Modified Active Control of Metal Transfer and Pulsed GMAW of Titanium

A control method that delivers one drop per pulse transfer in a robust and repeatable manner is proposed

BY Y. M. ZHANG AND P. J. LI

ABSTRACT. Conventional pulsed gas metal arc welding (GMAW-P) achieves stable and repeatable spray transfer by using correct pulse parameters. Because the optimal pulse parameters depend on welding parameters, technology is needed to improve the robustness of the transfer process respective to the variations in welding parameters. To resolve this problem, active control technology is proposed to ensure a desirable and repeatable metal transfer mode, *i.e.*, one drop per pulse (ODPP) mode. It uses a peak current lower than the transition current to prevent accidental detachment and takes advantage of the downward momentum of the oscillating droplet to enhance the detachment. When the droplet moves toward the weld pool, the current is switched to peak level and the combination of increased electromagnetic detaching force and downward momentum ensures detachment. Hence, the metal transfer process becomes controllable and robust against variations in welding parameters. However, in order to ensure the combination of increased electromagnetic force and downward momentum, the oscillation process must be monitored. In this study, a modified method is proposed in which the droplet starts to oscillate by first moving toward the weld pool. As a result, the detaching pulse can be applied after a very short period of time and the combination of increased electromagnetic force and downward momentum is guaranteed. Thus, the control system is simplified and the metal transfer's robustness is further improved. This modified active control technology has been used to weld titanium.

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Introduction

Titanium is characterized by its high strength and light weight. Such attributes make titanium a primary choice for more and more components and structures in aircraft, tanks and naval vessels (Refs. 1, 2), as well as in certain commercial applications (Ref. 3). In general, titanium alloys have good weldability and can be welded with most arc welding processes. However, a strict atmospheric shield is required to ensure weld quality. Gas tungsten arc welding (GTAW) uses a nonconsumable tungsten electrode and generates a stable arc. It is an ideal process for titanium welding. However, its low productivity is not desirable for thick section structures and components. The use of a process such as gas metal arc welding (GMAW) would significantly improve productivity and reduce manufacturing costs if adequate shielding could be achieved.

GMAW of titanium has been investigated for decades. The mode of metal transfer plays a critical role in ensuring the shield. In particular, globular and uncontrolled short-circuiting transfers generate significant amounts of spatter, which cause turbulence. Also, the strong cathode jet in globular transfer, a unique phenomenon to the GMAW process with titanium, tends to project the droplets outward when they break up upon entering the weld pool (Ref. 4), making the shielding additionally difficult. On the other hand, spray transfer generates a low level of spatter and has a relatively stable arc. It provides a better shield. Unfortunately, however, when a constant current is used, spray transfer is only achieved at high currents in an argon shield. Low currents will produce globular and short-circuiting transfer, and thus, an unstable arc and severe spatter (Refs. 4–8).

KEY WORDS

Titanium Welding
GMAW-P
Pulsed Current Welding
Peak Current
Metal Transfer
Electromagnetic Force

Pulsed GMAW uses a low base current to maintain the arc and a high peak current to melt the electrode and detach the droplet. It is capable of achieving spray transfer at low mean currents (Refs. 9, 10). Also, GMAW-P tends to detach the droplet during the base current period. According to an earlier study by Eager, *et al.* (Ref. 4), droplets are subject to a rejecting force due to the plasma jet issuing from the weld pool, resulting in a condition that may eject coarse spatter. Because the rejecting force is proportional to the amplitude of the welding current, it is very low in the base current period of pulsed GMAW and the plasma-jet-related spatter is minimized. Hence, pulsed GMAW has been used to avoid globular transfer, reduce spatter and improve arcing stability in titanium welding (Refs. 11, 12).

Although GMAW-P is capable of reducing spatter and improving arc stability through spray transfer, such capability is conditional. To ensure a stable arc and an adequate shield, the transfer process must be repeatable and controllable. That is, the transfer rate, number of droplets detached in a unit of time, and the droplet size must be consistent and in an appropriate range. For GMAW-P, an applicable method to ensure the repeatability and controllability has been to detach one, and only one, droplet per pulse (ODPP) with a droplet diameter close to that of the electrode (Refs. 10, 13, 14). In conventional pulsed GMAW, this is achieved by selecting an appropriate duration and amplitude for the peak current. However, in order to ensure the detachment or

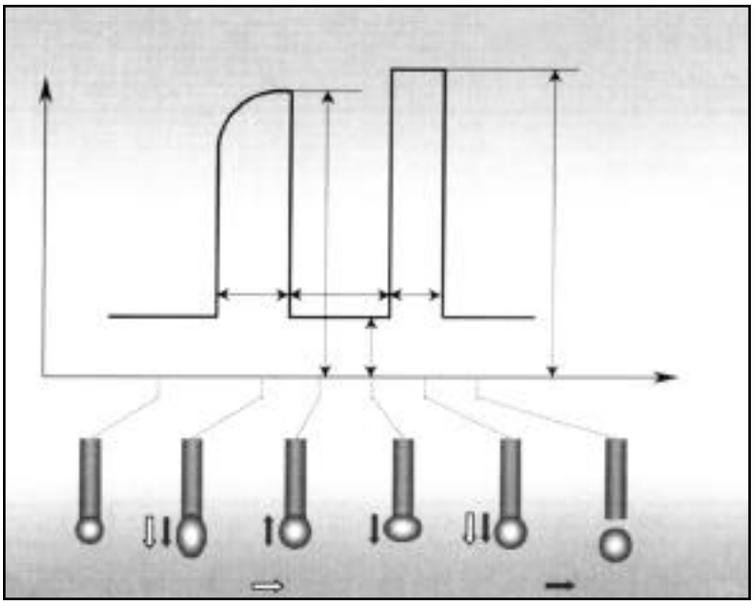

Fig. 1 — Current waveform used for active droplet transfer control.

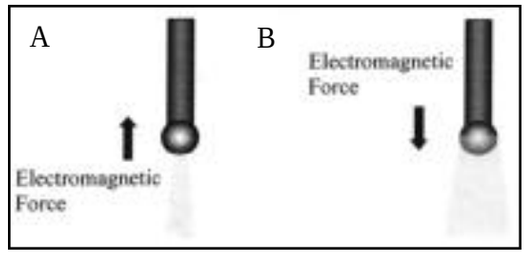

Fig. 2 — Arc distribution and arc force. A — Low current; B — high current.

avoid one-droplet multiple pulses (ODMP), a peak current higher than the transition current (Ref. 14) must be used.

The use of high current narrows the range of peak current duration for generating stable ODPP. If the duration of the peak current period is longer than required, multiple droplets may be detached in a single pulse (Ref. 15), resulting in a streaming spray transfer. If the duration is shorter, multiple pulses may be needed to develop and detach one droplet (Ref. 13). In addition, such peak current duration depends on, and varies with, welding parameters and conditions. In fact, to determine the 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 a given electrode material, electrode wire diameter and composition of shielding gas (Refs. 10, 13, 14). However, because of the narrow range and its dependence on welding conditions, such an open-loop selection of duration is often not robust with respect to welding parameters and conditions. Repeatable and controllable metal transfer and adequate shielding are not guaranteed.

Modified Active Control

Active Control

To achieve a robust control technology for repeatable and controllable metal transfer, the authors have proposed oscillating the droplet, utilizing the downward momentum of the oscillating droplet to enhance detachment controllability (Refs. 17–19). As seen in Fig. 1, during period T_1, the droplet grows gradually and is dragged in the weld pool direction by a downward electromagnetic force generated by the exciting pulse. During period T_2, the current is switched to a low level and, therefore, the electromagnetic force is decreased significantly. As a result, the droplet moves towards the electrode and then springs back toward the weld pool due to the surface tension of the melted droplet. During T_3 period, the current is switched to a higher level (detaching pulse). With the assistance of downward momentum, the increased electromagnetic force ensures the droplet is detached with a current lower than the peak current needed in conventional pulsed current GMAW. This method has been referred to as active control of metal transfer (Refs. 17–19).

Analysis

Although satisfactory droplet transfer can be achieved with active metal transfer control technology, further improvements will be beneficial for production of high-quality GMAW, especially for titanium welding. Specifically, analysis shows that the free oscillation period T_2 is critical in ensuring detachment. Droplet mass, electrode material property and excitation level (the difference between the exciting pulse and the base current) all influence the selection of T_2 and the efficiency in using the downward momentum. To take advantage of the downward momentum, the phase match condition must be satisfied, *i.e.*, the detaching pulse must be applied when the droplet moves toward the weld pool. To take maximal advantage of the downward momentum, the detaching pulse was applied when downward motion of the droplet was first detected [based on analysis of vertical coordinates of the electrode tip after oscillation was excited in our previous work (Ref. 17)].

This study reveals the active control method may be modified to further improve robustness of metal transfer repeatability and controllability. Such improvements could be particularly beneficial for titanium welding. As can be seen, in the previous method (Ref. 17), the droplet is dragged toward the weld pool by the electromagnetic force in the exciting pulse period. The droplet starts to oscillate toward the electrode when the current is switched from the exciting level to the base current level. When the droplet starts moving toward the weld pool, the detaching pulse is applied to detach the droplet. Because of the damping force, the oscillation energy decreases gradually. The downward momentum, which can be used to enhance the detachment, also decays. Because the droplet first moves toward the electrode after the current is switched to the base level, the detaching pulse can only be applied after the oscillation energy decays for a half oscillation period. As a result, the effective downward momentum for detachment decreases, and the required amplitude of the detaching pulse increases. If the droplet begins the oscillation by first moving toward the weld pool, such decrease in the effective downward momentum and increase in the amplitude of the detaching pulse will be eliminated. In this paper, such a scheme is referred to as modified oscillation. The resultant control is referred to as modified active control.

In addition to the increase in effective downward momentum and the decrease in the detaching current, the modified os-

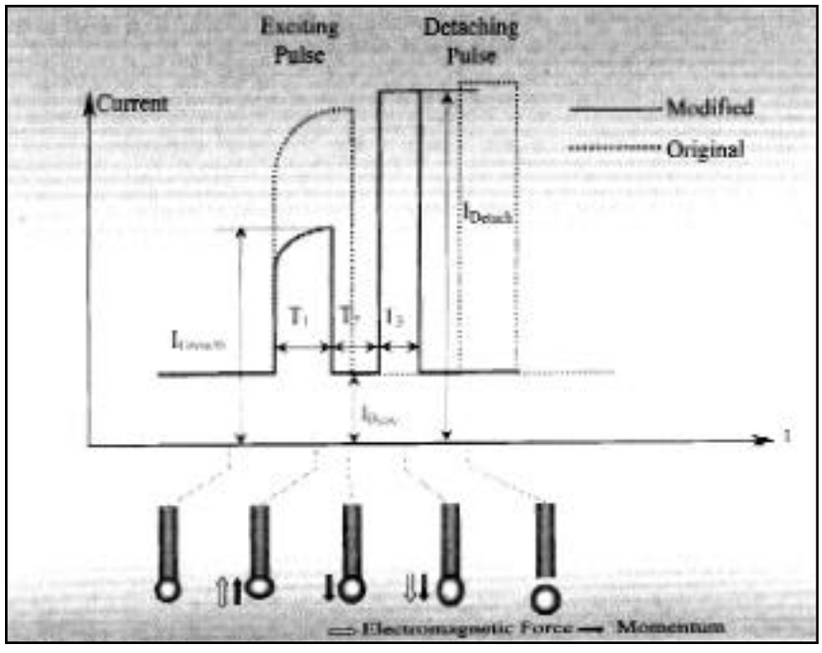

Fig. 3 — Comparison of current waveforms for active control and its modification.

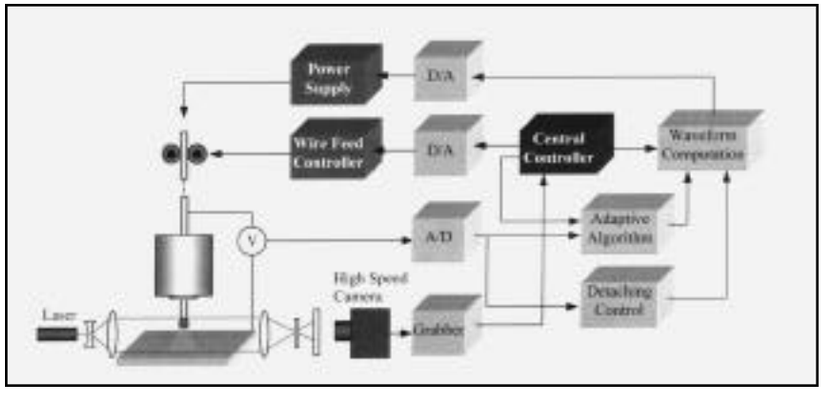

Fig. 4 — Experimental apparatus diagram.

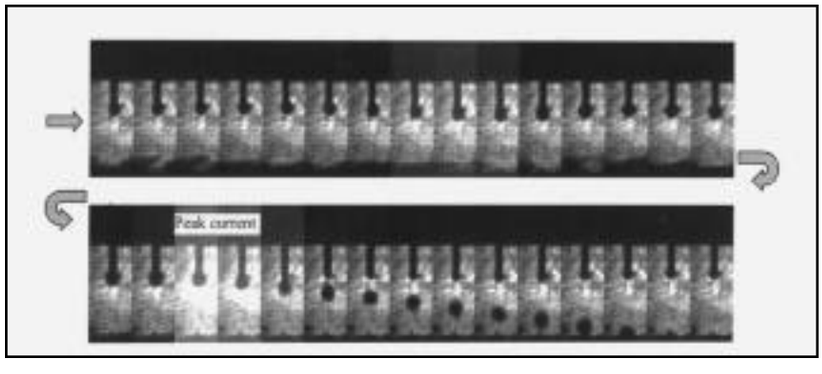

Fig. 5 — Droplet detachment with pulsed current 200/35 A, 50 Hz, 22 V and electrode positive. The electrode is 0.9-mm (0.035-in.) ERTi-1, 800 frames per second.

cillation scheme also generates two additional and important advantages. First, in active control, the droplet is not detached until half an oscillation period has gone. Such a mandatory waiting period lowers the upper limits of the transfer rate and achievable welding current. For example, when 0.9-mm (0.035-in.) wire is used, the upper limit of the metal transfer rate is 80 Hz, lower than it is in conventional GMAW where the typical range of transfer is from 40 to 120 HZ. If a greater diameter wire is used, the frequency limit will be further lowered. Second, the frequency of oscillation depends on the mass of the droplet (Ref. 17). In active control, the detaching current is applied after half an oscillation cycle. To ensure the phase match, the oscillation must be monitored. If the phase match condition is not satisfied when the detaching pulse is applied, the droplet cannot be detached. In that case, the performance of the active control would be even worse than conventional-pulsed GMAW. In previous studies, the oscillation was monitored by high-frame camera (Ref. 17) or the arc voltage signal (Ref. 19). If the modified oscillation scheme is used, the detaching pulse can be applied shortly after oscillation. The phase match is guaranteed. The monitoring system becomes unnecessary, the control system becomes simpler and the process becomes more robust.

Depending on the amplitude of the exciting pulse, the droplet can either be lifted towards the electrode or dragged downwards to the weld pool, as shown in the previous studies (Refs. 20, 21). In fact, when the welding current is low, the arc force pushes the droplet back to the electrode, as shown in Fig. 2A. The electromagnetic force directs to the electrode. As the welding current increases, the arc root covers more and more of the surface of the droplet. When approximately half the droplet is covered by the arc root, the arc force changes its direction, pointing to the weld pool, as illustrated in Fig. 2B. For a given diameter of electrode, the welding current can be selected to fully control the direction of the electromagnetic force, either toward or away from the electrode. For example, for the titanium electrode used in this study, a 100-A or lower current always produces an electromagnetic force pointing toward the electrode, despite the size of the droplet and other welding conditions. A 140-A or higher current always generates an electromagnetic force away from the electrode. That is, the direction of the electromagnetic force is controllable. Hence, the authors propose a method, as illustrated in Fig. 3, to realize the modified oscillation scheme. As

shown in Fig. 3, the modified active control uses a relatively low exciting current to lift the droplet toward the electrode. After the current is switched from the exciting level to the base level, the droplet moves toward the weld pool because of the reduction in the lifting electromagnetic force. After a short period, the detaching pulse current is applied. The detaching current has been designed to ensure the electromagnetic force is away from the electrode. The combination of the detaching electromagnetic force and the downward momentum of the droplet ensures detachment. Hence, the modified oscillation scheme and modified active control are realized.

Experiments revealed the time interval for "free" oscillation (the base current level is very low), *i.e.*, T_2 in Fig. 3, determines the efficiency of the detaching pulse. A correct time interval maximizes the efficiency of the downward momentum, which offers the advantage of reducing the amplitude of the detaching pulse to guarantee the detachment. The relationship between the downward momentum and exciting pulse current value and period was investigated as well. The current waveform was modified based on all these results, as shown in Fig. 3. The details will be discussed later in this paper.

Experimental Procedure

All experiments were performed with bead-on-plate welding. Titanium alloy (ERTi-1) workpiece and 0.9 mm (0.035 in.) titanium wire (ERTi-1) were used. The shielding gas was pure argon (99.999% purity) with a flow rate of 20 L/min. The power supply was an inverter welding power source with current output range from 5 to 450 A (pulse current). This power supply can be used for either constant current (CC) or constant voltage (CV) mode. In this study, the welding current was produced by CC mode. The welding equipment was computer controlled to produce a specific pulsed current waveform and constant arc length. The workpiece was clamped on a transversing weld table, allowing the welding torch to remain stationary. The experimental set-up is shown in Fig. 4.

Observation of the droplet was facilitated by a laser backlighting system. A high-speed camera, 800 frames per second, was positioned to record the transfer of the droplet. The camera's resolution is 128 x 128. For monitoring the droplet transfer process, a 15 x 15 mm field of view surrounding the end of the wire was selected. The corresponding resolution of the camera is about 0.12 mm (0.0048 in.). It can be seen from the images given in this work that the reso-

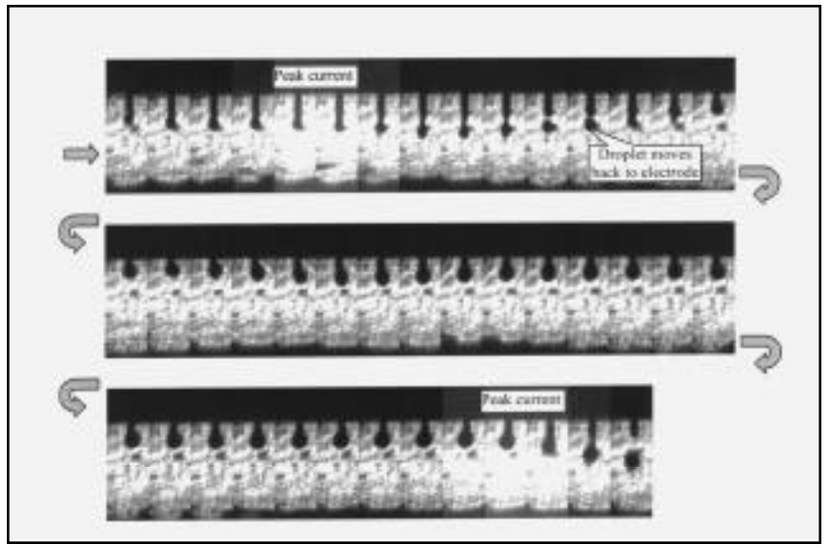

Fig. 6 — Droplet detachment with pulsed current 200/35 A, 50 Hz, 22 V and electrode positive. The electrode is 0.9-mm (0.035-in.) ERTi-1, 800 frames per second.

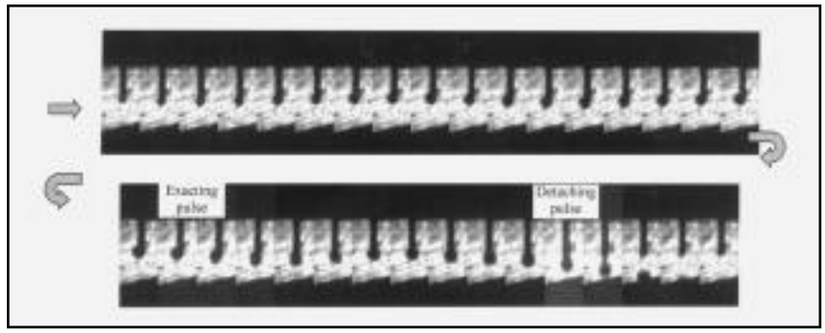

Fig. 7 — Droplet detachment with active detachment control method, detaching current 165 A, base current 35 A, 50 Hz, 20 V and electrode positive. The electrode is 0.9-mm (0.035-in.) ERTi-1, 800 frames per second.

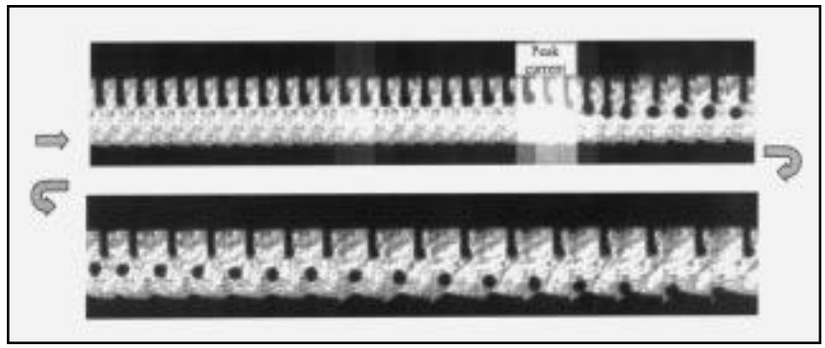

Fig. 8 — Droplet detachment with pulsed current 230/35, 40 Hz, 22 V and electrode positive. The electrode is 0.9-mm (0.035-in.) ERTi-1, 800 frames per second.

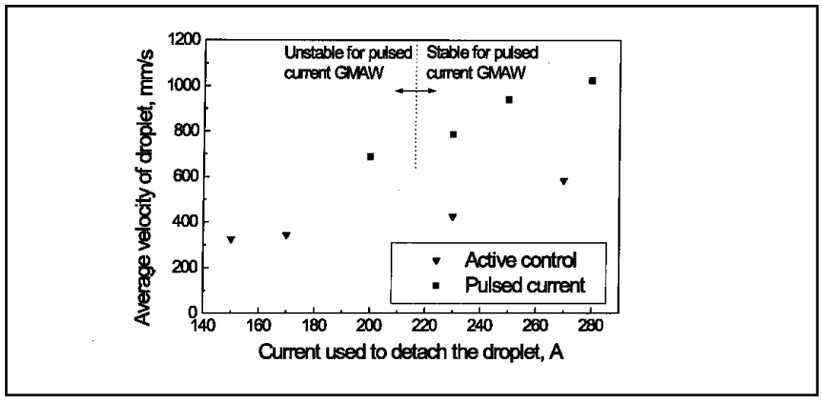

Fig. 9 — Average velocity of droplet transfer in active detachment process and conventional pulsed current process.

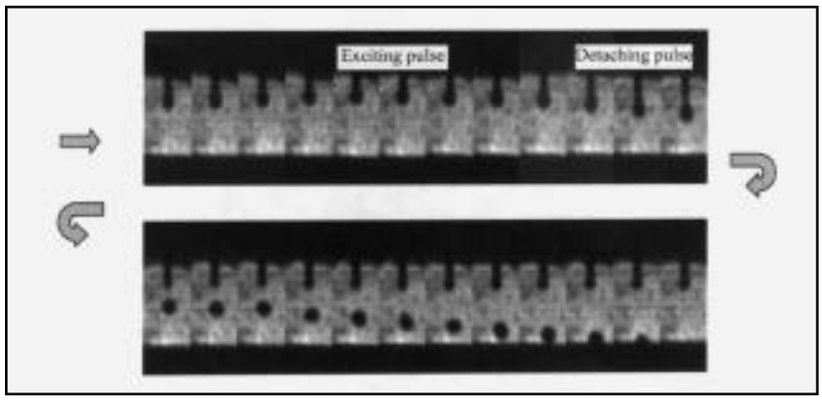

Fig. 10 — Droplet detachment with modified active control, detaching current 160 A, base current 35 A, 50 Hz, 22 V and electrode positive. The electrode is 0.9-mm (0.035-in.) ERTi-1, 800 frames per second.

lution of the camera is sufficient to extract the geometrical parameters of the droplet. Thus, the droplet can be monitored at least 6 times per cycle during oscillation. Under this monitoring rate, the oscillation phase of the droplet can be monitored reliably. During experiments, the computer output the specific current form and grabbed the images. The images were processed later to investigate the effect of modified active control on droplet detachment.

Results and Discussion

Stability plays a critical role in reducing spatter and improving the shielding of the weld area in GMAW of titanium. In the conventional-pulsed GMAW process, if a constant ODPP transfer is obtained, the process is stable because the variation of arc length caused by droplet transfer is small. Furthermore, the droplet is detached in the base current period, resulting in a low rejecting force (Ref. 4). Figure 5 shows images taken during a constant ODPP transfer. The droplet was detached after the peak current period. The rejection effect is not observed.

However, the range of pulsed current parameters for achieving ODPP mode under a certain condition is narrow. Although parameters were tuned carefully, random interruption always impairs the stable droplet transfer process, such as the variation of arc length or contact tube wear. As shown in Fig. 6, with the same parameters for the process shown in Fig. 5, after the droplet detached from the wire tip, it returned to the wire due to relatively insufficient pulse energy. It appears the energy required by each pulse to detach the droplet reliably may vary according to the welding conditions. If pulse energy is relatively low, the droplet cannot transfer until its gravity is larger than the surface tension after several pulses. The process becomes unstable, especially for thin wire, because the variation of arc length is larger due to the relatively large surface tension. In order to ensure detachment, high peak current value and long peak current period may be used. However, in addition to high droplet impact speed, the corresponding detachment process tends to proceed asymmetrically. Also, due to the violence of the detachment, the droplet sometimes breaks apart, resulting in coarse spatter.

Stable droplet transfer has been ensured by using the active droplet transfer control technique. As shown in Fig. 7, during the exciting pulse, the droplet moves downwards to the weld pool due to electromagnetic force. The droplet moves symmetrically or asymmetrically about the electrode's axis, depending on the distribution of arc root on the droplet surface. Equilibrium is established between the electromagnetic force, gravity and the retaining force due to surface tension. When exciting pulse current is switched to the base current level, the droplet begins to oscillate because of the decrease of electromagnetic force, which is proportional to the welding current's power. The spring force derived from surface tension and the damping force from viscous stresses dominate the movement of the droplet. Because they are symmetrical, the motion of the droplet tends to be symmetrical about the electrode's axis. When the droplet starts to move downward, the current is switched to the detaching level and the droplet is detached reliably and axially. The oscillation of the droplet is beneficial for achieving a stable transfer process from two points of view. The oscillation retrieves the droplet's symmetric shape, and the downward momentum decreases the peak current needed for constant ODPP process. In Fig. 7, the droplet's form was asymmetrical when the exciting pulse was applied. After the oscillation, the motion of the droplet tends to be symmetrical and then it is detached axially. The detaching current needed is only 165 A. However, in the conventional-pulsed current GMAW process of titanium, the droplet is sometimes asymmetrical and when pulsed current is applied, the droplet does not move axially. The droplet may be detached away from the wire to produce coarse spatter, as shown in Fig. 8. The peak current needed is about 230 A for constant ODPP transfer mode.

Besides constancy, another characteristic of the transfer process with active control is the speed of the droplet decreases significantly, to only half of that in conventional pulsed current welding. As shown in Fig. 9, the average speed of the droplet in GMAW-P is 816mm/s for 0.9-mm (0.35-in.) wire with ODPP mode using 230-A pulsed current. The average

speed of the droplet with the active control technique is 423 mm/s, with the same detaching current value. Furthermore, the active control uses a much lower detaching current than the peak current in conventional-pulsed GMAW, resulting in a droplet transfer speed decrease to 345mm/s.

The modified active control inherits all of the advantages of the active control method. In addition, the modified control technique further eliminates remaining problems in its origin. As seen in Fig. 10, the droplet is first lifted toward the electrode by the exciting pulse current. Then it springs downwards to the weld pool after the exciting pulse current switches to base current level. After a short period, the detaching pulse current is applied to detach the droplet.

The modified method results in several advantages. First, because the detaching current is applied after less than half the period of droplet oscillation, the time needed for each droplet detachment cycle is decreased significantly. The upper limit of the frequency is increased to 120 Hz, reaching the same range as conventional-pulsed GMAW process. Thus, the welding current range is enlarged, especially for thicker wire, which has a longer oscillation period (Ref. 17). Second, the exciting current decreases to 100 A, which is much smaller than that used by the previous method (140 A). The duration of the exciting pulse is not correspondingly increased. Therefore, the energy used for exciting the oscillation of the droplet decreases significantly and less heat input is produced by the exciting pulse. This characteristic is useful for many applications that need low input energy. Third, the controllability of the droplet detachment is improved. As shown in Fig. 11, in conventional-pulsed GMAW, the droplet is detached only by the electromagnetic force. There is a trade-off between the robustness and the high pulse current. In the previous active control method, the droplet is detached by electromagnetic force and downward momentum. With the assistance of the downward momentum, the requirement for the detaching current is decreased and the allowance of the detaching current is increased. Thus, the controllability is improved. However, because in the exciting pulse current, the droplet is dragged down by electromagnetic force, the energy difference that assists the droplet detachment is not large. In the modified active control method, the electromagnetic force caused by the exciting pulse lifts the droplet. Hence, the energy difference caused by the detaching action and the exciting action is

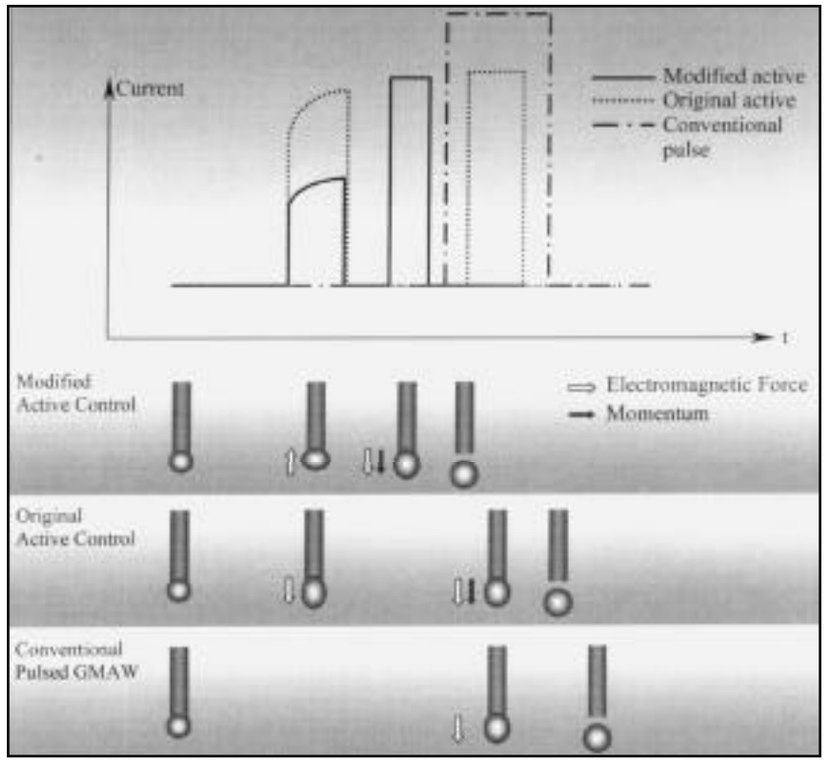

Fig. 11 — Comparison of controllability in different control methods.

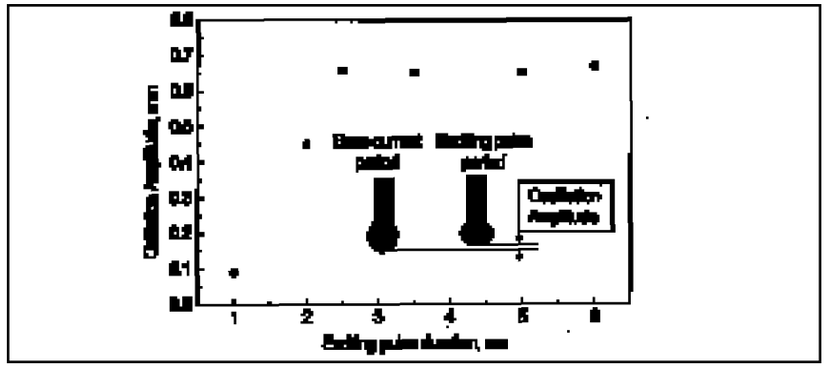

Fig. 12 — Relationship between exciting pulse duration and oscillation amplitude of droplet. Exciting current is 100 A, electrode diameter is 0.9-mm (0.035-in.) ERTi-1.

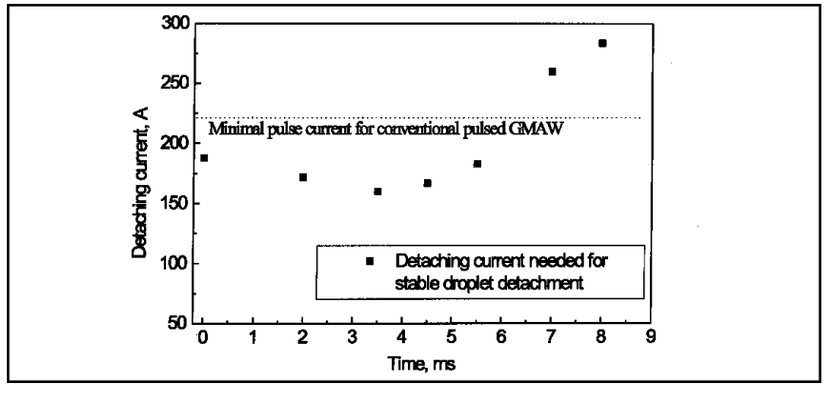

Fig. 13 — Influence of time to apply detaching pulse on the required detaching current value in active detachment process.

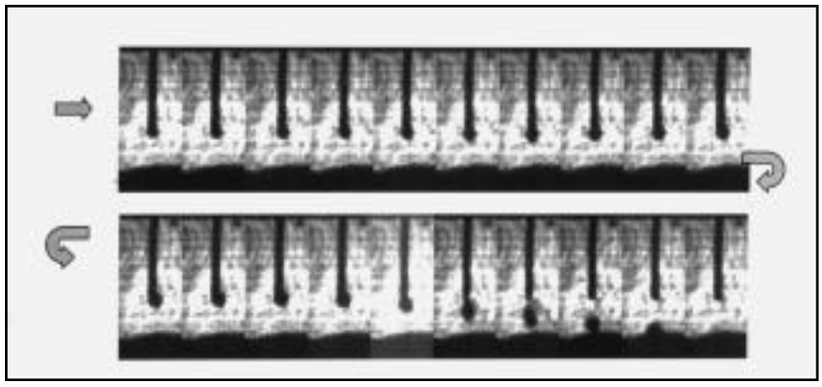

Fig. 14 — Droplet transfer with 25-mm (1-in.) contact-tube-to-workpiece distance with modified active control, 400 frames per second.

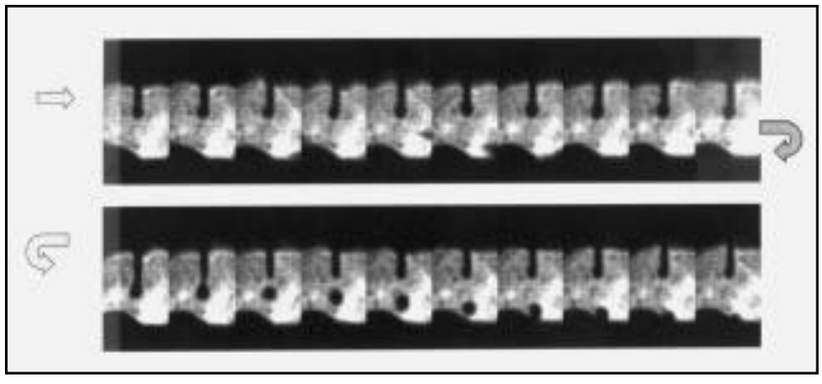

Fig. 15 — Droplet transfer with 12-mm (0.5- in.) contact-tube-to-workpiece distance with modified active control, 400 frames per second.

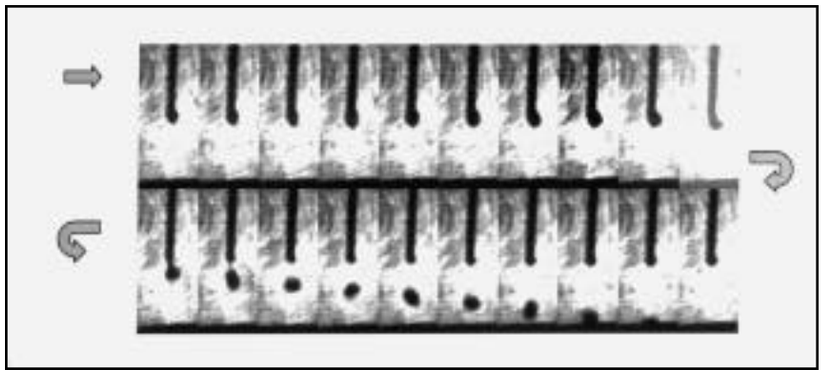

Fig. 16 — Droplet transfer with 9-mm (0.36- in.) arc length with modified active control, 400 frames per second.

larger. This difference eases the prevention of accidental detachment. As a result, the controllability is increased further, and both the size and transfer instant of the droplet become more controllable. Fourth, the robustness of the detachment process is improved because after the exciting pulse current switches to base current, the droplet must spring back due to surface tension. The detaching current is applied after a short period. The downward momentum must be in phase with the detaching arc force. Therefore, this method eliminates the necessity for real-time monitoring and analysis of the oscillation process.

Experiments have also been conducted to investigate the influence of the exciting pulse period on oscillation amplitude. It was found that the exciting pulse current value determines the maximum amplitude of the droplet movement. As can be seen in Fig. 12, for a certain exciting current value and electrode diameter, there is an optimal exciting pulse period. If the exciting period is set at this optimal period, the droplet can be lifted to maximum amplitude. The exciting pulse current period has been set slightly higher than the optimal period to ensure robustness of the process in this study.

This study has also investigated the optimal time to apply the detaching current. It was found the time used in the previous active method is not optimal. As shown in Fig. 13, the needed detaching pulsed current for reliable detachment varies with the instant to apply it during the droplet's downward motion. At a certain instant, the needed detaching pulse current reaches minimum value. The phenomenon is complicated. Oscillation of the droplet is like as a vibration system with viscous damping. If the detaching pulse current is applied as soon as the droplet moves downwards, the velocity of the droplet is additionally accelerated, resulting in an excessive increase of the dumping force, which is proportional to velocity. Thus, excessive energy provided by the detaching current is consumed during downward movement of the droplet. In order to detach the droplet reliably, either higher detaching current or longer detaching period should be used. If the detaching force is applied too late, phase mismatch may occur. In the modified method, the detaching current is applied shortly after the current is switched to the base level, so the phase match is guaranteed. Also, the efficiency of the detaching pulse is improved and the need for detaching pulsed current is decreased.

Robustness

In order to demonstrate the stability of the modified active control method, experiments were conducted to investigate droplet transfer under varied conditions. Welding parameters selected as variables include arc length and contact-tube-to-workpiece distance because they have significant influence on the droplet transfer process. Additionally, they are prone to variations during production welding, especially in semiautomatic welding. Variation in contact-tube-to-workpiece distance and arc length changes the heat

generation and arc efficiency. If the allowance of the controllability of a droplet is small, the process cannot withstand change of conditions. Multidroplet per pulse or multipulse per droplet mode will occur. However, with improved controllability, the modified active control method does not have these problems. As shown in Figs. 14 and 15, with quite different contact-tube-to-workpiece distance, the droplet transfer process remains constant even though the heat generation conditions change. As seen in Figs. 16 and 17, the arc length changed from 9 mm (0.36 in.) to 3 mm (0.12 in.), but the active control method still detached the droplet constantly and reliably. The modified active control does withstand variation in the welding condition within a reasonable range.

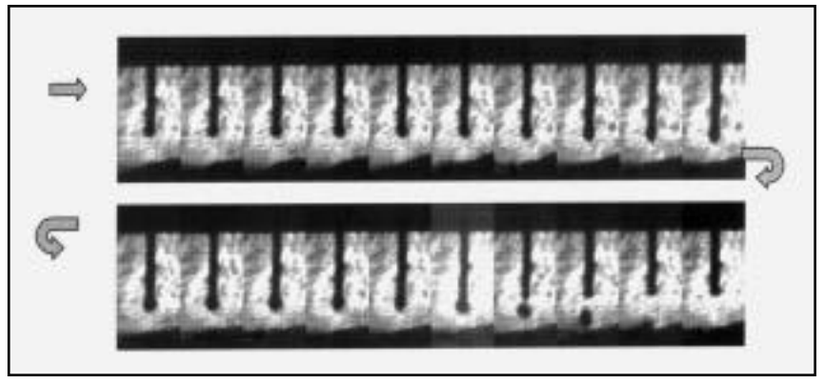

Fig. 17 — Droplet transfer with 3-mm (0.12- in.) arc length with modified active control, 400 frames per second.

Conclusions

By utilizing active control technology, the robustness of the metal transfer process in GMAW of titanium is significantly improved in comparison with the conventional-pulsed GMAW process. The use of downward momentum decreases the peak current needed for constant ODPP process. The process is stable and free from spatter, which is highly desirable in GMAW welding of titanium.

The major difference between active control and modified active control lies in the method for oscillation generation. In active control, both the exciting and detaching pulses are selected to be at peak level. Hence, oscillation is generated by switching current from the peak level to the background level. The electromagnetic force corresponding to peak current is a detaching force. After the current is switched from peak level to background level, the droplet initially moves toward the electrode. The detaching action can be taken only after half of the oscillation cycle. Because oscillation depends on welding parameters such as material and diameter of the electrode, the oscillation process must be monitored. The system is complicated and robustness of the metal transfer depends on the reliability of the monitoring system. In the modified active control, the oscillation is generated by switching the current from the exciting pulse level to background level. Because the exciting pulse in this case is much lower than the detaching pulse, it can be so selected that the resultant electromagnetic force is a retaining force or support force. As a result, before the current is switched to the background level, the electromagnetic force pushes the droplet toward the electrode. After the current is switched, the droplet oscillates by immediately moving toward the weld pool. Hence, the detaching pulse can be applied after a short period of time, and the phase match between oscillation and the detaching force is guaranteed. Consequently, the need to monitor oscillation is eliminated. The control system is simplified and robustness is improved. Of course, because of the elimination of a half cycle of waiting time, the modified active control also improves the range of the metal transfer rate. Because modified active control inherits all other advantages of active control, modified active control is a better solution for applications where highly repeatable metal transfer is desirable.

Acknowledgment

The authors thank Thermal Arc, Inc., Troy, Ohio, for its technical and equipment support.

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