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ARTICLE

Arc Characteristic and Droplet Transfer Behavior in Plasma-GMAW-P Hybrid Welding

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Abstract: The arc characteristics and droplet transfer behavior in plasma-GMAW-P hybrid welding were investigated. The effect of plasma arc current on GMAW-P arc shape and metal transfer was discussed. The results indicate that the plasma arc will change the electrical conductivity and stress state of GMAW arc to affect the morphology of GMAW arc and droplet transfer behavior. When the plasma arc current is small, the GMAW arc in the base current period basically burns along the wire axis, and the bell-shaped GMAW arc in the peak current period is compressed due to two opposite forces (the electromagnetic force generated by the plasma arc and the wire) in the welding direction. At this time, the drag force of plasma flow and its downward component increase, the droplet transition is promoted, and the detached time of droplet is shortened. When the plasma arc current reaches a certain value, the metal vapor in the atmosphere near the plasma arc increases, and the conductive path of the GMAW arc will be changed to bias the GMAW arc to the plasma arc. At this time, the downward component of the drag force of the plasma flow on the droplet decreases, the promotion of the droplet transition is weakened, and the detached time of droplet is increased.

Key words: arc characteristic; droplet transfer; hybrid welding; plasma-GMAW-P

For aluminum alloy welding, gas metal arc welding (GMAW) has the advantages of easy automation and high production efficiency[1,2]. GMAW-P(pulse) can also achieve droplet transfer at a low average current to reduce the heat input. However, for medium and heavy plate aluminum alloy, multi-layer and multi-pass welding are needed, and a large welding current will increase the welding heat input and reduce the mechanical properties of welded joints[3-5]. The plasma-GMAW hybrid welding can effectively utilize the characteristics of high energy density, high jet speed and strong arc force of plasma beam to realize one-sided welding with back formation of aluminum alloy medium and thick plates, and improve the performance of joint[6].

GMAW-P welding is a modified spray transfer process, which can provide the optimal short-circuiting and spray transfer by a low base current to maintain the arc and a high peak current to melt the electrode wire and detach the droplet[7-9]. GMAW-P is capable of reducing spatters and improving arc stability through obtaining spray transfer[10]. According to the relative position of the heat source space, plasma-GMAW hybrid welding is divided into coaxial and side-axis. For coaxial plasma-GMAW hybrid welding, Ton[11] demonstrated that part of GMAW current flows toward the outer region of the plasma arc zone through optical spectroscopy analysis. Terasaki et al[12] proposed that plasma arc can not only heat the welding wire but also change the current channel and the stress state of welding droplet. Essers et al [13] found that arc around the tip of welding wire tends to rotate at high currents, which results in less concentrated droplet transfer to the pool. Bai et al[14,15] investigated the droplet transition modes. Chen et al[16] studied the coupling of arc and droplet transfer. For the paraxial plasma-GMAW hybrid welding, the plasma arc nozzle is smaller, which is beneficial to obtain the arc with more concentrated energy. Han et al[17-19] studied the arc shape and droplet transition characteristics of paraxial plasma-GMAW hybrid welding, which indicates that the shape of the hybrid arc is changed due to the magnetic field produced by each other, and the droplet momentum can be increased after adding plasma arc. However, there is little research on the effect of plasma arc parameters on hybrid arc characteristics

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and droplet transfer behavior. The shape of GMAW arc will change with the change of plasma arc current, and it does not show the same shape under different parameters, and the change of arc state will affect the droplet transfer behavior[20-22]. Therefore, it is necessary to study the influence of plasma arc on GMAW arc behavior and droplet transfer.

The effect of plasma arc current on GMAW-P arc shape and metal transfer was analyzed in plasma-GMAW-P hybrid welding. The arc shape and droplet transfer were obtained with images from a high-speed camera.

1 Experiment

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. SUPER-MIG welding torch includes a plasma torch perpendicular to working plane and a GMAW torch at an angle of 16° with the plasma torch. The distance between plasma and GMAW torch keeps 8 mm, and the distance from the nozzle to workpiece keeps 6 mm.

Bead weld with various parameters was performed on the flat position by plasma-GMAW process. 7075 aluminum alloys with thickness of 10 mm and ER5356 with diameter of 1.6 mm were employed as base metal and welding wire, respectively. The orifice and GMAW shielding gas was surrounded by the overall shielding gas. Pure 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 in inner shrinkage was used as the electrode for the plasma arc. GMAW current was 200 A. Tungsten electrode was the cathode in plasma arc welding. The welding speed was controlled at 400 mm·min^{-1}.

2 Results and Discussion

2.1 Arc characteristics

As shown in Fig. 2, with the increase of the plasma arc current, the arc plasma volume biased towards the plasma arc of the GMAW arc at the base current period increases. When the plasma arc current reaches 130 A, the GMAW arc appears as a non-bell-shaped at the peak current period. For arc plasma, its trajectory is mainly determined by two factors: plasma jet effect and electrons natural path effect [23]. For paraxial plasma-GMAW hybrid welding, the motion of arc is also related to the electromagnetic force due to the induction magnetic field produced by plasma arc, GMAW arc and wire. The plasma jet effect is mainly related to the arc current. The larger the current, the stronger the plasma flow effect. The electrons natural path effect plays a leading role when the arc current is small, and the arc burns in the path with minimum impedance. The distribution of the magnetic induction line in the hybrid arc is shown in Fig.3. According to Lorenz theorem and Biot-Savart law, GMAW arc and plasma arc repel each other when tungsten is the cathode. Once the GMAW arc deviates from the wire axis, it will be subjected to the force of the induced magnetic field generated by the wire, which promotes the GMAW arc to maintain the same axis as the wire, and the greater the arc current, the greater the electromagnetic force.

The current of GMAW arc is small in the base current period, the plasma jet effect is weak, and the electromagnetic force is also small. At this time, the plasma arc reaching a certain current value has a strong heating effect on the aluminum alloy test plate, which will produce a large amount of metal vapor. The thermal ionization formula proposed by Saha can be applied as follows:

$$\lg\frac{n_e^2}{n_n} = -\frac{5040}{T}V_i + 1.5\lg T + 15.385 \tag{1}$$

in which, when the temperature T is constant, the lower the ionization potential V_i, the greater the ionization degree. The ionization potential of Al vapor is 5.96 V, which is much smaller than that of Ar (15.7 V). Therefore, a large number of free electrons in the anode region of plasma arc will provide a stable cathode spot for GMAW arc. It is shown that partial

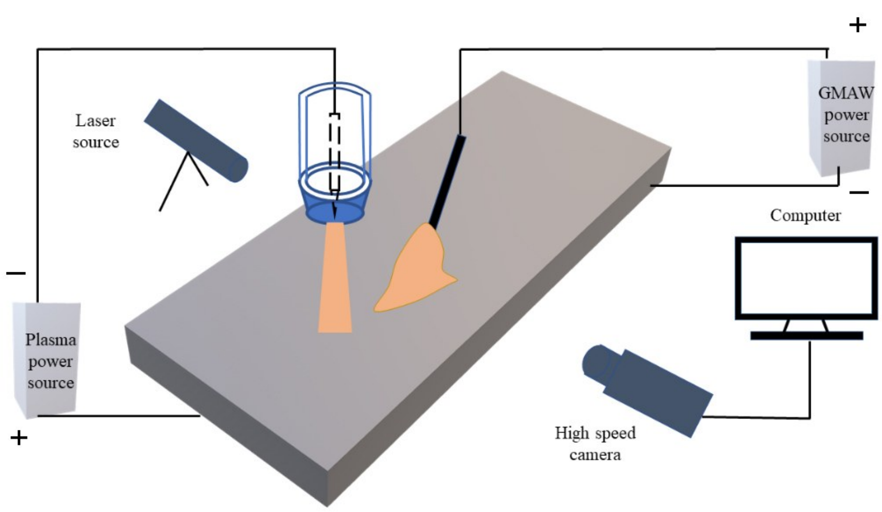

Fig.1 Experimental setup including data acquisition system for plasma-GMAW welding

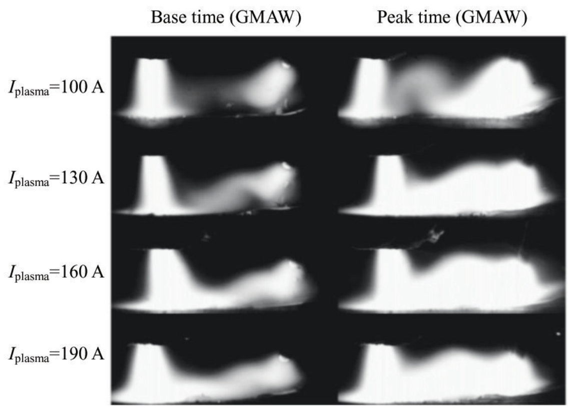

Fig.2 High-speed photographs of hybrid arc under different plasma arc currents

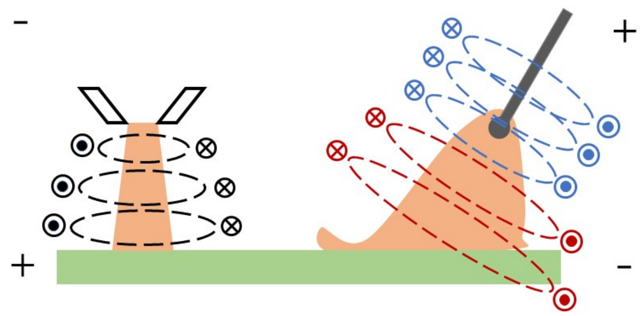

Fig.3 Schematic of magnetic field distribution in plasma-GMAW hybrid welding

GMAW arc plasma is biased to plasma arc in the base current period. Divide GMAW arc during base current period into two regions ("1" and "2"), as shown in Fig.4. Region 1 is mainly affected by plasma jet effect and region 2 is mainly affected by electrons natural path effect. With the increase of plasma arc current, the heating effect of plasma arc on aluminum alloy test plate is more intense, resulting in more metal vapor and free electrons, and the electrons natural path effect is more significant, which is manifested with the increase in GMAW arc volume in region 2.

The electrons natural path effect is mainly related to the conductivity, and the conductivity σ can be expressed by the following formula[24]:

$$\sigma = \frac{e_2 n_e}{\sqrt{8mkT/\pi}} \cdot \frac{1}{n_n Q_n + n_e Q_i} \tag{2}$$

where e is the charge of electrons, T is the temperature, n_n and n_e represent the density of neutral particles and electrons, respectively; Q_n and Q_i represent the effective cross-sections of neutral particles and cations, respectively. As the GMAW arc current increases, the arc temperature and the ionization will increase, and when the temperature is enough to ionize the gas medium sufficiently, there will occur $n_e Q_i >> n_n Q_n$, according to Eq.(2):

$$\sigma \propto \frac{1}{\sqrt{T}\, Q_i} \tag{3}$$

At this time, the ionization of gas medium is sufficient, the density and effective cross-section of cation increase, resulting in the decrease of conductivity. Therefore, when the GMAW current is large enough, even if there is a certain amount of metal vapor in the atmosphere, the arc conductivity will not decrease. However, the welding arc has thermal inertia. When the current increases or decreases rapidly, the change of arc column temperature lags, and the faster the current changes, the more significant this phenomenon is. The GMAW arc current increases rapidly from the base to the peak (up to 330 A·ms^{-1}), and the peak duration is only about 1 ms. Therefore, the arc temperature will not increase instantaneously, and the arc atmosphere will not be fully ionized. The metal vapor generated by the plasma arc will still increase the conductivity of the GMAW arc, and the electrons natural path effect is still significant. Therefore, if the electrons natural path effect causes a certain volume of plasma at region 2 for GMAW arc during the base current period, the GMAW arc will expand in the direction of biasing to the plasma arc at the peak. For the case that the plasma arc current is small and the GMAW arc is still bell-shaped during the peak current period, the GMAW arc will be subject to the repulsion force (F_p) from the plasma arc. When the arc axis deviates from the wire axis, the magnetic force (F_w) generated by the wire will make the arc as close as possible to the wire axis, as shown in Fig.5. At this time, the GMAW arc will be subjected to two opposite forces in the welding direction at the same time, so the arc plasma is compressed, as shown in Fig.6.

2.2 Droplet transfer characteristics

Fig. 7 shows the process from droplet generation to

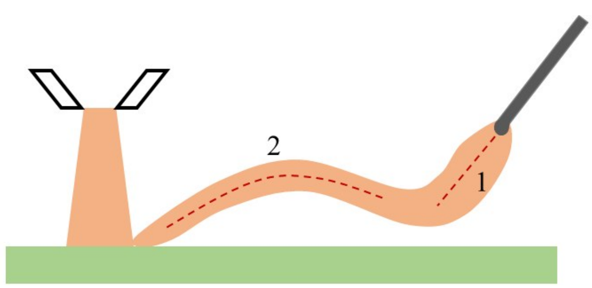

Fig.4 Schematic of plasma-GMAW hybrid arc during the base current period of GMAW

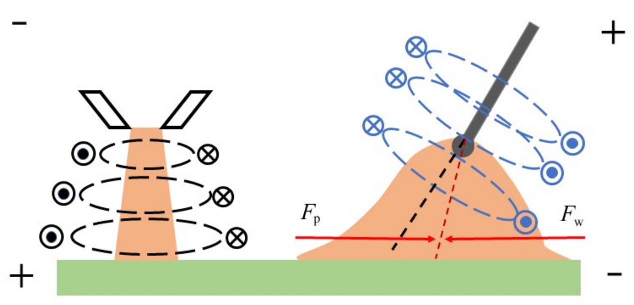

Fig.5 Force schematic of bell-shaped GMAW arc during peak current period in plasma-GMAW hybrid welding

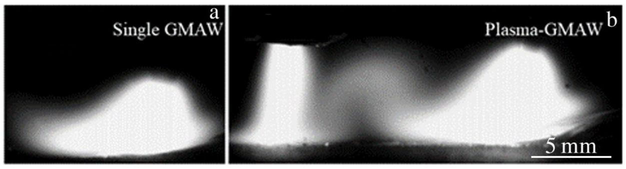

Fig.6 High-speed photographs of single GMAW arc (a) and plasma-GMAW (b)

separation under different plasma arc currents, and the high-speed camera acquisition frequency was 3000 frame·s^{-1}. As shown in the figure, the detached time of droplet is 2.33 ms at 100 A plasma arc current, which is lower than 2.67 ms at single GMAW. When the plasma arc current reaches 130 A, the detached time of droplet increases to 3 ms. When the plasma arc current continues to increase to 160 and 190 A, the detached time of droplet continues to increase to 3.33 and 4.33 ms, respectively. The number of two pulses and one drop per 20 cycles under the same parameter is counted. Each parameter is counted five times and the average value is taken. When the plasma arc current reaches 130 A, the phenomenon of two pulses and one drop begins to appear. With the increase of plasma arc current, the number of two pulses and one drop also increases, as shown in Fig.8.

The droplet stress in plasma-GMAW hybrid welding is shown in Fig.9. Gravity (F_g) and the drag force of plasma flow (F_d) promote droplet transfer. Surface tension hinders droplet transition, and the effect of electromagnetic force (F_{em}) on droplet is related to arc state. In addition, the plasma arc also has a repulsion force (F_p) on the droplet, which is related to the current of the hybrid arc. According to Fig. 2, for the plasma-GMAW-P hybrid welding, there are mainly two types of GMAW arc shapes during droplet transfer. At the peak current, the bell-shaped arc and the arc bias towards the plasma arc direction. Different arc shapes can affect the drag force of plasma flow on droplet. The drag force of plasma flow can be expressed as follows:

$$F_d = 0.5\pi v_f^2 \rho_f r_d^2 C_d \tag{4}$$

where v_f is fluid velocity, ρ_f is plasma density, r_d is radius of sphere and C_d is plasma flow coefficient. The greater the arc pressure P_r, the greater the fluid velocity v_f, and arc pressure can be calculated by Eq.(5):

$$P_r = K\frac{I^2}{\pi R^4}(R^2 - r^2) \tag{5}$$

where R is the radius of GMAW arc column and r is the vertical distance from any point in the arc column to the arc axis. According to Eq. (5), when the plasma arc current is small, the bell-shaped GMAW arc is compressed at the peak current (Fig. 6), the radius of GMAW arc column decreases, and P_r increases. Therefore, the fluid velocity v_f increases, and the drag force of plasma flow on the droplet increases, according to Eq.(4). The drag force of plasma flow (F_d) along the axis of GMAW arc can be decomposed into horizontal component (F_{d2}) and vertical downward component (F_{d1}). The angle between drag force and vertical downward component is α, as shown in Fig.10a. When the peak current period is bell-shaped GMAW arc by plasma arc repulsion, α angle becomes smaller, the downward component (F_{d1}) increases to promote the transition of droplet, as shown in Fig. 10b. When the plasma current increases to a certain value, the GMAW arc expands in the direction of biasing to the plasma arc at the peak current, the α angle increases, the downward component (F_{d1}) decreases, and the promoting effect on the droplet transition decreases, as shown in Fig.10c. With the increase of plasma arc current, the greater the electrons natural path effect on GMAW arc, the greater the degree of bias to the plasma arc, the greater the α angle, and the smaller the promotion of droplet. In summary, in plasma-GMAW hybrid welding, when the GMAW arc is not biased towards plasma arc expansion at the peak current, the promoting effect of the drag force of

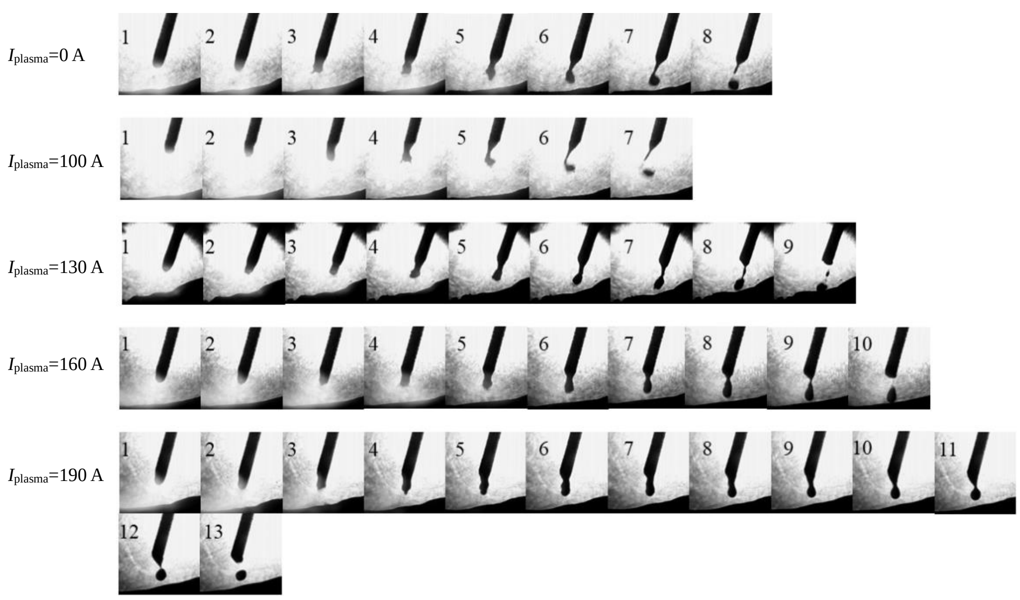

Fig. 7 High-speed photographs of droplet transfer under different plasma arc currents

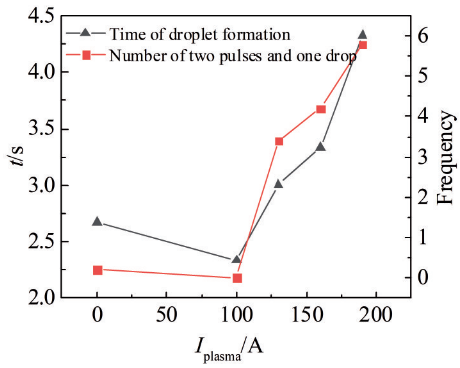

Fig. 8 Time of droplet formation t and number of "two pulses and one drop" per 20 cyclesunder different plasma arc currents

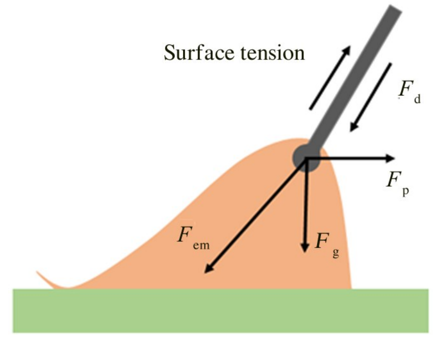

Fig.9 Schematic of forces affecting droplet in hybrid welding

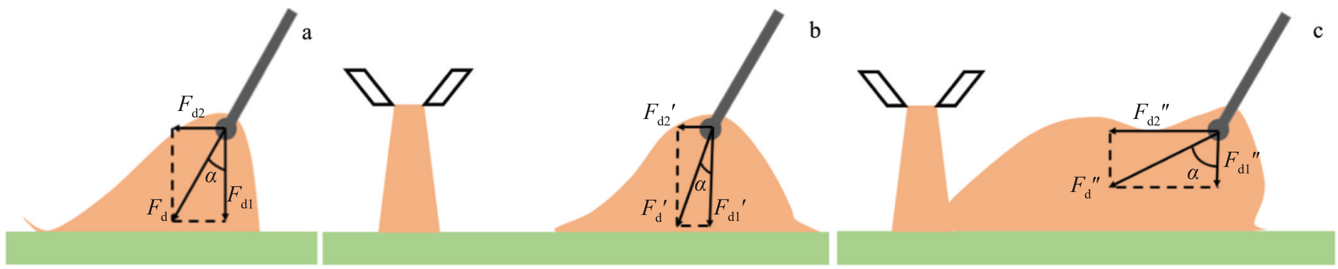

Fig.10 Schematics of the drag force of plasma flow under different GMAW arc shapes during peak current period: (a) single GMAW, (b) GMAW arc is compressed, and (c) GMAW arc expands in the direction of biasing to the plasma arc

plasma flow (F_d) on droplet transfer is improved. When the plasma of GMAW arc expands in the direction of biasing to the plasma arc at the peak current, the promoting effect of the drag force of plasma flow (F_d) on droplet transfer is weakened. Therefore, the phenomenon shown in Fig. 7 and Fig.8 appears.

3 Conclusions

1) Plasma arc current will affect the GMAW arc shape. When the plasma arc current is large enough, a large amount of metal vapor will be generated near the plasma arc to change the conductive path of the GMAW arc. At this time, the GMAW arc burns near the plasma arc direction during the pulse base current period. And the GMAW arc also expands in the direction of biasing to the plasma arc at the peak current due to the thermal inertia. When the plasma arc current is small, the GMAW arc basically burns along the wire axis during the base current period, and the bell-shaped GMAW arc plasma is compressed in the welding direction during the peak current period.

2) With the increase of plasma arc current, the detached time of droplet decreases first and then increases. When the GMAW arc is still bell-shaped during the peak current period, the downward component of the drag force of plasma flow increases. At the same time, the drag force of plasma flow also increases due to the arc compression, which makes the droplet transition in hybrid welding easier than in single GMAW. However, when the GMAW arc is biased towards the plasma arc during the peak current period, the downward component of the drag force of plasma flow on the droplet is reduced, and the effect of promoting the droplet transition is weakened, which is the reason why the droplet transition in hybrid welding is more difficult than that in single GMAW.

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铝合金Plasma-GMAW-P复合焊接电弧特性及熔滴过渡行为

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摘　要：研究了Plasma-GMAW复合焊接过程中的电弧特性以及熔滴过渡行为。结果表明，不同电流的等离子弧通过改变GMAW电弧的导电以及受力状态来影响GMAW电弧形态以及熔滴过渡行为。等离子弧电流较小时，GMAW电弧的等离子流效应对GMAW电弧形态影响显著，基值时期的GMAW电弧基本沿焊丝轴线燃弧，峰值时期由于在焊接方向上同时受到方向相反的2个力而被压缩，熔滴所受的等离子流力以及等离子流力垂直向下的分力因此增加，对熔滴过渡的促进作用增强，熔滴更易从焊丝脱落。等离子弧电流增加，氛围中金属蒸气增多，电荷流效应对GMAW电弧的影响增强，基值时期GMAW电弧偏向等离子弧方向燃弧，由于焊接电弧存在热惯性，MIG电弧在峰值时仍偏向等离子弧，熔滴所受等离子流力垂直向下的分力因此减小，熔滴脱离焊丝的时间增加。

关键词：电弧特性；熔滴过渡；复合焊接；Plasma-GMAW-P

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