Solution to problems of arc interruption and arc length control in tandem pulsed gas metal arc welding

T. Ueyama*, T. Uezono, T. Era, M. Tanaka and K. Nakata

In the tandem pulsed gas metal arc welding, it is the most important issue to prevent adverse effects caused by electromagnetic interaction between the two adjacent arcs to prevent arc interruption. A pulse timing control can reduce arc interference in tandem pulsed gas metal arc welding. One effective way is to delay the pulse end timing of trailing arc by 0·4–0·5 ms from that of leading arc. In addition, arc length control is assured by pulse frequency modulation for the leading wire and pulse peak modulation for the trailing wire with the pulse timing synchronised with the leading pulse. Consequently, leading and trailing arcs are maintained stable without arc interruption and a stable arc length control is established, which is hardly affected by fluctuations of wire feedrate and extension length.

Keywords: Tandem, GMA, Welding, Pulse current, Arc length, Arc interaction, Shielded gas

Introduction

During tandem pulsed gas metal arc welding (TP-GMAW), a couple of arcs is closely generated, so the action of the magnetic field formed by both arcs causes arc interaction and in the worst case, arc interruption occurs. An investigation was carried out to study the effects of the interwire distance and the Ar_2–CO_2 shielding gas mixture ratio on abnormal increases in arc voltage (abnormal voltage), and the consequential frequency of arc interruption. The results demonstrated that these occur frequently at the time of staggered phase where one side arc is the pulse peak current (PPC) and the other arc is the base current, and under conditions where the CO_2 mixture ratio exceeds 10% with an interwire distance of around 10 mm. Consequently, in order to avoid these problems, it is considered that the interwire distance should be reduced to $\sim$5 mm and the Ar_2–CO_2 shielding gas should be employed with the CO_2 mixture ratio which decreased to less than 5%.[1]

By contrast, the authors examined the effects of the configuration of the two wires on the bead formation during high speed steel sheet welding[2] and demonstrated that high speed welding performance improves most significantly when interwire distance is 9–12 mm and $80Ar_2$–$20CO_2$ mixed gas is used as a shielding gas. Satisfactory high speed welding performance cannot be achieved when the interwire distance is 5 mm. With a reduced CO_2 mixture ratio, the penetration becomes shallow and in some cases, a problem of poor penetration is apparent during high speed welding. In addition, there may be an increase in the cost of shielding gas. Therefore, $\sim$10 mm interwire distance and the employment of a shielding gas no greater than 20%CO_2 mixture ratio are required to achieve holding without arc interruption.

Furthermore, it has been reported that pulse timing control, which can pass current to the leading and trailing wires, is essential for the arc stabilisation during TP-GMAW.[3–7] However, to date, there is no report of a detailed investigation into arc length control for external disturbances such as wire feeding fluctuations and variations in wire extension during pulse timing control.

Accordingly, for this paper, with the aim of arc stabilisation during TP-GMAW, an investigation was carried out to study methods that prevent abnormal voltage and arc interruption, and which maintain a stabilised arc length even under circumstances where external disturbances occur, such as fluctuations in the wire feeding and variations in the wire extension.

Set-up of TP-GMAW power sources

Figure 1 shows a schematic diagram of the TP-GMAW power sources. The welding power source for the leading wire is an inverter control type where the three phase alternating current can be converted to a direct current using a rectifying circuit and a high frequency alternating current is created by a high speed switch element; this is the input to the primary side of a transformer and is again changed to a direct current by the rectifying circuit positioned at the secondary output of the transformer. A desired current can be obtained at high speed by controlling the switching time on the primary side so that the current command value I_{Lset} and the output i_L of the current detector become equal during welding.

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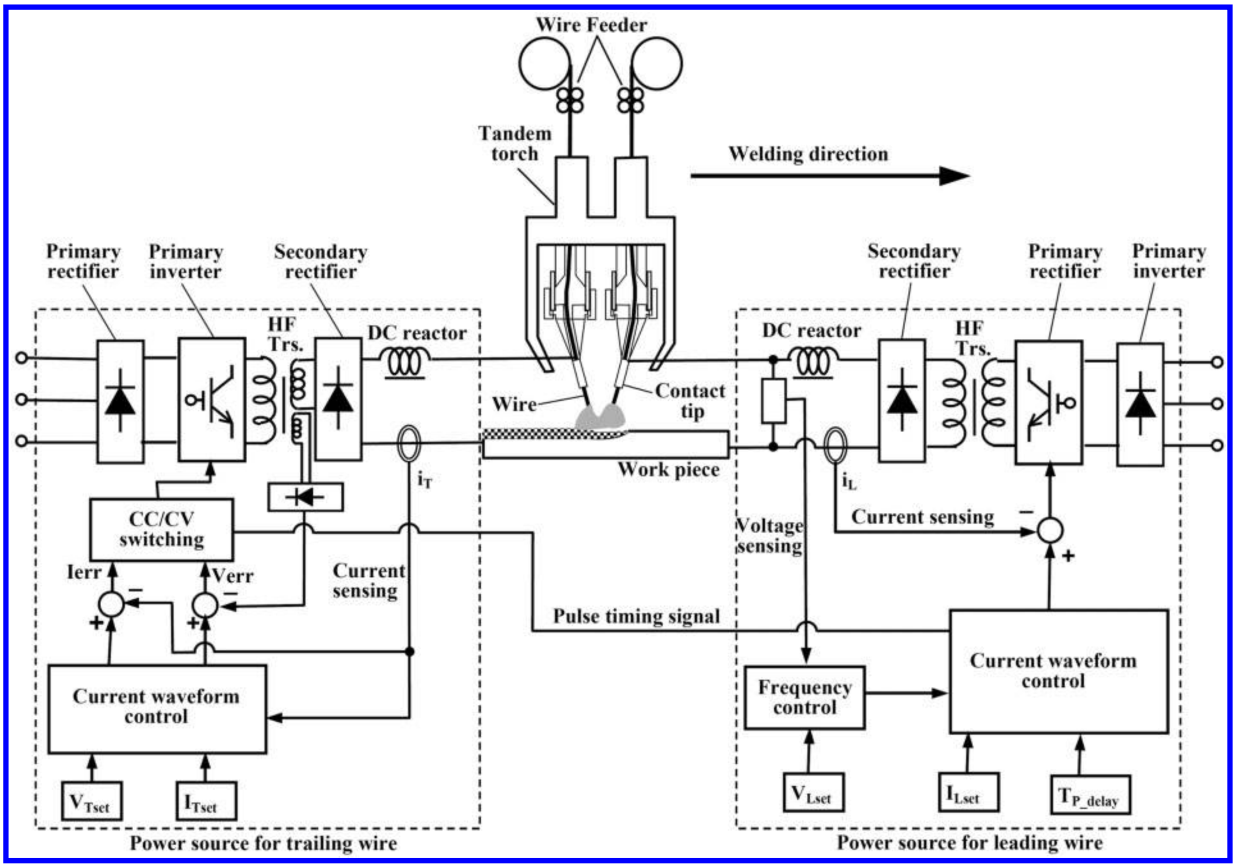


1 Schematic diagram of TP-GMAW power sources

In addition, the voltage is detected by a voltage detector, and the voltage error compared with the set voltage is obtained and arc length control during welding is carried out by the pulse frequency modulation (PFM),[8] which converts the signal into a pulse frequency in the pulse frequency control unit. Therefore, the pulse frequency is decreased when the arc voltage is high (the arc length is long) and the frequency is increased when the arc voltage is low (the arc length is short). The wire melting rate is controlled by increasing or decreasing the frequency and the arc length can be maintained at a constant value. In general, the average arc voltage and arc length are proportional to each other, which means that this voltage feedback control controls the arc length.

The current waveform control unit outputs the phase control signal from the PPC through the leading wire and the PPC through the trailing wire by means of pulse timing command; it is then input to the current waveform control unit of the welding power source on the trailing wire side and synchronous control of the pulse welding current is performed.

The primary circuit arrangement of the power source on the trailing wire side is the same as that of the leading wire side power source but different controls of the PPC from the base current are carried out at the current waveform control unit. In detail, the selection of the PPC and the base current is carried out for set times only determined by the phase control signal from the power source on leading wire. The PPC duration is synchronised with the inverter control cycle, the present current value is input to the external characteristic control unit, reference is made to the current and voltage data stored in advance and a value, to which the output voltage setting is added, is output as the output voltage value of the PPC duration. The switching time is then controlled so that voltage in the auxiliary winding, which monitors the secondary side output voltage of the transformer, and the output voltage of the PPC duration, become equal. By this means, control is applied to create optional external characteristics.[9,10] In this experiment, the external characteristics of the PPC duration were selected to be −10 V/100 A and it was possible to obtain current variation where appropriate arc length control could be carried out in response to the voltage variation accompanying the fluctuation in the arc length.

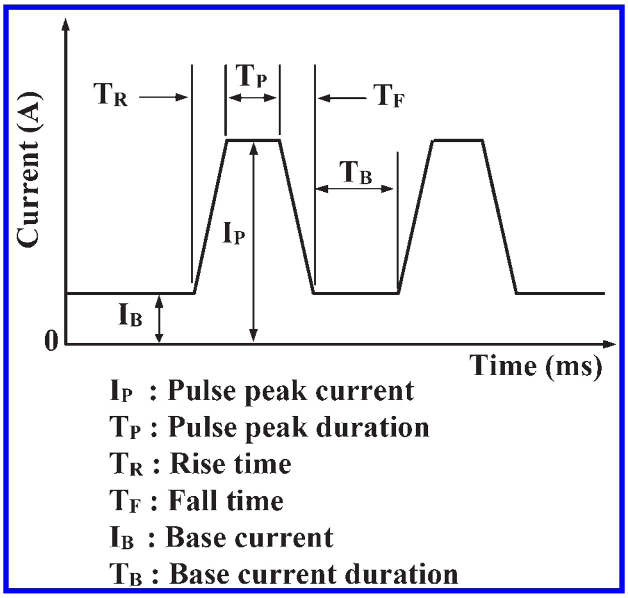
Furthermore, the primary side switching time was controlled so that set current command value I_{Tset} and the output of the current detector i_T became equal during the base duration, while base current I_B was used for current command value I_{Tset}.

Consequently, while ensuring that the trailing arc is synchronised with the pulse current of the leading arc, it is feasible to control the arc length by means of the pulse peak modulation (PPM),[11] even though external disturbances occur in the trailing arc due to fluctuations in the wire feedrate and variations in wire extension.

Material used and experimental method

The base metal of mild steel sheet (3·2 mm thick, 65 mm wide and 450 mm long) was used; the welding solid wire had a diameter of 1·2 mm. To investigate the effect on arc interruption, a premixed $80Ar_2$–$20CO_2$ shielding gas was used at a flowrate of 50 L min^{-1}.

Figure 2 and Table 1 show the pulsed current waveform and the waveform parameters respectively. Bead



2 Definition of pulsed current waveform parameter

on plate welding was carried out using the experimental welding conditions shown in Table 2; the waveforms of welding current and arc voltage were recorded by the waveform recorder (MEMORY HiCORDER 8841 made by HIOKI) for 7 s out of 9 s of one bead welding time, cutting out 1 s for each of the start and end periods of welding. The data were input to a personal computer and then analysed. The number of sudden rises in the arc voltage and the number of arc interruptions caused by arc interference were processed statistically. Explanation for the counting method of abnormal voltage is omitted since it is the same as in the previous report.[1]

A high speed digital video camera was used to investigate the arc interaction. The tandem welding torch was fixed, and the base metal was conveyed by a single axis X table actuator that was set at the height where the welding arcs could reach the base metal, and the high speed video camera and a xenon back light were arranged on both sides perpendicularly to the welding direction. During the high speed video recording, the images at 8000 frames/s were synchronised to the waveforms of welding current and arc voltage.

Effect of base current on arc interaction

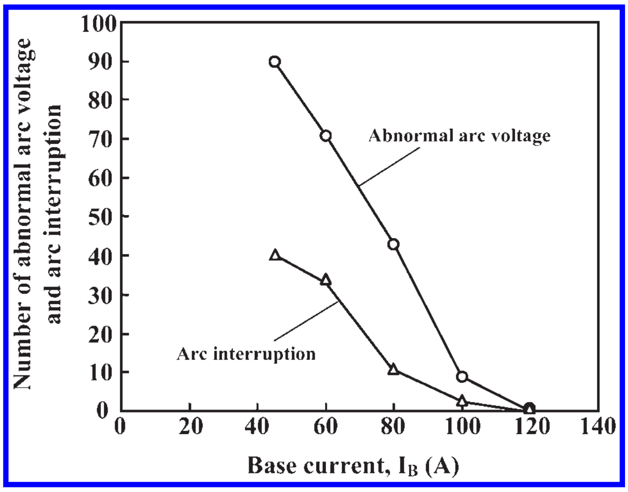
Figure 3 shows the relationship between the frequencies of arc interruptions and the abnormal trailing arc voltage rises when the trailing arc base current value was increased from 45 to 120 A, while the PPC value (450 A) of the leading arc, the pulse width (1·5 ms) and the base current value (45 A) were fixed.

In all cases, the abnormal voltage and arc interruption of the trailing arc occur when the leading arc was in the PPC duration and the trailing arc was in the base current duration; the frequency of such occurrences decreased with increasing base current. The results of this experiment demonstrated that abnormal voltage and arc interruption can be prevented by setting the base current to more than 100 A. The deflected length for the trailing arc l_T can be expressed by the following equation[1]

$$l_T = \frac{I_L L_T^2}{2 I_T D_E} \qquad (1)$$

The calculated values l_T for each base current value are shown in Table 3 for conditions when the interwire distance D_E was 10 mm and the trailing arc length L_T was 5 mm during staggered phase where the leading arc became the PPC, I_L=450 A, and the trailing arc became the base current, I_T=45–120 A. Therefore, the displacement of the trailing arc decreases with increasing base current; at 120 A, the displacement was 3·9 mm and it was deduced from the decreased extension of the arc plasma that an abnormal trailing arc voltage rise is unlikely to occur and arc interruption ceases to occur.

Figure 4 shows the results of arc phenomena when the base current of the trailing arc was set to 120 A. In spite of the PPC in the leading wire, as shown in frame (a), deflected trailing arc can be observed but the degree is minimal and an abnormal voltage did not occur. Furthermore, with regard to the trailing wire, bright



3 Effect of base current on occurrences of abnormal voltage and arc interruption

Table 1 Pulsed current waveform conditions

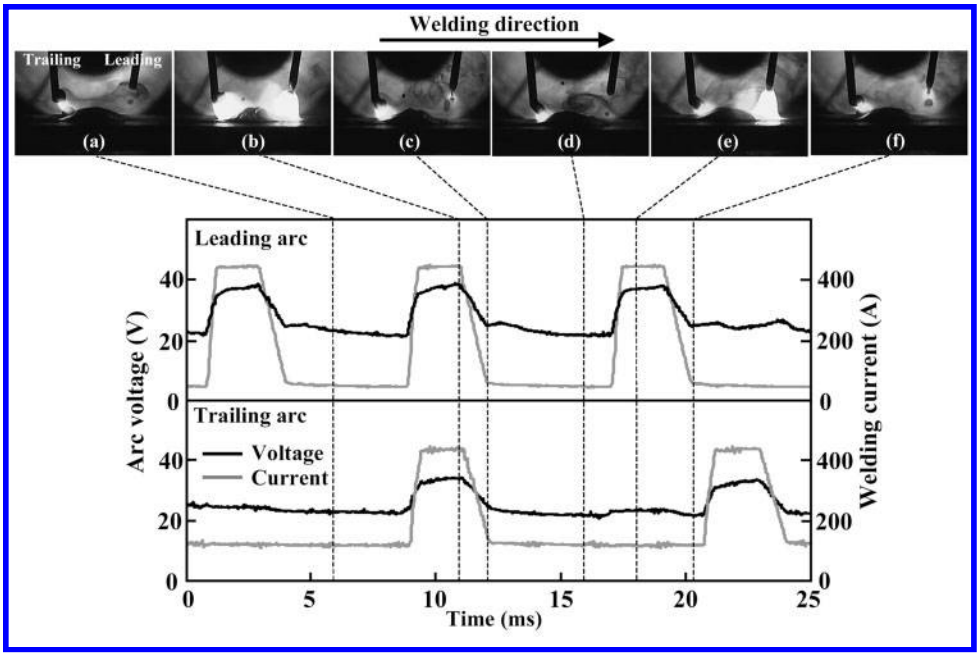
Common of leading and trailing arcs	
Pulse peak current, A	450
Pulse peak duration, ms	1·5
Rise time, ms	0·4
Fall time, ms	1·1
Leading arc	
Base current, A	45
Trailing arc	
Base current, A	45, 60, 80, 100 and 120

Table 2 Experimental conditions

Wire feedrate, m min^{-1}	5
Average welding current, A	145–150
Welding speed, m min^{-1}	2
Interwire distance, mm	10
Shielded gas	80Ar_2–20CO_2 and 75Ar_2–25CO_2
Gas flowrate, L min^{-1}	50

Table 3 Calculated deflection length of trailing arc

Base current, A	Deflected length of arc, mm
45	9·88
60	9·38
80	7·03
100	5·63
120	3·90



4 Metal transfer of trailing arc at 120 A base current

arc plasma occurred from the lower part of the droplet and the size of droplet at the wire tip is seen to be larger than the wire diameter. Consequently, it is evident that arc interruption can be prevented with a higher base current. However, when the base current in the trailing wire was increased to 120 A, the mean welding current became constant and the pulse frequency decreased while the base duration increased. Thus, the wire tip melted during the base duration and a large droplet formed. Even though the PPC flowed in the trailing wire, the arc could not flare further upwards than the enlarged droplet, as shown in frame (b), and the pinch effect did not work effectively for droplet detachment from the wire. Therefore, one droplet per pulse transfer becomes difficult. As a result, as shown in frames (c) and (d), the enlarged droplet tip makes contact with the molten pool and an instantaneous short circuit can occur. When a PPC flows, as shown in frames (e) and (f), the droplet is pushed upwards as in repelled transfer and detaches at the point of deviation from the wire axial direction and scatters as a large spattering without transferring to the molten pool.

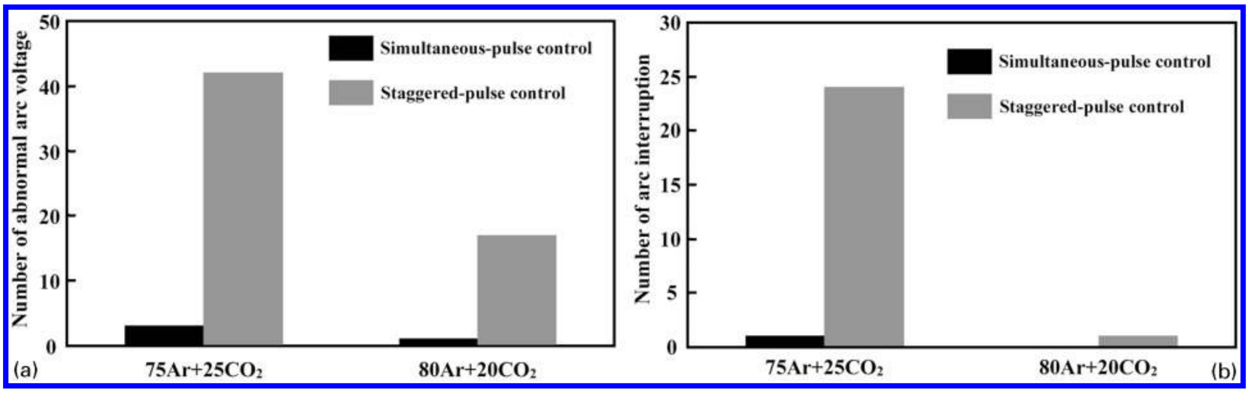
Effect of pulse timing control on arc interaction

Abnormal voltage and subsequent arc interruption occur frequently when the pulsed welding current flowing to both wires becomes staggered phase during welding without pulse timing control. By contrast, it was identified in previous report[1] that when the PPC is simultaneously output to both wires (simultaneous phase), there is a low incidence of abnormal voltage and subsequent arc interruption.

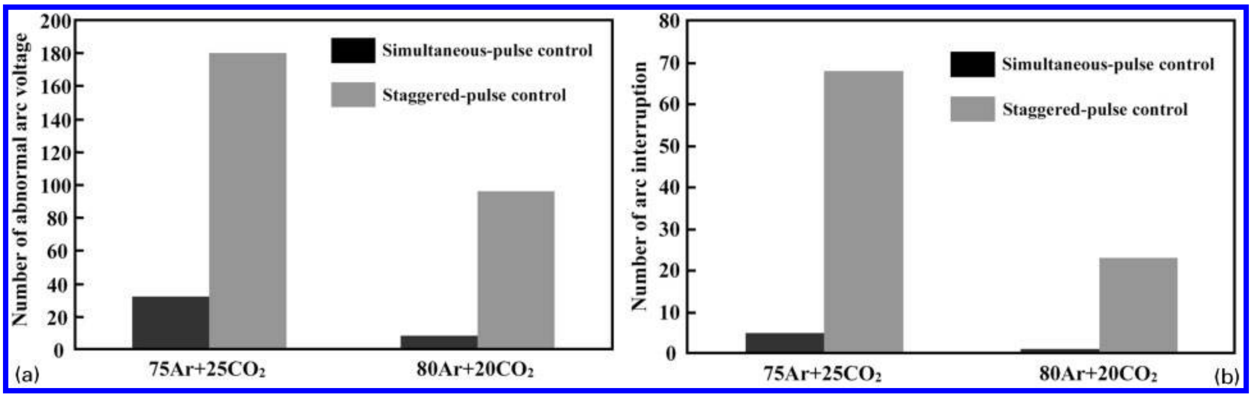
Accordingly, an investigation was carried out to study the occurrence of abnormal voltage and arc interruption for simultaneous phase pulse timing control.

The conditions of the pulsed current waveform in both wires were shown in Table 1 and the base current of the trailing arc was 45 A.

Figure 5 shows comparison between simultaneous phase and staggered phase pulse timing control for the incidence of arc interruption and the abnormal voltage in the leading arc with the conditions of 10 mm interwire distance and 20 or 25%CO_2 mixture ratio in



5 Occurrences of *a* abnormal voltage and *b* arc interruption on leading arc



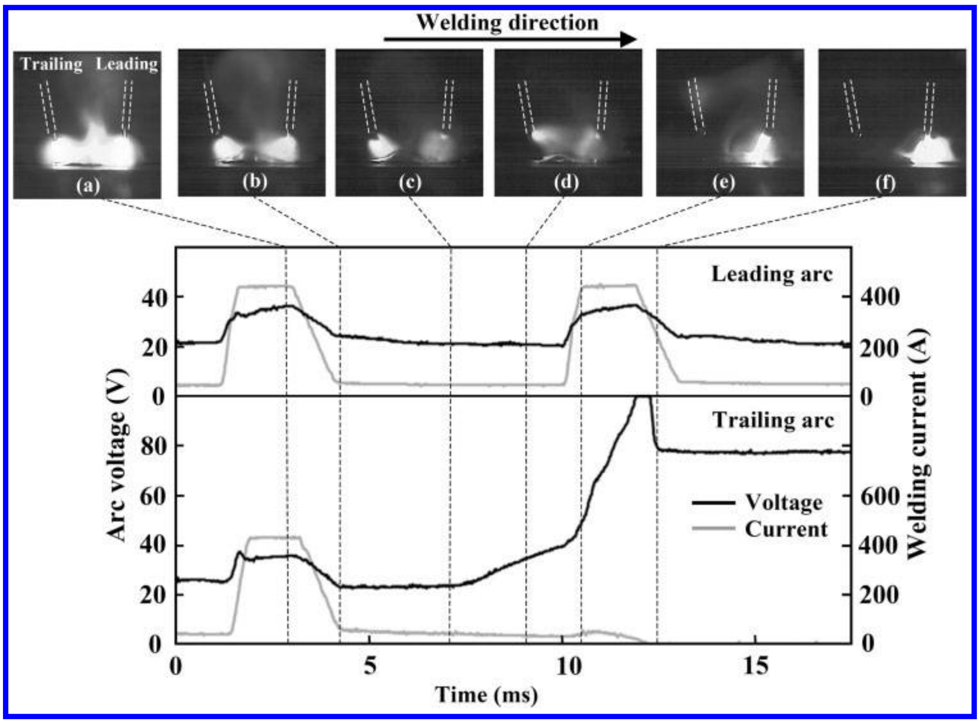
6 Occurrences of *a* abnormal voltage and *b* arc interruption on trailing arc

the Ar_2–CO_2 shielded gas. With the use of simultaneous phase pulse timing control, the number of abnormal voltage of the leading arc was three times using 75Ar_2–25CO_2 and once using 80Ar_2–20CO_2; arc interruption was once using 75Ar_2–25CO_2 and zero using 80Ar_2–20CO_2.

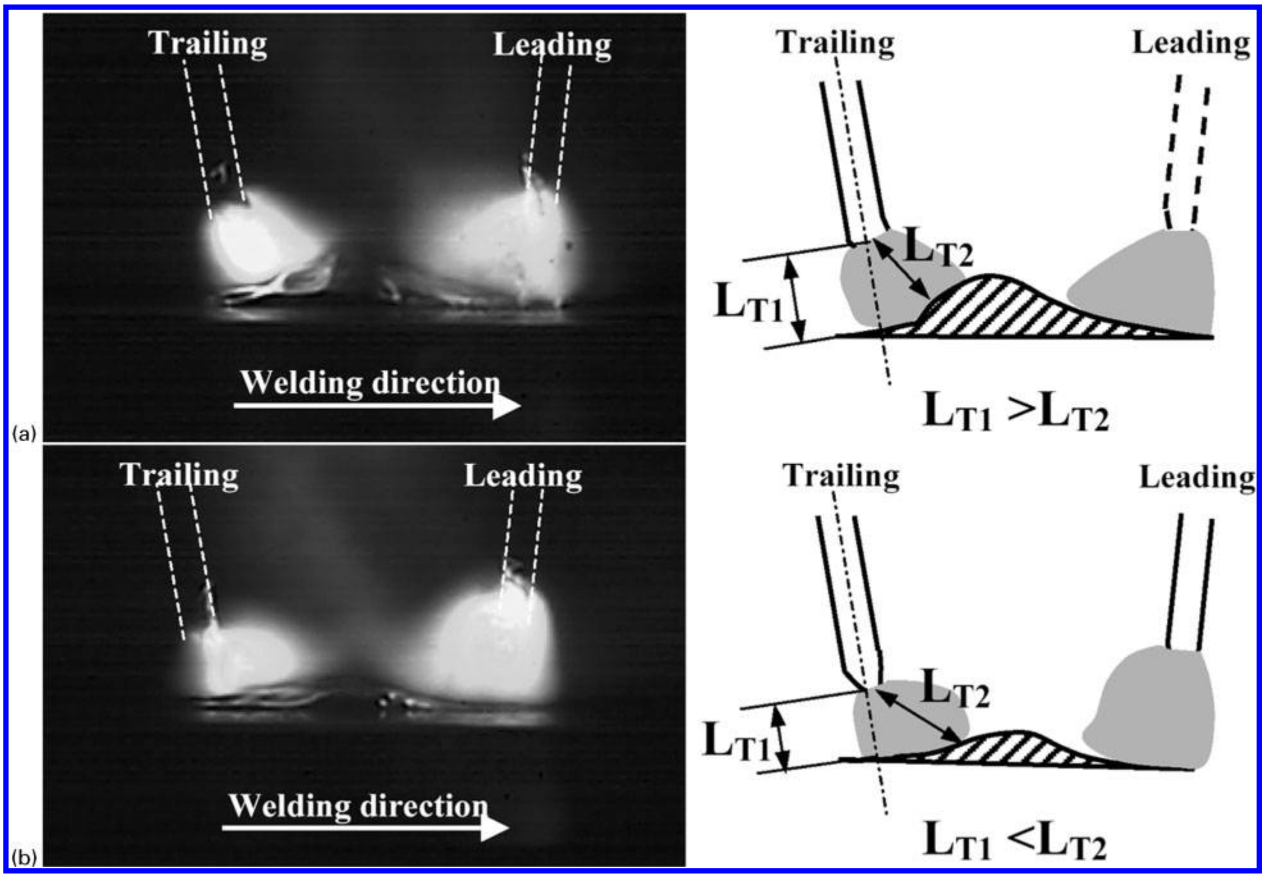
Figure 6 shows comparison between simultaneous phase and staggered phase pulse timing control for the incidence of arc interruption and the abnormal voltage in the trailing arc with the conditions of 10 mm interwire distance and 20 or 25%CO_2 mixture ratio in the Ar_2–CO_2 shielded gas. It became evident that in the case of the simultaneous phase, the incidence of abnormal voltage substantially decreased compared with the staggered phase and there were marked effects on abnormal voltage, and decreased occurrence of arc interruption achieved by means of simultaneous-phase pulse timing control.

However, abnormal voltage and arc interruption still occur with a trailing arc and it is hard to ascertain that simultaneous phase pulse timing control can prevent these from occurring entirely.

Figure 7 shows the results of arc phenomena during the occurrence of arc interruption by simultaneous phase pulse timing control. Frame (a) shows the state of the arc just before the completion of the pulse peak duration in both wires. Both arcs were deflected inward each other as they were subjected to mutual electromagnetic force and had an inclination towards the inner side with respect to the extension of the wire axis, but an strong arc stiffness was thought to be acting, caused by the PPC, and its inclination was minimal. At right after the fall from the PPC to the base current, a low base current occurred simultaneously in both wires, as shown in frame (b). Consequently, the degree of arc deflection owing to the effects of mutual electromagnetic force is assumed to have decreased simultaneously and both arcs showed an approximately similar degree of inclination compared with frame (a). However, as shown in frames (c) and (d), the root of the trailing arc moved toward the leading arc and the arc voltage rose. As soon as the leading arc reached the PPC duration, as shown in frame (e), the trailing arc was rapidly blown and the arc voltage rose sharply. In contrast, the PPC in the trailing



7 Occurrences of abnormal voltage and arc interruption by simultaneous phase pulse timing control



a abnormal voltage occurrence; *b* without abnormal voltage occurrence
8 Trailing arc on bulged molten metal just before abnormal arc voltage occurrence

wire flowed simultaneously with that in the leading wire, but the welding source output became insufficient because the arc voltage had already risen and the PPC could not be output. Only the arc voltage rose, as shown in frame (f), and eventually arc interruption occurred when the no load voltage was exceeded.

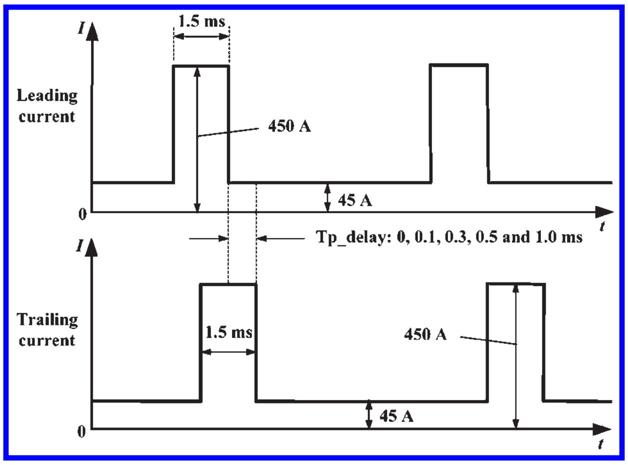
Furthermore, it became evident that although arc interruption did not result when the arc phenomena were observed in the case of abnormal voltage of the trailing arc, in most cases, just before the abnormal voltage, the root of the trailing arc moved onto the inclined surface of the bulged molten metal formed by the bulge between the wires, as shown in Fig. 8*a*.

Therefore, regarding the relationship of the geometry between the trailing arc and the bulged molten metal, when the distance L_{T2} between the inclined surface of the bulged molten metal and the wire tip is shorter than the distance L_{T1} between the molten pool just below the wire axis and the wire tip, as shown in Fig. 8*a*, the arc root is susceptible to be formed on the inclined surface of the bulged molten metal. As a result of approaching the leading arc, the root of the trailing arc is surmised to be susceptible to be drawn close, even though the leading arc is at the base current. In contrast, as shown in Fig. 8*b*, when the bulged molten metal is small and the bulge is leaning towards the leading arc and away from the trailing arc, the distance L_{T1} between the molten pool underneath the wire axis and the wire tip becomes shorter than the distance L_{T2} between the slanted surface of the basin and the wire tip, so the arc root of the trailing wire is likely to settle down at the molten pool underneath the wire. Consequently, it is assumed that the trailing arc is unlikely to approach the leading arc side and the arc root of the trailing arc is unlikely to be drawn close, and an abnormal voltage does not occur.

Development of arc interruption preventive measures

For the ac pulsed metal inert gas welding of aluminium alloys, there are problems with the occurrence of abnormal voltage and arc interruption caused by the cathode spot moving further away from the molten pool underneath the arc during the base current duration, in spite of successful restrike when the polarity is reversed from electrode negative to electrode positive. Tong and Ueyama[12] showed that the cathode spot can be returned to the vicinity of the molten pool by previous detection of arc interruption by means of observation of abnormal voltage rate and stimulation of prompt output of the succeeding PPC so that arc interruption during the normal base duration can be prevented.

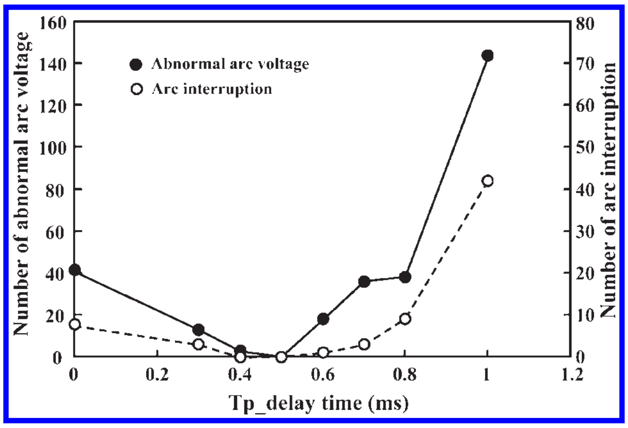
Accordingly, the start of the PPC flow through the trailing wire is delayed until after the start of PPC passing through the leading wire, as shown in Fig. 9; a method of pulse timing control was devised such that the phase of the PPC flowing through both wires is staggered slightly. An attempt was made to prevent abnormal voltage and arc interruption with the aim of achieving the effect of pulling back the cathode spot of the trailing arc near the molten pool underneath the arc by the stiffness of the high current arc[13] by PPC.



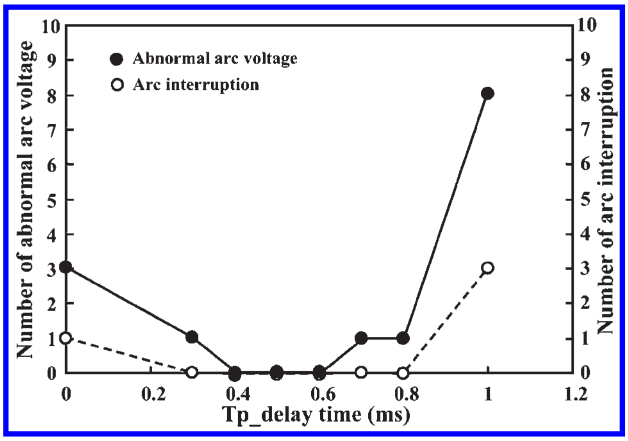
9 Pulse timing control with 0·5 ms delayed PPC for trailing arc

Figure 10 shows the effects of the delay time T_P_delay of the PPC completion on the occurrence of abnormal voltage and interruption of the trailing arc under a 75Ar$_2$–25CO$_2$ shielding gas atmosphere. When the T_P_delay was 0 ms, abnormal voltages occurred 40 times and arc interruption occurred 16 times. When the T_P_delay was set to 0·3 ms, the incidence of abnormal voltage decreased to less than one-third and the number of times where arc interruption occurred decreased to less than one-fifth. When the T_P_delay was 0·4–0·5 ms, the abnormal voltage became less than three times and the incidence of arc interruption was zero. When the T_P_delay became more than 0·6 ms, the incidence of both abnormal voltage and arc interruption increased; the incidences of both abnormal voltage and arc interruption were reduced compared with the simultaneous phase conditions where there was no provision of T_P_delay, up to 0·8 ms. However, when the T_P_delay was 1·0 ms, the trailing arc is thought to have been susceptible to influence by the leading arc, in which the PPC flowed, before the time when the trailing arc reached the PPC; the incidences of abnormal trailing arc voltage rise and arc interruption increased substantially compared with the simultaneous phase conditions where there was no provision of T_P_delay and the result had the opposite of the intended effect.

Figure 11 shows the effects of T_P_delay on the occurrence of abnormal voltage and arc interruption in the leading arc. The relationship between the T_P_delay time and the incidences of abnormal voltage and arc interruption shows a similarity to that of the trailing arc; however, the incidences of these were very low and the incidence of arc interruption was hardly noted within the range where the T_P_delay was 0·3–0·8 ms.



10 Effect of T_P_delay time on occurrences of abnormal voltage and arc interruption in trailing arc

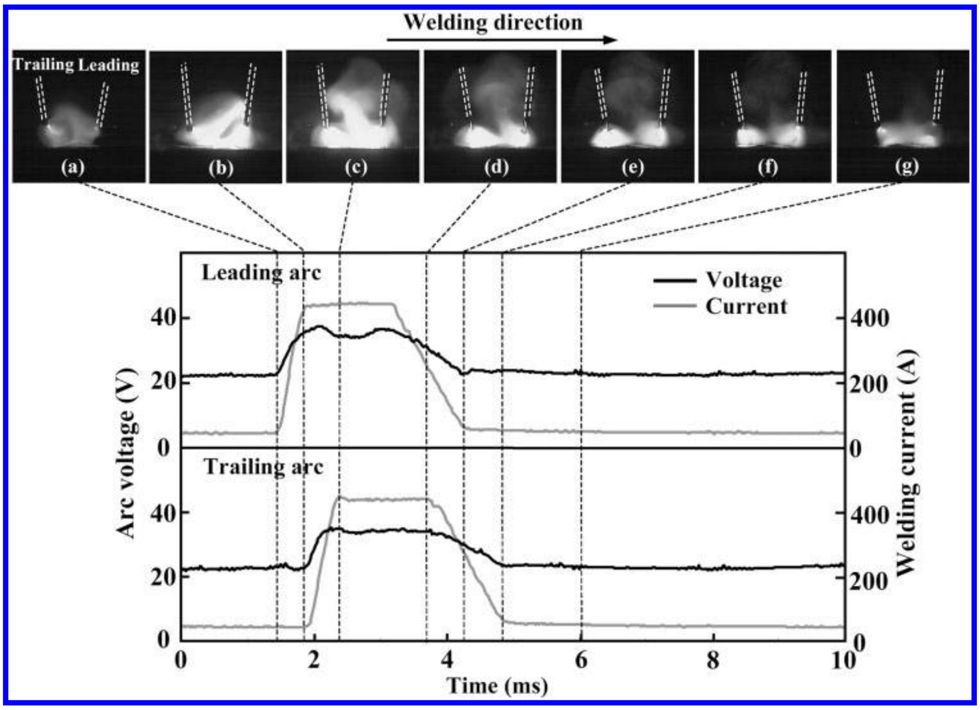


11 Effect of T_P_delay time on occurrences of abnormal voltage and arc interruption in leading arc

Figure 12 shows the results of observation of arc phenomena by means of pulse timing control where T_P_delay was set to 0·5 ms. As shown in frames (a) and (b), when the PPC was output to the leading wire, it was observed that the trailing arc root at the base current duration was drawn near the leading arc. However, due to the output of the PPC to the trailing arc 0·5 ms later, the arc root returned to the extension of the trailing wire axis, as shown in frame (c). PPC was output to both arcs at this stage so both arc roots inclined slightly to the inner side from the extension of the wire axis due to the mutual electromagnetic forces. When the leading arc fell to the base current, the trailing arc was drawn near due to its own arc stiffness, as shown in frames (d) and (e), and its arc root returned to the molten pool underneath the trailing wire axis. Even when the trailing arc reached the base current duration, as shown in frames (f) and (g), the arc root was hardly displaced and settled down above the molten pool underneath the wire axis.

Furthermore, in frames (d) and (e), the leading arc pressure was only released due to the fall of the leading arc to the base current; as a result of the susceptibility to bulged molten metal formation a little towards the leading arc, it became unlikely for the trailing arc root to run onto the inclined surface of the bulged molten metal. Consequently, as shown in frames (f) and (g), the arc root was formed with the cathode spot hardly moving towards the leading arc even though the trailing arc reached the base current duration and a stable arc was maintained until the PPC duration of the succeeding cycle.

In contrast, the leading arc reached the base current duration before the trailing arc but, as shown in frame (d), the leading arc was in the state where the current (~250 A) had fallen half way to the base current and was not easily subjected to the influence of the pull to the trailing arc, even though the trailing arc was at the PPC. Furthermore, at the time when the leading arc continued to be at the low base current, the trailing arc was by then halfway through the decline to the base current and was similarly not easily subjected to the effects of pull. Consequently, where a T_P_delay was set, abnormal



12 Arc phenomena in pulse timing control with 0·5 ms delayed PPC for trailing arc

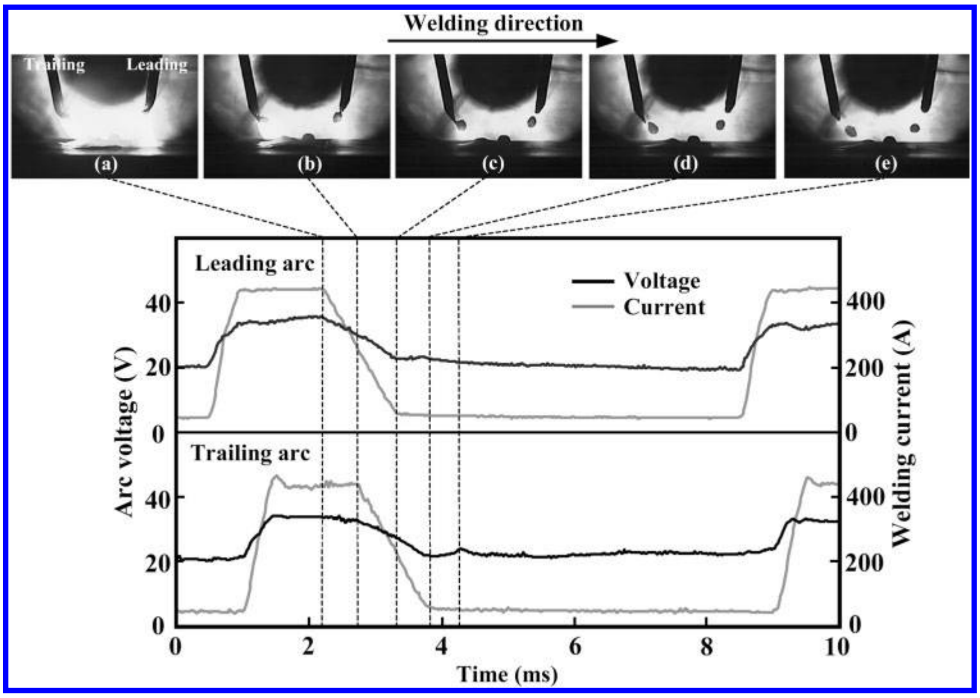
voltage and arc interruption were unlikely to occur even with the leading arc using pulse timing control.

Figure 13 shows the results of the metal transfer. The leading and trailing wires showed with stable one droplet per pulse transfer. When the pulse peaks occurred simultaneously in both wires, the arcs were pulled close to each other and the droplet were also subjected to these effects. However, by optimising the pulse current waveform conditions so that detaching the droplet from wire tip was appropriately timed after the completion of PPC duration, spatter was unlikely to occur and metal transfer did not deviate greatly from the wire axis.

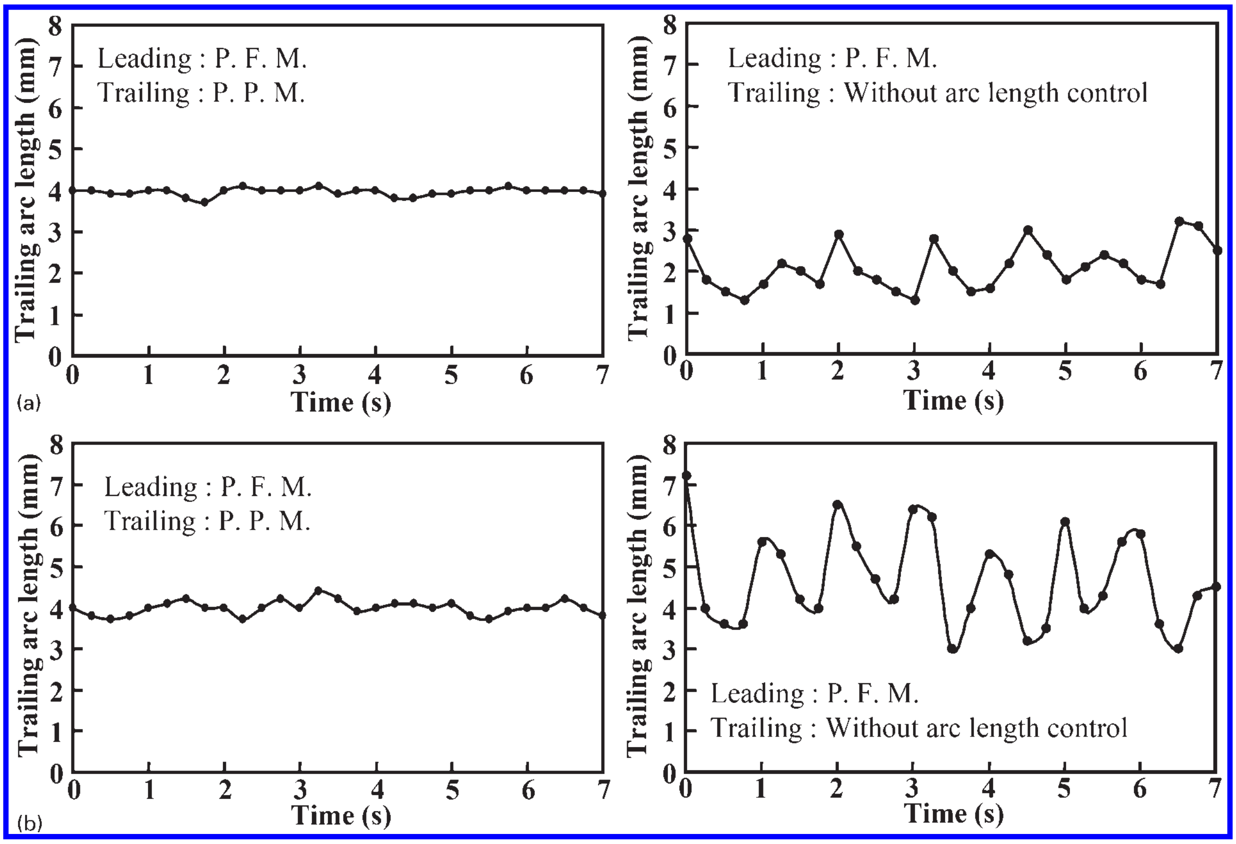
Arc length control

During TP-GMAW, the two wires are independently fed and the arcs are output. Therefore, external disturbances such as wire feeding fluctuations and variations in the wire extension are also assumed to occur individually.

On the other hand, in order to prevent arc interference between the two adjacent wires and subsequent arc interruption, a novel pulse timing control method for the pulse current in both wires was devised where a delay of 0·5 ms was provided to the timing of the trailing arc PPC against the timing of the leading arc PPC. However, it is necessary to control the arc lengths of



13 Metal transfer in pulse timing control with 0·5 ms delayed PPC for trailing arc



a fluctuation of leading wire feedrate; *b* fluctuation of trailing wire feedrate

14 Comparison of arc length fluctuation between PPM control and without control at trailing arc

the respective wires independently while maintaining this timing control. Accordingly, by the arrangement of the PFM system for the arc length control of the leading arc and the PPM system for the arc length control of the trailing arc, an attempt was made to arrange compatibility of the pulse timing control and independent arc length control for the leading and the trailing arcs respectively. In order to identify the efficacy of the scheme, the following experiment was carried out with the assumption of the case where feed fluctuations of several per cent could occur over a long cycle of less than 0·5 Hz, depending on the performance of the wire feeding motor. First, the feedrate for both the leading and trailing wires was set to 5 m min^{-1}. Second, the feedrate command was given to one or other of the wire feed units with the frequency 1 Hz and a fluctuation range of $\pm 10\%$ against the set wire feedrate. The trailing arc length fluctuations were then observed by means of high speed video photography (1000 frames/s).

Figure 14 shows the results of the relationship between the distance between the wire tip and the base metal with time. The distance between the wire tip and the base metal without feed fluctuation was 4 mm.

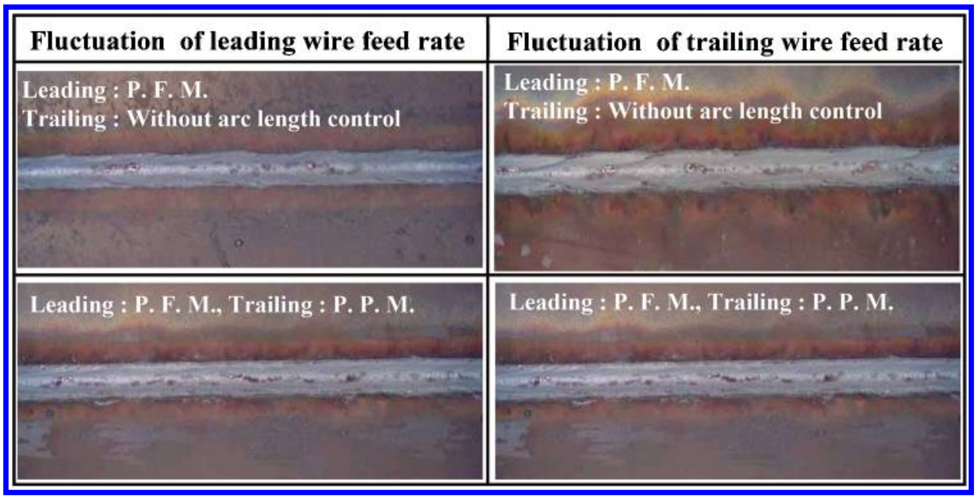
When a fluctuation signal was given to the leading wire feed command, the distance between the trailing wire tip and the base metal became as low as 2 mm. Arc length fluctuations of approximately ± 1 mm occurred when subjected to the effects of pulse frequency modulation of the leading arc where PFM was carried out for arc length control of the leading arc, and only pulse timing control but not arc length control was carried out for the trailing arc. By contrast, when both pulse timing control and arc length control were employed, there were few fluctuations in the distance between the trailing wire tip and the base metal and the gap previously set between the wire tip and the base metal was maintained.

When a fluctuating signal was given to the trailing wire feed command, the trailing wire had no control to compensate the arc length against the feed fluctuations. The distance between the wire tip and the base metal substantially fluctuated in response to the feed fluctuations where PFM was carried out for arc length control of the leading arc and only pulse timing control but not arc length control was carried out for the trailing arc. In contrast, with the employment of both pulse timing control and arc length control, the trailing arc varied on the external characteristic curve where the PPC had a gradient of -10 V/100 A for the feeding fluctuations. The arc length was compensated for this so that the distance between the trailing wire tip and the base metal hardly fluctuated and the previously set distance between the wire tip and the base metal was maintained.

Figure 15 shows the bead appearance obtained by the test welding carried out for Fig. 14. When the arc length control of the leading arc was carried out by PFM and pulse timing control only, but not arc length control, was carried out for the trailing arc, undulated bead appearance was seen for feed fluctuation of either the leading or trailing wire; in contrast, with the use of both pulse timing control and arc length control, arc length fluctuations did not take place and a bead appearance of almost uniform width was evident.

Conclusions

1. When the value of the base current in the trailing arc is increased, the frequencies of the occurrence of



15 Comparison of bead appearance between PPM control and without control at trailing arc

abnormal voltages and arc interruptions decrease, and these problems can be avoided with the value of the base current set to 120 A. However, with the set base current value at 120 A, one droplet per pulse transfer synchronised with the pulse becomes difficult and this becomes a primary factor for the occurrence of spatter.

2. Simultaneous phase pulse timing control, where PPC flows simultaneously to the leading and trailing wires, had the effect of reducing the occurrence of abnormal voltage and arc interruption; however, these could not be prevented entirely for the trailing.

3. During pulse timing control, where the PPC in the trailing wire was slightly delayed against the start of the PPC in the leading wire, arc interruptions in the leading and trailing arcs could be prevented with a delay time $T_{P\_}$ delay in the range of 0·4–0·5 ms for the completion of PPC in the trailing arc. Furthermore, a stable one droplet per pulse transfer was also made feasible.

4. A technique was devised for the compatible use of both pulse timing control and independent arc length control for the leading and trailing arcs by means of a PFM system for the leading arc length control and a PPM system for the trailing arc length control and the efficacy was clarified.

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