Effect of plasma welding current on heat source penetration ability of plasma-GMAW hybrid welding

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Abstract
The weld penetration under different plasma welding currents was compared in the plasma-gas metal arc welding (GMAW) hybrid welding of aluminum alloy. When the plasma welding current was lower than 150 A, the hybrid welding penetration was greater than the sum of the single plasma welding and the single GMAW penetration. When the plasma welding current reached 130 A, with the increase of the plasma welding current, the advantage of the weld penetration of the hybrid welding was gradually weakened, compared with that of the single welding. The above change mechanism is revealed from heat source energy distribution and molten pool stress. The results show that when the plasma welding current is lower than 110 A, the area of the high-temperature region in the arc zone of GMAW in the hybrid welding increases, compared with that in the single GMAW. The trend of arc energy transfer to the penetration direction increases under the action of arc pressure, arc shear force, electromagnetic force, and droplet impact. With the increase of plasma welding current, the high-temperature area of the GMAW arc first increases and then decreases. When the plasma current reaches 130 A, the effect of arc pressure, arc shear force, electromagnetic force, and droplet impact on increasing the penetration begins to weaken.

Keywords Penetration ability · Hybrid welding · Pool behavior · Plasma-GMAW

1 Introduction
Gas metal arc welding (GMAW) is widely used in aluminum alloy welding because of its easy automation and high production efficiency [1]. When welding thick-plated high-strength aluminum alloys using GMAW process, the weld requires multilayer welding because the GMAW arc energy is not concentrated. However, high heat input will lead to a series of welding problems, such as coarse grain, and crack, which will reduce the mechanical properties of welded joints [2]. In order to solve the above problems, the high energy beam was combined with GMAW to increase the penetration and reduce the welding heat input. The most common is laser-GMAW hybrid welding and plasma-GMAW hybrid welding. For laser-GMAW hybrid welding, aluminum alloy has a strong reflection on laser, and plasma absorbs laser energy, which reduces laser efficiency. Moreover, pores are easily formed due to the high welding speed [3]. Plasma-GMAW hybrid welding can effectively avoid the above problems.

According to the relative position of the heat source space, plasma-GMAW hybrid welding is divided into coaxial and paraxial. In 1972, Essers and Liefkens [4] in Philips Research Laboratories firstly introduced the coaxial plasma-GMAW process. The wire is surrounded by double arcs and the number of melting coating increases [5–7]. However, due to the plasma arc surrounding the GMAW arc, the plasma arc compression effect decreases. Nonetheless, given the coaxial welding torch structure and the coupling effects between the plasma and GMAW arc [8, 9], the arc divergence has the effect of reducing the speed of the droplets arriving at the weld pool [10, 11]. Divergence of plasma arc and reduction of droplet momentum are unfavorable to weld penetration [12, 13]. Therefore, coaxial plasma-GMAW has little advantage for welding thick plates. Paraxial plasma-GMAW hybrid welding is different from coaxial welding. The welding process is stable and can give full play to the advantages of plasma and GMAW arc. The paraxial plasma-GMAW hybrid welding has a wider parameter range than single plasma welding and has better penetration ability than single GMAW [14, 15]. Compared with single...
GMAW, plasma-GMAW hybrid welding can refine grains and improve the mechanical properties of welded joints [16, 17]. For the penetration ability of plasma-GMAW, Sun et al. established a hybrid heat source model and considered that increasing the plasma power appropriately can increase the weld penetration [18]. Wei et al. considered that the weld penetration increased with the increase of plasma arc current (50-120A) [19]. Although the penetration ability of plasma-GMAW has been studied, the mechanism of welding parameters affecting the penetration ability of heat source is lack in-depth discussion.

In this research, the influence of plasma welding current on the penetration ability of plasma-GMAW hybrid arc is studied. The penetration forces between the hybrid and single heat sources under different welding parameters are compared. The mechanism is discussed by analyzing the arc energy distribution and the stress of the molten pool.

2 Experimental procedure

Plasma-GMAW hybrid welding system consists of plasma welding power supply (Fronius MagicWave3000), GMAW power supply (Fronius TPS4000), SUPER-MIG welding torch, and KUKA robot. The experimental setup including data acquisition system is schematically illustrated in Fig. 1. The cross-section of the molten pool along the welding direction was observed by a “sandwich” method. SUPER-MIG welding torch includes a plasma torch perpendicular to the working plane and a GMAW torch at an angle of 16° with the plasma torch. The distance between plasma torch and the wire keeps 18 mm, and the distance from the nozzle to the workpiece keeps 6 mm.

Fig. 1 Experimental setup including data acquisition system for plasma-GMAW welding

Bead weld with various parameters was performed on the flat position by plasma-GMAW process. Aluminum alloys (7075) with thickness of 10 mm and ER5356 with a diameter of 1.6 mm were employed as base metal and welding wire, respectively. The orifice and GMAW shielding gases were surrounded by the overall shielding gas. Purity argon (99.9%) was used as the three gases, with gas flow rates of 2.3, 23, and 40 L min⁻¹. Thoriated tungsten with 2-mm inner shrinkage was used as the electrode for the plasma arc. GMAW current was 200 A. Tungsten electrode was used as the cathode in plasma arc welding. The welding speed was controlled at 400 mm-min⁻¹.

3 Results and discussion

3.1 Weld penetration statistics

To ensure the reliability of the experimental results, each group of test parameters in Table 1 is welded three times, and the section is taken 3 cm from the beginning of the weld, as shown in Fig. 2. Then the average weld penetration was counted. The weld cross-section and weld penetration are shown in Fig. 3. Figure 4 describes the relationship between the weld penetration of single plasma welding and the hybrid welding with the plasma current, and Fig. 5 compares the sum of single plasma weld penetration and single GMAW penetration with the hybrid weld penetration under different plasma currents. The GMAW current is maintained at 200 A, and the weld penetration of hybrid welding increases first and then decreases with the increase of plasma current. When the plasma welding current is less than 150 A, the weld penetration of hybrid welding is greater than the sum of the single plasma weld penetration and single GMAW penetration.
penetration, and the single GMAW penetration is greater than the single plasma weld penetration. After the plasma welding current reaches 130 A, the advantages of hybrid welding compared with single welding begin to weaken gradually. Under the same conditions, the weld depth depends on the penetration ability of the heat source. It can be seen from the above results that the plasma welding current has a significant indigenous effect on the penetration of the plasma-MIG hybrid heat source. Still, the relationship between them is not a simple linear increase. With the increase of plasma current, the penetration depth of single plasma welding increases gradually, while that of hybrid welding increases first and then decreases. Therefore, it is inferred that when the plasma current increases to a certain value in the hybrid welding, the penetration ability of the GMAW arc may be reduced.

### 3.2 Mechanism of plasma welding current affecting hybrid arc penetration

#### 3.2.1 Energy distribution of hybrid welding heat source

The welding arc’s energy distribution greatly influences its penetration ability. The change of plasma welding current will change the coupling state of hybrid arc, thus changing the energy distribution of hybrid arc. In the spectral diagnosis of arc plasma, the arc characteristic image is connected with the emission coefficient according to the change trend of the gray value, and then the arc temperature is calculated by the standard temperature method [20–22]. This method can establish a qualitative relationship between the brightness of the arc characteristic image and the arc temperature. Under general conditions, the higher the brightness of the character arc image is, the higher the arc temperature is. The hybrid arc images at different plasma welding currents were collected by a high-speed camera with Ar 794.8 nm ± 1.5 nm narrow-band filter. The obtained images are pseudo-colored according to the gray value of the image, as shown in Fig. 6. With the increase of plasma welding current, the plasma arc temperature in hybrid welding increases gradually. When the plasma welding current is lower than 110 A, there is almost no difference between the plasma arc temperature in hybrid welding and the single plasma arc at the same current. When the plasma welding current is 90 A, the high-temperature area of GMAW arc in hybrid welding is larger than that of single GMAW. When the plasma welding current increases to 110 A, the high-temperature area of GMAW arc in hybrid welding increases further. In the plasma-GMAW hybrid welding, due to the opposite direction of the current flowing through the plasma arc and the GMAW arc, the GMAW arc will be a repulsive force from the plasma arc in the welding direction. When the GMAW arc deviates from the wire axis under the action of repulsive force, the magnetic field generated by the electric wire will act on the GMAW arc to make it return to the wire axis as far as possible. At this time, the GMAW arc will simultaneously be subjected to two forces in the opposite direction. So that the GMAW arc is compressed in the welding direction, and the arc energy is more concentrated than the single GMAW arc. The advantages of hybrid arc in energy distribution are reflected. From Fig. 6, when the plasma welding current reaches 130 A, the cathode region of GMAW extends to the plasma arc. In hybrid welding, the GMAW current is constant. When the plasma current reaches a certain value, the electrons’ natural path

![Fig. 2](image)

**Table 1** Regulation parameters for tests

| Test | Plasma welding current (I/A) | GMAW current (I/A) | Welding speed (mm min⁻¹) |
|------|-----------------------------|-------------------|-------------------------|
| 1    | 0                           | 200               | 400                     |
| 2    | 90                          | 200               | 400                     |
| 3    | 110                         | 200               | 400                     |
| 4    | 130                         | 200               | 400                     |
| 5    | 150                         | 200               | 400                     |
| 6    | 170                         | 200               | 400                     |
| 7    | 190                         | 200               | 400                     |
effect begins to dominate the arc trajectory [23], and the GMAW arc will shift to the plasma arc during the base current period, as shown in Fig. 7. Due to the thermal inertia of the welding arc, the GMAW arc will also bias to the plasma arc in the period from \( t_0 \) (the time when GMAW current reaches the pulse peak is \( t_0 \)) to \( t_0 + 0.5 \) ms, so that the arc energy will diverge. When it reaches \( t_0 + 1 \) ms, the GMAW arc shape is similar to that when the plasma welding current is 90 A and is subject to certain compression in the welding direction. At the same time, when the plasma welding current reaches 130 A, the plasma arc temperature of the hybrid welding is obviously higher than that of the single plasma arc with the same current from \( t_0 \) to \( t_0 + 0.5 \) ms. Therefore, the reason why the penetration advantage of the hybrid heat source begins to decrease or even disappear after the plasma welding current reaches 130 A cannot be considered only from the perspective of the energy distribution of the heat source.

### 3.2.2 Weld pool behavior of hybrid welding

To obtain a larger welding penetration, more energy is needed to be transferred to the bottom of the molten pool. In the molten pool behavior, the flow direction of molten metal and the impact of droplets on the molten pool will affect the transmission of arc energy to the bottom of the molten pool. Since the plasma arc temperature in the hybrid welding is higher than that in the single plasma after the plasma welding current reaches 130 A, the advantages of the hybrid welding begin to decrease, compared with that...
when the plasma welding current is 110 A, so the GMAW area in the hybrid pool should be the focus of consideration. The relative spatial position of plasma arc and GMAW arc makes the influence of plasma arc on GMAW mainly reflected in the welding direction. Figure 8 shows the weld pool cross-section of plasma-GMAW hybrid welding along the welding direction under different plasma welding currents. The greater the angle $\alpha$ between the solid–liquid interface line and the $X$-axis (welding direction) in the GMAW area, the arc energy can be transferred to the $Z$-axis (penetration direction). As shown in the figure, when the plasma welding current is 90 A, the angle $\alpha$ between the solid–liquid interface line and the $X$-axis in the GMAW area is greater than that of the single GMAW, and the plasma current is 150 A.

The following special driving forces mainly drive the molten pool: arc pressure, arc shear force, electromagnetic force, capillary pressure, Marangoni force, gravity, buoyance, and droplet impact. For plasma-GMAW hybrid welding, with the change of plasma welding current, the capillary pressure, gravity, and buoyance of the GMAW pool changed little and had little effect on welding penetration.

Marangoni force is caused by the surface tension gradient of the pool. Surface tension can be expressed as:

$$\text{Surface tension} = \frac{d\gamma}{d\theta}$$
where \( T \) is the temperature of the metal melt; \( x_i \) is the component mass content of the melt; and \( \sigma_0 \) is the surface enthalpy of the metal material; \( s \) is the surface entropy; \( \sigma \) is the surface tension of the melt. Since the surface entropy is always greater than zero, the temperature coefficient of surface tension is always less than zero, that is, the higher the surface temperature is, the smaller the corresponding surface tension is. The temperature at the center of the weld pool is higher than that at the edge of the pool, and the resulting surface tension gradient causes the surface metal to flow from the center to the edge. Compared with the single GMAW welding and the paraxial plasma-GMAW hybrid welding, the heating of the specimen by the plasma arc is equivalent to the increase of the pre-welding temperature of the GMAW area. The increase in the specimen temperature will reduce the temperature gradient of the weld pool surface, thereby reducing the surface tension gradient of the pool. The trend of the pool surface metal from the center to the edge will be weakened to a certain extent. However, the plasma arc is close to the GMAW arc, and the welding speed is 400 mm·min\(^{-1}\). The influence of plasma arc on the temperature gradient in the GMAW region may be small. The weld width can reflect the influence of Marangoni force on the flow of the pool. Figure 9 shows the weld section under different plasma welding currents. When the GMAW current is 200 A, the weld width of the hybrid welding does not decrease, compared with that of the single GMAW welding, indicating that only when the plasma welding current changes, the influence of Marangoni force on the hybrid welding penetration is limited.

It can be seen from Fig. 6 that the arc shape of GMAW will change with the increase of plasma current, and the change of arc shape will directly affect the arc pressure on the weld pool. Figure 10 shows the arc pressure \((F_a)\) of the GMAW pool under different plasma welding currents. The smaller the angle \( \theta \) between arc pressure and Z-axis is, the greater the component force \((F_a')\) in the penetration direction...
is. For the single GMAW, the arc basically maintains the same axis as the welding wire. When the plasma welding current is 90 A, the GMAW arc is repelled by the plasma arc in the welding direction, the angle $\theta$ decreases, and the component force of the arc pressure in the penetration direction increases, compared with the single GMAW. The increase of arc pressure in the penetration direction is conducive to the generation of weld pool depression and better transfer of arc energy to the bottom of the pool. When the plasma welding current is 150 A, the GMAW arc is biased towards the plasma arc from $t_0$ to $t_0 + 0.5$ ms. At this time, the angle $\theta$ between the arc pressure of the weld pool and the Z-axis increases, and the component force of the arc pressure in the penetration direction decreases. When the time reaches $t_0 + 1$ ms, the GMAW arc is repelled by the plasma arc in the welding direction, the angle $\theta$ decreases, and the component force of the arc pressure in the penetration direction increases. The arc shear force acts on the surface of the molten pool, which drives the metal flow from the center of the weld pool to the edge of the weld pool. Therefore, the smaller the arc shear force is, the more favorable the welding penetration is. For arc shear force, the larger the contact area between the arc and the test plate, the greater the arc shear force. From Fig. 6, when the plasma welding current is 90 A, the GMAW arc is compressed in the welding direction. In hybrid welding, the arc shear force of the weld pool in the GMAW area in the welding direction is less than that of the single GMAW. When the plasma welding current is 150 A, the cathode area of the GMAW arc becomes larger in the period from $t_0$ to $t_0 + 0.5$ ms and is compressed in the welding direction at $t_0 + 1$ ms. Therefore, when the plasma welding current is 150 A, the arc shear force of the GMAW pool in the welding direction is greater than that of the GMAW pool when the plasma welding current is 90 A.

In hybrid welding, the GMAW pool is also affected by the electromagnetic force ($F_e$) from the plasma arc and the current passing through the plasma weld pool. As shown in Fig. 11, the current in the GMAW pool will produce electromagnetic force ($F_{e1}$) in the penetration direction of the molten metal. Moreover, because the current direction in the GMAW pool is opposite to that in the plasma arc and the current direction in the plasma weld pool, the molten metal in the GMAW area is also subject to repulsion from the plasma area, and the GMAW molten pool near the plasma arc side is subject to the downward electromagnetic force ($F_{e2}$). And far away from the plasma side by upward electromagnetic force ($F_{e3}$), the molten pool metal downward flow is conducive to energy downward transfer and increases the penetration. Since the front side of the GMAW pool is close to the plasma arc, the electromagnetic force $F_{e2}$ from the plasma area is greater than $F_{e3}$. For the electromagnetic force $F_{e1}$ in the GMAW pool itself, the size of the arc cathode area determines the electromagnetic force. When the plasma current is 90–110 A, the GMAW arc is compressed in the welding direction, and $F_{e1}$ is increased, compared with the single GMAW welding. When the plasma welding current increases to 130 A, the GMAW arc expands to the plasma arc in the period from $t_0$ to $t_0 + 0.5$ ms, and $F_{e1}$ decreases, compared with the plasma welding current of 90 A.

In GMAW welding, the droplet carrying energy into the molten pool will also affect the weld penetration. After the droplet is separated from the wire, it will be accelerated by the arc plasma flow. The arc pressure acting on the droplet surface is expressed as:
where \( R \) is the radius of the GMAW arc column, and \( r \) is the distance from any point to the center of the arc column. In the plasma-GMAW hybrid welding, because the droplet flows through the current before it falls off from the wire, the droplet is subject to the repulsion force of the plasma arc in addition to gravity, plasma flow force, and surface tension. According to Biot-Savart law, the greater the plasma welding current is, the greater the repulsion force of the droplet is, and the farther the droplet deviates from the arc center (\( r \) is greater). Figure 12 shows the position of the droplet in the arc space under different plasma welding currents in hybrid welding. When the droplet falls off the welding wire, the GMAW current is at the base value stage. Compared with the single GMAW welding, when the plasma welding current is 90 A, the GMAW arc in the hybrid welding is compressed, and the droplets of the two are basically located in the arc center. Therefore, the arc pressure on the droplets in the hybrid welding is higher than that in the single GMAW welding, and the impact on the weld pool is thus increased. When the plasma welding current is 150 A, the arc radius of GMAW in the hybrid welding increases, and the distance between the droplet and the arc center increases, so the arc pressure on the droplet decreases.

4 Conclusion

In plasma GMAW hybrid welding of aluminum alloy, when the welding current of GMAW is 200 A, with the increase of plasma welding current (90–190 A), the advantages of plasma-GMAW hybrid welding in the depth of penetration compared with single welding are increased first and then decreased. When the plasma welding current is 110 A, the advantage of composite welding is the largest compared with that of single welding. The mechanism is discussed by using the energy distribution of the heat source and the force on the weld pool. The following conclusions were drawn.

1. With the increase of plasma welding current, the arc burning path of GMAW in hybrid welding changes, and
the area of the GMAW high-temperature zone increases first and then decreases. When the plasma welding current is lower than 110 A, the GMAW arc is compressed in the welding direction, the arc energy is more concentrated, and the penetration force increases. When the plasma welding current is greater than 130 A, the GMAW arc is close to the plasma arc, the GMAW arc divergence, and the penetration ability decrease.

2. The change of plasma welding current changes the GMAW arc morphology in the hybrid welding, thus changing the force of the weld pool and affecting the weld penetration. When the plasma welding current is lower than 110 A, the GMAW arc is compressed, the arc pressure in the deep direction of the pool increases, the arc shear force decreases, the electromagnetic force increases, the droplet impact increases, and the penetration ability increases. When the plasma welding current is greater than 130 A, the GMAW arc is biased towards the plasma arc. The arc pressure in the penetration direction decreases, the arc shear force increases, the electromagnetic force decreases, the droplet impact decreases, and the penetration ability begins to decrease.

Author contribution Yongquan Han, and Jiao Han contributed to the conception of the study; Jiao Han and Haitao Hong performed the experiment; Jiao Han contributed significantly to the analysis and manuscript preparation; Jiao Han, Yongquan Han performed the data analyses and wrote the manuscript; Jiao Han, Yongquan Han, and Zhenbang Sun helped perform the analysis with constructive discussions.

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Code availability The codes used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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Consent to participate Written informed consent was obtained from all the authors.

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Conflict of interest The authors declare no competing interests.

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