Arc interference and a unique push–pull arc solution in alternating current plasma arc welding of aluminium alloys

B Zheng[1], **Q L Wang**[2] and **R Kovacevic**[1]*
[1]Department of Mechanical Engineering, Southern Methodist University, Dallas, Texas, USA
[2]Welding Engineering Department, Harbin Institute of Technology, Harbin, People's Republic of China

Abstract: This paper analyses the arc interference in an a.c. combined (both the pilot arc and the plasma arc exist in the welding process) plasma arc welding of aluminium alloys. This phenomenon results in an unstable welding process and weld formation. To maintain the pilot arc during the period when the electrode is positive, a cathode region must be formed in front of the tungsten electrode tip. However, to guarantee plasma arc initiation during the same period, this region must be the anode region. Consequently, neutralization of the positive and negative charge in the region in front of the tungsten electrode tip will occur. This will result in the instantaneous disappearance of the conducting region in front of the tungsten electrode tip, which will cause the plasma arc or pilot arc or both to be instantaneously extinguished. Arc interference appears because the potential of the nozzle is unable to adapt to that of the conducting plasma arc column in the d.c. positive electrode mode. A unique push–pull arc solution for solving the trade-off between the arc interference and the reliable initiation of the a.c. plasma arc is proposed and implemented. In addition, high-quality weld formation in the keyhole mode, which is energy efficient and avoids a double arc, is achieved.

Keywords: a.c. PAW, arc interference, potential of the nozzle, push–pull arc

1 INTRODUCTION

For welding aluminium alloys, it is preferable to use a.c. technology in plasma arc welding (PAW) or gas–tungsten arc welding (GTAW) [**1**, **2**]. This is because the oxide film existing on the workpiece surface cannot be removed in a welding process using only the d.c. electrode negative (DCEN) mode. In this case, a sound weld bead cannot be easily achieved because the oxide film impedes the flow of molten metal in the weld pool. However, although the oxide film can be removed in the d.c. electrode positive (DCEP) mode by the cathodic cleaning action of the arc, the deterioration in the tungsten electrode is much more severe than that in the case of the DCEN mode [**3**, **4**]. Consequently, both the arc and the welding processes are extremely unstable. The trade-off between the oxide film removal and the tungsten electrode deterioration can be fairly well solved by using an a.c. welding power source. This technology features the combination of DCEP and DCEN mode.

In an a.c. welding process, an arc needs to be initiated in every period of DCEP because the electrons cannot be easily emitted from the workpiece, i.e. the cold cathode. Hence, a d.c. pilot arc between the nozzle and the tungsten electrode is initiated at the start of welding and maintained throughout the process [**1–3**]. According to the original design, this pilot arc can set up a conducting path between the tungsten electrode and the workpiece for the plasma arc. Therefore, plasma arc initiation is guaranteed at the beginning of the welding process and also in the period of DCEP during the so-called combined a.c. PAW process.

For the combined a.c. PAW, there still exists the following possibility. Some of the current from the plasma arc welding power source in the period of DCEP may flow through the pilot arc power source.

The MS was received on 20 November 1997 and was accepted after revision for publication on 13 August 1998.
**Corresponding author: Department of Mechanical Engineering, Southern Methodist University, PO Box 750337, Dallas, TX 75275, USA.*

Also, some of the current from the pilot arc power source may flow through the plasma arc welding power source. Since the combined a.c. PAW is generally used for welding plates of aluminium alloys less than 6.0 mm in thickness, the maximum welding current is about 120 A. Thus, these possible current flows will not cause damage to the rectifier inside the pilot arc power source or nozzle. However, in the case of welding thicker plates of aluminium alloys, the existence of this type of current flow will result in an unstable arc and weld formation in a.c. PAW, and even in damage to the rectifier inside the pilot arc power source. The objective of this paper is to present a solution for achieving a stable a.c. plasma arc that will result in stable weld formation in the keyhole mode.

2 EXPERIMENT SET-UP

A schematic diagram of a conventional combined a.c. PAW set-up is shown in Fig. 1. The plasma arc welding power source 2 and the pilot arc welding power source 1 are a Syncrowave-300 (S) a.c./d.c. power source and a d.c. transformer rectifier power source respectively. The maximum currents obtained from the power sources are 300 A and 30 A respectively. The rated current of the water-cooled welding torch is 300 A. The resistance R_1 of the variable resistor R1 is in the range 0–10 Ω. The function of R1 is to limit the flow of current from the plasma arc power source through the pilot arc power source. When R_1 equals 0 Ω, the pilot arc current value is not readable on the current probe and the power diodes D inside the pilot arc power source are often damaged because of the current flow from the plasma arc power source in the DCEP period (SCR2 in Fig. 1 is enabled). Also, a double arc easily forms between the nozzle and the workpiece. When R_1 is increased to 1.0 Ω and the plasma arc is initiated, the diodes D are not damaged. As R_1 increases, the pilot arc current decreases. When R_1 is increased to 5.2 Ω, the maximum output current from the pilot arc power source is 20 A. Therefore, to avoid the double arc and the damage of the power diode, R_1 is fixed at 5.2 Ω for the following experiment.

3 EXPERIMENTAL PROCEDURE

The weld bead was made in the vertical-up position with melt-in mode or keyhole mode. The welding conditions are shown in Table 1. The welding material is aluminium alloy 2024 plates with a thickness of 4.0–8.0 mm. The plasma arc voltage and pilot arc voltage were observed with an oscillograph during the welding process.

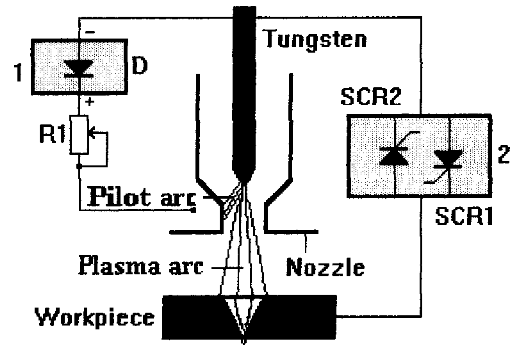

Fig. 1 Electrical block diagram of conventional a.c. PAW: 1, d.c. pilot arc power source; 2, a.c. welding power source; SCR1, SCR2, thyristors; D, set of diodes

4 RESULTS AND DISCUSSION

4.1 Results

The results of the welding experiments are as follows:

1. At the beginning of welding, when the power source 2 is enabled after the pilot arc is initiated, the pilot arc often extinguishes and the plasma arc cannot be initiated.
2. When the plasma arc is initiated and the a.c. is higher than 120 A, the plasma arc is unstable and loud arc noises are present. When the a.c. is lower than 120 A, the plasma arc is stable in most cases.
3. The pilot arc voltage between the tungsten electrode and the nozzle is a d.c. voltage without the presence of the plasma arc. When the plasma arc is initiated and stable, the pilot arc voltage will change into an a.c. voltage with the same frequency as the a.c. plasma arc voltage. When the a.c. is higher than 120 A, the pilot arc voltage randomly varies from a.c. to d.c. voltage. In this case, the plasma arc voltage changes from a.c. to d.c. voltage with a synchronous change of the pilot arc voltage. However, the voltage across R1 is still a continuous d.c. voltage whether the plasma arc is stable or not. This means that the pilot arc power source outputs continuous

Table 1 Welding conditions

Initial welding current during start-up segment (A)	80–100
Welding current during main body segment (A)	80–160
Plasma arc voltage (V)	27
Plasma gas flowrate (m^3/min)	8.0×10^{-3}
Shielding gas flowrate (m^3/min)	10.5×10^{-3}
Welding speed (m/min)	0.08
Time ratio of DCEN to DCEP (%)	68/32
Pilot arc current (A)	5–20
Pilot arc voltage (V)	27
Plasma arc voltage (V)	27
Resistance R_1 (Ω)	0–10
Torch stand-off (mm)	4–6
Orifice diameter (mm)	4
Orifice length (mm)	4
Tungsten set-back (mm)	4

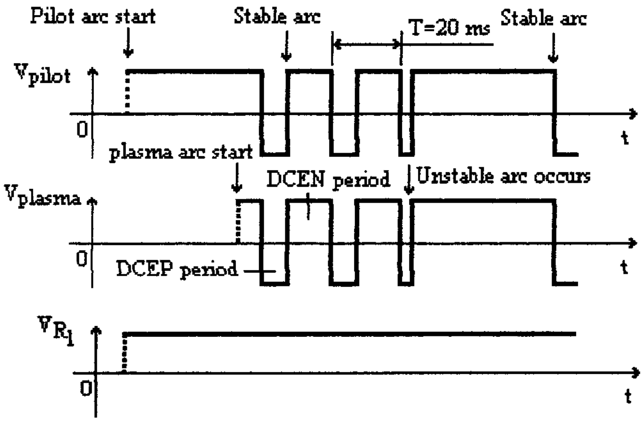

Fig. 2 The voltage waveform when unstable arc occurs

current during the process. The above voltage variations are shown in Fig. 2.

4. When the combined d.c. PAW in DCEP mode is adopted, the phenomenon of an unstable arc is more severe than with the same current in a.c. PAW. While the combined d.c. PAW in DCEN mode is adopted, the plasma arc is stable regardless of whether the current is higher than 120 A.

The above-mentioned results show that there exists a serious unstable arc problem in a.c. PAW, especially in welding thicker plates with a higher current. This problem, defined in this paper as arc interference, is closely related to the arc behaviour during the DCEP period in an a.c. PAW process.

4.2 Discussion

The best way to analyse the arc behaviour is to know the electric charge status inside the nozzle passage during welding. However, it is currently impossible to measure or record it because of the high temperature inside and inaccessibility, but the arc behaviour in the welding process could be analysed on the basis of the theory of arc physics.

4.2.1 Arc behaviour in the DCEP period

For comparison, in the DCEN mode, the possible direction of current flow and the distribution of the electric charges are shown in Fig. 3a and Fig. 4a respectively. In the DCEP mode, the possible flow of current is shown in Fig. 3b. The current I_{p1}, which is used for maintaining the pilot arc and is provided by power source 1, flows through the path R1 → nozzle → upper part of the conducting arc column → tungsten electrode → power source 1. The current $I_{p2,}$ which is also provided by power source 1, flows through the path R1 → nozzle → lower part of the conducting arc column → workpiece → SCR2 inside power source 2 → tungsten electrode → power source 1. This was confirmed by the increase in current measured by the current probe inside power source 2. There are three possible current flow paths for the output current from power source 2. The first path for I_{M1} is power source 2 → tungsten electrode → conducting arc column → workpiece → power source 2. The second path for I_{M2} is power source 2 → tungsten electrode → upper part of the conducting arc column → nozzle → lower part of the conducting arc column → workpiece → power source 2. The third path for I_{M3} is power source 2 → power source 1 → R1 → nozzle → lower part of the conducting arc column → workpiece → power source 2. This was also confirmed by the increase in current measured by the current probe inside the power source 1. So, the total current flowing through power source 1 is the sum of I_{p1}, I_{p2} and I_{M2}, while the total current flowing through power source 2 is the sum of I_{M1}, $I_{M2,}$ I_{M3} and I_{p2}. This means that a part of the output current, generated by one power source, will flow through the other power source, and the nozzle will easily conduct the current from the power source 2. In this case, a double arc forms more easily because of I_{p2}, I_{M2} and I_{M3}.

Based on the theory of arc physics [**5**, **6**], to maintain the pilot arc, it is necessary that the positive charge for I_{p1} exists in the region adjacent to the tungsten electrode tip (Fig. 4b). However, to maintain the plasma

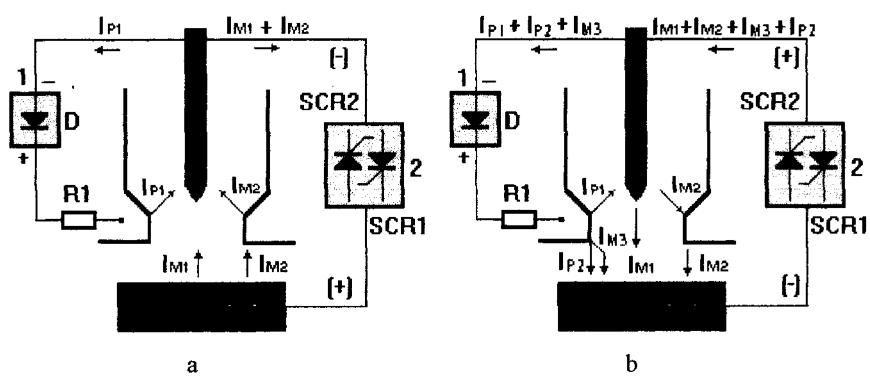

Fig. 3 Direction of the welding current in a.c. PAW (a) in DCEN mode and (b) in DCEP mode

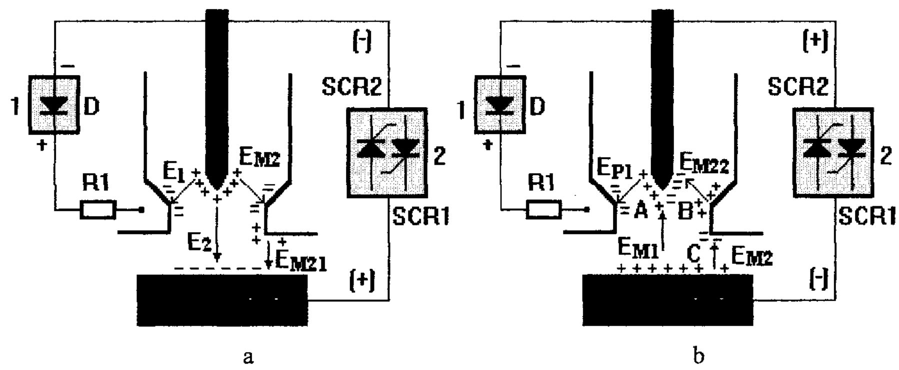

Fig. 4 Distribution of electric charges adjacent to the surfaces of the tungsten, the nozzle and the workpiece in a.c. PAW (a) in DCEN mode and (b) in DCEP mode

arc, a negative charge in the region adjacent to the tungsten electrode tip for I_{M1} should exist, while a positive charge for I_{M2} in the region adjacent to the workpiece surface is needed. Therefore, in the region adjacent to the tungsten electrode tip, for a pilot arc there should exist a cathode drop region with positive charges, but for a plasma arc there should exist an anode drop region with negative charges. However, it is impossible to have both the anode drop and the cathode drop region at the same time and in the same region for an arc discharge.

If I_{M2} exists, the charges accumulated in region B (see Fig. 4b), adjacent to the upper inner surface of the nozzle, and in region C, adjacent to the exit of the nozzle, will be positive and negative respectively. The charges accumulated in region A, adjacent to the upper surface of the nozzle, will be negative if I_{p1} exists. Therefore, the electric field E_{p1} of the conducting arc column for I_{p1} and the electric field E_{M22} of the conducting arc column for I_{M2} are both needed. This means that two regions would exist, with positive and negative charges respectively, adjacent to both the tungsten electrode tip and the upper surface of the nozzle. That is, E_{p1} and E_{M22} would be separated and possess opposite directions.

In fact, the charges that are accumulated in the region adjacent to the tungsten electrode tip are determined by the potential of the tungsten electrode. These charges are also correlated to the potential of the nozzle. The reason for this is as follows. On the one hand, the potential of the nozzle is dependent upon the power source 1 because of its connection to one end of R1 (the other end of R1 is connected to the positive terminal of the power source 1, shown in Fig. 4b). On the other hand, the potential of the nozzle is also dependent on the potential of the conducting plasma arc column. Thus, there are two possibilities.

1. If the effect of the former factor on the potential of the nozzle is larger than that of the latter factor, the potential of the nozzle will be positive, and region B will not exist. This means that E_{M22} will not exist. Thus, the charges accumulated in the region adjacent to the upper surface of the nozzle will be negative. The charges accumulated in the region adjacent to the tungsten electrode tip will be positive. This is because the negative terminal of the power source 1 is connected to the tungsten electrode. In this case, only region A and E_{p1} for I_{p1} will exist and the pilot arc will be maintained. The voltage between the nozzle and the tungsten electrode will be positive. The negative charges accumulated in the region adjacent to the tungsten electrode tip will not exist. Therefore, it will be unfavourable to maintain a plasma arc in this case. The plasma arc will extinguish because I_{M1} does not exist.
2. In the case when the potential of the nozzle is negative, region A will not exist, and E_{p1} will not exist either. The charges accumulated in the region adjacent to the upper surface of the nozzle are positive. In this case, there will only be E_{M1} for I_{M1} (probably there will also be E_{M2} for I_{M2}), and the plasma arc will be maintained and the pilot arc will extinguish.

In short, the above-mentioned charges in the DCEP period, which are accumulated in the region adjacent to the tungsten electrode tip, are to some extent dependent on the potential of the nozzle in the conducting plasma arc column. They will affect the stability of the pilot arc or plasma arc; i.e. either of the two arcs will go off instantaneously. This phenomenon is defined as arc interference. If the pilot arc extinguishes, the plasma arc will be maintained and will be stable, and the welding process will be stable, too. If the plasma arc extinguishes, the pilot arc will be maintained, and the welding process will be unstable. In this case, the stability of weld formation cannot be guaranteed, especially in the keyhole mode.

The potential of the nozzle with respect to the tungsten electrode is related to some random factors, such as the resistor R1, the power source 2, the power source 1, the tungsten electrode set-back and the torch stand-off. Therefore, the potential of the nozzle is also a random value, which will make the phenomenon of arc interference a random phenomenon in an a.c. PAW process. This was confirmed in the combined d.c. PAW experiment with the DCEP mode. In the combined d.c. PAW experiment with the DCEN mode, this was also confirmed if the nozzle and tungsten electrode are connected to the negative and positive terminals of the power source 1 respectively.

If the plasma arc current I_{M1} exists, flowing through the path tungsten electrode → conducting arc column → workpiece, the total output current from the power source 1 will be I_{p2}, shown in Fig. 3b. The potential of the nozzle does not conflict with that of the conducting plasma arc column because the negative charge will accumulate at the exit surface of the nozzle in region C. With N_2 as the plasma gas in a d.c. transferred plasma cutting with the DCEP mode, it was found that the potential (−70 V) of the nozzle is close to that of the conducting arc column (−80 V) at the exit of the nozzle passage [**7**]. A double arc therefore does not easily form. However, if the potential of the nozzle is raised because of its connection to one end of R1, the potential difference between the nozzle and region C will increase to some extent. The circular film wall of the cooling gas between the plasma arc column and the orifice easily breaks down, and a double arc easily forms because of the current I_{p2}. The current I_{M2} may form if the resistance of the inner plasma column through the nozzle passage (orifice) is higher than the body resistance of the copper nozzle itself. The double arc current will consist of I_{p2}, I_{M2} and I_{M3}. In reference [**1**], the following phenomenon was also found: a double arc easily forms if the DCEP period in variable-polarity PAW is more than 6.0 ms, and the stability of both the welding process and the weld formation in the keyhole mode will be significantly decreased. To avoid a double arc, the DCEP period should be less than 6.0 ms (normally 3.0–4.0 ms). From the above analysis, it can be concluded that this phenomenon possibly results from the higher current I_{M3} and I_{P2}.

The resistor R1 limits the current I_{M3} flowing through the power source 1; therefore, the current I_{M1}, the majority of the output current from power source 2, cannot be significantly decreased and the life of the nozzle is improved. If R1 is removed, arc interference will not occur, but the diodes inside the power source 1 may be damaged and the nozzle may easily burn down. Furthermore, the plasma arc will not be well constricted. Thus, there is a trade-off here. On the one hand, the purpose of using the power source 1 is to initiate the plasma arc at the instant of polarity transformation of the power source 2 from the DCEN period to the DCEP period. However, there is arc interference in the DCEP period when R1 is present. On the other hand, there is no arc interference without the power source 1, but the plasma arc cannot be reliably initiated in the DCEP period.

4.2.2 *Arc behaviour at the start-up segment when the a.c. welding power source 2 is enabled*

When the power source 2 is enabled to output current at the start-up welding segment, the plasma arc is difficult to initiate after the pilot arc is initiated and the pilot arc often extinguishes automatically. Based on the mechanism of arc interference mentioned above, this phenomenon could be fairly well understood. The charges, which are favourable to maintain the pilot arc, will be neutralized if the output polarity of power source 2 is just in the DCEP period. This is because the power source 2 tries to initiate the plasma arc. The negative and positive charges, being favourable for the plasma arc, should be accumulated in the region adjacent to the tungsten electrode tip and the upper surface of the nozzle, and the positive charges should be accumulated in the region adjacent to the workpiece surface. Since the temperature of the pilot arc column in this case is much lower than that of the plasma arc in the welding process, once the positive charge is neutralized, the pilot arc will extinguish because I_{p1} does not exist. At this moment, if insufficient negative and positive charges are accumulated to the nozzle surface at the exit of it and to the workpiece surface, the plasma arc and the arc between the nozzle and the workpiece will not be initiated.

4.2.3 *Arc behaviour at the start of the DCEP period transforming from the DCEN period in the welding process*

In a welding process, the temperature of a conducting plasma arc column is high, and the ionizing status of the arc column is in a good condition. There is thus a possibly instantaneous process that the output current I_{p1} from the power source 1 changes into I_{p2} at the beginning of the DCEP period (see Fig. 3b). As I_{p1} decreases, the amount of charges adjacent to the surfaces of the nozzle, tungsten electrode tip and workpiece, which are needed for I_{p2} and I_{M1}, will increase. This is because the efflux of the bright cone of the pilot arc from the exit of the nozzle contacts the workpiece surface. In this case, when the amount of the charges for I_{p2} is enough, the arc between the nozzle and the workpiece will initiate. However, at this instant, the pilot arc may not have gone off yet. This condition is very favourable to initiate the plasma arc. Therefore, the plasma arc may be easily initiated with the help of I_{p1} and I_{p2}. Once the plasma arc initiates, I_{p1} will be decreased to zero and the total output current from the power source 1 will be I_{p2}. The potential of the nozzle will be negative.

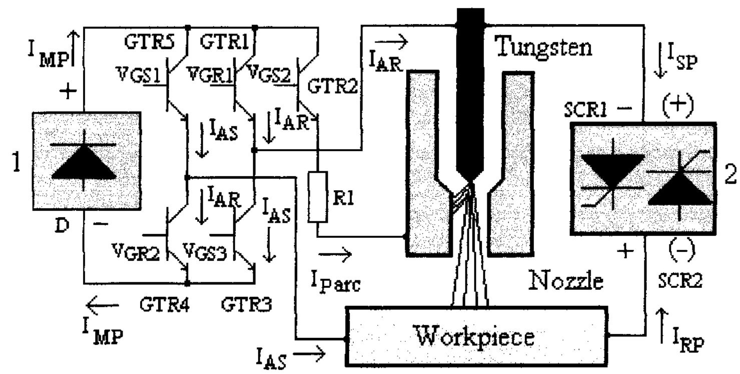

Fig. 5 A push–pull arc solution to arc interference in a.c. PAW: 1, d.c. welding power source; 2, a.c. welding power source

5 THE PUSH–PULL ARC SOLUTION TO ARC INTERFERENCE

There are three possible solutions to arc interference in a.c. PAW:

1. Decrease the DCEP time and/or the magnitude of the DCEP current.
2. Change the potential of the nozzle.
3. Switch off the pilot arc power source.

The first two solutions may just reduce the times of arc interference but not avoid it. The last solution is effective, but the initiation of the DCEP plasma arc should be guaranteed.

Based on the experimental results and performed analysis, a unique solution to the DCEP plasma arc initiation and arc interference avoidance is presented in Fig. 5. This solution makes use of the pilot arc and the arc between the nozzle and the workpiece at the transition from the DCEN period to the DCEP period during the welding process. The d.c. power source 1 is also used as a continuous welding power source, but its output current is changed into an a.c. with the help of transistors GTR1 to GTR5, which constructs an H-bridge. The current I_{P_1} from the power source 1 is used as a pulse current for initiating the plasma arc at the beginning of every DCEP period. This means that the arc between the tungsten and the nozzle is a pilot arc for a very short period: from t_2 to t_4 (shown in Fig. 6). Therefore, the pilot arc is a discontinuous arc. After the plasma arc is initiated, during the rest of the time (from t_5 in the DCEP period to t_2 in the following DCEN period), the current from the d.c. welding power source 1 is also used as a part of the plasma arc current. This current will flow through the conducting plasma arc column between the tungsten electrode and the workpiece. In this case, the pilot arc and the plasma arc will consist of a type of push–pull arc; the DCEP plasma arc is initiated with the help of the discontinuous pilot arc that is initiated with the help of the DCEN plasma arc. The results of the experiment show that the trade-off between avoiding arc interference and initiating the DCEP plasma arc can be solved very well. Furthermore, the current from the d.c. welding power source 1 can be used to heat the workpiece. This is favourable for utilizing energy efficiency and for avoiding nozzle overheating. The double arc can also be avoided to a great extent, and weld formation in the keyhole mode can be guaranteed. The photographs of the voltage waveforms related to the push–pull arc solution are shown in Fig. 7. The photographs of weld bead on plates 10 mm thick are shown in Fig. 8 with 210 A output current from the a.c. plasma arc power source.

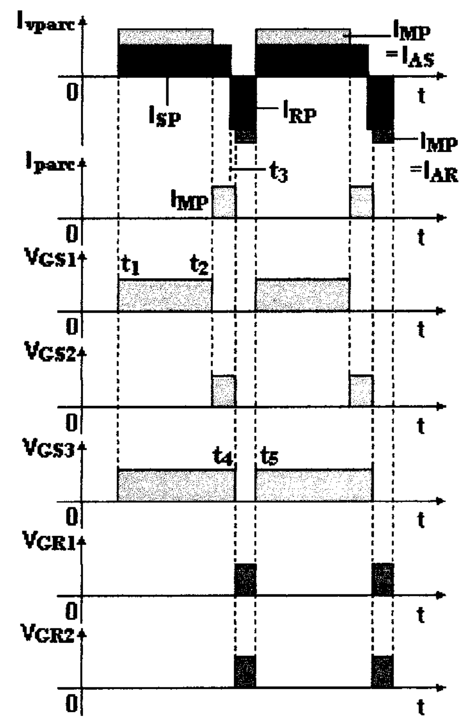

Fig. 6 Scheme of waveforms of welding currents and voltages related to the push–pull arc solution

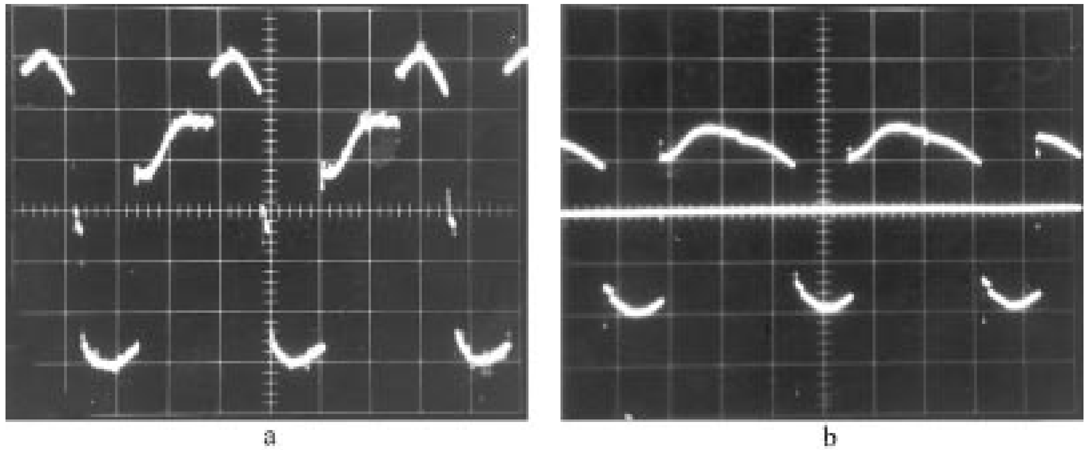

Fig. 7 Photographs of the voltage waveforms in push–pull arc a.c. PAW of aluminium alloys showing (a) the voltage between the nozzle and the tungsten and (b) the plasma arc voltage

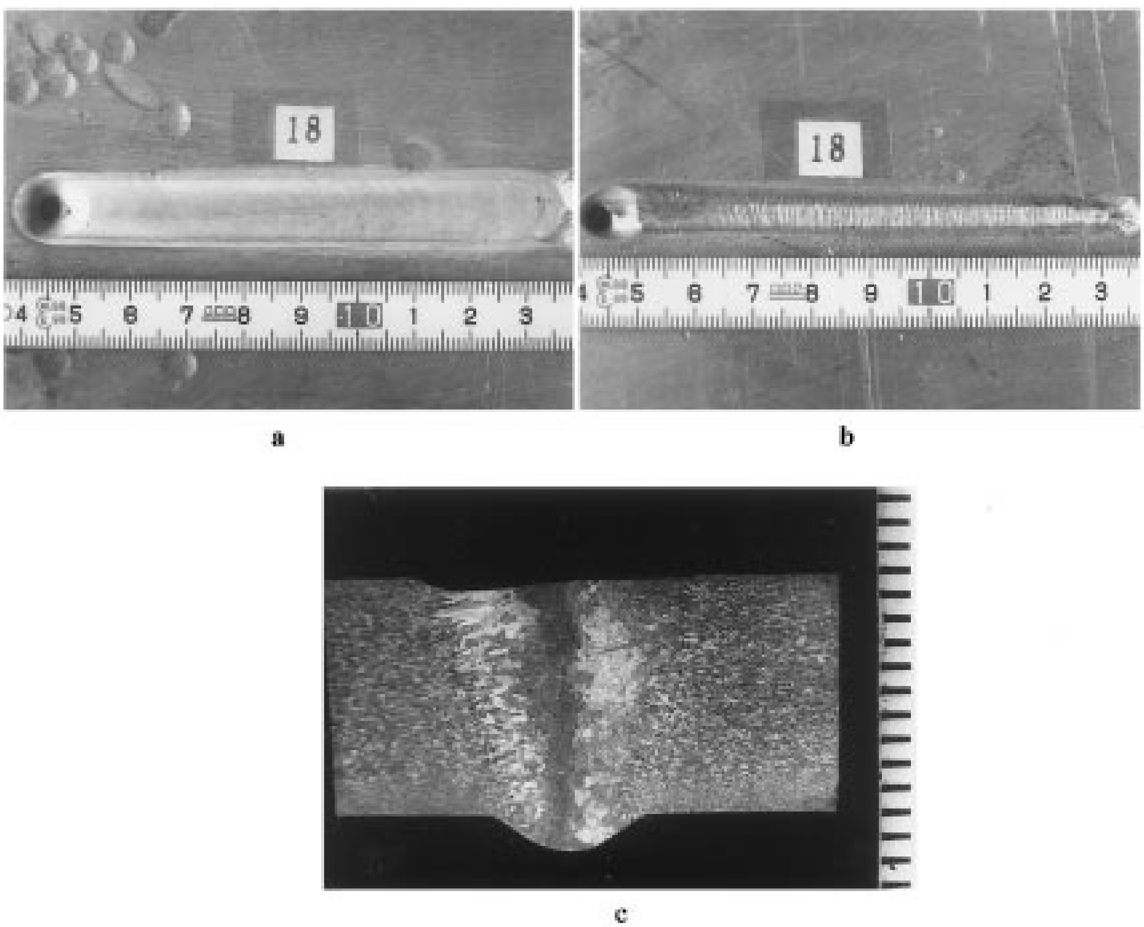

Fig. 8 Photographs of weld formation using the push–pull arc: (a) top side, (b) bottom side and (c) cross-section

6 CONCLUSIONS

1. Arc interference exists in a combined a.c. PAW of aluminium alloys, which results in an unstable welding process and weld formation.
2. The mechanism of arc interference is reflected in the form of neutralization of the positive charge and negative charge that are accumulated to the adjacent surface of the tungsten electrode tip during the DCEP period. Arc interference occurs because the

nozzle potential is unable to adapt to that of the conducting plasma arc column.

3. The DCEP plasma arc can be reliably initiated with the help of both the pilot arc and the arc between the nozzle and the workpiece at the transition from the DCEN period to the DCEP period in a welding process.
4. The push–pull arc solution is an effective way to solve the trade-off between the arc interference avoidance and initiation of the DCEP plasma arc in a.c. PAW of aluminium alloys and guarantees the stability of the weld formation in the keyhole mode. Other features of the solution are the utilization of energy efficiency and the avoidance of a double arc.

ACKNOWLEDGEMENTS

The authors wish to thank the National Key Laboratory of Advanced Welding Production Technology of the People's Republic of China for its funding and support from the Southern Methodist University, Dallas, Texas, USA.

REFERENCES

1 **Nunes, A. C.** and **Bayless, E. O.** Variable polarity plasma arc welding on the space shuttle external tank. *Weld. J.*, 1984, **36**(9), 15–25.
2 **Zheng, B.** and **Wang, Q. L.** Forming conditions of keyhole puddle in aluminum alloys during vertical-up a.c. PAW process. *Weld. Trans.*, 1993, **14**(3), 162–171.
3 **Dong, S. S.** and **Li, T. W.** Study of a.c. square wave plasma arc welding of aluminum alloys. In Proceedings of the Academic Exchanging Conference, 1983 (Harbin Institute of Technology, Harbin).
4 **Dong, T.** Development of a.c. square wave power source for plasma arc welding with dual-passages. *Welding*, 1985, **5,** 10–16.
5 **Lancaster, J. F.** *Physics of Welding*, 1984 (Pergamon, Oxford).
6 **Ando, K.** *Arc Phenomenon* (translated from Japanese), 1985 (Mechanical Industry Publication, Beijing).
7 **Li, T. W.** and **Wang, Q. L.** Study of the electric characteristic of the nozzle for transferred plasma arc cutting. In Proceedings of Papers of Welding Conference, Hangzhou, PR China, 1984 (Mechanical Industry Publication, Beijing).

