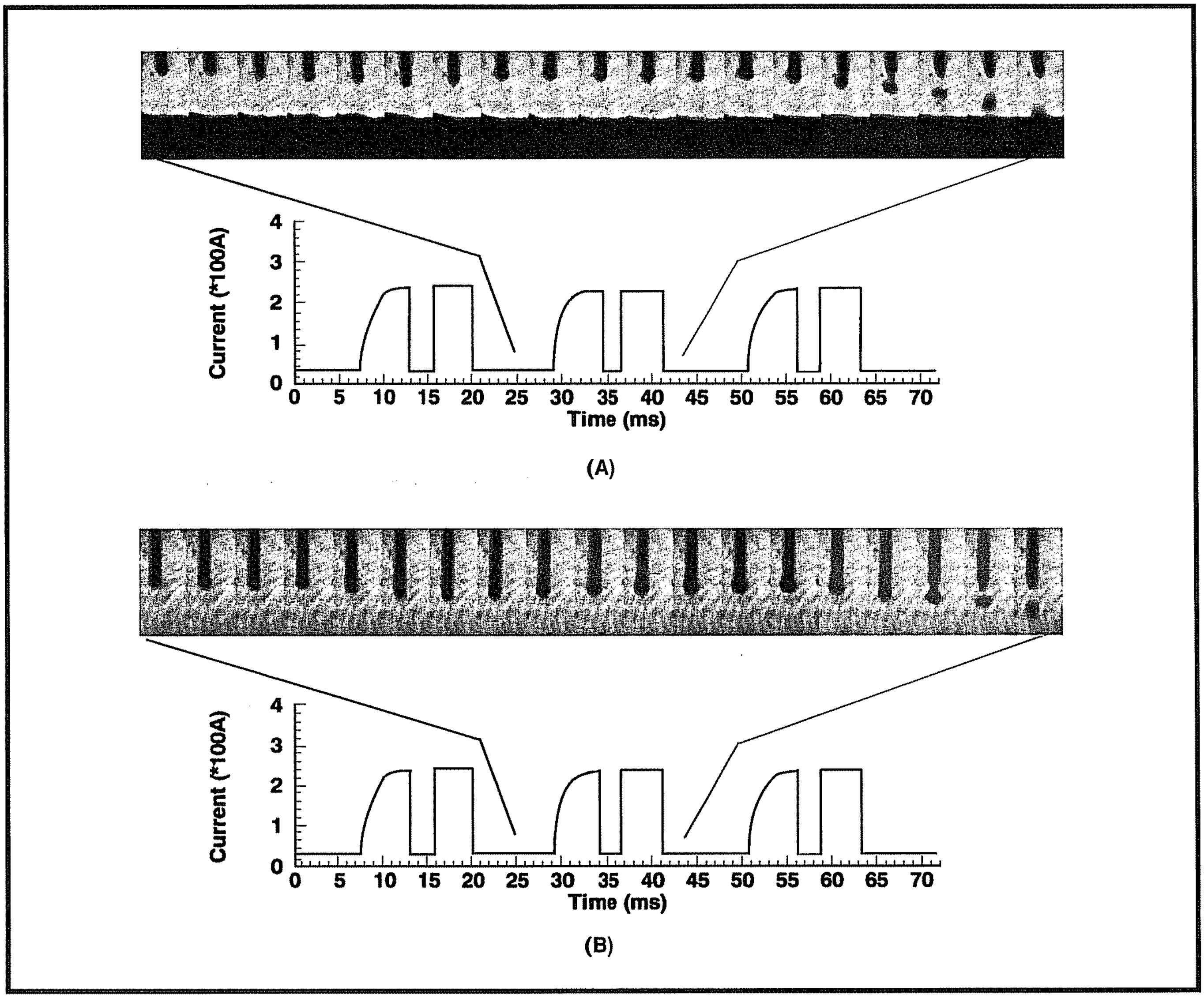

Fig. 10 — Active control of metal transfer under different contact tube-to-work distances. A — 13.5 mm of contact tube-to-work distance; B — 22.5 mm of contact tube-to-work distance.

the detaching force caused by downward momentum and ejection action can not be balanced by the maximum possible surface tension, which could be generated using different shielding gas. Hence, the independence of metal transfer from shielding gas in the proposed approach is quite understandable. In the experiment shown in Fig. 9, the shielding gas is pure argon instead of 95%Ar + 5%CO_2. Its flow rate is 17 L/min. Other settings, average current and transfer rate are the same as in Fig. 9. It can be seen that the change in shielding gas does not prevent ODPP from being achieved.

Electrode Extension

When electrode extension changes, the melting rate of the electrode alters for the given wire speed or welding current. As a result, pulse parameters may need to be reoptimized in conventional GMAW-P. When the proposed approach is used, careful selection of pulse parameters becomes unnecessary.

Figure 10 illustrates the results of experiments conducted using two different contact tube-to-work distances, 13.5 mm and 22.5 mm. Shielding gas is (95%)Ar + 5%CO_2 and its flow rate is 17 L/min. The average current is 100 A. It can be seen that ODPP is achieved in both cases.

It is known that the robustness of stability of the metal transfer process against variation in the contact tube-to-work distance is very useful for manual GMAW. Hence, the proposed approach offers a potential method to improve the quality of manual welding if a lost-cost compact sensor can be developed to monitor the droplet oscillation.

Conclusions

A novel approach is proposed to control the metal transfer process. This approach takes advantage of downward momentum of oscillation of the droplet to reduce the current level required to detach the droplet. The reduction in the current level guarantees the droplet is not detached unless the active ejection action is applied. Also, the oscillation, which is excited by an active excitation action, is on-line monitored by a high-frame rate imaging system. The phase match between excited oscillation and ejection action is guaranteed. Hence, the detachment of the droplet is precisely and reliably controlled. Experimentation demonstrated effectiveness of the proposed approach.

A significant limitation of the developed control system is the use of the imaging system. To actually apply the proposed metal transfer control principle to GMAW, a low-cost compact sensor must be developed.

Acknowledgment

This work was supported by the Center for Robotics and Manufacturing Systems at the University of Kentucky.

References

1. Larson, L. J. 1942. Metal transfer in the metallic arc. *Welding Journal* 21(2): 106-s to 112-s.

2. Jackson, C. E. 1960. The science of arc welding, part 2: consumable-electrode welding arc. *Welding Journal* 39(5): 177-s to 190-s.

3. Essers, W. G., and Van Gompel, M. R. M. 1984. Arc control with pulsed GMA welding. *Welding Journal* 63(6): 26–32.

4. Jones, L. A., Eager, T. W., and Lang, J. H. 1992. Investigation of drop detachment control in gas metal arc welding. *Proceedings of the 3rd International Conference on Trends in Welding Research*, Gatlinburg, Tenn., 1009–1013.

5. O'Brien, R.L, ed. 1991. *Welding Handbook*. 8th ed., Vol. 2: American Welding Society, Miami, Fl.

6. Lesenewich, A. 1958. Control of melting rate and metal transfer. *Welding Journal* 37(9): 418-s to 425-s.

7. Essers, W. G., and Walter, R. 1981. Heat transfer and penetration mechanisms with GMA and plasma-GMA welding. *Welding Journal* 60(2): 37-s to 42-s.

8. Ueguri, S., Hara, K., and Komura, H. 1985. Study of metal transfer in pulsed GMA welding. *Welding Journal* 64(8): 242-s to 250-s.

9. Quintino, L., and Allum, C. J. 1984. Pulsed GMAW: interactions between process parameters—part 1. *Welding and Metal Fabrication* 52: 85–89.

10. Kim, Y. S., and Eagar, T. W. 1993. Analysis of metal transfer in gas metal arc welding. *Welding Journal* 72(6): 269-s to 278-s.

11. Kim, Y. S. 1989. Metal transfer in gas metal arc welding. Ph.D. thesis. MIT, Cambridge, Mass.

12. Allum, C. J. 1985. Welding technology data: pulsed MIG welding. *Welding and Metal Fabrication* 53: 24–30.

13. Amin, M. 1983. Pulse current parameters for arc stability and controlled metal transfer in arc welding. *Metal Construction* 15: 272–278.

14. Ma, J., and Apps, R. L. 1983. Analyzing metal transfer during MIG welding. *Welding and Metal Fabrication* 51: 119–128.

15. Adam, G., and Siewert, T. A. 1990. Sensing of GMAW droplet transfer modes using ER 100s-1 Electrode. *Welding Journal* 69(3): 103-s to 108-s.

16. J. A. Johnson, Carlson, N. M., Smartt, H. B., and Clark, D. E. 1991. Process control of GMAW: sensing of metal transfer mode. *Welding Journal* 70(4): 91-s to 99-s.

17. Siewert, T., Madigan, B., Quinn, T., and Mornis, M. 1992. Through-the-arc sensing for gas metal arc weld quality in real time. *Materials Evaluation* Nov.: 1314–1318.

18. Liu, S., and Siewert, T. A. 1989. Metal transfer in gas metal arc welding: droplet rate. *Welding Journal* 68(2): 52-s to 58-s.

19. Wang, Q. L., and Li, P. J. 1997. Arc light sensing of droplet transfer and its analysis in pulsed GMAW process. *Welding Journal* 76(11): 458-s to 469-s.

20. Rhee, S., and Kannatey-Asibu, Jr., E. 1992. Observation of metal transfer during gas metal arc welding. *Welding Journal* 71(10): 381-s to 386-s.

21. Allemand, C. D., Schoeder, R., Ries, D. E., and Eager, T. W. 1985. A method of filming metal transfer in weld arcs. *Welding Journal* 64(1): 45–47.

22. Jacobsen, N. 1992. Monopulse investigation of drop detachment in pulsed gas metal arc welding. *Journal of Physics, Part D: Applied Physics* 25: 783–797.

23. Kovacevic, R., Zhang, Y. M., Beardsley, H. E., and Erlenbeck, M. 1995. On-line sensing of metal transfer for adaptive control of GMA welding. *Proceedings of the 4th International Conference on Trends in Welding Research*, Gatlinburg, Tenn., pp. 350–364.

24. Kovacevic, R., Zhang, Y. M., Beardsley, H. E., and Erlenbeck, M. 1996. Real-time image acquisition and processing of metal transfer. 77th Annual American Welding Society Exposition and Convention, Chicago, Ill.

25. Jones, L. A. 1996. Dynamic electrode forces in gas metal arc welding. Ph.D. thesis. MIT, Cambridge, Mass.

26. Watkins, A. D., Smartt, H. B., and Johson, J. A. 1992. A dynamic model of droplet growth and detachment in GMAW. *Proceedings of the 3rd International Conference on Trends in Welding Research*, Gatlinburg, Tenn., pp. 993–997.

27. Reutzel, E. W,. Einerson, C. J., Johnson, J. A., and Smartt, H. B. 1995. Derivation and calibration of a gas metal arc welding (GMAW) dynamic droplet model. *Proceedings of the 4th International Conference on Trends in Welding Research*, Gatlinburg, Tenn., pp. 377–384.

28. Jones, L. A., Eagar, T. W., and Lang, J. H. 1995. The temporal nature of forces acting on metal drops in gas metal arc welding. *Proceedings of the 4th International Conference on Trends in Welding Research*, Gatlinburg, Tenn., pp. 365–370.