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ORIGINAL ARTICLE

Arc characteristics and metal transfer behavior of twin-arc integrated cold wire hybrid welding

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Abstract Twin-wire arc served as a high-efficient technology has been fully developed and widely used in the manufacturing industry. In order to further increase welding deposition rate, a novel high-efficient welding system entitled twin-arc integrated cold wire hybrid welding was proposed in this paper. The study focuses on the effect of welding electrical parameters on alternative arcing and metal transfer process for the purpose of optimizing electrical parameters to realize a stable welding process. Characteristics of the metal transfer processes and the influence mechanism of welding electrical parameters on metal transfer modes were studied. The results showed that the two leading wires kept regularly alternative arcing with the phase difference of 180° between the pulse currents supplied to wires, and the alternating frequency increased with arc voltage and welding current. Besides, the metal transfer modes were divided into three types by varying welding parameters: short circuiting transfer, projected transfer, and streaming transfer. What is more important, the metal transfer mode highly depended on arc length, which was determined by arc voltage when welding current was kept constant. The metal transfer mode would change from short circuiting transfer to projected transfer, and then converted into streaming transfer eventually with the increase of arc voltage.

Keywords Alternative arcing · Short circuiting transfer · Projected transfer · Streaming transfer · Metal transfer mode

1 Introduction

With social and economic rapid development, high-efficient welding technology has become one of the most important development directions for welding subject. In recent years, scholars and professionals in many countries devoted themselves to working on how to further increase the welding efficiency from the several aspects of welding material, welding process, arc welding equipment, and so on. The welding efficiency can be increased in two ways: one is increasing the welding speed, and the other is increasing the welding deposition rate. Given the above two methods, typical technologies such as multi-wire submerged arc welding (SAW) [1, 2] and multi-wire gas metal arc welding (GMAW) [3–5] were proposed successively.

In recent years, twin-wire arc welding technology has broken threshold and been widely used in the manufacturing industry. In this welding system, the two mutually isolated wires were arranged either in a welding torch according to a certain angle or in two welding torches. For the latter, the two wires were separately equipped with individual power supply to realize the independent regulation of welding parameters. Besides, the two power supplies can output the reverse-phase pulse current through the pulse synergic control, which

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realized good control of arcs to decrease the interference between two arcs [6–8]. One of the most widely used in the shipbuilding industry was tandem arc welding [9–11], which greatly increased the deposition rate as well as the welding speed on the premise of realizing a stable metal transfer. In consideration of further increasing the deposition rate or welding speed by adding the third wire, advanced 3-electrode MAG welding [12, 13] and integrated cold wire (ICE^{TM}) submerged arc welding (SAW) [14] have been successively developed. From the development of twin-wire GMAW to multi-wire GMAW, the basic principle was based on increasing the deposition rate by increasing the number of wires while keeping the welding heat input constant. In the first welding system above, a filler wire was added as the third electrode between the leading and trailing wire. The leading and trailing wires that can perform positional shift around its own axis of rotation were designed as a straight line. Moreover, the addition of the filler wire can cool down the liquid weld pool metal to increase the liquid metal viscosity, which would be a benefit to better formation of weld bead. This welding technology was mainly used in the shipbuilding industry. In the second welding system, three wires were integrated in a special welding torch, and the cold wire was parallelly arranged between the two molten wires and mainly melted by the excess arc heat, which significantly increased the deposition rate and reduced the flux consumption and deformation.

Summarizing the above research results, we have realized that further increase of the deposition rate or welding speed can be achieved by increasing the number of no arcing wires. Therefore, a novel high-efficient welding technology entitled twin-arc integrated cold wire hybrid welding was proposed in this study. In this welding technology, three wires arranged into an equilateral triangle were integrated in a special welding torch, and the stable welding process can be carried out at the deposition rate of 7.476 Kg/h. While all of the welding parameters were kept constant, the deposition rate for the twin-wire GMAW only reached 6.097 Kg/h. Compared with the twin-wire GMAW, the deposition rate for the twin-arc integrated cold wire hybrid welding has increased about 23 % [15]. The main characteristic of this novel welding technology is greatly increasing the welding deposition rate on the premise of realizing a stable metal transfer process.

As is known to all, the metal transfer plays an important role in the whole welding process, which can directly affect the quality of final weld formation. In this paper, the study focuses on the effect of welding electrical parameters on alternative arcing process and metal transfer process for the purpose of optimizing electrical parameters (mainly welding current and arc voltage) to realize a more stable metal transfer process. Characteristics of the metal transfer processes and the influence mechanism of welding electrical parameters on metal transfer modes were studied. The research results would provide a good guidance for the establishment of welding procedure.

2 Experimental system

The experimental system of twin-arc integrated cold wire hybrid welding established in this study is illustrated in Fig. 1. The arc system included two arc welding power sources (AOTAI Pulse MIG-500) that can achieve the pulse modes of multiple phase relationships through the communication line between each other, three wires (including two wires with arcs and a cold wire), three wire feeders, a special welding torch, and some other accessories. The anode of welding power sources were all connected simultaneously with the two consumable electrodes while the cathode of the power source was connected with the workpiece.

In the arc welding system, three wires were arranged into an equilateral triangle at the same circumference and integrated in a special welding torch. In order to gather together arcs to form a single weld pool, three wires that were bent towards the center axis of welding torch formed a 7° angle relative to the central axis of the welding torch. Three wires were isolated to each other and respectively equipped with independent shielding gas and cooling water channels. In this way, it could serve as both a good gas protective effect for the weld bead to reduce welding defects and a good cooling effect for the welding torch to ensure service life. During the welding process, the two wires with arcs in the front heated and melted the base metal to form a single weld pool, and the cold wire was directly fed into the weld pool and mainly melted by the heat from the weld pool. Three wires were arranged in a special mode for two reasons: (1) the third electrode served as a cold wire was mainly melted by excess heat from weld pool, which significantly increased the deposition rate with the constant heat input. (2) The addition of cold wire can cool and calm down the weld pool to improve the welding stability. The two wires in the front were defined as leading wire 1 and leading wire 2, respectively. The third trailing wire was defined as cold wire, which indicated that there was no arc established between this wire end and the workpiece. The welding direction was perpendicular to the connecting line between the endpoints of the leading wires 1 and 2.

The monitoring system for the welding process was consisted of the high-speed photography system (MotionPro-Y3) and the electrical signal acquisition system (NI USB6251). 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 that was a 5000-W xenon light source. The shooting direction was perpendicular to the connecting line between the endpoints of the leading wire 2 and cold wire, and the backlight source was placed behind the leading wire 1. In addition, the

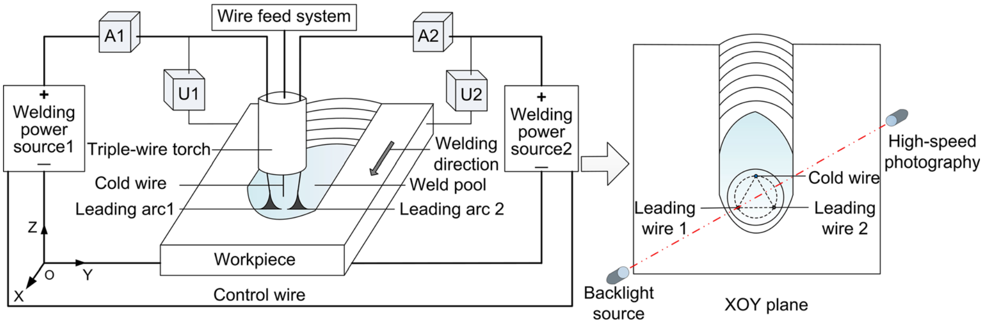


Fig. 1 Schematic diagram of twin-arc integrated cold wire hybrid welding

high-speed photographs for arc behavior and metal transfer process were captured synchronically with the electrical signals to accurately demonstrate the detailed information of the welding process. The electrical signal acquisition system that contained two current sensors and two voltage sensors was used for real-time monitoring of current and voltage transients at rate of 150 KHz. For all the experimental cases, all of the wires were H08Mn2SiA with a diameter of 1.2 mm. Bead-on-plate welding was carried out on mild steel (Q235) at a welding speed of 0.24 m/min. Table 1 depicts the chemical composition of the workpiece and wires. The shielding gas used in this experiment was 85 % Ar + 15 % CO2 with a flow rate of 25 L/min. The feed speed of the cold wire was kept constant at 0.8 m/min.

3 Results and discussion

3.1 Improvement on pulse waveform

In order to realize a more stable metal transfer process, the pulse current waveform was improved based on the common pulse waveform, as shown in Fig. 2. It is well known that the control over pulse waveform can determine the transition property of a droplet, and the area size (under the waveform) constituted by the waveform line, current axis, and time axis determines the amount of energy supplied to the wire. Based on the above principles, a novel pulse current waveform with a transition zone was put forward [16]. A transition zone was added between the peak zone and base zone, and the current of the transition zone was higher than the original base current. In this way, the base time t_p was divided into two parts, i.e., t_{b1} and t_{b2}. The main reason for this improvement on pulse waveform was increasing the electromagnetic force to promote the detachment of droplet from the filler wire end, which can realize a stable and smooth metal transfer process. Besides, the detachment of droplet from the filler wire end almost completely occurred in the transition zone, which ensured the regularity and predictability of metal transfer.

Table 1 Chemical composition (values in wt%)

Workpiece (Q235)	C	Mn	Si	S	P
	0.14–0.22	0.3–0.65	≤0.3	≤0.05	≤0.045
Wire (H08Mn2SiA)	C	Mn	Si	S	P
	≤0.11	1.8–2.1	0.65–0.95	≤0.03	≤0.03

3.2 Analysis of the arc alternating process

The two welding power sources connected with the leading wires 1 and 2 can output the reverse-phase pulse currents by the communication line between each other, i.e., phase difference of 180° between the pulse currents through the two leading wires. Similarly, the output voltages also followed the above phase difference. This specific phase relationship between two welding power sources resulted in a particular arcing phenomenon, i.e., alternative arcing.

What is indicated in Fig. 3 are the electric signals and corresponding high-speed photographs of the arc alternating process with the preset current of 120 A for the two leading wires. Moreover, three wires, in turn, are the leading wire 2, leading wire 1, and cold wire from left to right in high-speed photographs. The position of high-speed photographs is indicated on an arcing period with green numbers from 1 to 8. It can be observed that the leading wires 1 and 2 kept regularly alternative arcing [17]. The current and voltage of leading wire 1 was in the pulse peak phase while the current and voltage of leading wire 2 was in the base phase. Besides, the starting point of the pulse peak phase for one of the leading wires exactly corresponded to the starting point of the base phase for another leading wire (see images 1 and 7). Accordingly, the practical acing process showed that one of the leading wires kept intense arcing in pulse peak period while the other leading wire only had an extremely faint arc established between the wire end and the workpiece in base period (see images 2, 3, and 8). At the moment, the base current maintained at a small value of about 50 A. In the base current phase, it was greatly difficult to observe the arc between the wire end and the workpiece because the arc light was extremely faint and offset by the luminance of the backlight, such as the arcing situation of the leading wire 2 in

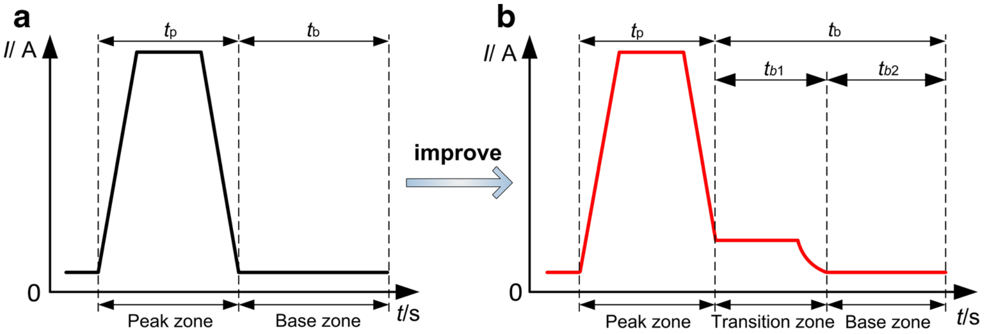


Fig. 2 Schematic diagram of the improvement on pulse current waveform

images 1–6. Thus, it seemed that there was no arc between the wire end and the workpiece, but in fact, this wire was in a micro-heated state so as to reserve energy for the next pulse period. In other words, the visible and invisible arc ignited alternatively between the two leading wires. The time span for a filler wire visible arcing was defined as one visible arcing period, which is only one part of the complete pulse period.

The alternating frequencies at different currents and voltage are presented in Fig. 4. The alternating frequency increased with welding current and arc voltage. Moreover, the welding current had a more pronounced effect on alternating frequency than arc voltage. In practical welding, the magnitude of welding current was adjusted by changing the wire feed speed, and welding current increased with the increase of the wire feed speed. As a result, when the wire feed speed increased, the more energy should be needed to melt the continuous feeding wire in case the wire end could contact the base metal. Therefore, the number of pulses per second increased with the increase of welding current, which resulted in the increase of alternating frequency. However, the pulse peak current always kept constant at about 580 A although the welding current and arc voltage continuously increased. What is more important, the peak period duration hardly varied with the variation of welding current and arc voltage, but kept at around 3 ms. However, the total base period duration (including base and transition period duration, as shown in Fig. 2) decreased with the increase of welding current and arc voltage.

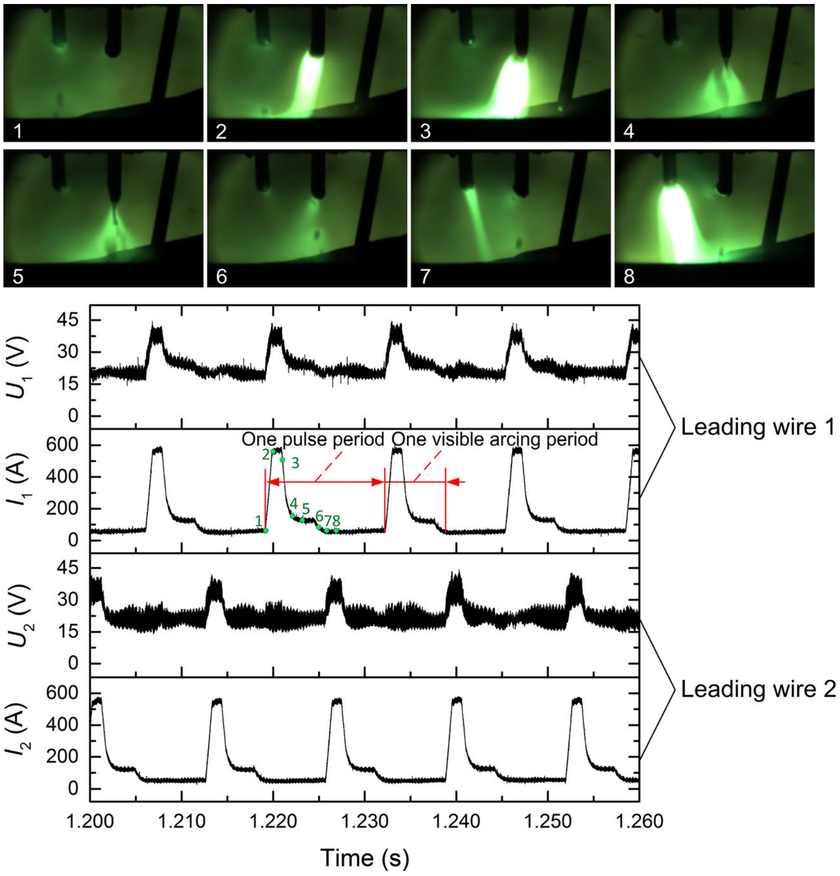


Fig. 3 Electric signals and high-speed photographs of arc alternating process

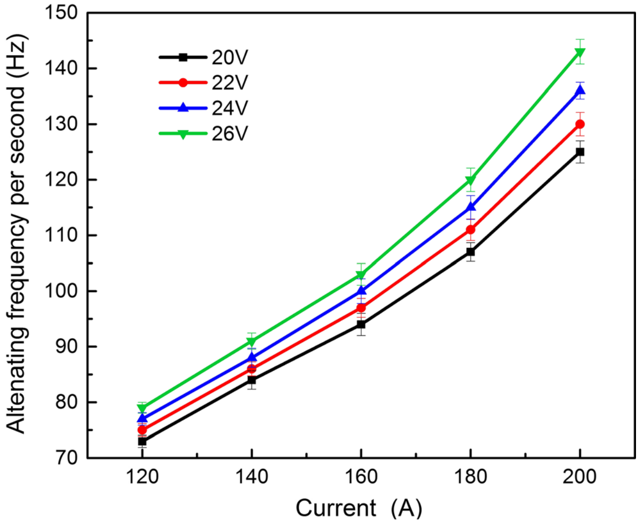


Fig. 4 Effect of welding current and arc voltage on alternating frequency

3.3 Analysis for three types of metal transfer process

3.3.1 Short circuiting transfer process

Modes such as “short-circuiting,” “globular,” and “spray” occur as a function of the set electrical parameters, i.e., welding current and arc voltage. Thus, the metal transfer process was studied by varying a serial of preset currents and voltages. The preset current varied from 120 to 200 A, and the preset voltage varied from 16 to 26 V. The experimental results showed that the metal transfer modes were mainly divided into three types: short circuiting transfer, projected transfer, and streaming transfer. Therefore, the electrical signals and the high-speed photographs for the preset voltages of 18, 20, and 22 V at a given preset current of 140 A were taken to demonstrate the above three characteristic transfer modes, respectively.

What is illustrated in Fig. 5 is the metal transfer process at the preset voltage of 18 V. At these parameter settings, the main transfer mode was short circuiting transfer. There was a complete metal transfer process during the time period from 2075 to 2092 ms. At 2075 ms, the droplet had already formed at the end of the leading wire 2. With continuous feeding of the two leading wires, the droplet contacted the weld pool surface at 2079 ms, and then the arc 2 extinguished, which can be confirmed by the corresponding voltage signal plunging to 0 V, whereas the current signal starting to rise. At the same time, a liquid metal bridge formed and then grew as the droplet was suck into a molten pool by surface tension. As the short circuiting current increased to about 600 A, there was a strongly pronounced electromagnetic force to make the liquid metal bridge rupture at 2083 ms, and then the arc voltage recovered to above the open-circuit voltage. Meanwhile, the strong electromagnetic force had an effect of intense impact on the weld pool, which caused the intense oscillation of the weld pool and then an obvious molten pit formed at the weld pool surface under the leading wire 2, as shown in the high-speed photographs from 2083 to 2085 ms. At 2085 ms, the droplet at the end of the leading wire 1 contacted the weld pool surface just because of the intense oscillation of the weld pool caused by short circuiting transfer, and then the arc 1 extinguished. As a consequence of increasing current, the bridge was necked out mainly by the progressive electromagnetic forces, and the arc 1 initiated and ignited once again until the moment of 2091 ms. At 2092, the arc 2 also ignited with the next pulse peak current. From 2092 to 2094 ms, the leading wire 2 performed a complete process of projected transfer.

The short circuiting transfer mode is characterized by the parameter settings for a short arc with a very high wire feed speed, and the main governing force is strongly pronounced electromagnetic pinch force [18]. At these parameter settings, the arc length was so short that short circuiting transfer frequently occurred in the welding process. This transfer mode would cause the intense oscillation of the weld pool, which easily led to the arcing wire being extinguished. Therefore, this transfer mode was not beneficial to the stability of the welding process.

Figure 6 shows the corresponding relationship between the phase of electric signals and transition process. The different stages of the metal transfer process marked with the number 1 to 7 respectively corresponded to the different periods of electrical signals. Every stage of short circuiting transfer was the same as the above described process from 2075 to 2088 ms. The whole transfer process also experienced from the droplet contacting the weld pool surface and forming the “liquid metal bridge” to the bridge ruptured by electromagnetic force at last. It is worth noting that the electric signals became disordered, which was caused by the combined effect of short circuiting signal and pulse signal. As the metal transfer was governed by the strong electromagnetic force, the droplets were of small size (no time to reach larger volume), which caused a high level of spatter. Therefore, the short circuiting transfer was not the desired transfer mode in this experimental system.

3.3.2 Projected transfer process

When the preset voltage increased to 20 V, the main transfer mode was projected transfer (one droplet per pulse or one droplet multiple pulses), as shown in Fig. 7. With the increase of arc voltage, the arc length increased, which resulted in the less possibility of droplet contacting the weld pool. Therefore, projected transfer was the main transfer mode instead of short circuiting transfer in the welding process.

At first, the current and voltage of the leading wire 2 was in the base phase from 2683 to 2687 ms. Then, the arc started to ignite with the pulse peak current supplied to the leading wire 2 at 2688 ms. Until 2691 ms, the droplet detached from the

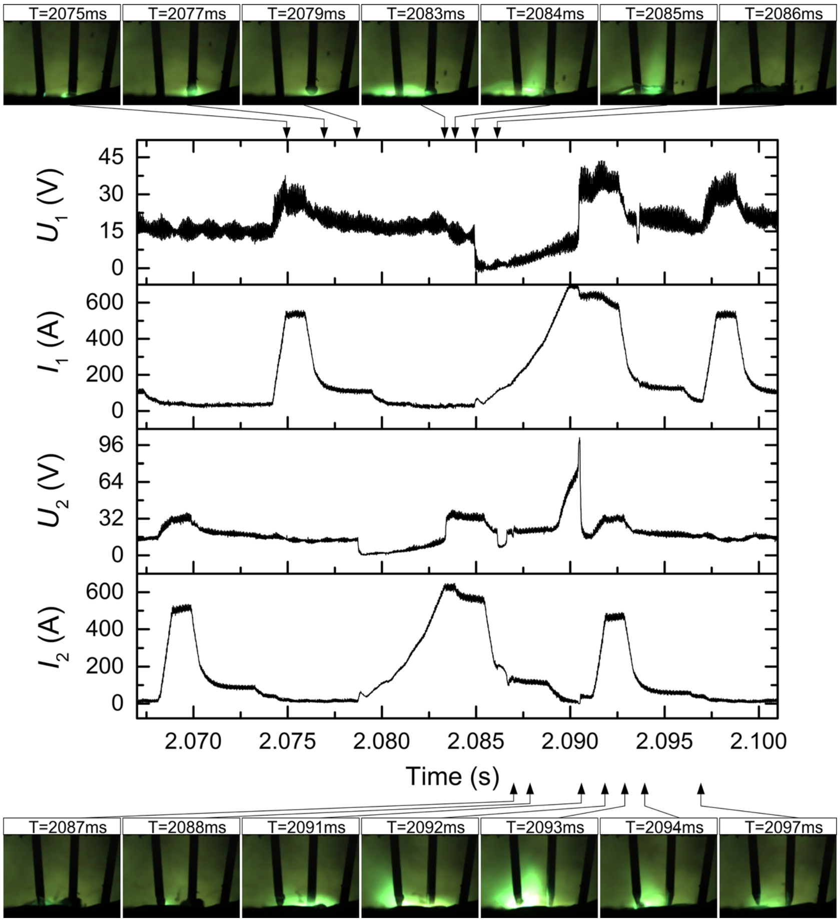


Fig. 5 High-speed photographs with corresponding electric signals of short circuiting transfer

end of the leading wire 2 under the combined effect of the electromagnetic force and the plasma flow force, and the droplet has transferred into the molten weld pool at 2693 ms. The transition process was so transient that the time from forming a droplet to detachment from the wire end was just about 2 ms. Based on the above analysis, the projected transfer process was characterized by one droplet per pulse for the leading wire 2. However, the projected transfer process was characterized by one droplet multiple pulses for leading wire 1, as shown in high-speed photographs from 2683 to 2699 ms. At first, the droplet formed and grew, but not detached from the end of leading wire 1 in the first pulse period from 2683 to 2693 ms. Then, in the next pulse periods from 2693 to 2699 ms, firstly, the arc 1 ignited again at 2693 ms, and the wire end was intensely heated and melted to continually increase the volume of the droplet. Secondly, the most area of droplet surface was enveloped by the arc 1 and the necking formed at the interface between the wire end and the droplet until 2696 ms. At last, the droplet detached from the end of the leading wire 1 under the combined effect of the electromagnetic force and the plasma flow force and transferred into the molten weld pool from 2697 to 2699 ms.

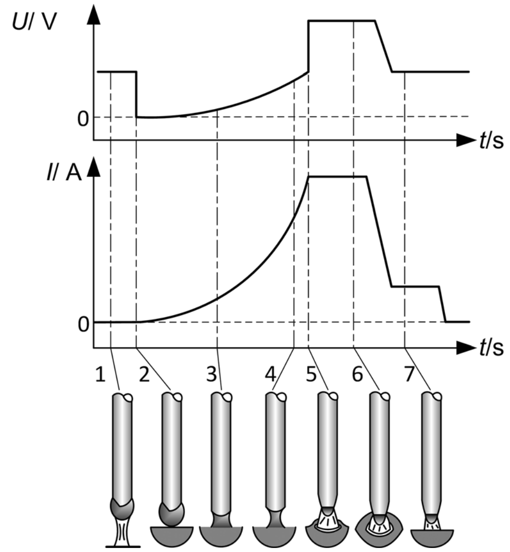
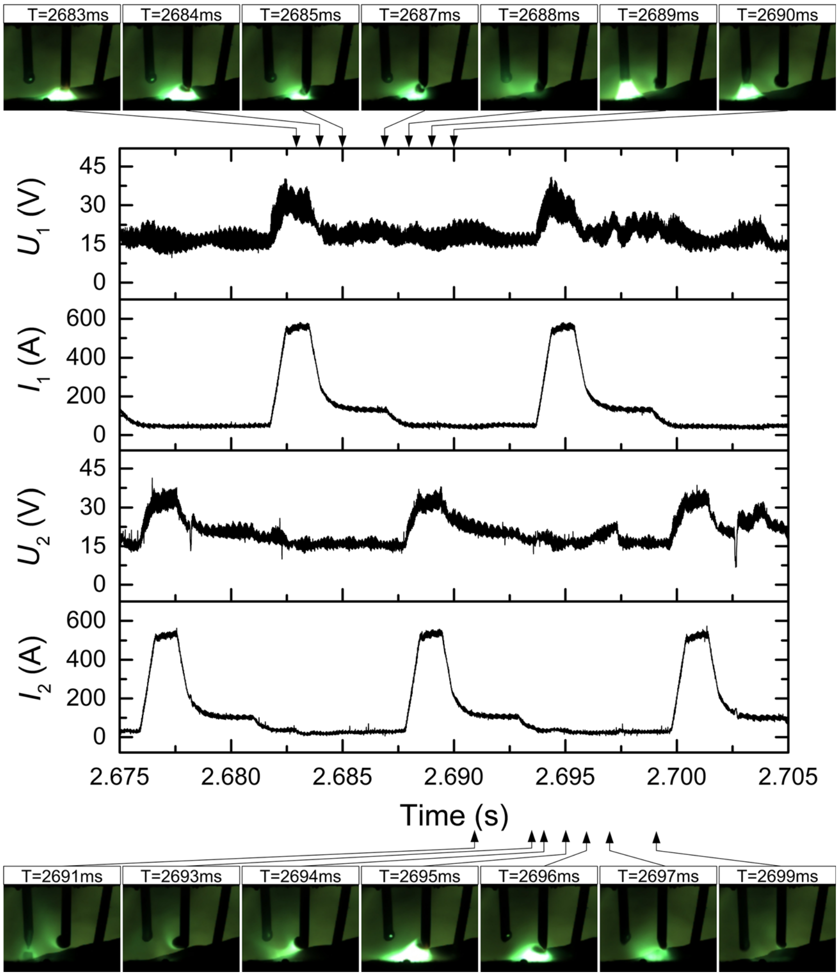


Fig. 6 Corresponding relationship between period of electric signals and different stages of short circuiting transfer

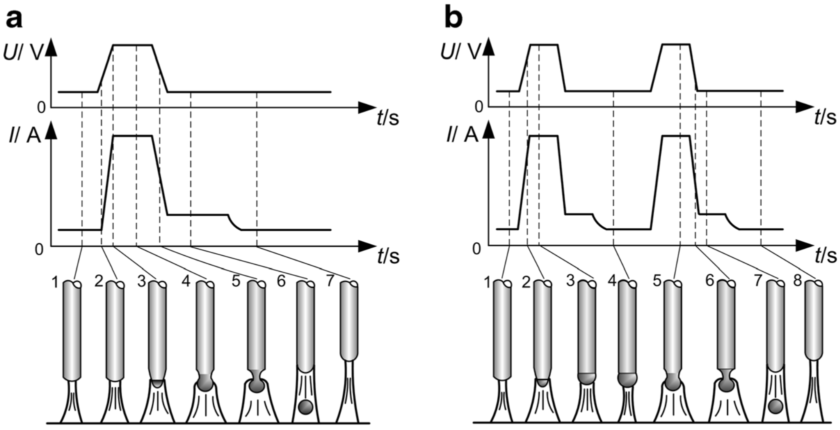
Figure 8 shows the corresponding relationship between the phase of electric signals and the transition process. Figure 8a shows the projected transfer process characterized by one droplet per pulse, but Fig. 8b shows the projected transfer process characterized by one droplet multiple pulses. For the

Fig. 7 High-speed photographs with corresponding electrical signals of projected transfer



transfer mode of one droplet multiple pulses, the wire end was heated and melted to form a certain volume of droplet in the first few pulse periods, but the droplet only had a detached tendency from the wire end at the moment. Only by repeatedly applying one or several pulse periods can a greater volume of droplet accumulate (larger than wire diameter), which increased the probability of droplet detaching from the wire end. At the same parameter settings, there would be one droplet two pulses or one droplet three pulses in the welding process. Therefore, there was no explicit corresponding relationship between whether the droplet detachment or not and the number of pulse periods.

Fig. 8 Corresponding relationship between period of electric signals and different stages of projected transfer



3.3.3 Streaming transfer process

When the preset voltage increased to 22 V, the metal transfer mode changed from the projected transfer to the streaming transfer, as shown in Fig. 9. The streaming transfer is characterized by the very fine droplets (one third or one sixth of wire diameter) transferring from the tapered wire end to the weld pool at an extremely high speed.

There was a complete process of streaming transfer from 664 to 678 ms, and it was clearly seen that the whole process was possessed of obvious regularity and repeatability. Taking the metal transfer process of the leading wire 1 for instance, in the beginning, the end of the leading wire 1was heated and melted to form a droplet at 664 ms. Then, the most area of droplet surface was enveloped by the arc 1, and the necking formed at the interface between the wire end and the droplet at 665 ms. At this moment, a very high current passed through the necking region to accelerate heating and vaporization of liquid metal, which created conditions for enlarging and climbing of anode spot area. Therefore, the "arc jumping" phenomenon was occurred. There are two necessary conditions for the arc jumping phenomenon: firstly, the necking region was possessed of the conditions of generating the metal vapor, i.e., conductive to generate the anode arc root; Secondly, the energy consumption of the arc passing the new conductive channel should be less than that of the arc passing the original conductive channel when the new arc root generated. After arc jumping, the shape of the arc 1 changed from bell shape to tapered shape, and the larger droplet was rapidly pushed off from the tapered end of the leading wire 1 under the stronger plasma flow force at 666 ms. Besides, the wire end changed into an almost molten stream towards the weld pool. At the wire end, very fine droplets were sprayed to the molten weld pool at a high speed from 667 to 668 ms. Likewise, every stage of streaming transfer for leading wire 2 was the same as the above described process for the leading wire 1.

Figure 10 shows the corresponding relationship between the phase of electric signals and transition process. It can be observed that the arc jumping always occurred in the end of the pulse peak zone, and then the very fine droplets detached from the wire end and transferred into the weld pool in the period of the transition zone. Besides, this metal transfer process was possessed of good welding stability, and as long as

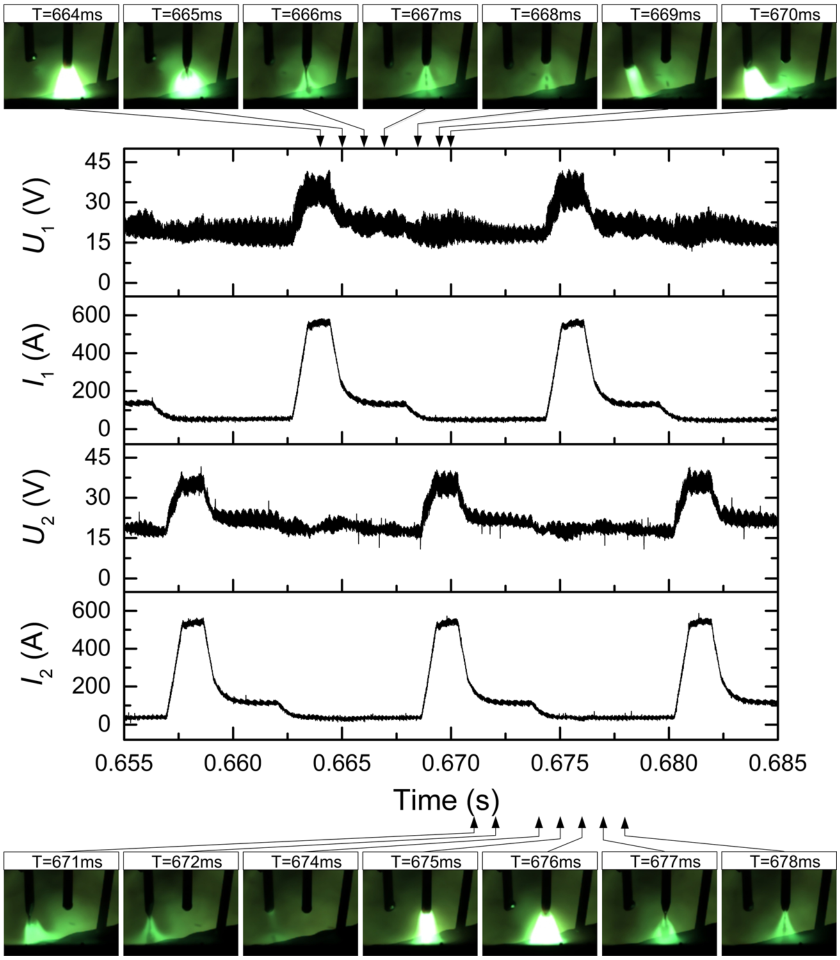


Fig. 9 High-speed photographs with corresponding electrical signals of streaming transfer

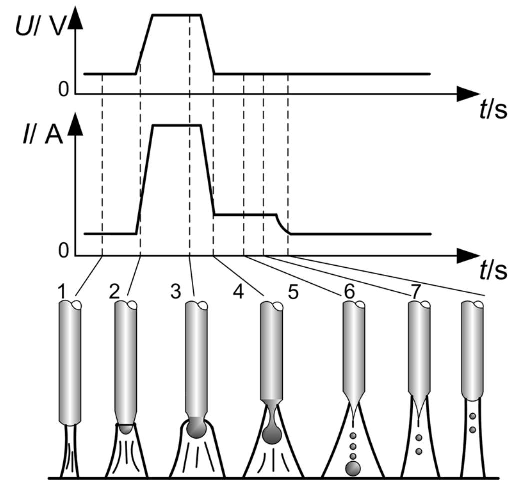


Fig. 10 Corresponding relationship between period of electric signals and different stages of streaming transfer

this tapered end did not touch the weld pool, there was no spatter. Therefore, the spray transfer was an optimal transfer mode in this experimental system.

3.4 Effect of arc voltage on the metal transfer process

When the pulse peak current reached as high as 580 A for the filler wire of 1.2 mm, the metal transfer mode should be streaming transfer. However, the short circuiting transfer or projected transfer also occurred in the welding process because of a shorter arc length. The length of arc had an effect on the magnitude of the force acting on the droplet. Accordingly, the metal transfer mode would also change with it. The simplified force analysis of droplet was made so as to better understand the effect of arc length on metal transfer mode.

As shown in Fig. 11, the droplet was mainly subjected to gravity F_g, electromagnetic force F_e, and plasma flow force F_d. The directions of the above three forces were all downward to accelerate the detachment of droplet from the wire end. Besides, the droplet was also subjected to surface tension F_σ and metal vapor acting force F_v from the weld pool, which all prevented the droplet detaching from the wire end [19–21]. When the arc length was too short, it was too late for the droplet to grow and detach from the wire end, but it frequently contacted the weld pool surface, which caused the short circuiting metal transfer. With the arc voltage increased, the arc length also increased. At this moment, the droplet did not frequently contact the weld pool, but it was closed to the weld pool surface. Therefore, the droplet would be subjected to the greater resistance generated by the metal vapor from the weld pool, which greatly increased the difficulty of droplet detachment and made the droplet kept at the wire end to grow up [22]. Moreover, the droplet size has a noticeable effect on the component forces of surface tension, i.e., $F_{\sigma(0)}$ and $F_{\sigma(r)}$. A lot of experimental results showed that the droplet size of easier detachment needs to meet a special condition, i.e., r/R = 1.15~1.5. When the value of r/R is bigger than 1.5 or smaller than 1.15, the droplet detachment and the necking formation will become very difficult [23]. The inhibition of the metal vapor acting force to the droplet detachment was extremely pronounced so that the droplet was kept at the wire end to grow up. As a result, the surface tension F_σ stopped from the droplet detachment with the increase of droplet size beyond a certain value. In addition, as the time span of pulse peak current was just 3 ms, it was so transient that the anode spot area had not enough time to enlarge and climb. In conclusion, the metal transfer mode would be projected transfer instead of streaming transfer when the arc length was relatively shorter.

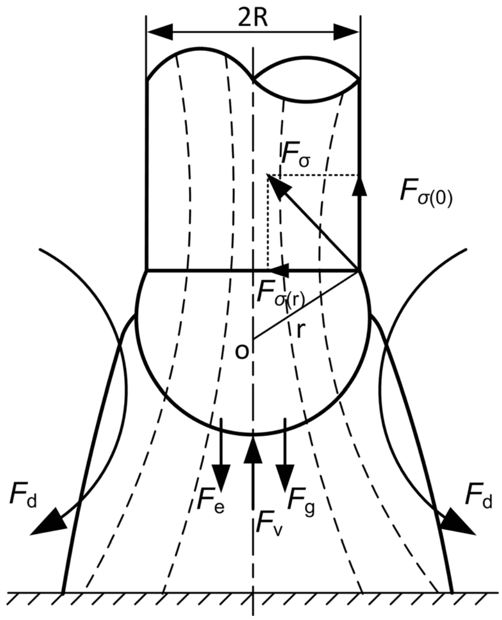


Fig. 11 Force analysis of the droplet in projected transfer

3.5 Effect of welding parameters on the metal transfer mode

In order to better optimize welding electrical parameters, the corresponding relationship between metal transfer modes and electrical parameters (welding current and arc voltage) was investigated, as shown in Fig. 12. In this experimental system, the metal transfer modes were mainly divided into three categories: short circuiting transfer, projected transfer, and streaming transfer. As shown in Fig. 12, the main metal transfer mode of the region below the black dash line was short circuiting transfer mixed with occasional projected transfer. The main transfer mode of region between the red dash line and black dash line was projected transfer mixed with occasional short circuiting transfer. Besides, the shaded area with the width of 0.5 V represented the critical region of streaming

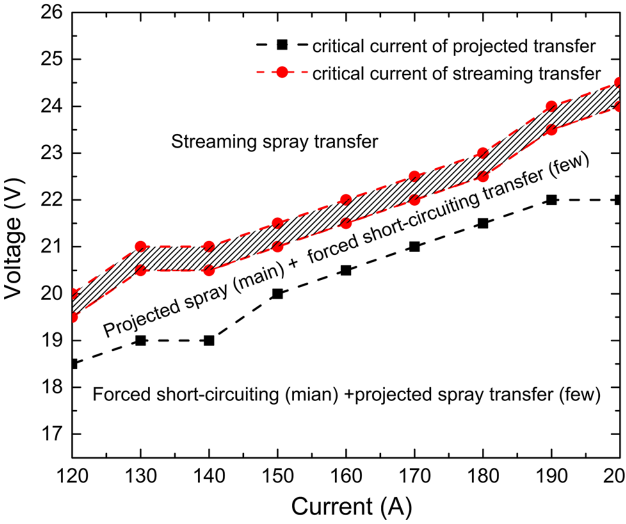


Fig. 12 Effect of welding electrical parameters on metal transfer mode

transfer, and the main metal transfer mode in this region was streaming transfer mixed with projected transfer. However, above the critical region, the main metal transfer mode converted into a completely stable streaming transfer, which was exactly the most stable transfer mode we wanted. What is more important, the metal transfer mode was highly dependent on arc voltage when the welding current was kept constant. The metal transfer mode would change from short circuiting transfer to projected transfer, and then converted into streaming transfer with the increase of arc voltage.

4 Conclusions

A novel high-efficient welding system titled twin-arc integrated cold wire hybrid welding has been set up, and the characteristics of metal transfer and arc behavior during the welding process were studied. Meanwhile, the effect of welding electrical parameters on metal transfer mode and corresponding relationship between them were investigated by a great amount of trial. The following conclusions can be drawn from this paper:

(1) As the phase difference of 180° between the pulse currents through the two leading wires, the two leading wires kept alternative arcing. The alternating frequency increased with the increase of welding current and arc voltage, and the main reason was the more energy should be needed to melt the continuous feeding wire when the welding current increased. Therefore, the number of pulses per second increased with the increase of the welding current, which resulted in the increase of alternating frequency, but the pulse peak current always kept constant at about 580 A. Besides, the peak period duration did not vary with the variation of welding current and arc voltage, but kept at around 3 ms. However, the total base period duration including base and transition period duration decreased with the increase of welding current and arc voltage.

(2) Three different metal transfer modes of the two leading wires were observed during the welding process, which were short circuiting transfer, projected transfer, and streaming transfer. The streaming transfer was an optimal transfer mode, which was processed of good regularity and stability, closely followed by projected transfer. The welding stability of short circuiting transfer was worst because of a high level of spatter. Therefore, the short circuiting transfer was not the desired transfer mode in this experimental system.

(3) The metal transfer mode was highly dependent on arc length, i.e., arc voltage when the welding current was kept constant. The main reason was arc voltage have a remarkable effect on magnitude of force acting on the arc. The metal transfer mode would change from short circuiting transfer to projected transfer, and then converted into streaming transfer eventually with the increase of arc voltage.

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Conflict of interest The authors declare that they have no competing interests.

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