Influences of laser in low power YAG laser-MAG hybrid welding process

Ruisheng Huang (黄瑞生), Liming Liu (刘黎明), and Fan Zhang (张 帆)

State Key Laboratory of Materials Modification & School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024

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The influences of laser defocusing amount Δz, laser power P, space distance $D_{\rm LA}$ between laser and arc on weld penetration, arc modality and stability are investigated in low power YAG laser and metal active gas (laser-MAG) hybrid welding process. The experimental results indicate that the effects of laser-induced attraction and contraction of MAG arc are emerged in hybrid welding process, which result in the augmentation of hybrid welding energy. When $D_{\rm LA} = -0.5 - 2$ mm, $\Delta z = -2 - 2$ mm and $P \geq 73$ W, the synergic efficiency between laser and MAG arc is obvious, the cross section at the root of hybrid arc is contracted and the hybrid weld penetration is increased. The maximal ratio of hybrid/MAG weld penetration is 1.5 and the lowest YAG laser power that augments MAG arc is 73 W. The input of YAG laser makes the stabilities of arc ignition and combustion prominent in hybrid welding process.

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Since the investigation of laser and tungsten inert gas (laser-TIG) hybrid welding was carried out by Steen *et al.* in 1979[1], further researches on the hybrid welding technology have been done[2,3] due to the advantages of weld penetration, efficiency and capacity of gap tolerance etc in laser-arc hybrid welding process[4]. In recent years, with the industrial demands of shipbuilding and car manufacturing, investigations of laser-arc hybrid welding are focused on high power laser and metal inert gas (laser-MIG) hybrid welding of thick steel plates and Al alloys[5−7]. And the practical industrial application of laser-MIG hybrid welding is achieved[8,9]. However, high power laser-arc hybrid welding will result in the increase of energy consumption and welding cost. Therefore, the low power laser-arc hybrid welding technology is studied to avoid the disadvantages mentioned above. The influences of welding parameters, theoretical lowest laser power input, arc discharge, arc stability, molten efficiency etc. have been investigated largely in low power laser-TIG hybrid welding process[10−13]. But a small quantity of researches on welding parameters, droplet transfer, arc voltage, arc cathode spot etc in low power laser-MIG hybrid welding process have been reported[14]. At present, researches on the interaction between laser and arc in laser and metal inert/active gas (laser-MIG/MAG) arc hybrid welding process still focus on high power laser input[15,16], while few researches on interaction between laser and arc in low power YAG laser-MAG arc hybrid welding process are reported. In this paper, the influences of space distance between laser and arc $D_{\rm LA}$, laser defocusing amount Δz, laser power P on weld penetration and arc characteristic are investigated in low power pulsed YAG laser and direct current (DC) pulsed MAG arc hybrid welding process of Q235B steel.

A low power pulsed YAG laser (LWS-500YAG) combining with a MIG/MAG welding equipment (YD-350AG1) was used in the bead-on-plate welding process. And a high speed camera (CPL 250K CMOS) with the sampling frequency of 1072 frames/second was placed at the vertical direction to welding seam to monitor the transformation of arc. The sketch of set up in hybrid welding process is shown in Fig. 1. The YAG laser acted on the $t_{\rm p}$ peak current region and $t_{\rm i}$ current increase region of pulsed MAG arc separately with the control and adjustment of YAG laser output. The sketch of laser action region is shown in Fig. 2. The specimen of Q235B steel plate with the dimension of 300 × 120 × 8 (mm) was used in the experiment. The surface of Q235B steel

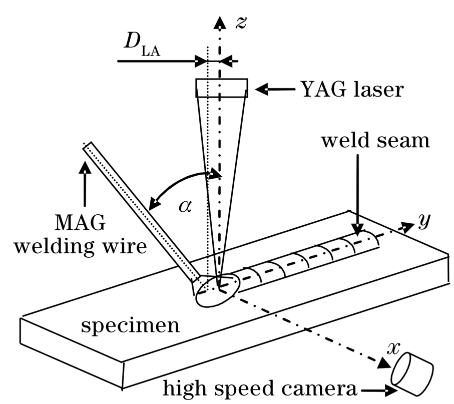


Fig. 1. Set up of hybrid welding.

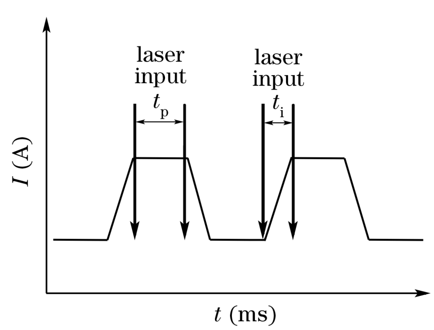


Fig. 2. Sketch of laser action region in current wave.

Table 1. Welding Conditions

Welding Parameters	Values
Pulse Laser Pwer, P (W)	65 − 380
Focal Length, f (mm)	121
Defocusing Amount, Δz (mm)	−3 − 2
Pulse MAG Current, I (A)	170
Pulse MAG Voltage, U (V)	31
Feed Rate of Welding Wire (m/min)	10.2
Flow Rate of Shielding Gas (L/min)	15
Welding Speed, v (m/min)	1 − 1.9
Space Distance of Laser and Arc, D_{LA} (mm)	−2 − 3.5
Angle between Laser and Nozzle, α (deg.)	40

plate was cleaned with acetone and was scratched brush to maintain consistent surface conditions. The welding wire of ER50-6 with the diameter of 1.2 mm was used in the experiment. And the shielding gas composed of Ar (80%) and CO_2 (20%) was spurted out from the nozzle of MAG welding torch. The welding conditions are shown in Table 1.

Figure 3 shows the cross-sectional microstructures of low power laser-MAG hybrid welding, single MAG welding and laser welding. Comparing with single MAG welding, the penetration and wire melting efficiency of hybrid welding increase, and the maximal ratio of hybrid/MAG weld penetration (hybrid weld penetration divides by MAG weld penetration) is about 1.5. The modality of hybrid arc comparing with that of single MAG arc in t_{p} region is shown in Fig. 4. When $D_{\mathrm{LA}} = -0.5 - 2$ mm, $\Delta z = -2 - 2$ mm and $P \geq 73$ W, the attraction and contraction effects of MAG arc induced by the YAG laser at laser-heated spot are generated in low power laser-MAG hybrid welding process, and the cross section at the root of MAG arc is contracted obviously.

When YAG laser acts on the molten pool surface in hybrid welding process, laser-induced plasma will be

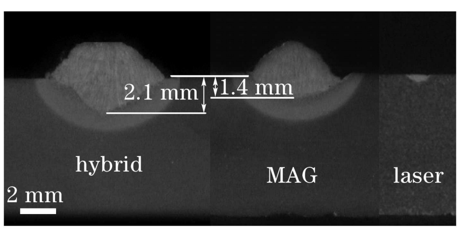


Fig. 3. Comparison of cross-sectional microstructures of the bead-on-plate weld ($P = 350$ W, $\Delta z = 0$ mm, $D_{\mathrm{LA}} = 0.5$ mm, $v = 1$ m/min).

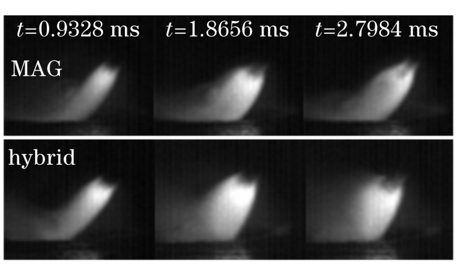


Fig. 4. Influence of YAG laser on arc modality in t_{p} region ($P = 350$ W, $\Delta z = 0$ mm, $D_{\mathrm{LA}} = 0$ mm, $v = 1$ m/min).

generated from the evaporation and ionization of liquid metal, and it makes the conductance of arc at laser-heated spot increase. According to the lowest voltage principle of arc, the MAG arc is attracted to the laser-heated spot, and the cross section at the root of MAG arc is contracted obviously. Then the utilization of arc energy will be more efficient. At the same time, a high temperature zone with greater density of charged particle (electron, ion) in comparison with MAG arc will be existed above the laser-heated spot, and it leads to the increase of current density of MAG arc column. The hybrid arc is contracted due to the electromagnetic contraction effect, and the utilization of arc energy is increased too. On one hand, the attraction and contraction effects of hybrid arc cause the utilization of MAG arc energy increased. On the other hand, the utilization of laser energy is increased in hybrid welding process due to the specimen preheated by MAG arc. Therefore, the welding efficiency of low power laser hybrid welding is greater than that of the sum of both MAG welding and YAG laser welding. The energy augmentation effect emerges in low power laser hybrid welding process due to the intensive effects of hybrid arc attraction and contraction. The synergy effect between laser and MAG arc results in the increase of weld penetration and wire melting efficiency.

D_{LA}, Δz and P have great influences not only on the hybrid arc modality, but also on the ratio of hybrid/MAG weld penetration. The ratios of hybrid/MAG weld penetration under different D_{LA}, Δz and P are depicted in Fig. 5.

Figure 5(a) shows the influence of D_{LA} on the ratio. It indicates that the ratio increases with the increment of D_{LA}. It reaches the maximum value when $D_{\mathrm{LA}} = 0.5$ mm. Then, when $D_{\mathrm{LA}} > 0.5$ mm, the ratio decreases gradually with the increment of D_{LA}. When $D_{\mathrm{LA}} < -0.5$ mm, the hybrid arc with small effects of attraction and contraction is acting on the foreside of molten pool that closes to the unmelted base metal. Energy of hybrid arc is mainly used to make the base metal melting down rather than to increase the weld penetration. And with the further decrement of D_{LA}, on one hand, YAG laser and MAG arc will act separately on the molten pool, the synergy effect disappears. On the other hand, the regularities of droplet transition and arc burning will be interfered by the YAG laser when laser radiation acts on the transferring droplet or the tip of welding wire. Therefore, when $D_{\mathrm{LA}} < -0.5$ mm, the ratio ≤ 1. The effects of laser-induced attraction and contraction of arc are intensive when $D_{\mathrm{LA}} = -0.5 - 2$ mm. The energy of MAG arc will be contracted to the central area of molten pool where the arc energy is used to increase the weld penetration mainly. The effect of energy augmentation in hybrid welding process will come true, and then result in the increment of weld penetration and the ratio of hybrid/MAG penetration greater than 1. When $D_{\mathrm{LA}} = 0.5$ mm, the synergic efficiency between laser and MAG arc becomes optimal, which makes the weld penetration reach maximum value. The effects of attraction and contraction of arc induced by laser radiation will weaken quickly when $D_{\mathrm{LA}} > 2$ mm. The molten pool is heated by YAG laser and MAG arc separately with the increment of D_{LA}, and the effect of energy augmentation

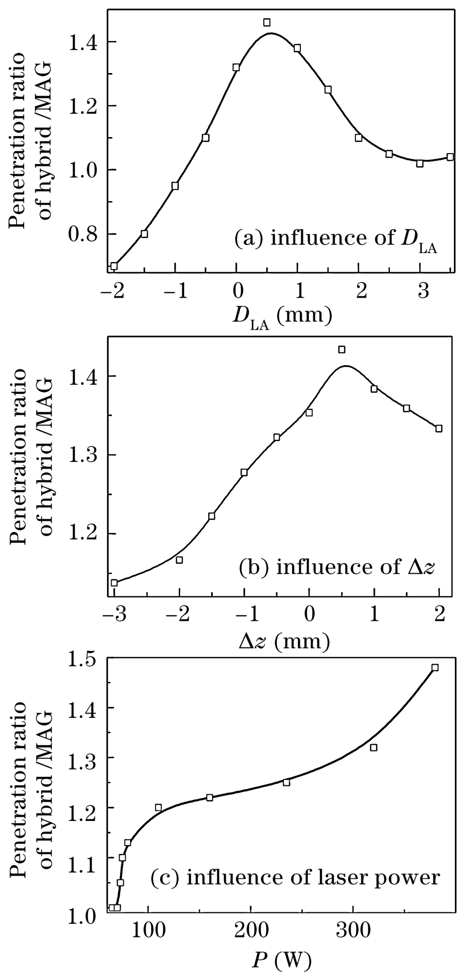


Fig. 5. Influence of YAG laser on the ratio of weld penetration. (a) $P = 350$ W, $\Delta z = 0$ mm, $v = 1$ m/min; (b) $P = 350$ W, $D_{\mathrm{LA}} = 0$ mm, $v = 1$ m/min; (c) $\Delta z = 0$ mm, $D_{\mathrm{LA}} = 0$ mm, $v = 1$ m/min.

will disappear, therefore, the penetration depth of hybrid welding appears the same characteristic of single MAG welding, and the ratio ≈ 1.

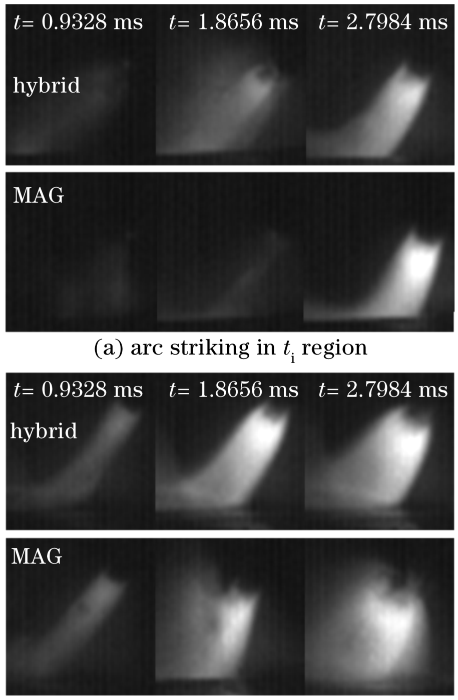
Figure 5(b) shows the influence of Δz on the ratio. It indicates that the ratio increases with increment of Δz, the maximum ratio is achieved when $\Delta z = 0.5$ mm. Then, when $\Delta z > 0.5$ mm, the ratio decreases gradually with the increment of Δz. In the range of Δz given, evaporation and ionization of liquid metal will be generated due to the large density of YAG laser radiation at laser-heated spot, so that, laser-induced plasma is produced, and a high temperature zone with greater density of charged particle in comparison with MAG arc emerges above the laser-heated spot. The effects of laser-induced attraction and contraction of arc are obvious, the energy augmentation effect will be achieved and it results in the increase of hybrid weld penetration. When the focus point of YAG laser is 3 mm under the surface of specimen ($\Delta z = -3$ mm), larger energy of YAG laser will be reflected and absorbed by laser-induced plasma, and the synergic efficiency between laser and MAG arc is low. Therefore, the increase of hybrid weld penetration is unconspicuous. With the increment of Δz, the effects of laser-induced attraction and contraction of arc become more intensive, and the energy augmentation effect will be increased too. It causes the synergic efficiency between laser and MAG arc more obvious, and arc energy and laser energy will be mainly used to increase the weld penetration. Therefore, the hybrid weld penetration increases gradually. When $\Delta z = 0.5$ mm, the synergy of hybrid arc becomes optimal, namely the weld penetration ratio reaches the maximum value; When $\Delta z > 0.5$ mm, the intensity of laser radiation on the surface of specimen decreases, and the quantity of laser-induced plasma decreases too. It leads the effects of attraction and contraction of arc to be weakened gradually, and the synergic efficiency between laser and MAG arc to become more unconspicuous.

Figure 5(c) shows the influence of P on the ratio. It indicates that the ratio increases with increment of P, when $P \geq 73$ W, the ratio > 1. A mall quantity of evaporation and ionization of liquid metal will exist above laser-heated spot due to the small density of YAG laser radiation when $P \leq 70$ W. The attraction and contraction of arc will be feeblish due to the small quantity of laser-induced plasma. It makes the penetration depth of hybrid welding appear the same characteristic of single MAG welding when the ratio ≈ 1; When 70 W $< P \leq 110$ W, the ratio increases quickly with the increment of P. With higher input of laser power, the density of laser radiation at the laser-heated spot will be much greater, a larger quantity of plasma above the laser-heated spot is induced by the radiation of YAG laser, and the effects of attraction and contraction of arc will become more obvious. It accelerates the contraction of arc root, and the energy of MAG arc is augmented. Therefore the ratio increases quickly with the quicker increment of synergic efficiency between laser and MAG arc. In the range of P given, the higher the laser power input, the greater effects of laser-induced attraction and contraction of arc are, and the ratio increases with the increment of P. The lowest laser power that augmented MAG arc is about 73 W.

YAG laser has great influences on the stability of arc ignition and combustion when YAG laser is acting on the t_{i} current increase region and the t_{p} peak current region of pulsed MAG arc. The modality of hybrid arc comparing with that of single MAG arc in t_{i} and t_{p} region of current wave is showed in Fig. 6.

The modality of arc striking in t_{i} region is shown in Fig. 6(a). When YAG laser acts on the arc ignition region, large quantity of metallic vapour with lower ionization potential will emerge above laser-heated spot. And the metallic vapour is ionized intensively and easily by the laser radiation, the high electric field and the high temperature of arc. The plasma induced by radiation of YAG laser and ionization of metallic vapour will result in the increase of conductance of hybrid arc. Therefore, the requisite current, electric field and time of duration in hybrid arc striking region decrease effectively, which makes the ignition of hybrid arc more steady and quick in comparison with MAG arc in hybrid welding process.

The modality of arc burning in t_{p} region is shown in Fig. 6(b). When YAG laser acts on the arc burning region, laser-induced plasma not only increases the conductance between specimen and welding wire, but also provides hybrid arc with larger quantity of charged particles (electrons, ions) in comparison with MAG arc



(b) arc burning in t_p region

Fig. 6. Comparison of arc stability in welding process. (a) $P = 380$ W, $\Delta z = 0$ mm, $D_{LA} = 0.5$ mm, $v = 1$ m/min; (b) $P = 380$ W, $\Delta z = 0$ mm, $D_{LA} = 0.5$ mm, $v = 1.9$ m/min).

to participate in the directional movements of charged particles under the effect of electric field. The laser-induced attraction and contraction effects of arc not only increase the centric temperature and temperature gradient of hybrid arc, but also expand the high temperature zone. Therefore, the electronic emission potential in hybrid arc will be augmented. The stability of hybrid arc burning is increased in hybrid welding process, and it is prominent especially with high welding speed, as showed in Fig. 6(b). The input of YAG laser makes the combustion of arc more steady and regular in hybrid welding process in comparison with the instability of MAG arc.

In conclusion, the attraction and contraction effects of MAG arc induced by YAG laser emerge in low power laser-MAG hybrid welding process, which result in the augmentation of hybrid welding energy. When $D_{LA} = -0.5 - 2$ mm, $\Delta z = -2 - 2$ mm and $P \geq 73$ W, the synergic efficiency between laser and MAG arc is increased and it makes the hybrid weld penetration increase. The stabilities of hybrid arc ignition and combustion in hybrid welding process are prominent due to the input of YAG laser.

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