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ORIGINAL ARTICLE

Arc characteristics and metal transfer process of hybrid laser double GMA welding

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Abstract Hybrid laser gas metal arc (GMA) welding can provide higher productivity than either autogenous laser welding or GMA welding alone. In order to further enhance the welding efficiency of the hybrid laser arc welding process, a novel triple-heat-source welding system entitled hybrid laser double GMA welding was proposed in this study. This hybrid welding system was established based on a double GMA welding and laser welding system. During the hybrid welding process, two consumable electrodes kept alternative arcing at relatively low welding current while they changed to arc synchronically at relatively high welding current. This research is mainly focused on the mechanism of the alternative arcing phenomena and the influences of wire feed speed and laser beam on the arc alternating process. It was found that the arcing period decreased with the increase of wire feed speed which was positively correlated with the welding current. The arcing period also decreased with the introduction of the laser beam into the arc welding system. The arcing period can be decreased as short as possible until it was equal to the pulse period of the welding power source. Based on the analysis of the driving forces acting within the molten weld pool, it can be inferred that the hybrid laser double GMA welding process could be in favor of homogeneous alloying elements distribution and weld metal microstructure.

Keywords Laser · Double GMA · Hybrid welding · Alternative arcing

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1 Introduction

Novel welding method can largely contribute to the welding quality and welding efficiency. In recent years, a considerable number of studies are focused on hybrid laser arc welding. In a typical hybrid laser arc welding system, one laser beam and one electric arc are combined together to obtain the benefits of both of the two welding processes [1, 2]. The synergistic effect from the combination of the laser and arc plasma can help in increasing the melting efficiency, in which process the arc is constricted and its energy density increases significantly [3, 4]. The plasma electron temperatures, electron and ion species densities, electrical conductivity, and arc stability can be enhanced significantly when the separation distance between the arc and laser beam is within an appropriate range [5].

The hybrid laser arc welding with a non-consumable electrode can be coaxial or paraxial according to the relative location of the arc and laser beam [6]. It is usually set as paraxial form in the typical hybrid laser gas metal arc (GMA) welding system, which includes two different modes: laser leading arc mode or arc leading laser mode [7, 8]. The configuration mode of the heat sources in the hybrid welding system developed by Dilthey et al. was more complex. There were three heat sources, one laser beam and two electric arcs, in this welding system and the laser beam was positioned between two electric arcs [9, 10]. The relative location of the laser beam with one arc was laser leading arc mode and the laser beam with the other arc was arc leading laser mode.

The influences of the relative location of the laser and arc on plasma interactions, driving forces for the fluid flow and alloying elements distribution within the molten weld pool as well as the final weld bead profiles were studied for typical hybrid laser arc welding [7, 8, 11]. The optimal separation distance between the two heat sources to obtain the largest weld penetration depth is larger for arc leading laser mode than the laser leading arc mode because of the different separation distance upper limits for effective synergistic interactions of the laser and arc plasma [7, 8]. The distribution of wire feeding elements is more homogeneous in laser leading arc than in arc leading laser mode, which is resulted from different molten pool metal fluid flow patterns caused by different directions of drag force of the plasma jet and droplet momentum [11]. Consequently, the mixing and diffusion of the filler droplets into the base metal is greatly affected by the dynamics of the weld pool fluid flow which is significantly influenced by the relative location of the heat sources in hybrid laser arc welding. The competition between the mixing and solidification rates determines the compositional homogeneity of the weld pool [12]. Relatively low content of alloying elements in the low molten region was observed in CO_2 laser GMA hybrid welding [13]. The molten metal flows from the center to the periphery of the weld pool when there is no significant amount of surface active element in the hybrid laser arc welding process. However, the fluid changes to flow from the periphery to the center of the weld pool on the surface and flows down back to the bottom just behind the keyhole wall if sufficient amount of surface active elements such as sulfur or oxygen exists [11]. The Marangoni force which pushes the molten metal to the weld pool center and the electromagnetic force are the dominant driving forces for this inward flow [14]. This kind of inward flow pattern can result in a larger penetration depth and improved homogenous distribution of the alloying elements, which is subsequently in favor of the formation of uniform weld metal microstructure [11, 15].

The lower part of the weld by typical hybrid laser arc welding has finer grain size, higher microhardness, and smaller alloying elements content than the upper weld [16, 17]. The lower weld also has a higher tendency to obtain microstructures with high hardness such as martensite or bainite mainly because of the higher cooling rates and inhomogeneous alloying elements distribution at the lower region [18]. The inhomogeneous distribution of alloying elements and the final microstructure within the weld metal in typical hybrid laser arc welding are closely related with the driving forces within the molten weld pool. These driving forces can be significantly affected by the configuration of the hybrid welding system and the interactions among the heat sources. In order to improve the above conditions, a novel triple-heat-source hybrid welding system with one laser beam and two electric arcs was proposed in this paper.

For traditional gas metal arc welding process (GMAW), the workpiece is connected with the cathode of the power source while the filler wire is connected with the anode of the power source. Several novel welding methods based on the gas metal arc welding process have been developed recently [19–22]. In this study, another variant of GMAW is proposed to serve as the arc welding part for the triple-heat-source hybrid welding system. In this arc welding system, the workpiece was connected with the cathode of the arc welding power source while the two filler wires were both connected with the anode of the same power source. There were particular welding phenomena under certain welding parameters for this welding system. Furthermore, a laser welding system was combined into this double arc welding system. This new triple-heat-source hybrid welding system is entitled hybrid laser double GMA welding.

In this paper, the main characteristics of the hybrid laser double GMA welding system were studied. The mechanism of the alternative arcing phenomena and the influences of the wire feed speed and laser beam on the arc alternating process were discussed. The alloying elements distribution and microstructure homogeneity within the weld metal of the hybrid welding process will be studied in the future.

2 Experimental system

The experimental system of hybrid laser double GMA welding is illustrated in Fig. 1. The arc welding system included one arc welding power source (Lincoln INVERTEC V350-PRO), two consumable electrodes, two wire feeders, two welding torches, and some other accessories. The hybrid laser double GMA welding system was established by coupling one Nd/YAG laser (JK2003SM) with nominal power of 2 kW produced by GSI Corporation into the arc welding system. The welding system can be either double GMA welding or hybrid laser double GMA welding, depending on whether the laser beam welding system was applied.

In the arc welding system, the anode of the arc welding power source was connected simultaneously with two consumable electrodes while the cathode of the power source was connected with the workpiece, which was the same as typical GMAW. The arc welding power source was working at pulse mode. The wire feed speed of the two filler wires was set at the same value for all welding conditions.

The front filler wire along with the welding direction was defined as the leading wire while the other filler wire was the trailing wire. The welding parameters of the hybrid laser double GMA welding process are indicated in Table 1. The incident position of the laser on the workpiece was at the midpoint of the connecting line of the two filler wire tips. The distance between the tips of the two filler wires on the workpiece surface was 8 mm for all conditions. The current through the leading wire was I_1 and the current through the trailing wire was I_2. The voltage between the leading wire and the workpiece was U_1 while U_2 was the voltage between the trailing wire and the workpiece.

The monitoring system for the welding process was constituted of the electrical signal acquisition system and the high speed photography system. The electrical signal acquisition system contained two current sensors which monitored, respectively, the current through the leading wire and the trailing wire, and two voltage sensors which monitored the voltage

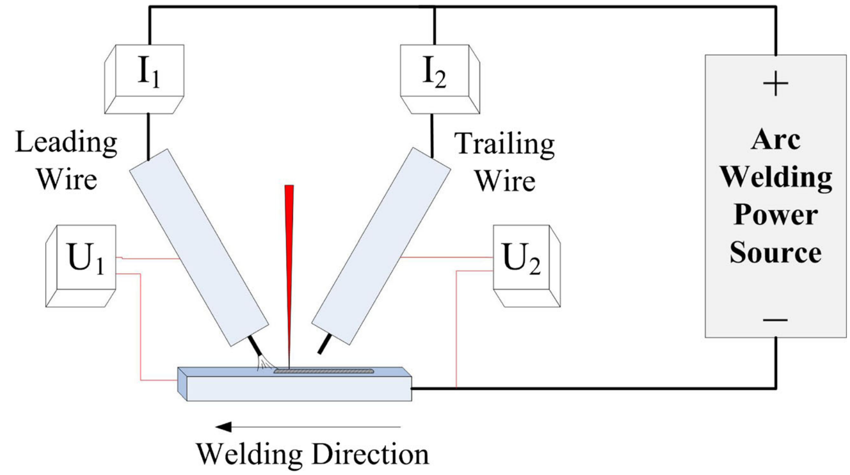

Fig. 1 Illustration of the hybrid laser double GMA welding system

between the leading wire and the workpiece as well as the voltage between the trailing wire and the workpiece. The acquisition rate of the electrical signals was 500 kHz. The high speed photography system contained a high speed camera which worked with a capturing rate of 1000 frames per second and an auxiliary illumination which was a 500-W xenon light source.

3 Results and discussion

As depicted in Fig. 1, the leading wire and trailing wire were both connected with the anode of the arc welding power source. This type of welding system configuration can contribute to particular arcing phenomena under different welding parameters. The two filler wires kept arcing alternatively when the wire feed speed was relatively low.

The arcing processes with wire feed speed of 1.5 m/min for both of the two filler wires are indicated in Fig. 2. It can be observed from the electrical signals that the leading wire and trailing wire kept arcing alternatively and regularly. One of the two filler wires kept on arcing for several pulse periods while the other wire had no arc established between the wire tip and the workpiece, which can be confirmed by the current signals at zero level. Then, this arc extinguished after an arcing period of about 0.23 s and another arc initiated and ignited between the other filler wire and the workpiece exactly at the extinguishing time point of the former arc. It was, in short, an alternative arcing process for these two filler wires.

The time span for a filler wire arcing turn is defined as one arcing period, as shown in Fig. 2, which is different from the pulse period of the welding power source. As for one filler wire, there is no current through the electrode between two arcing periods while a relatively low level current is still maintained between two pulse periods of the welding power source. In other words, one arcing period is composed of several pulse periods in the alternative arcing process. The correlation between the arcing period and pulse period of the welding power source can be influenced by the main welding parameters of the hybrid laser double GMA welding system such as the laser power and the wire feed speed of the leading wire and trailing wire. The arc alternating mechanism in the hybrid laser double GMA welding process is discussed in the following part.

4 Effects of wire feed speed on the arc alternating process

The wire feed speed for both of the leading and trailing wire was varied from 2 to 3 m/min to study the effect of wire feed speed on the arc alternating process. The electrical signals are shown in Figs. 3 and 4, respectively. It can be seen from Fig. 3 that there were 17 pulse periods for the arcing period of I_1 from 0.075 to 0.252 s while I_2 kept 0 throughout this time period. Alternatively, there were 19 pulse periods for I_2 but I_1 kept 0 throughout the time period from 0.252 to 0.452 s. So, the arcing period for the filler wires was approximately 0.20 s at 2.0 m/min wire feed speed. The number of pulsing periods in one arcing period significantly decreased when the wire feed speed increased to 3.0 m/min from 2.0 m/min, as illustrated in Fig. 4. There were only 3 to 4 pulse periods in one arcing period compared with the previous 17 to 19 pulse periods in Fig. 3. Nevertheless, the leading wire and trailing wire still kept the main characteristic of alternative arcing.

Table 1 Welding parameters of the hybrid laser double GMA welding process

Laser power	Shielding gas	Gas flow rate	Filler wires	Welding speed	Workpiece
1 800 W	Argon	20 L/min	H08Mn2SiA	5 mm/s	Mild steel

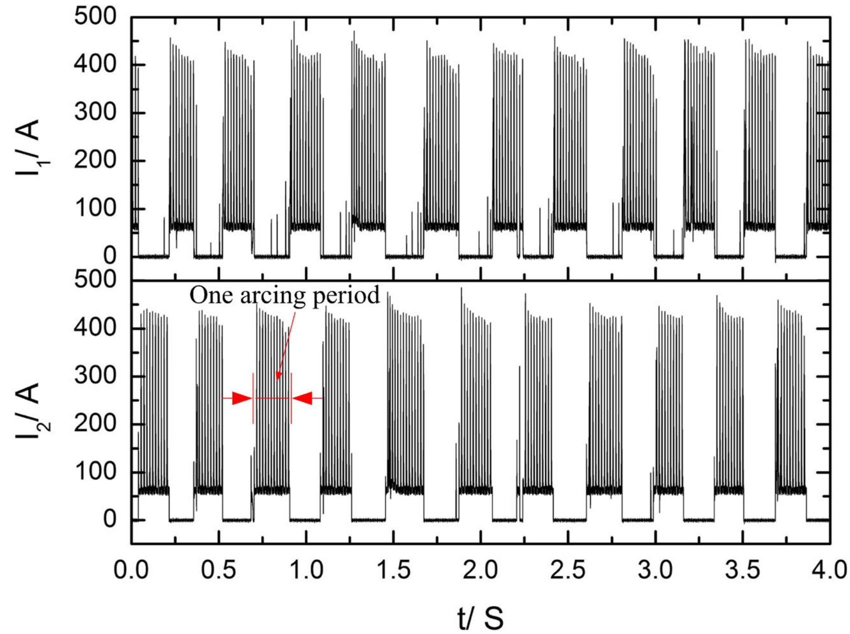

Fig. 2 Welding current signals of the arc welding process with wire feed speed of 1.5 m/min

It should be noticed that there were voltage signals for U_1 and U_2 through all the welding process. It is because that there was always at least one arc existing in the welding system in either condition. In the time period from 0.075 to 0.252 s, U_2

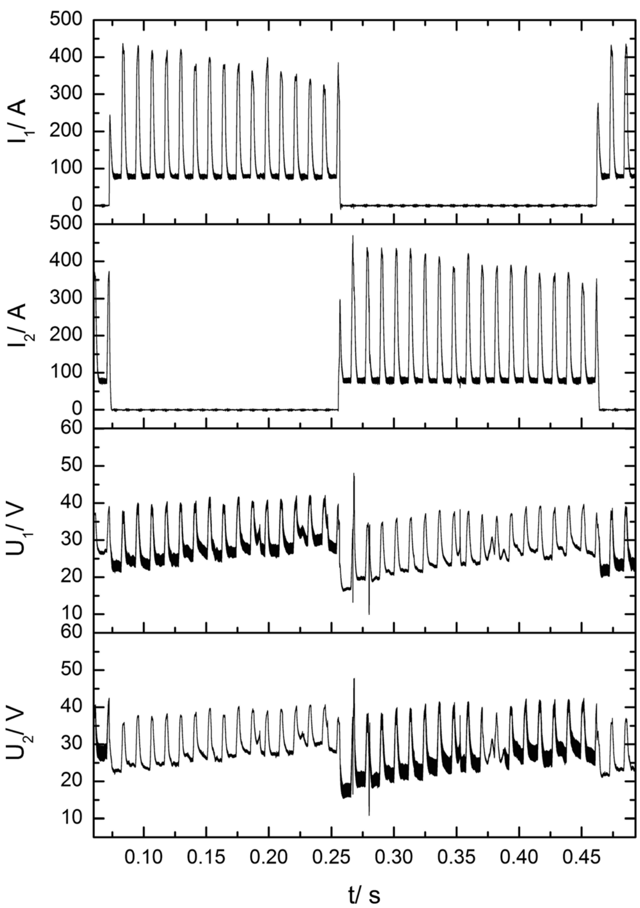

Fig. 3 Electrical signals of the double GMA welding process with wire feed speed of 2.0 m/min

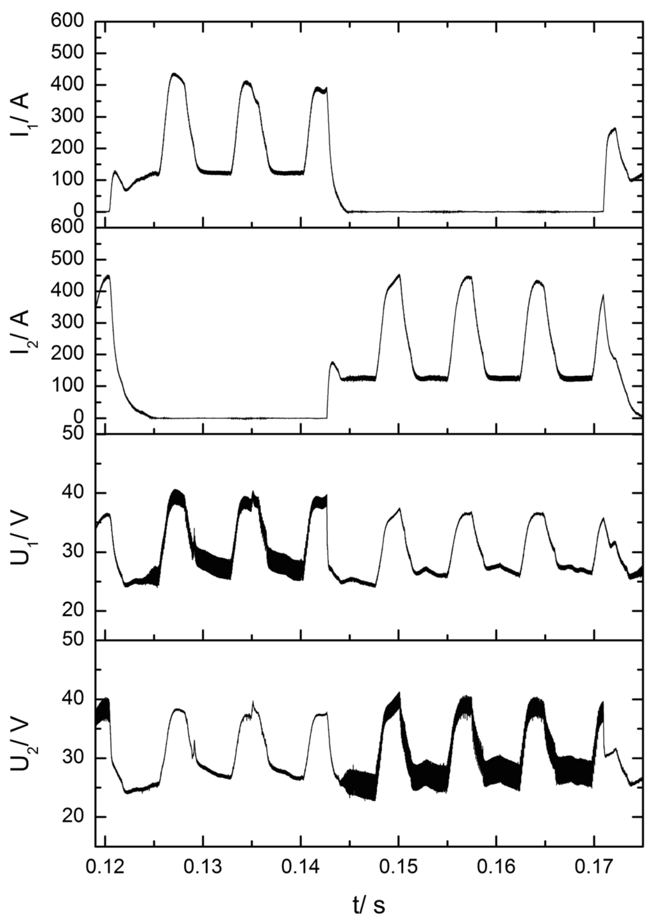

Fig. 4 Electrical signals of the double GMA welding process with wire feed speed of 3.0 m/min

was the voltage between the leading wire and the workpiece but not the voltage between the trailing wire and the workpiece. Correspondingly, when the trailing wire was arcing, i.e., no leading arc, U_1 was the voltage between the trailing wire and the workpiece.

As described above, the two filler wires were both connected with the anode of the power source, which meant an equivalent electric potential of the two filler wires. The tip of the leading wire was initially set more close to the surface of the workpiece than the following wire. In the arc initiation process, the tip of the leading wire hit the workpiece first and one arc was initiated between the wire tip and the workpiece immediately. The trailing wire tip was moving close to the workpiece surface as the leading wire was arcing. Subsequently, the arc transferred from the leading wire to the trailing wire at a critical relative location of the two filler wires and the workpiece. Nevertheless, there was still only one arc in the welding system. This was mainly because of the relatively low current level which corresponded to the low wire feed speed. The requirement of the electron emission could be fulfilled by only one arc and there was no sufficient supportive power for the maintenance of two arcs. Consequently, the particular phenomenon that one arc transferred between the two filler wires and the workpiece appeared at relatively low wire feed speed.

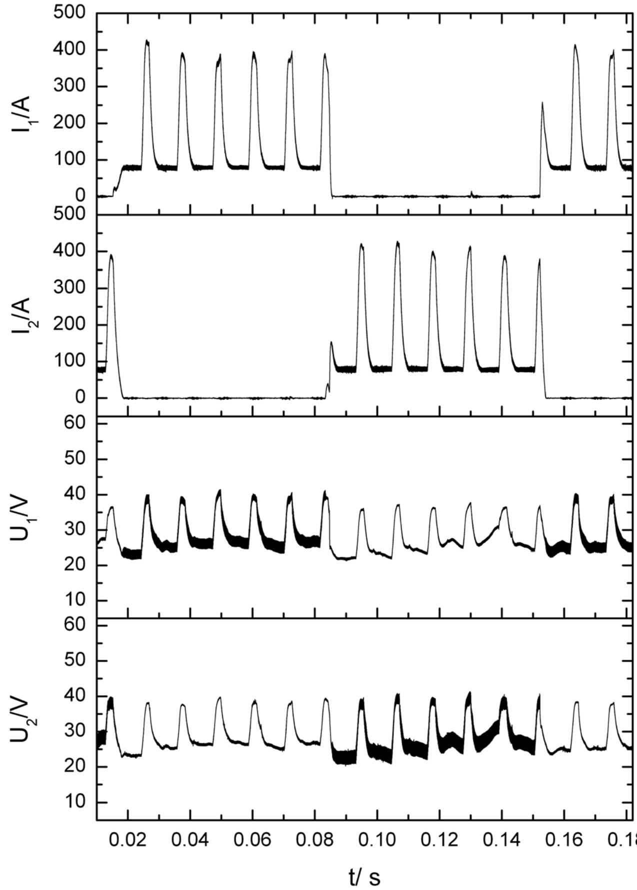

Fig. 5 Electrical signals of the hybrid laser double GMA welding process with wire feed speed of 2.0 m/min

5 Effects of laser beam on the arc alternating process

The laser beam was coupled into the arc welding system to perform the hybrid laser double GMA welding process, and the effect of laser beam on the arc alternating process was studied at wire feed speed of 2 and 3 m/min. The electrical signals are shown in Figs. 5 and 6, respectively.

It can be observed from Figs. 5 and 3 that the number of pulse periods in one arcing period decreased to about 6 pulse periods from 18 pulse periods in the hybrid laser double GMA welding process at wire feed speed of 2 m/min. The variation was even more dramatic at wire feed speed of 3 m/min when the laser beam was added into the welding system. It can be seen from Fig. 6 that the pulse periods in one arcing period decreased to only 2 or 3 and the alternative arcing process even disappeared in some parts of the welding process. The whole welding process became a combination of alternative arcing and simultaneous arcing of the leading wire and trailing wire.

The average arcing period time span of the arc welding and hybrid laser double GMA welding process at different wire feed speeds is presented in Fig. 7. It can be inferred that the arcing period decreased with the increase of wire feed speed. The addition of the laser beam also led to the decrease of the arcing period at the same wire feed speed.

6 Discussions

Different from thermionic cathode material which is able to operate at sufficiently high temperature for thermionic emission of electrons to play a significant role [23], the electron emission of the workpiece as non-thermionic cathode material largely depends on field emission. The electron emission current density j_e of a cathode heated to a sufficiently high temperature of T Kelvin could be given by the Dushmann equation [23]:

$$j_e = AT^2 e^{-eV_w/kT} \tag{1}$$

where A is a constant with the value about $60A \cdot cm^{-2} \cdot K^2$ for most metal materials. V_w is the work function of the cathode material, and k is the Boltzmann's constant.

Electrons would be emitted with a current density j_e' if an external electric field with a potential gradient of X is applied on the cathode surface:

$$j_e' = AT^2 e^{-e\left(V_w - \sqrt{eX}\right)/kT} = e^{e\sqrt{eX}/kT} \cdot j \tag{2}$$

It can be inferred that j_e' is $e^{e\sqrt{eX}/kT}$ times of j_e, which means a higher current density brought about by the external

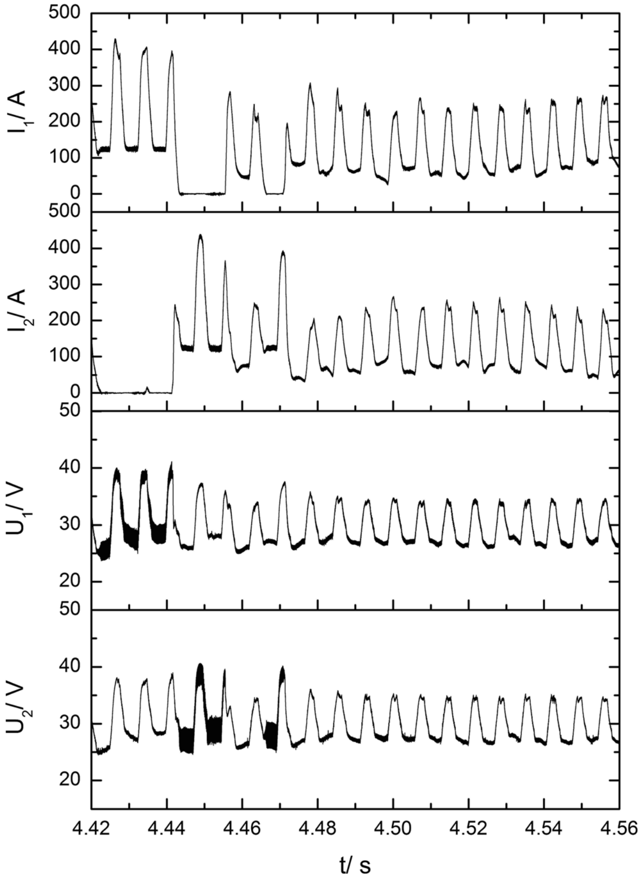

Fig. 6 Electrical signals of the hybrid laser double GMA welding process with wire feed speed of 3.0 m/min

electric field. Or equivalently, the work function of the cathode material is reduced to $V_w - \sqrt{eX}$ from V_w when an electrical field is applied. It is apparent that the electron emission becomes easier and the extent is positively related to the potential gradient of the external electric field. In addition, the electric field intensity is inversely proportional to the distance between the cathode and the anode. So, the influence

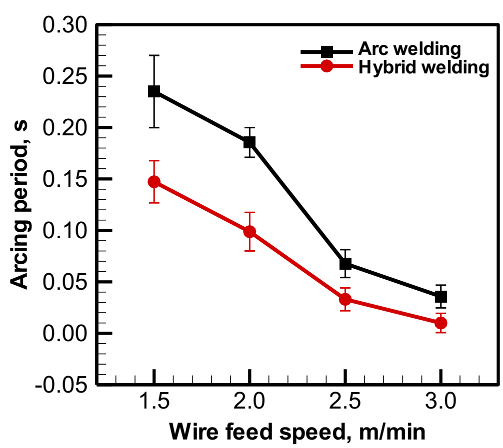

Fig. 7 Effects of wire feed speed on the arcing period of the double GMA welding and hybrid laser double GMA welding process

of the external electric field on electron emission will be enhanced when the distance between the fill wire tip and the surface of the workpiece gradually decreased.

The detailed transient process of the arc from the trailing wire to the leading wire in the double GMA welding process when the wire feed speed was 2.0 m/min is depicted in Fig. 8. The last pulse peak period of the trailing wire as well as the first pulse peak period of the leading wire were both contained in the time period from 0.461 to 0.466 s. The arc became longer and longer along with the arcing process of the trailing wire. Simultaneously, the tip of the leading wire was becoming closer and closer to the workpiece due to its continuously feeding all through the time. Then at a critical point, which was 0.462 s in Fig. 8, the tip of the leading wire became close enough to generate a sufficiently strong electric field for electron emission which was apparently stronger than that between the tip of the trailing wire and the workpiece, as indicated in the discussion of Eq. 2. Consequently, the conduct path for electron emission transferred to a stronger electric field from the weaker one, i.e., the arc of the leading wire initiated and the trailing wire arc extinguished. The moving velocity of the filler wire towards the workpiece surface increased with the increase of filler wire feed. In addition, the arc current also increased with the increase of the filler wire speed, which can help in enhancing the electron emission significantly. Consequently, the time span for the switching of the arc from one filler wire to the other can be significantly reduced when the filler wire speed is increased.

What is illustrated in Fig. 9 is the transient process of the arc from the trailing wire to the leading wire during the hybrid laser double GMA welding when the wire feed speed was 2.0 m/min. The combination of the waveform of I_1 and I_2 was quite similar to that in Fig. 8. Nevertheless, there was an obvious difference on the comparison of distances between the workpiece and the tips of the two filler wires at the two transient moments illustrated in Figs. 8 and 9. It can be seen from Fig. 10 that at the arc alternating critical point, the distance between the tip of the leading wire and the workpiece increased from 2.9 to 4.7 mm. In other words, the critical distance between the leading wire and workpiece increased at the time point when the arc transferred from the trailing wire to the leading wire in the hybrid laser double GMA welding system. It can be inferred from the increased critical distance that the conducting intensity of the conductive particles in the arc atmosphere increased. However, the increase of the distance means a weaker electric field intensity for the cathode electron emission, which tends to result in a decreased filler wire-workpiece critical distance. Therefore, it can be assumed that the electron emission process in hybrid laser double GMA welding was intensified by some extra conductive particles which did not exist in the double GMA welding process.

In high power laser welding process, a condensed metal vapor will be induced from the interaction between the high

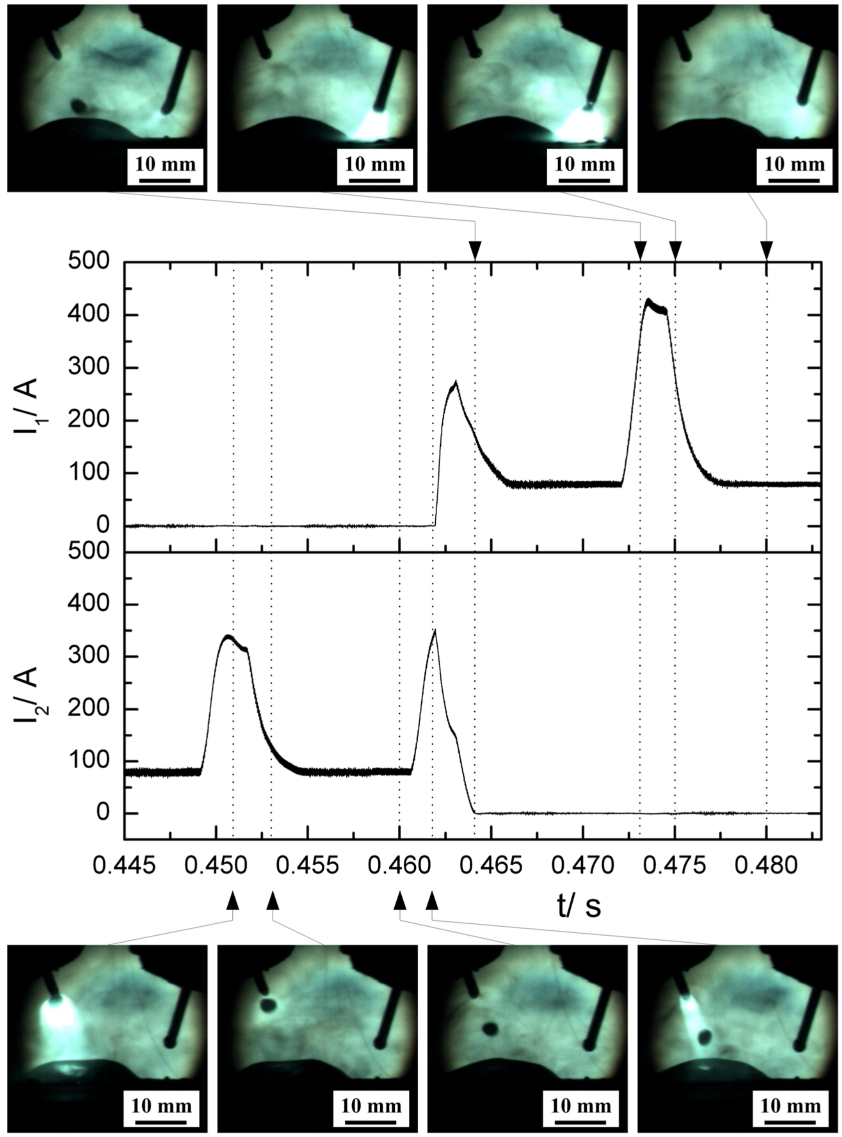

Fig. 8 Transient process of the arc from the trailing wire to the leading wire in the double GMA welding process with wire feed speed of 2.0 m/min

energy density laser beam and the workpiece or the shielding gas. Pronounced vaporization of alloying elements due to the high power density can lead to increased plasma electrical conductivity, electron density, electron temperature, and arc current density [24, 25]. The modified Langmuir equation has been used to calculate the vaporization flux during laser and laser arc hybrid welding [5, 26].

$$J_i = \frac{\lambda P_v}{b\sqrt{2\pi RMT}} \tag{3}$$

where λ represents the compensation coefficient for condensation in the liquid-vapor interface. P_v is the equilibrium partial pressure of alloying element. T is the temperature, b is a dimensionless constant which accounts for the reduced vaporization rate at atmospheric pressure compared to that in perfect vacuum, R is the ideal gas constant, and M is the atomic mass of alloying element. P_v can be calculated by:

$$P_v = P_0 \exp\left[\frac{H_v}{RT_v}\left(1 - \frac{T_v}{T}\right)\right] \tag{4}$$

where P_0 is the atmospheric pressure, H_v is the latent heat of vaporization, and T_v is the vaporization temperature. During the hybrid laser arc welding process, there is significant vaporization of the workpiece material at the location where the laser impinges on the surface of the workpiece and then the vapor was transported into the arc plasma [3, 5]. The ionization potential of the atmosphere surrounding the arc could be effectively reduced. Furthermore, a part of the laser beam energy could be absorbed by the arc plasma, which would

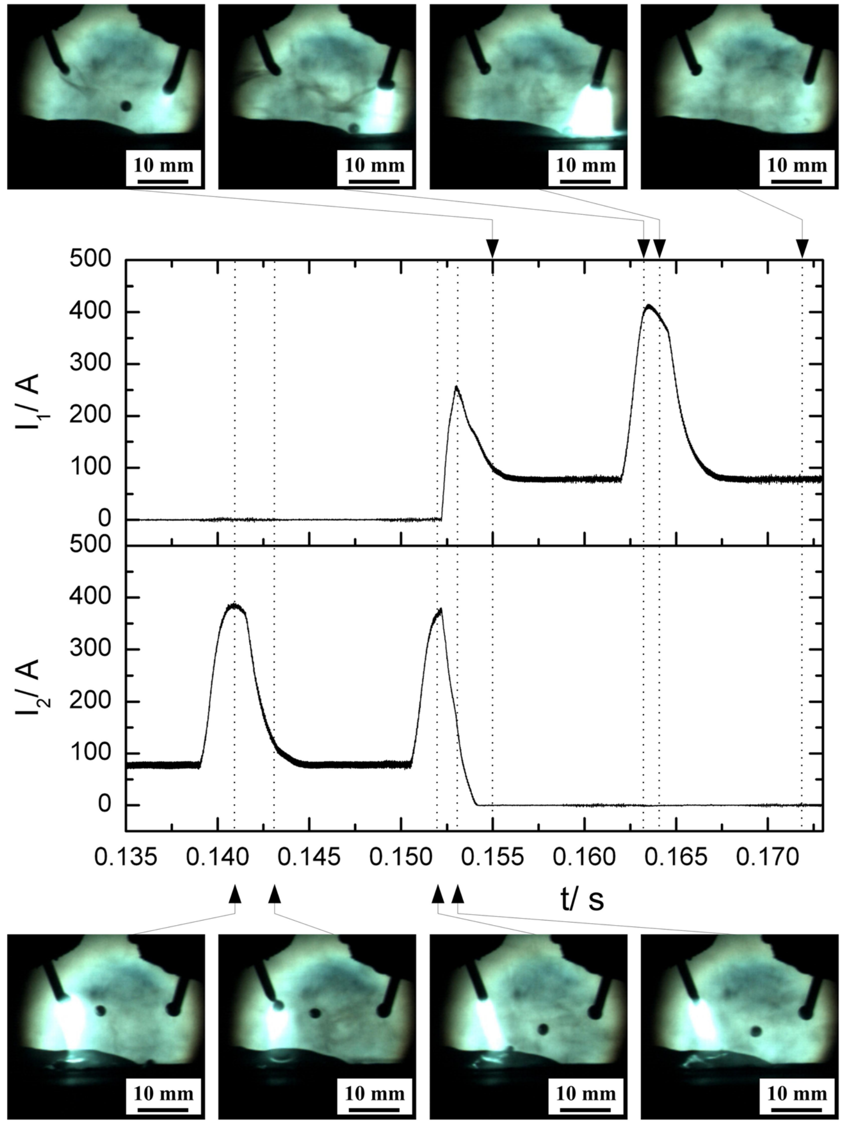

Fig. 9 Transient process of the arc from the trailing wire to the leading wire in the hybrid laser double GMA welding process with wire feed speed of 2.0 m/min

contribute to a further ionization of the arc plasma. The shielding gas used in the experiments could also be ionized by the interaction between the laser and the surrounding atmosphere. However, its extent is less than iron because the

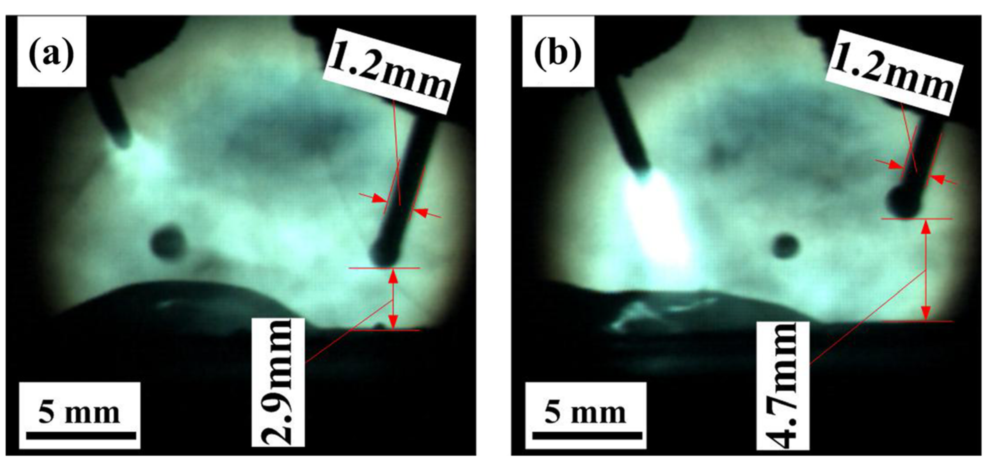

Fig. 10 Comparison of filler wire-workpiece distance at the arc alternating critical point in the double GMA welding and hybrid laser double GMA welding process. **a** arc welding, **b** hybrid welding

iron atoms have an ionization potential of 762.5 kJ mol^{-1}, which is much lower than the argon ionization potential of 1,520.6 kJ mol^{-1}.

Consequently, during hybrid welding, the number of conductive particles surrounding the arc atmosphere was increased, and then the resistance of the arc was decreased for the presence of the laser induced metal vapor. So, the large amount of conductive particles from the laser-induced metal vapor can be accounted for by the increase of the critical filler wire-workpiece distance; as in hybrid welding conditions, the arc could be initiated under a relatively low electric filed intensity. As a result, the arcing period significantly decreased in hybrid laser double GMA welding than in the double GMA welding process.

7 Advantages of hybrid laser double GMA welding and future work

There are several advantages for the hybrid laser double GMA welding process than the typical hybrid laser arc welding process. The preheat effect of the leading arc can enhance the absorption coefficient of the laser beam energy of the base metal [27]. With certain configuration parameters in hybrid welding, the electric field of the arc plasma can influence the laser-induced plasma as the additional electric field and increase the absorptivity of the laser beam energy, which is beneficial for the weld penetration depth [28]. The detailed study about this will be done in the future.

The main driving forces for the fluid flow acting within the molten weld pool in the hybrid laser double GMA welding process when the two filler wires keep arcing synchronically is illustrated in Fig. 11. The driving force which pushes the liquid metal from the weld pool center to the periphery is mainly the Marangoni force when there is no surface active element within the weld pool [11, 14]. The temperature coefficient of surface tension of the molten weld metal is negative in this case. The driving forces which cause inward fluid flow are mainly electromagnetic force, droplet momentum, and drag force of the arc plasma jet.

The temperature coefficient of surface tension will change to positive if there is significant amount of surface active elements such as sulfur or oxygen. The surface tension of a Fe-S or Fe-O system can be given as a function of both temperature and activity of sulfur or oxygen [11, 29]:

$$\gamma = \gamma_{\mathrm{m}} - A[T - T_{\mathrm{m}}] - RT\Gamma_{\mathrm{s}}\ln[1 + a_{\mathrm{i}}K] \tag{5}$$

$$K = k_1 \exp\left(-\frac{\Delta H^\circ}{RT}\right) \tag{6}$$

where γ is the local surface tension, γ_{m} is the surface tension of the pure metal at melting point, A is negative of $\partial\gamma/\partial T$ for pure metal, T is the local temperature, T_{m} is the melting point of the materials, R is the gas constant, Γs is the surface excess at saturation, and a_{s} is the activity of sulfur. k_1 is the entropy factor and ΔH° is the standard enthalpy of adsorption.

By differentiating Eq. (5) with respect to temperature, the expression for temperature coefficient of surface tension $\partial\gamma/\partial T$ as a function of both temperature and sulfur concentration can be obtained as:

$$\frac{\partial\gamma}{\partial T} = -A - R\Gamma_{\mathrm{s}}\ln\left[1 + a_{\mathrm{i}}K_{\mathrm{seg}}\right] - \frac{a_{\mathrm{i}}K_{\mathrm{seg}}}{1 + a_{\mathrm{i}}K_{\mathrm{seg}}}\frac{\Gamma_{\mathrm{s}}\Delta H^\circ}{T} \tag{7}$$

$$K_{\mathrm{seg}} = k_1 \exp\left({}^{-\Delta H^\circ}/_{RT}\right) \tag{8}$$

The transition temperature from positive to negative for the temperature coefficient of surface tension increases with increasing the weld sulfur or oxygen content. The pushing out effect of the Marangoni force on the molten weld metal can be weakened or even inversed when the surface active elements amount is sufficiently high.

Compared with the typical hybrid laser GMA welding process, the hybrid laser double GMA welding system tends to promote inward flow more effectively, especially when the welding system works at the synchronal arcing mode. The

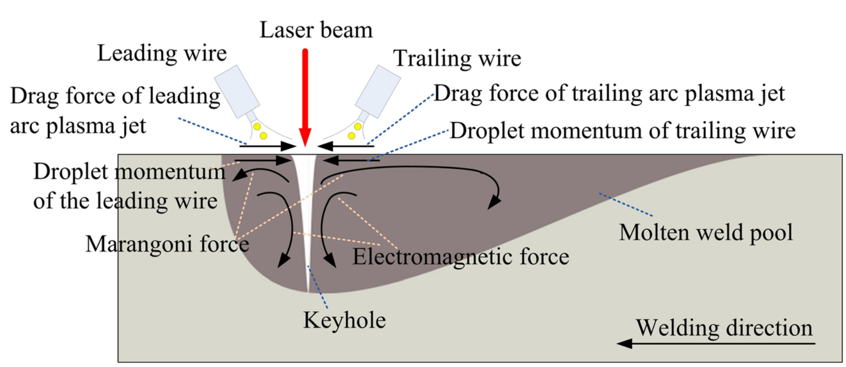

Fig. 11 Illustration of the driving forces acting within the molten weld pool of hybrid laser double GMA welding

droplet momentum and arc plasma jet drag force of the leading wire and trailing wire are both driving forces for the inward flow. The inward flow can be beneficial for the mixing of the alloying elements from the filler wire with the weld metal. Further study about the heat transfer and fluid flow conditions in the hybrid laser double GMA welding process will be done in the future work.

8 Conclusions

A triple-heat-source welding system entitled hybrid laser double GMA welding which was based on a double GMA welding system was developed in this study. The two consumable electrodes kept alternative arcing at relatively low welding current while they changed to simultaneously arcing when the welding current was relatively high. Therefore, the hybrid welding process can vary between double-heat-source and triple-heat-source welding with different current levels.

The alternative arcing process and mechanism of these two welding processes was studied. The arcing period decreased with the increase of wire feed speed in both the double GMA welding and hybrid laser double GMA welding processes. The increase of the wire feed speed can significantly enhance the electron emission in the arcing process and reduce the time span for the switching of the arc from one filler wire to the other. The arcing period was shorter in the hybrid laser double GMA welding process than in the double GMA welding process when all other welding parameters were constant, which was for the reason that the laser-induced metal vapor provided extra conductive particles that contributed to the enhancement of the arc plasma electrical conductivity.

The driving forces acting within the molten weld pool of the hybrid laser double GMA welding can be in favor of homogenous alloying elements distribution and final microstructure within the weld metal. Further researches about this will be done in the future.

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