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ORIGINAL ARTICLE

The effect of external longitudinal magnetic field on laser-MIG hybrid welding

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Abstract Applying the external longitudinal magnetic field to laser-metal inert gas (MIG) hybrid welding, its influence on the arc/plasma shape, motion characterization, and coupling of these two sources are researched using a high-speed camera. It is revealed that the essential effect of the external longitudinal magnetic field on laser-MIG hybrid welding arc/plasma is to make the arc and the coupling process more stable. Through analyzing the position of arc and laser-induced plasma and the mechanical model of charged particles, the energy coupling mechanics of arc and plasma under this welding condition has been proposed. The results showed that an application of a magnetic field can change the arc shape from pyramidal and static to spiral and rotational with high-speed stage and make the arc root diameter increase. It has also been found that the external longitudinal magnetic field can obviously enhance the stability of the process during laser-arc hybrid welding under the best magnetic induction intensity, which promoted efficient coupling and formed a good weld.

Keywords Magnetic field · Laser-MIG hybrid welding · Arc · Plasma

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1 Introduction

Laser-arc hybrid welding technology has acquired a high value in recent years because of its advantages, including its deeper welding penetration, the ability to bridge relatively large gaps, and a higher welding speed, among others [1–5]. Laser-metal inert gas (MIG) hybrid welding is one of the most promising processes in the development of a high-efficiency and high-quality manufacturing because it overcomes the individual drawbacks associated with the MIG and laser welding processes.

The arc and laser-induced plasma contains an amount of charged particles, which will circle, according to the electromagnetism principle, if they are in the magnetic field. And it is this rule that makes controlling the arc/plasma motion using the external longitudinal magnetic field come true. At present, previous research at home and abroad has concentrated on laser welding with the magnetic field and arc welding with the magnetic field.

The study of the application of the longitudinal magnetic field to the arc welding started early. As early as the 1970s, scholars abroad started to study the interaction between the longitudinal magnetic field and tungsten inert gas (TIG) arc [6]. In recent years, it is widely investigated, including the application to TIG welding, MIG welding, short-circuit metal active gas (MAG) welding, swiveling-jet MAG welding, and submerged-arc welding. All of these studies showed that the arc would rotate at high speed and the shape would be changed into a spiral shape under an external longitudinal magnetic field. At the same time, the arc stiffness would be promoted, which increases the stability of the arc welding process. And the aim of refining the grain, controlling the porosity, and decreasing the spatter is reached. Chang [7] improved the frequency of metal transfer and reduced the spatter through applying the external longitudinal magnetic field to

Table 1 The chemical compositions of base metal and filler wire

	C	Mn	Si	S	P	Cr	Ni	N	Fe
Base metal	≤0.03	≤2.00	≤1.00	≤0.030	≤0.045	16.0–18.0	6.0–8.0	≤0.02	Bal.
Filler wire	≤0.03	1.0–2.5	≤0.065	–	–	19.5–22.0	9.0–11.0	–	Bal.

short-circuit gas metal arc welding (GMAW). Moreover, arc welding supported by the magnetic field promoted the shaping quality and performance of welding [8–11]. Wu [12] proposed that the added electromagnetic force was able to change the flow conditions of molten metal and the momentum of backward flow jet in the weld pool, which would suppress the humping bead during high-speed gas metal arc welding.

In addition, the research of laser welding supported by an external longitudinal magnetic field has also been paid attention by scholars. The way of moving for charged particles of laser-induced plasma will change under Lorenz force, and charged particle density and the distribution, shape, and location of laser-induced plasma also would change. Selecting the suitable magnetic induction intensity and parameters can effectively decrease charged particle density when it is in the laser transmission path. And the shielding effect made by laser-induced plasma reduced, which can promote the laser efficiency [13–15]. Yang [16] described that the increasing penetration of laser welding has an optical value under laser welding supported by an external magnetic field. It has been found that the effect of an external magnetic field on laser welding penetration depends on the drifting radius and drifting velocity of the electron. Bachmann [17] pointed out that the longitudinal magnetic field can break the flow velocity, change the local temperature distribution in the laser weld pool, and change the weld cross-section shape from a wine-glass shape to a V shape, which benefited a more uniform stress distribution inside.

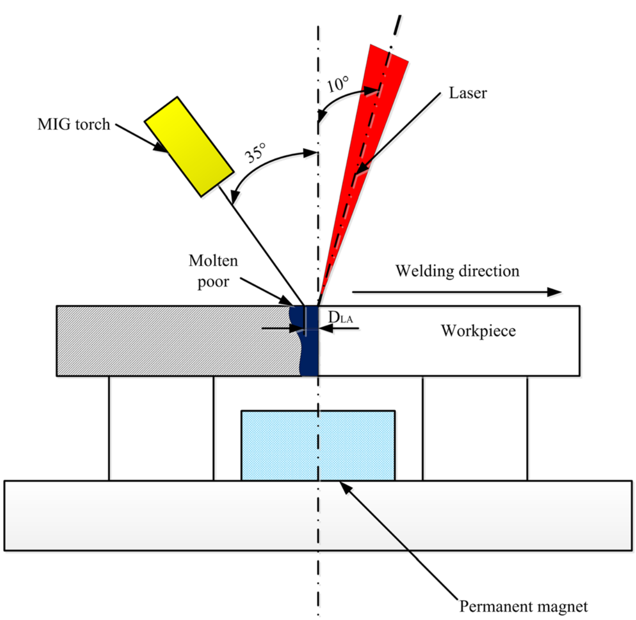


Fig. 1 Schematic of laser-MIG hybrid welding with external longitudinal magnetic field setup

In conventional laser-arc hybrid welding, the stability of the hybrid welding process, in terms of weld performance, relies mainly on the stability of arc and coupling effect. So, many scholars at home and aboard focused on the interaction of arc and the laser-induced plasma during the hybrid welding process. The laser-induced plasma can both attract and concurrently stabilize the arc, and it can contribute to improve the efficiency of energy imported into the work piece [18]. The current, laser power, and distance of the laser and arc (D_{LA}) are the three most important parameters which influence the interaction of the arc and laser-induced plasma. A high welding current can increase the arc stiffness and make it less attracted to the laser-induced plasma. A high laser power can make the laser-induced plasma easier to attract the arc. The laser-induced plasma has a higher temperature and degree of ionization. Results of simulation demonstrated that a laser beam can increase the welding speed of GMAW-P [19]. When D_{LA} is a larger level, the conduct path connecting the laser-induced plasma and arc cannot be formed, which can hinder the interaction between laser-induced plasma and the arc. Therefore, an appropriate D_{LA} should be chosen to ensure the formation of the arc stiffness and overcome the distance of these two sources [20]. Wang [21] indicated that heat source separation (D_{LA}) and laser power significantly affect arc voltage distribution. High laser power and short D_{LA} reduce the voltage of phase pulse base time. Gao [22] simulated the weld pool dynamic considering the coupling effect in laser-MIG hybrid welding, which was in good agreement with experimental results. For the mechanism of the attraction, the most commonly accepted explanation was that the laser-induced plasma produced ionized plasma and this ionized

Table 2 Process parameters

Welding parameters	
Laser power P (kW)	1.5
MIG current I (A)	120
Welding speed v_m (m/min)	2
Angle of MIG torch and laser torch θ (°)	45
Defocusing amount Δf (mm)	0
Distance between laser and arc D_{LA} (mm)	1–5
Magnetic induction intensity B (mT)	0–33

Fig. 2 Schematic of MV-D1024E high-speed camera

plasma has a number of charged particles to form a current path which offers less resistance than the arc. According to the principle of minimum voltage, the welding current tries to pass through the path with the least resistance and a low voltage [23, 24].

Integrating recent research achievements, it has seldom been reported in laser-MIG hybrid welding applying an external longitudinal magnetic field. Therefore, the influence and role of longitudinal magnetic field on laser-MIG hybrid welding has not been defined. Given this, in this paper, an external longitudinal magnetic field was brought into laser-MIG hybrid welding. The influence of the external longitudinal magnetic field on arc/plasma shape and motion character is investigated employing a high-speed camera. In addition, the coupling of these two heat sources was also analyzed, and it is revealed to study essential effect. And the influence of different distances between the laser beam and arc (D_{LA}) of the arc/plasma and coupling effect with a longitudinal magnetic field is presented and discussed.

2 Experimental method

2.1 Materials

SUS301L austenitic stainless steel with the dimension of 200 mm×150 mm×4 mm was used in the study. The specimen surface was chemically cleaned by acetone before welding to eliminate surface contamination. Austenitic stainless steel ER301 filler wire 1.2 mm in diameter was also employed. The chemical compositions of base metal and filler wire are shown in Table 1.

2.2 Experimental equipment

Bead-on-plate welds were made using a 4-kW fiber laser (IPG YLR-4000). The fiber laser with an emission wavelength of 1.07 μm can deliver in continuous-wave (CW) mode. The laser beam was passed through a focusing mirror with a focal length of 250 mm and was finally focused as a spot of 0.3 mm in diameter. A Fronius TPS4000 digital arc-welder power which can achieve the integration of regulation of current, voltage, and wire feed rate was used as the MIG welding power. So, the current is the only parameter to express the arc parameters in this paper. A ferrite permanent magnet with a dimension of 110 mm×105 mm×15 mm, which has a surface magnetic induction intensity of 120 mT, was used as the source of magnetic field. And the magnetic induction intensity can change by adjusting the distance between the permanent and the base metal. A high-precision gauss meter was used to measure the magnetic induction intensity. The angle between

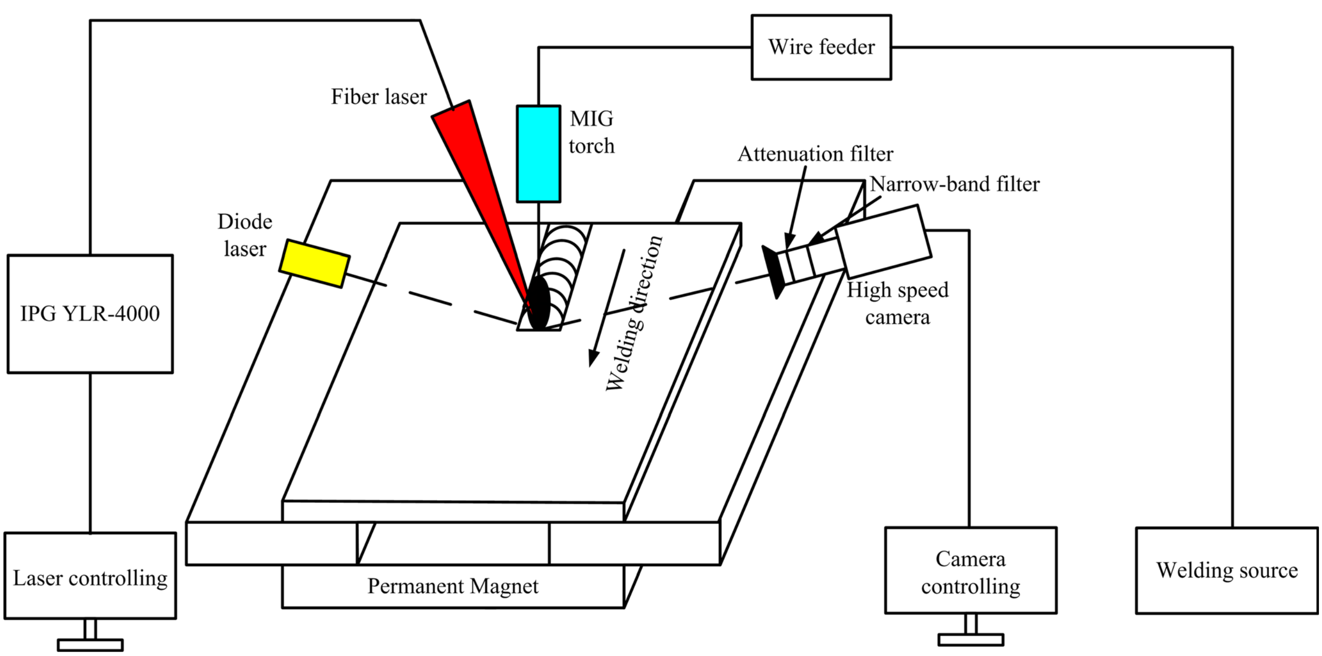


Fig. 3 Schematic of the experimental setup for observation of hybrid welding phenomena

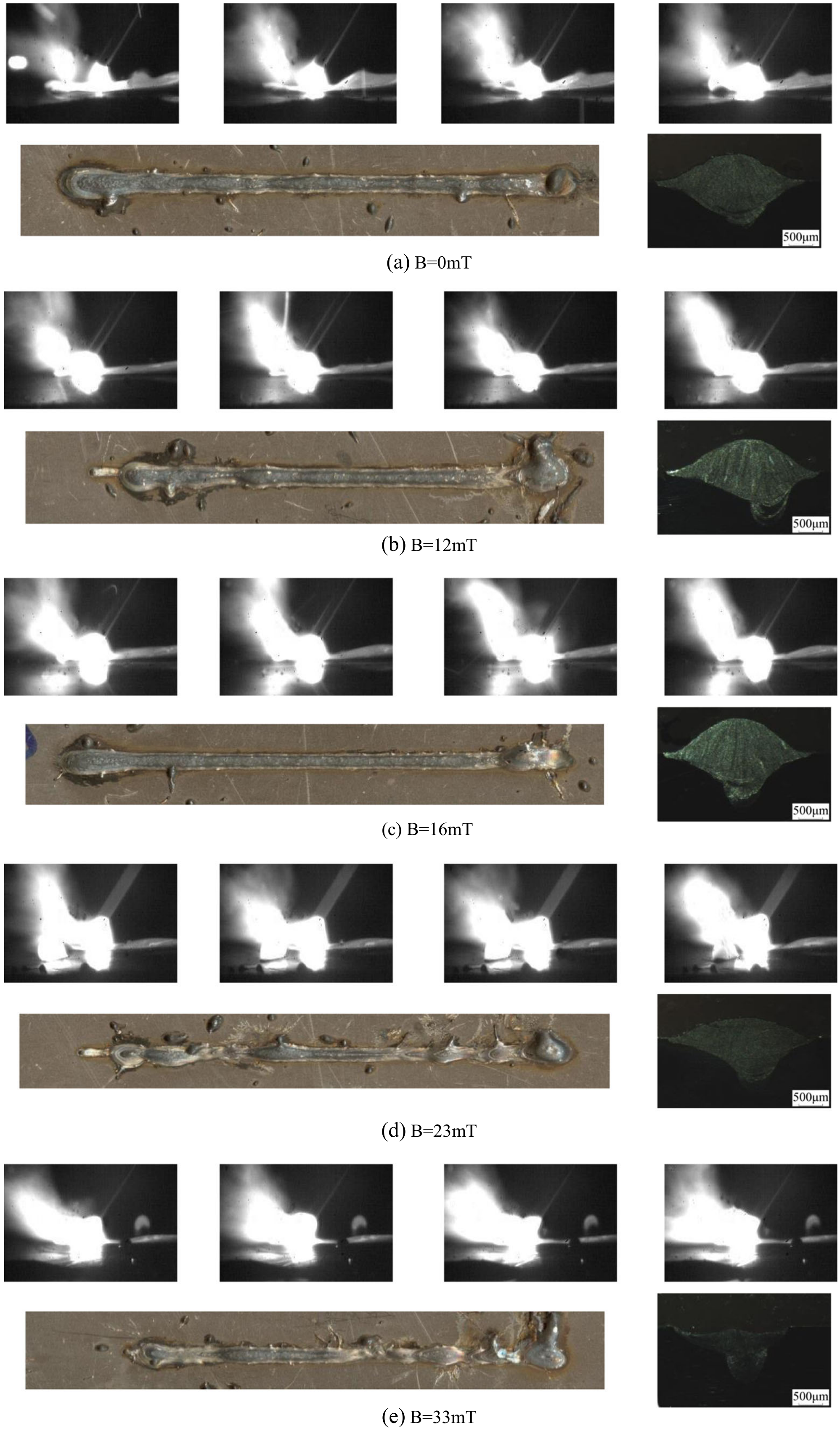


Fig. 4 The shape of arc and plasma and weld appearance with different B. **a** B=0 mT, **b** B=12 mT, **c** B=16 mT, **d** B=23 mT, **e** B=33 mT

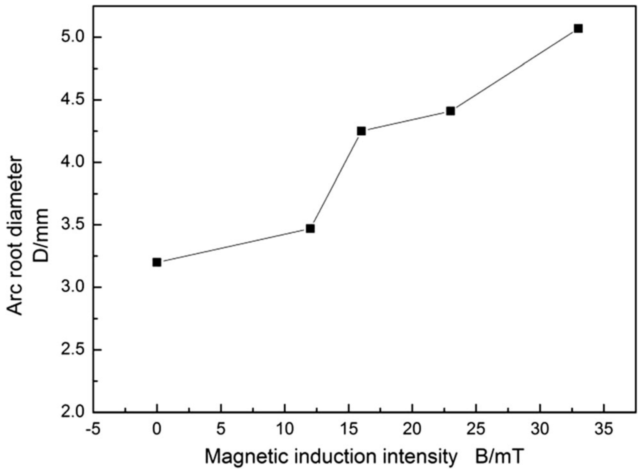


Fig. 5 The effect on arc root diameter at different B

the laser and perpendicular direction is 10°, while the angle between the MIG torch and perpendicular direction is 35°. The schematic of the setup is shown in Fig. 1. And, the shielding gases used for the arc torch are a mixture of carbon dioxide and argon (20 % CO_2+80 % Ar), the flowing velocity of which is 25 L/min coursed directly through the MIG torch. The welding parameters are provided in Table 2.

A CMOS MV-D1024E high-speed camera (Photonfocus, Switzerland) for which the most recorded speed can achieve 38,000 frames per second was used to capture the welding phenomena, as shown in Fig. 2. There is a narrow-band filter in the camera lens to acquire backlight photos. Installing an attenuation slice is to reduce the whole light intensity into the photosensitive element from the laser-induced plasma/MIG arc; there is a cover glass outermost layer to protect the optical glass and avoid it damaging by the spatter.

2.3 Experimental process

The whole experimental system is shown in Fig. 3. The samples were firmly fixed flat on the jig so that the welding optics were inclined to the direction of the welding and the work piece surface to prevent splash metal from damaging the lens during the laser welding. And the permanent magnet was fixed under the samples concurrently. During this process, the welding speed was set up via controlling the numerical-controlled machine controls, which ensured the high-speed camera was aligned to the region of arc/plasma.

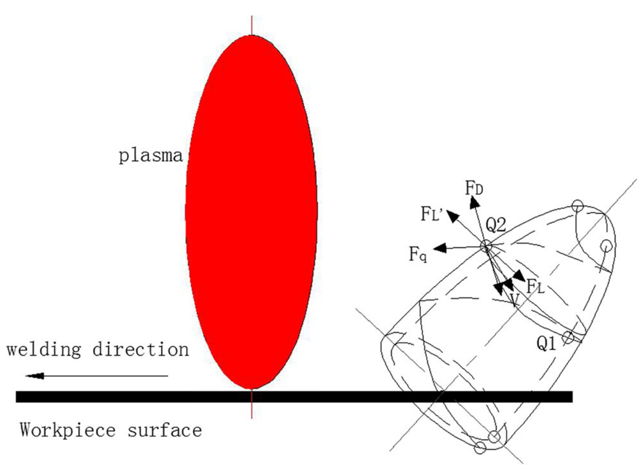


Fig. 6 Schematic of the mechanical model of a charged particle

3 Results and discussion

3.1 Effect of external longitudinal magnetic field on arc/plasma

Figure 4 shows images of MIG arc and laser-induced plasma shapes at different magnetic induction intensities with D_{LA} 2 mm laser-arc distance. As shown in Fig. 4a, it is clearly demonstrated that there is a weak plasma conduct path to connect the arc and laser-induced plasma when magnetic induction intensity is equal to 0 mT. The arc and plasma connect with each other directly sometimes, but at other times, they are separate like two independent heat sources. At the same time, because of the principle of minimum voltage, which makes the arc always seek the conductive path of which the resistance is minimum, so the arc will be attracted by plasma when the plasma degree of ionization increases, which the resistance of the plasma is lower. In the whole hybrid welding process, laser-induced plasma is in a dynamic state, so the degree of ionization is also dynamic, which makes the attraction dynamic. After which, it results in the unstable arc, making the weld appearance bad and discontinuous.

The images in Fig. 4b display the shapes of arc, and laser-induced plasma under a 12-mT magnetic field. It is obvious that the static arc becomes rotating with a high velocity which makes the stiffness of the welding arc increase. In addition, the arc root diameter increases, which makes the distance between the arc and plasma shorten. Because of this, the coupling of plasma and arc is better and the arc is more stable than that without the external magnetic field. As shown in Fig. 4c, with the magnetic induction intensity increasing to 16 mT, the shape of the plasma and arc is the most stable, and the coupling is the most optimum. From the images, it is observed that the shape, especially the arc, is very stable. The arc can contact with the laser-induced plasma due to the continuing

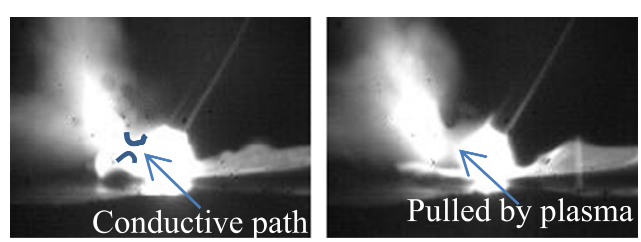


Fig. 7 Interaction between arc and plasma with B=0 mT

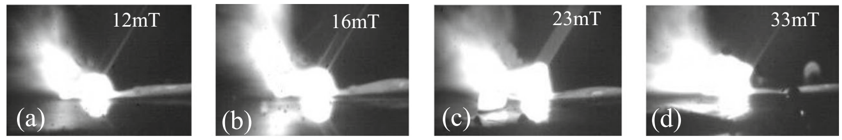


Fig. 8 **a**–**d** Interaction between arc and plasma with external magnetic field

increase of the arc root diameter. Simultaneously, the arc itself is stabilized on account of high-speed rotation, and it cannot be disturbed by laser-induced plasma. So, the coupling between the arc and plasma is very obvious and reaches the optimum.

But with an increase in B from 23 to 33 mT, the hybrid welding process becomes unstable, as shown in Fig. 4d, e. In this case, though the arc rotating velocity is very high and the arc inflection increases with the increasing of the rotating velocity, the arc root diameter expands excessively, which will shield the laser keyhole partially (23 mT) or entirely (33 mT), leading to the laser-induced plasma and metal vapor from the keyhole cannot eject well-off. This will result in the unstable hybrid welding process and, moreover, the occurrence of welding defects which are discontinuous and humped.

It is obviously observed that there is an optimal magnetic induction intensity B for each hybrid welding parameter. Under this optimal B, the coupling effect of the arc and plasma is the best, and the arc is the most stable. Figure 5 shows that the arc root diameter changed with the B changing. It is clearly demonstrated that the arc root diameter increases with B increasing. In order to simplify the analysis of the phenomenon, if the moving trajectory of a charged particle is considered as a current line and the external longitudinal magnetic field is regarded as a parallel longitudinal magnetic field, a unit of arc column will be acted upon by the ampere force from the parallel longitudinal magnetic field and the aerodynamic drag from the other arc column. When the unit remains in equilibrium, it will get the stable velocity of the unit of the arc column from this equation [25]:

$$\mathrm{Bl}\ \sin\ \theta = \frac{1}{2}\rho V^2 A C_D$$

where C_D is the coefficient of aerodynamic drag, V is the velocity of the unit of the arc column, ρ is the gas density, and A is the windward area of the unit of the arc column. At this moment, the arc will form a circumferential current I_ω. This I_ω is acted upon by the ampere force Fr which points to the center of the arc. Meanwhile, the charged particle is under the influence of the Lorentz force, and it is equal to the centripetal force, which is calculated based on the following equation:

$$qvB = m\frac{v^2}{r}$$

where q is the quantity of electricity, m is the quality of particles, and r is the radius of circling motion. However, the actual magnetic field is not parallel. It is such a non-uniform magnetic field whose central magnetic density is

Table 3 Weld appearances with different distances of laser and arc under the optimal B

Distance of laser and arc(D_{LA})	Weld appearances
1	
2	
3	
4	
5	

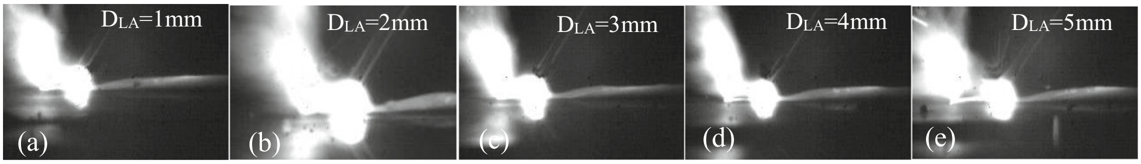


Fig. 9 **a**–**e** The arc and laser-induced plasma shape and their coupling effect with different D_{LA}

lower than the marginal magnetic density [26]. When the external longitudinal magnetic field passes the region of arc, the longitudinal component of *B* will reduce while the transverse component of *B* will increase. Simultaneously, in laser-MIG hybrid welding, the arc tends to be guided to the laser-induced plasma if the plasma forms an ionization duct that provides a significant number of charged particles to make the resistance of this duct smaller. This effect can be equivalent to an attracting force F_q that is laser-induced plasma for arc at macro level. So, the mechanical model of charged particles in laser-MIG welding actually is as shown in Fig. 6.

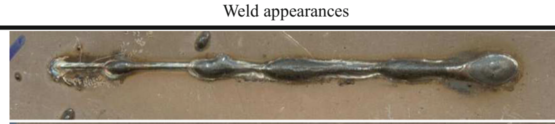
Figure 6 is the simplified moving model of a charged particle in a longitudinal magnetic field during hybrid welding. As shown in Fig. 6, the imaginary line and solid line are the shape of arc without magnetic field and with magnetic field, respectively. And charged particle Q1 moves in an imaginary line while charged particle Q2 moves in a helix line. Under the effect of the longitudinal magnetic field, the moving trajectory of the charged particle is a helix line [26]. In Fig. 6, F_D is aerodynamic drag, F_L is the Lorenz force, and $F_{L'}$ is the centrifugal force. Different from the arc welding, there is a laser-induced plasma in laser-MIG hybrid welding. And this plasma attracts the arc referring to the previous paragraph. In addition, F_q can be divided as F_{q1} which directs the direction of charged particles moving, and F_{q2} which is perpendicular to the moving direction. When charged particles move downward along the helix line, owing to the arc shielding the magnetic field, a decrease in the longitudinal component of *B* results in a reduction in Lorentz force F_L. In other words, the driving force which supports the charged particle moving decreases. Consequently, $F_{q1}+F_{L'}>F_L$, that is, the centrifugal force is greater than the Lorentz force. Meanwhile, on account of arc rotating, the arc maintains self-stability. So the radius of the circle moving increases and the arc diameter also does. Moreover, the more downward charged particles move, the more obviously the arc diameter increases.

From the analysis above, it is concluded that the arc rotates with high velocity and the arc root diameter increases with an external longitudinal magnetic field. Compared with the normal arc, the rotation of the arc tremendously increases the arc stiffness, strengthening the ability of the arc which resists the attraction from the plasma. And the expansion of the arc root diameter makes the distance of the arc and plasma decrease; then, the coupling effect is strengthened.

Figure 7a shows clearly there is a conduct path between the arc and the plasma without the external longitudinal magnetic field. This conduct path is unstable, and it changes with the laser-induced plasma changing. When the plasma is weak, the conduct path is also weak and the coupling of these two heat sources is weak. On the contrary, when the plasma expands, the plasma can provide a significant number of charged particles. This leads to the attraction increasing; in other words, the force F_q increases. And the coupling benefits it. But, if the plasma is too strong and F_q is big enough, the plasma pulls the arc forcibly to cause the arc to become unstable, as shown in Fig. 7b. The plasma is not stable in the whole process of hybrid welding, so the conduct path is not always stable. Consequently, the arc sways in the direction of hybrid welding.

When there is an external magnetic field, as discussed above, the arc is rotating and the arc root diameter increases. Therefore, the distance between the plasma and margin of arc decreases and the arc stiffness is strengthened. Thus, the effect of an increase in F_q on the attracting arc is weakened. With *B* increasing, the arc root expanding is more and more obvious and the distance is smaller and smaller. At last, the conduct path disappears. As *B* reaches 16 mT, coupling of these two heat sources is the best. In this case, the arc root connects with plasma directly, so F_q reduces to a small value. Moreover, these avoid connecting with the unstable conduct path and

Table 4 Weld appearances with different distances of laser and arc without magnetic field

Distance of laser and arc(D_{LA})	Weld appearances
1	
5	

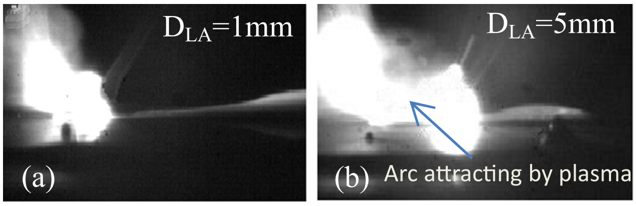


Fig. 10 **a**, **b** The arc and laser-induced plasma shape and their coupling effect with 1 and 5 mm of D_{LA}

the arc does not affect laser-induced plasma and metal vapor from keyhole spraying. However, when B exceeds the optimal value, the arc expands excessively and the arc root enters into plasma tanto. Meanwhile, arc stiffness is much strengthened because of high velocity rotating. It turns out that a more stable arc shields the laser keyhole partially or entirely, which causes the laser-induced plasma and metal vapor not to spray smoothly. The pressure to the arc would increase with the laser-induced plasma and vapor piling up more and more. When the pressure is big enough to break through the arc, it erupts and produces a large force, to make the arc distort, as shown in Fig. 8d. Finally, the process of hybrid welding is unstable exceedingly.

3.2 Effect of external longitudinal magnetic field on arc and plasma with different D_{LA}

Based on the experiments and analyses above, the effect of an external longitudinal magnetic field on the shape of the arc and plasma and their coupling with different laser-arc distances (D_{LA}) under the optimal B (16 mT) is investigated. Table 3 displays the weld appearances in which the D_{LA} is from 1 to 5 mm. It is obvious that the weld appearances are all good. Whatever the D_{LA} is identical, the external longitudinal magnetic field can be beneficial to the weld appearance.

Good weld appearance exactly illustrates that the coupling of laser-induced plasma and arc is very stable. Figure 9 exhibits the arc and laser-induced plasma shapes and their coupling effect. The analysis above has explained that the arc stiffness is strengthened with a high-speed rotating and the arc root diameter would increase under the magnetic field. So, though the laser-induced plasma has expanded to a high level and the attraction force F_q is big enough, the arc is still stable. It is not attracted by the plasma. Anatomizing these high-speed camera images, some differences can be found. When D_{LA} is a small value, like 1 and 2 mm, the stable arc contacts laser-induced plasma directly, and the coupling effect is strong. With D_{LA} increasing to 3 and 4 mm, a strong conductive path plays the role of connecting the arc and laser-induced plasma. But when D_{LA} increases to 5 mm, the conductive path is weakened, and the coupling effect is also weak. Under this condition, it has been close to tandem welding, not hybrid welding.

In addition, in order to make a comparison, the interaction of the arc and laser-induced plasma with 1 and 5 mm D_{LA} without the external magnetic field is investigated. As shown in Table 4, weld appearances are not good, and the weld is not continuous. From the high-speed camera images, as shown in Fig. 10, it can be explained. Under 1 mm of D_{LA}, the arc is attracted by plasma completely, and the arc is bent by the vapor and the plasma erupting from the keyhole. Even if D_{LA} increases to 5 mm, when the plasma expands to be enough to provide enough charged particles, the attracting force F_q would be very large, which pulls the arc to a wrong direction. It is clearly demonstrated that the external longitudinal magnetic field can strengthen the arc stability and increase the coupling effect between the arc and plasma again.

4 Conclusions

In this study, the effect of an external longitudinal magnetic field on laser-MIG hybrid welding has been reported. The results obtained in this research are summarized as follows:

(1) It is revealed that the essential effect of the external longitudinal magnetic field on laser-MIG hybrid welding arc/plasma is to make the arc stable and increase the coupling effect of these two heat sources. Under an external longitudinal magnetic field, the arc rotated and has a stronger stiffness.
(2) When the magnetic induction intensity B is the optimal value (it is 16 mT in this study), the shape and coupling are the most stable, and the appearance of the weld is good. When B is lower than the optimal value, the arc does not have enough stiffness, so that the arc is attracted by the plasma and the process of hybrid welding is unstable. When B is higher than the optimal value, the arc root diameter will expand exceedingly, so that the arc shields the keyhole, resulting in laser-induced plasma and metal vapor erupting toughly.
(3) Under different distances of the arc and the laser-induced plasma (D_{LA}=1–5 mm), the stability of the arc and coupling effect with the external longitudinal magnetic field are better than those without the magnetic field.

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