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ORIGINAL ARTICLE

Consumable double electrode with a single arc GMAW

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Abstract Double-electrode gas metal arc welding (DE-GMAW) was developed to control the heat input to the work piece when the filler wire deposition rate was increased. Consumable DE-GMAW was developed to enhance the welding productivity by replacing the non-consumable electrode in DE-GMAW with a consumable electrode. However, the process of consumable DE-GMAW was unstable without a particular control system. In order to improve the stability of the welding process on condition of keeping the main characteristics of DE-GMAW, a novel welding method named consumable double electrode with a single arc (DESA)-GMAW was proposed. In this welding system, there were two consumable electrodes but only one arc. The distance between the tips of the main wire and the bypass wire mainly determined whether the welding method was consumable DESA-GMAW or consumable DE-GMAW. The welding process could be very stable with appropriate welding parameters: one filler wire kept arcing stably with regular metal transfer process, and the other filler wire was kept short-circuited with workpiece all through the time and was fed into the welding pool stably and smoothly. The transverse section of the weld bead was analyzed, and it was found that the penetration could be effectively decreased with high metal deposition rate by using consumable DESA-GMAW.

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1 Introduction

Novel efficient welding method could greatly enhance the welding productivity and improve the welding quality. Gas metal arc welding (GMAW) is a widely used welding method, and in the past several years, some new welding technologies related with GMAW have been developed. For example, T.I.M.E. [1, 2], tandem [3, 4], laser-enhanced GMAW [5–7], and laser-arc hybrid welding [8–10]. Increasing the welding current is a common approach to enhance the filler wire melting rate in general GMAW process. The current passing through the filler wire is the same as the current passing through the workpiece. So the increase of the current passing through the filler wire will inevitably increase the current passing through the workpiece. And overlarge current will bring about undesirable heat input to the workpiece. What is more, the arc pressure is considered to be proportional to the square of the arc current [11]. Consequently, the extra heat input as well as the greatly increased arc pressure resulting from the rise of the arc current will cause serious welding defects such as burn through, especially in the case of thin-plate welding [12]. In order to deal with this problem, a welding method named double-electrode (DE)-GMAW was invented [13–18]. A modified method named consumable DE-GMAW was developed to enhance the utilization of the heat generated in the welding process [19–21]. In the consumable DE-GMAW process, the bypass filler wire could decouple a portion of current flowing from the main wire, and the heat generated by the arcs could be used to melt the bypass wire. Therefore, the current flowing through the workpiece could be smaller than that through the main wire. And the deposition rate could be largely raised without worrying about the possible weld defect mentioned above.

However, the welding process of consumable DE-GMAW without particular corresponding control system is unstable. The arc between the main wire and the bypass wire will impose a great influence on the metal transfer process and then the whole welding system [19, 20]. A more qualified welding process could be obtained if the negative effect of the bypass arc could be eliminated. One way is to establish a monitoring and controlling system as discussed in ref. [20]. Another effective way is to remove the bypass arc, without affecting the main characteristics of the consumable DE-GMAW system. Once the bypass arc no longer exists, the adverse effect it brings about will definitely disappear. On this account, a novel welding method named consumable double electrode with a single arc (DESA)-GMAW is proposed by the authors of this paper.

In the consumable DESA-GMAW system, there are two filler wires which are fed simultaneously but only one arc between one filler wire (main wire) and the workpiece. The other filler wire (bypass wire) keeps short circuit with the workpiece throughout the welding process. Compared with traditional GMAW, the heat input to the workpiece could be controlled more freely because of the introduction of the bypass wire. Compared with the consumable DE-GMAW system, the metal transfer process of the consumable DESA-GMAW system is much more stable because of the elimination of the bypass arc between the main wire and the bypass wire.

2 Consumable DESA-GMAW System

The welding system of the consumable DESA-GMAW is illustrated in Fig. 1. It can be seen that the welding system consisted two welding sources, the main power source (Lincoln INVERTEC V350-PRO) and slave power source (Lincoln INVERTEC V300-I), two welding torches, and two wire feeders. The output mode of the main power source was set as pulse, and the slave power source was set as constant voltage or constant current. The main wire was connected with the anode of the main power source and the anode of the slave power source together; the bypass wire was connected with the cathode of the slave power source and the cathode of main power source with the workpiece. The total current provided by the two welding sources flowed through the main wire. But it was divided into two parts after the current flows through the arc: one part through the workpiece back to the main power source and the other part through the bypass wire back to the slave power source. The principle of the welding gun configuration is shown in Fig. 2.

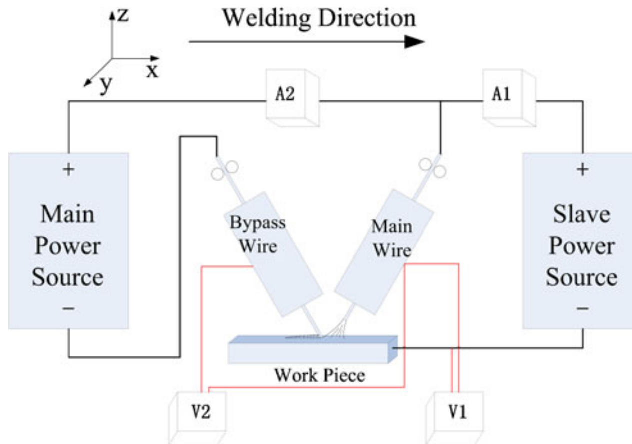

Fig. 1 Welding system of the consumable DESA-GMAW

The monitor system was consisted of the electrical signal acquisition system and the high-speed photography system. The electrical signal acquisition system mainly included two current sensors, two voltage sensors, and a computer with corresponding data acquisition card. In the welding process, the current flowing through the workpiece (I_1), the current flowing through the bypass wire (I_2), the voltage between the main wire and the workpiece (U_1), and the voltage between the main wire and the bypass wire (U_2) were monitored. U_0 was the voltage between the bypass wire and the workpiece. According to ref. [17], the current flowing through the main wire (I_0) could be computed by

$$I_0 = I_1 + I_2. \quad (1)$$

The high-speed photography system, as depicted in Fig. 3, mainly included a high-speed camera and a subsidiary illumination light source with a xenon lamp as core unit. The capturing rate was 1,000 frames per second. The electrical signals of the welding system and the high-speed photography were acquired synchronously to reflect the arc behavior and metal transfer process precisely. The welding parameters are shown in Table 1. The workpiece used in

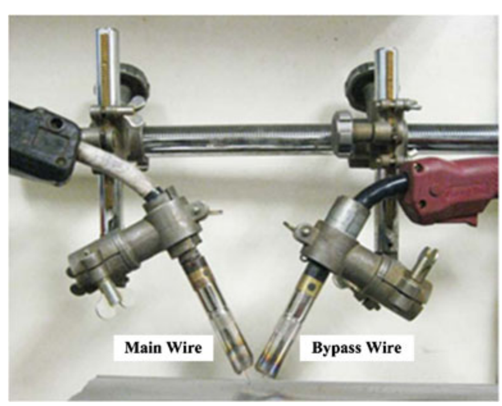

Fig. 2 Principle of the welding gun configuration

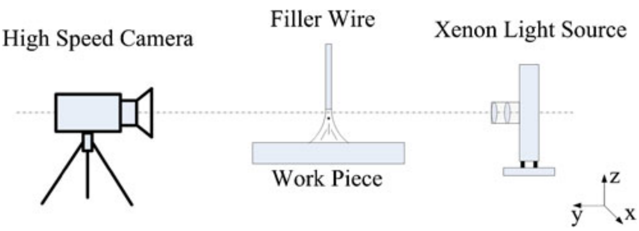

Fig. 3 High-speed photography system

the experiment was mild steel and the welding speed was 3 mm/s.

Both of the two welding guns should be arranged appropriately in order to successfully start the welding process. The main geometrical configuration parameters are illustrated in Fig. 4a. The distance between the tips of the main wire and the bypass wire on the workpiece surface (D_{ms}) was the most important parameter which determined whether the welding method could be successfully implemented or not. The angles between the main wire as well as the bypass wire and the normal are defined as α and β respectively. Key welding parameters such as α, β, especially D_{ms} should be kept within an appropriate range to avoid extreme bad welding conditions. A much too large D_{ms} will lead to insufficient melting condition of the bypass wire, while a much too small D_{ms} will lead to serious spatters and, thus, deteriorate the whole welding process.

The vertical distances between the main wire tip as well as the bypass wire tip and the workpiece surface are defined as D_m and D_s, respectively. D_m should be less than D_s at the instant when one of the wires was to touch the workpiece. In this case, the main wire tip first touched with the surface of the workpiece, and the bypass wire tip touched the workpiece surface on the condition of the establishment of the arc between the main wire and the workpiece. Otherwise, there will be no current flowing through the welding system when the bypass wire tip touches with the surface of the workpiece, and the bypass wire will not be melted at any extent, which will lead to an uncontrollable move of the bypass wire tip on the workpiece surface. There will be no arc initiated until the main wire tip touched the workpiece or the bypass wire in the above unnormal condition.

It was verified by the experiments that the filler wire configuration parameters depicted in Fig. 4b could be followed to establish a stable welding process. D_{ms} was 1.8 mm, α and β were 25° and 30°, respectively, and the vertical length of the arc was approximately 8.0 mm. The main wire was mainly melted by the heat generated by the arc and the heat generated from the filler wire between the contact tip and the tip of the wire. The workpiece was melted by the heat generated by the arc. The heat used to melt the bypass wire was constituted by two parts: the heat from the arc and the resistant heat generated by the section of the bypass wire between the contact tip and the welding pool [22].

3 Experiments and discussion

In the welding system illustrated in Fig. 1, the current flowing through the main wire was the sum of the current through the workpiece as well as the bypass wire. Compared with a general GMAW process with the same welding current, the melting rate of the main wire was not influenced. And a part of current used to melt the workpiece here was used to heat the bypass wire, which will increase the deposition rate. On the whole, the heat used to melt the workpiece was decreased, and the heat used to melt the filler wire was increased because of the new distribution of the current. The heat generation efficiency of the consumable electrode as the cathode is much higher than it as the anode. The heat generation efficiency of the anode and the cathode could be briefly analyzed by the following function [23]:

$$P_A = I \cdot (U_A + U_W + U_T) \tag{2}$$

$$P_C = I \cdot (U_C - U_W - U_T) \tag{3}$$

where P_A is the heat generation power of the anode and P_C, the cathode. U_A is the anode voltage drop, and U_C is the cathode voltage drop. U_A is a quite small value, proximately 0 V, in a very large current value range. Because of the high current density and high temperature of the neutral particles, there is no need for the electrons to obtain high energy by collision ionization. U_W is the work function of the electrode material, and it is about 4.7 V for the filler wire used in the experiments. U_T is the equivalent voltage of arc column energy. U_T could be calculated [23] by

$$U_T = 2kT/e = 1.72 \times 10^{-4} T(V) \tag{4}$$

where k is the Boltzmann constant. If the electron temperature of the arc column is below 10,000 K, U_T is a value

Table 1 Welding parameters

Main wire feed speed	Bypass wire feed speed	Filler wires	Wire diameter	Shielding gas	Gas flow rate
3.5 m/min	1.5 m/min	H08Mn2SiA	1.2 mm	Argon	25 L/min

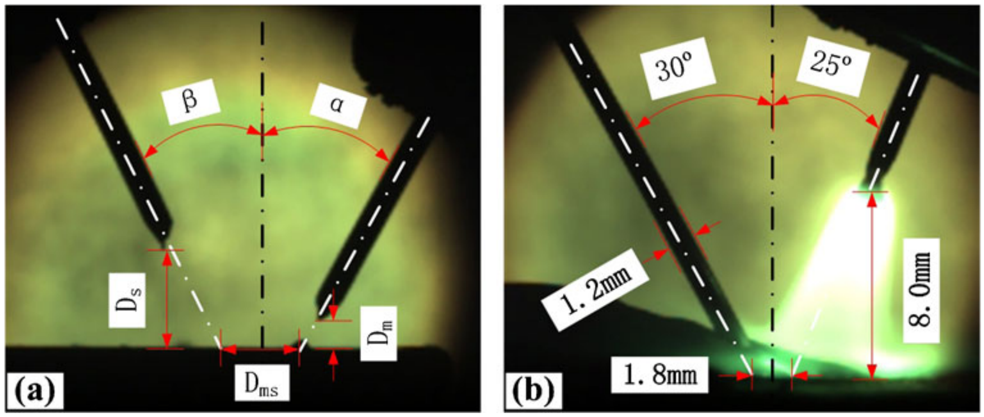

Fig. 4 Main parameters of filler wire configuration

smaller than 2 V. In the condition of GMAW, the filler wire is a non-thermionic material. The electron emission is largely dependent on field emission. So the value of U_C is relatively high, usually of the order of 15 V [24]. Conclusively, P_C is higher than P_A on the condition of the experiment discussed in this paper. The melting rate of the bypass wire is higher than the main wire. Hence, the change could largely enhance the deposition coefficient of the filler wire of the welding system.

3.1 Analysis of the bypass wire

In the welding system, there was only one arc which was established between the main wire and the workpiece. The main wire acted as the anode and the workpiece acted as the cathode. For the bypass wire, it was not playing directly as the cathode itself, although it was connected with the cathode of the slave power source. The electron emission process supported by the slave power source was indirectly realized by the welding pool on the workpiece which kept short-circuit condition with the bypass wire. As non-thermionic cathode, field emission and thermal ionization are of great significance in the mechanism of electron emission. As similar non-thermionic material, it is assumed that the work function of the bypass wire is also similar with the workpieces. Consequently, the electron emission ability is largely affected by the actual cathode electron emission area. In the welding process, the tip of the bypass wire kept connected with welding pool. It is apparent that the bypass wire tip had a much smaller size than the welding pool on the workpiece, which determined that the electron emission was largely from the welding pool rather than the bypass wire.

What is more, the temperature of the liquid welding pool was higher than the solid bypass wire. The electron emission current density j_e of a cathode heated to a sufficiently high temperature of T Kelvin could be given by Dushmann equation [25]:

$$j_e = AT^2 \exp(-eV_w/kT) \quad (5)$$

where A is a constant for most metal materials, e is the electron charge, and V_w is the work function of the cathode material and k is the Boltzmann constant. It can be inferred from formula 5 that the electron emission ability of the material is in positive correlation with the temperature. Consequently, the thermionic electron emission ability of the welding pool is stronger than the bypass wire tip, which further determines that the electron emission was mainly supported by the welding pool. On the whole, the electron emission was mainly from the welding pool rather than the bypass wire. The role played by the bypass wire here was as a conduct between the slave power source and the welding pool. Compared with the electron emission from the workpiece on the condition of the existence of the arc between the main wire and the bypass wire, there was an extra part in the electron emission transferring to the welding pool from the tip of the bypass wire. The bypass wire was not the direct cathode though, it absorbed heat from the most nearly welding pool with which it provided energy from the slave power source for electron emission . Consequently, a large part of heat used to melt the bypass wire was from the welding pool it contacted with.

3.2 Welding process with appropriate wire distance

The stable welding process of consumable DESA-GMAW was based on the appropriate selection of D_{ms}. If D_{ms} was so small, smaller than 0 mm in this paper, that the axes of the main wire and the bypass wire intersecting with each other above the workpiece, there will be two arcs: one established between the main wire and the workpiece and the other between the main wire and the bypass wire. As

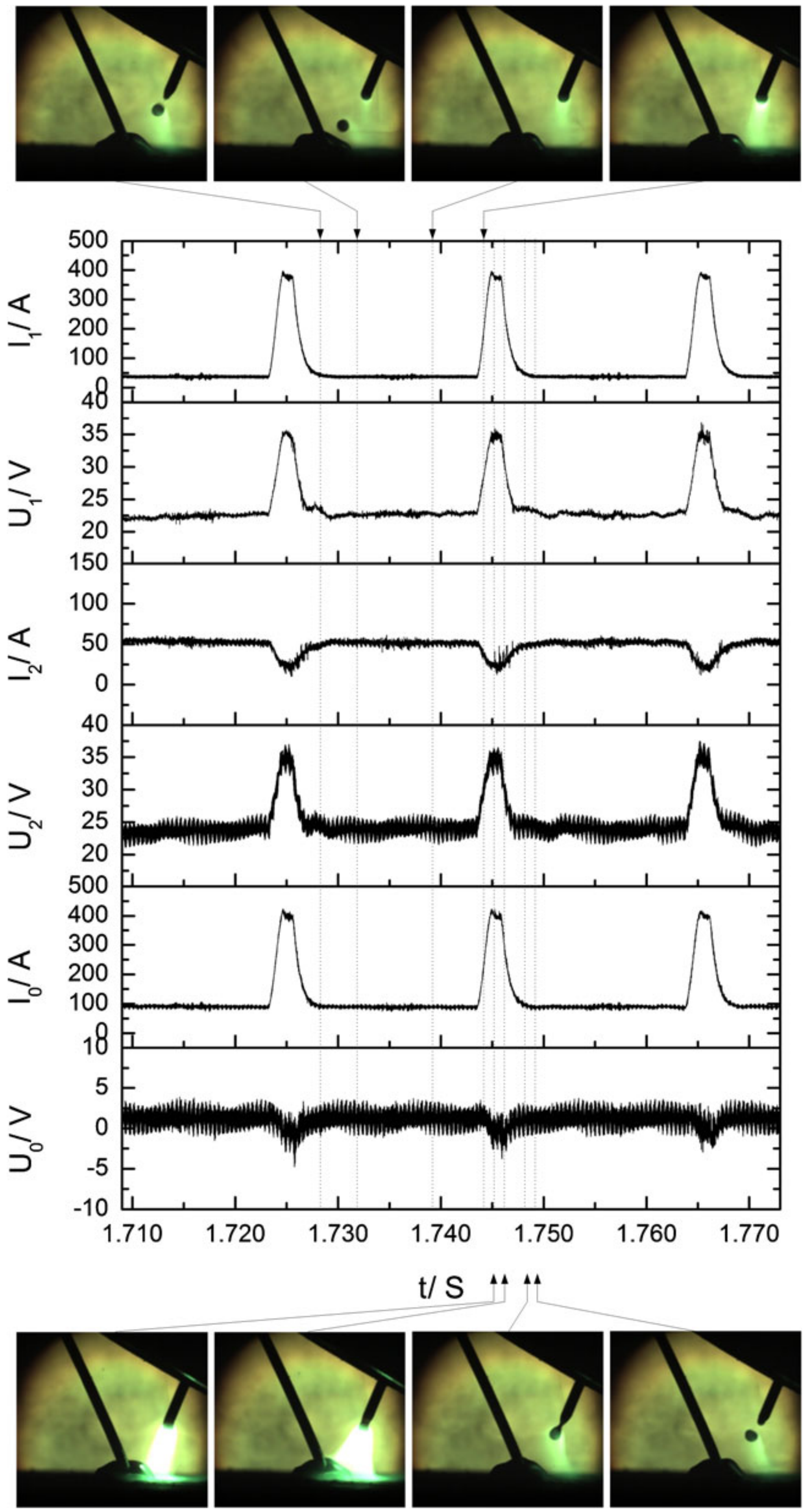

Fig. 5 Welding process with proper distance between the main wire and the bypass wire

analyzed in ref. [18], the welding process under this condition without particular control system was unstable. If D_{ms} was too big, bigger than 5 mm in this paper, there will be only one arc established between the main wire and the workpiece, though the welding process was not stable either. The bypass wire could not be melted sufficiently because of the inadequate heat condition from the arc, which was mainly resulting from the much too far away arc.

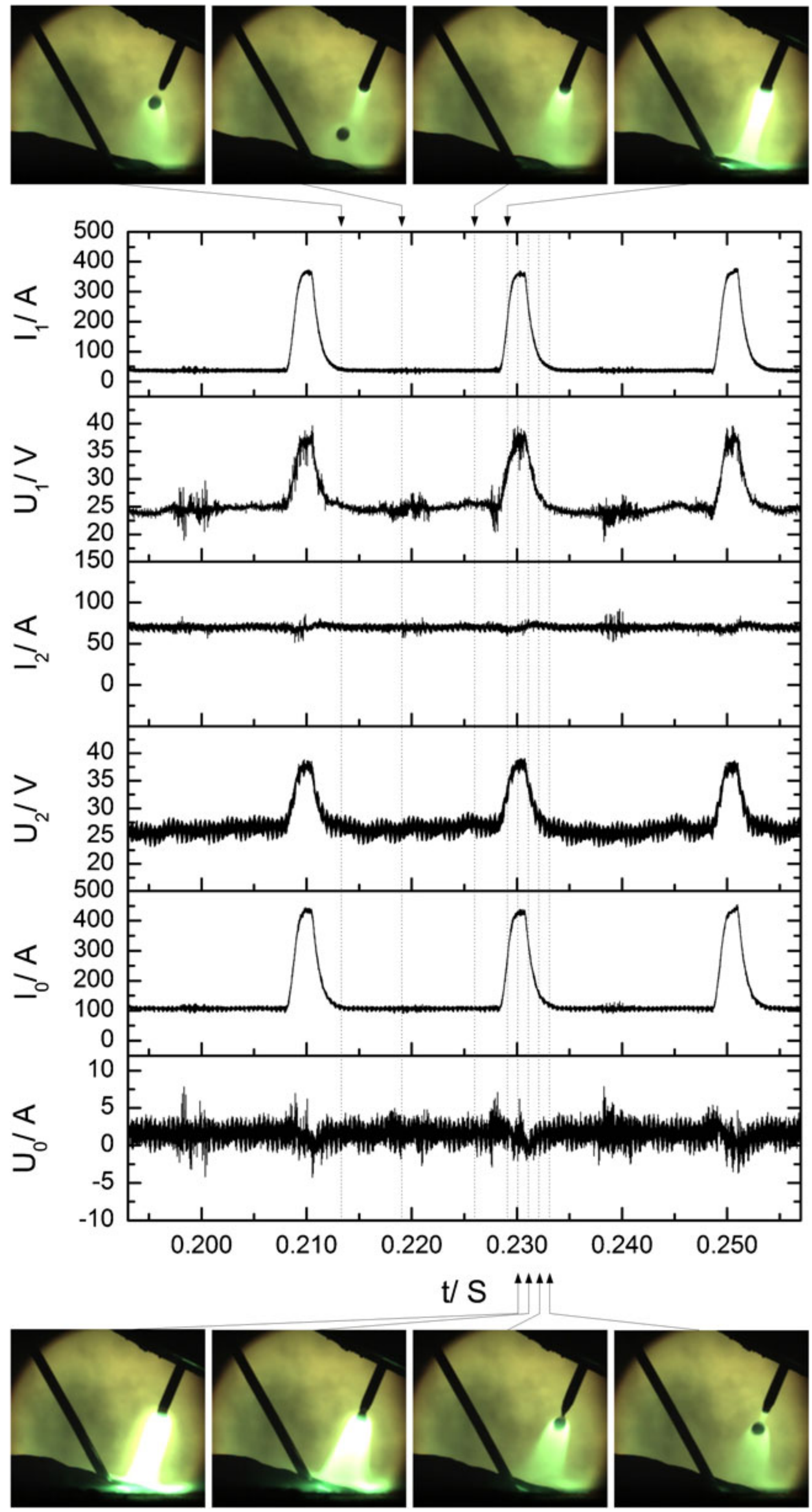

Fig. 6 Welding process with proper distance between the main wire and the bypass wire with constant current of the slave power source

There would be a stable welding process with appropriate D_{ms}: the main wire arced regularly along with the pulse output of the main power source with a regular metal transfer mode of one droplet per pulse; the bypass wire was melted by the arc heat and resistant heat and fed into the welding pool uninterruptedly and reposefully. There was no arc established between the main wire and the bypass wire or between the workpiece and the bypass wire in the whole welding process. The main wire here ignited the arc as normal pulse GMAW but simultaneously heated the bypass wire to deliver enough heat for its sufficient melt; the bypass wire here decoupled a part of the current used to flow through the workpiece and, thus, increased the melting rate of the welding process without bringing about any obvious negative effect.

What is illustrated in Fig. 5 is the electrical signal waveforms of I_1, U_1, I_2, U_2, I_0, and U_0 of a typical stable welding process, with corresponding high-speed photographs of one main wire metal transfer period. The output mode of the main power source was set as pulse, and the external characteristic of the slave power source was set as constant voltage. The peak value and base value of I_1 were 398 and 35 A, respectively, and one whole pulse period and base stage period of I_1 were 20 and 15 ms, respectively. The peak value and base value of I_2 were 55 and 15 A, respectively, and one whole pulse period and base stage period of I_2 were 20 and 5 ms, respectively. It can be seen from the figure that I_1 and I_2 were both pulse waveforms, and they maintained opposed phase regularly and accurately. One pulse period of the electrical signals from 1.728 to 1.748 s was selected to analyze the welding process.

When the output of the main power source increased from the base stage to the pulse stage at 1.744 s, the heat generated by the arc will increase correspondingly. In this case, there will be a decline of the output of the slave power source in order to maintain thermal equilibrium of the welding system. On the other hand, when the power output of the main power source declined from the pulse stage to the base stage at 1.746 s, the output of the slave power source would increase to contribute to enhancing the heat output used to melt the wires. It can be seen that the base stage of I_1 from 1.728 to 1.743 s corresponded accurately with the pulse stage of I_2. And the base stage of I_2 from 1.743 to 1.748 s in turn corresponded to the pulse stage of I_1. On the whole, the balance between the melting of the wires and the feeding of the wires could be guaranteed to a larger extent under this power source combination.

The balance of the wire feed speed and the wire melting speed is a basic requirement of a stable welding process. And the inherent self-regulation of the GMAW process with a constant voltage power source is normally stable and well behaved [26]. The constant voltage mode of the slave power source means a changing current according to different arc conditions. In the consumable DESA-GMAW system, the heat generated by the arc was partly provided by the slave power source. The inherent self-regulation mechanism was based on the only arc in the welding system. The variation of the arc condition, whether resulting from the power change of the main power source or from other external welding conditions, would induce the modification of the power output of the slave power source.

The basic welding process analyzed above could also be implemented with the external characteristic of the slave power source changed to constant current from constant voltage, with the main power source configuration fixed. It can be seen from Fig. 6 that a whole pulse period of the electrical signals could be contained from 0.213 to 0.233 s with a constant I_2 of 70 A. There was a droplet detached from the main wire at 0.213 s, corresponding with the end of the previous pulse period. The time period from 0.213 to 0.228 s was the base stage, and I_0 and I_1 were the lowest. A 0.230 s was the pulse peak point, and the tip of the main wire was mainly melted in the time period from 0.228 to 0.232 s. At 0.233 s, a droplet detached from the main wire, at which time a droplet transfer period completed. I_2 was basically unchanged during the above pulse period because of the constant current external characteristic of the slave power source.

3.3 Welding process with too small wire distance

As discussed above, an appropriate D_{ms} was of great significance for a stable welding process. The welding condition will become disordered if D_{ms} was too small, as illustrated in Fig. 7, e.g., the interference between the main wire and the bypass wire was so serious that there were lots of short circuits, spatters, and extinguishment of the arc in the welding process.

What is shown in Fig. 8 is an unstable welding process with too small D_{ms}. At 2.388 s, there was a droplet just detaching from the main wire. The tip of the bypass wire did not contact with the welding pool, and it seemed that there was no arc between the main wire and the bypass wire. However, the current through the bypass wire was about

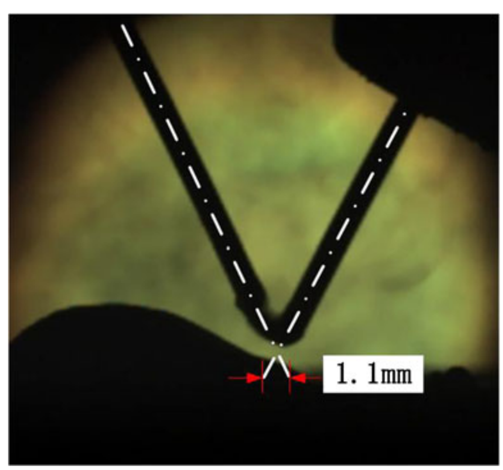

Fig. 7 A too small distance between the main wire and the bypass wire

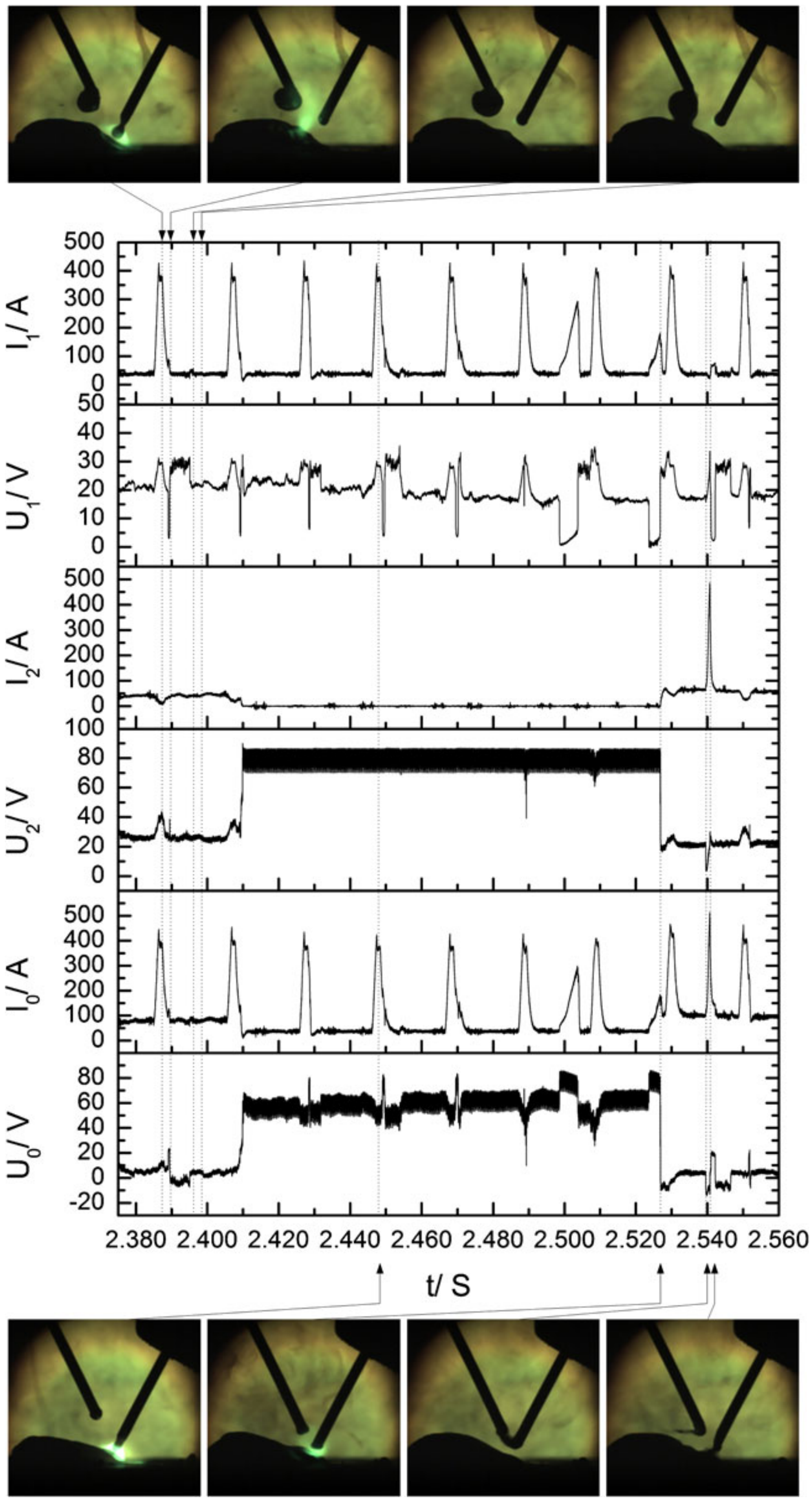

Fig. 8 The unstable welding process with too small distance between two wires

50 A rather than 0 A according to electrical signal waveforms. It meant that conductive particles were transferred between the main wire and the bypass wire, although it could not be seen in the photograph obviously. At 2.390 s, the droplet from the main wire had been transferred into the welding pool and two arcs appeared apparently: one arc between the main wire and the workpiece and the other between the main wire and the bypass wire. At 2.399 s,

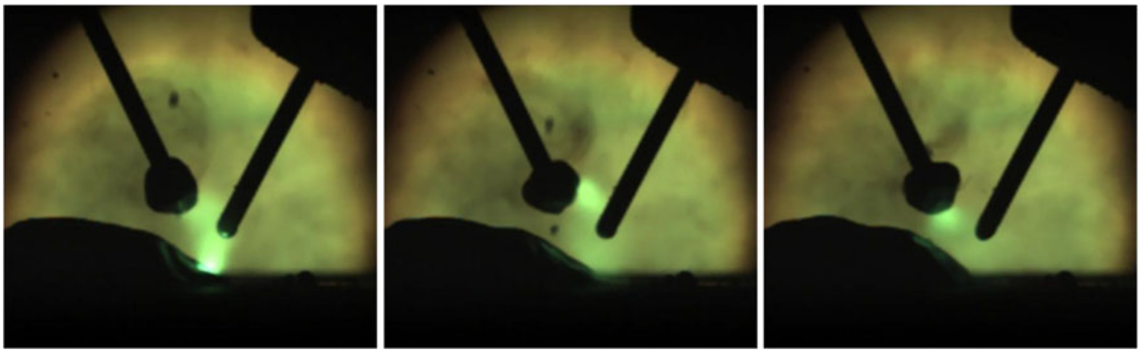

Fig. 9 Unstable arcing resulting from the moving cathode spots on the surface of the droplet

the droplet suspended on the bypass wire contacted with the welding pool and transferred under surface tension and gravity. After the transfer of this big droplet, the distance between the tips of the bypass wire and the main wire became so big that it was too hard to initiate an arc between them immediately. Consequently, the slave power source stopped output during the period from 2.409 to 2.527 s. At 2.527 s, the bypass wire tip got close enough to the main wire, and again, there was current flowing through the bypass wire. Nevertheless, the two wire tips got so close at 2.540 s that they shorted out just above the workpiece. The short-circuit current through the bypass wire rose dramatically to about 500 A, in which process the liquid metal on the tips of the two wires was repelled severely. In the following process, the tip of the bypass wire became higher and higher, and the droplet suspended on it became bigger and bigger. There was no promoting arc force, as the arc on the liquid metal on the main wire tip imposed on the bypass wire droplet. Therefore, it would not transfer until the gravity was big enough or the droplet has contacted the welding pool at 2.399 s as in Fig. 8.

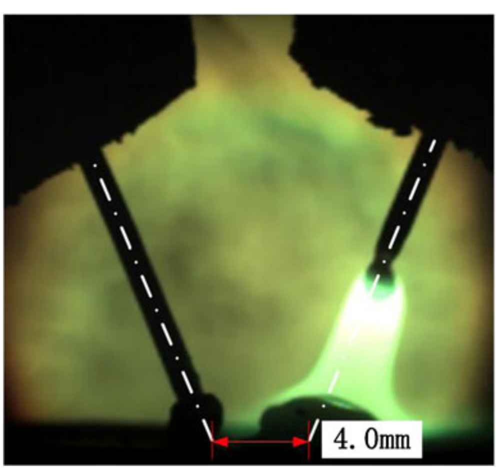

Fig. 10 A too big distance between the main wire and the bypass wire

As non-thermionic cathode, the mechanism of electron emission is a combination of field emission, thermal ionization, sheath ionization, photoemission, and electrons from ion impact at the cathode [24]. For the sake of low-boiling-pointing, the electrode cathode is unable to operate at a sufficient high temperature as in GTAW for thermionic emission of electrons to play a significant role [25]. The field electron emission is of great importance in the non-thermionic material arc-igniting process. Under certain conditions for thermionic materials, the cathode spots could be so hot that the current at the cathode is carried largely by thermionically emitted electrons. The cathode spot could be fixed or just moves slowly. As for the non-thermionic bypass wire, there are also cathode spots in the electron emission process. However, these cathode spots are quite erratic, which is very different from the thermionic material. As depicted in Fig. 9, the cathode spots moved rapidly on the surface of the droplet suspended on the bypass wire, which led to an unstable arcing process between the main wire and the bypass wire.

There was extra pressure on the cathode spots on the droplet. It was the fast-changing position of the cathode spots on the droplet that led to an unstable arc. Then the arc electromagnetic force will vary dramatically. The droplet oscillated obviously especially with the variation of the direction of the arc force. It also could be seen in Fig. 9 that the droplet on the bypass wire oscillated dramatically under the effect of the arc. Besides, there were also fine metal particles flying out from the bypass wire droplet, which further deteriorated the welding process.

It should be noticed that the length of the arc between the main wire and the workpiece in Fig. 9 was much shorter than that in Fig. 4b. The electrical configuration parameters were kept unchanged in these two experiments. It was mainly because the establishment of the arc between the main wire and the bypass wire. This arc occupied a part of power source so that the supportive power of the main arc was weakened, which in turned causes the

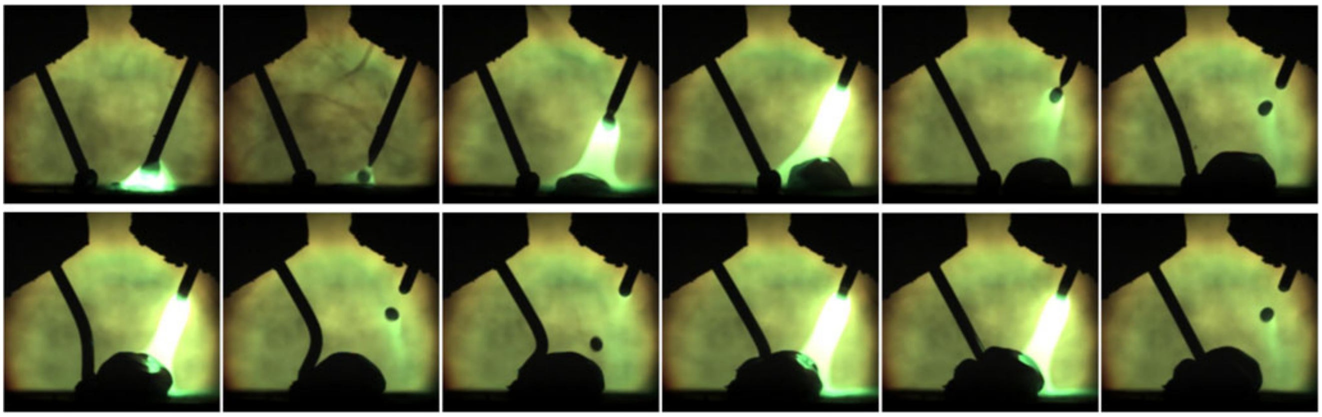

Fig. 11 Arc initiation process with too big distance between the main wire and the bypass wire

susceptibility of short circuit between the main wire and the workpiece.

3.4 Welding process with too big wire distance

As discussed in the previous part, a too small D_{ms} would lead to an unstable welding process. If D_{ms} is too big, as illustrated in Fig. 10, the welding process will also be irregular. In laser-arc hybrid welding, the horizontal distance between the laser focal point and the electrode tip determines whether the laser and the arc could interact with each other or not [27, 28]. If the distance is greater than the arc radius, the laser and arc plasmas will act separately, and it will become tandem rather than hybrid welding [9]. Similarly, in consumable DESA-GMAW, when D_{ms} became much too great, the interaction between the two filler wires would be weakened.

What is shown in Fig. 11 is the starting period of a welding process with too big distance between the main wire and the bypass wire. The main wire would still arc as normal as analyzed in Fig. 5, without shorting out with the bypass wire or the workpiece or producing spatters. It was mainly because that the bypass wire here is also kept short-circuited with the workpiece all along, although it was not sufficiently melted . As a result, the arc was both supported by the main power source and the slave power source. Furthermore, there was no other arc except the one between the main wire and the workpiece, so the interference between the two filler wires could be avoided. As for the bypass wire, the condition was not so good. According to the analysis about Fig. 4b, the heat used to melt the bypass wire was partly from the arc. The temperature in the thermal field of the arc would decline along with the distance away from the center of the arc. When D_{ms} increased to a certain large extent, the heat conducted to the bypass wire tip from the workpiece would not be enough to help sufficiently in melting the bypass wire with the resistant heat. Consequently, the bypass wire curved at the bottom part under the stress from the wire feeder. The part of the solid bypass wire below the curve point was buried in the welding pool, which would negatively affect the quality of the weld bead.

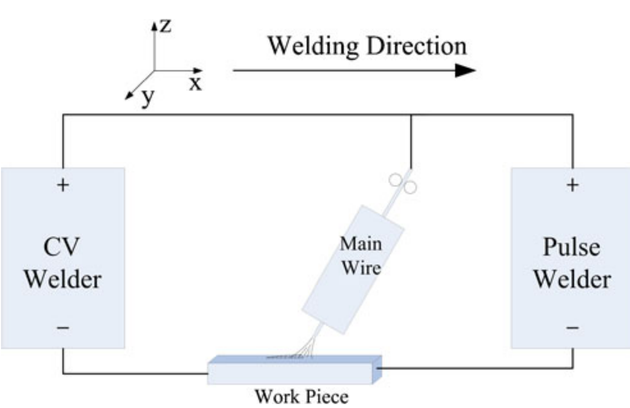

Fig. 12 Welding system with two welding sources and a single consumable electrode

3.5 Weld bead

The geometry of weld bead produced by consumable DESA-GMAW was compared with that produced by the

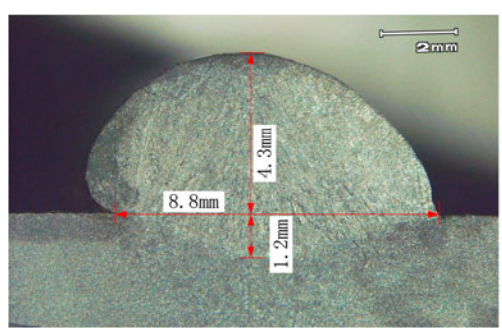

Fig. 13 Weld bead produced by consumable DESA-GMAW

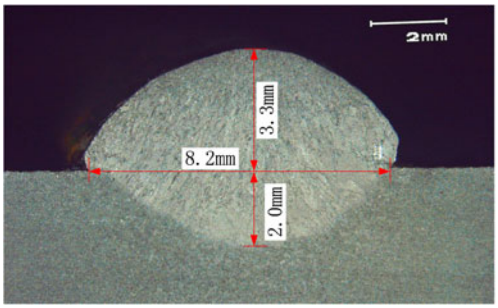

Fig. 14 Weld bead produced by a consumable DESA-GMAW system without a bypass wire

welding system without adding the bypass wire. In this comparison of the welding system, which is shown in Fig. 12, the cathode of the slave power source was also connected with the workpiece, the same as the main power source. The current through the workpiece was the same as the current through the filler wire. The filler wire was removed under the condition of the unchanging welding configurations, including the preset value of the two power sources, the wire feed speed of the main wire and the welding speed.

What is shown in Figs. 13 and 14 are the transverse sections of the weld beads. It can be seen that there were obvious differences between the geometrical dimensions of the two weld beads. The penetration of the weld could be effectively decreased, while the weld reinforcement and weld breadth were increased.

4 Conclusions

A welding system named consumable double electrode with a single arc GMAW was established. The welding process could be very stable with appropriate welding parameters. The distance between the tips of the main wire and the bypass wire mainly determined whether the welding process could be conducted successfully or not. The stable welding process was characterized by one filler wire that kept arcing stably with regular metal transfer process and the other filler wire that was kept short-circuited with workpiece all through the time and was fed into the welding pool stably and smoothly. When this distance was too small, there would be an arc established between the main wire and the bypass wire, which could lead to serious interference between them and cause lots of spatters in the welding process. When this distance was too big, the bypass wire could not be melted sufficiently, and an unstable welding process will be resulted. The transverse sections of the weld bead showed that, compared with general GMAW process, the penetration could be effectively decreased by using the proposed welding method.

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References

1. Lahnsteiner R (1992) The T.I.M.E. process—an innovative MAG welding process. Weld Rev Int 11(1):17–20
2. Church J (2001) T.I.M.E. process produces fracture-proof welds. Weld Des Fabr 74(5):32–35
3. Matsumoto T, Sasabe S (2005) Tandem MIG welding of aluminum alloys. Weld Int 19(12):945–949
4. Ueyama T, Ohnawa T, Tanaka M, Nakata K (2005) Effects of torch configuration and welding current on weld bead formation in high speed tandem pulsed gas metal arc welding of steel sheets. Sci Technol Weld Join 10(6):750–759
5. Huang Y, Zhang YM (2010) Laser-enhanced GMAW. Weld J 89(9):181s–188s
6. Shao Y, Wang ZZ, Zhang YM (2011) Monitoring of liquid droplets in laser-enhanced GMAW. Int J Adv Manuf Technol 57(1–4):203–214
7. Wang XW, Huang Y, Zhang YM (2013) Droplet transfer model for laser-enhanced GMAW. Int J Adv Manuf Technol 64(1–4):207–217
8. Bagger C, Olsen FO (2005) Review of laser hybrid welding. J Laser Appl 17(1):2–14
9. Ribic B, Palmer TA, DebRoy T (2009) Problems and issues in laser-arc hybrid welding. Int Mater Rev 54(4):223–244
10. Xu GX, Wu CS, Qin GL, Wang XY, Lin SY (2011) Adaptive volumetric heat source models for laser beam and laser+pulsed GMAW hybrid welding processes. Int J Adv Manuf Technol 57(1–4):245–255
11. Hu B, den Ouden G (2005) Laser induced stabilization of the welding arc. Sci Technol Weld Join 10(1):76–81
12. Mendez PF, Eagar TW (2003) Penetration and defect formation in high-current arc welding. Weld J 82(10):296s–306s
13. Li KH, Zhang YM (2007) Metal transfer in double-electrode gas metal arc welding. J Manuf Sci Eng-Trans ASME 129(6):991–999
14. Li KH, Chen JS, Zhang YM (2007) Double-electrode GMAW process and control. Weld J 86(8):231–237
15. Li KH, Zhang YM (2010) Interval model control of consumable double-electrode gas metal arc welding process. IEEE Trans Autom Sci Eng 7(4):826–839
16. Li KH, Wu CS (2009) Mechanism of metal transfer in DE-GMAW. J Mater Sci Technol 25(3):415–418
17. Li KH, Zhang YM (2007) Modeling and control of double-electrode gas metal arc welding process. Sec IEEE Conf Ind Electron Appl, Harbin, China, pp 495–500
18. Wu CS, Hu ZH, Zhong LM (2012) Prevention of humping bead associated with high welding speed by double-electrode gas metal arc welding. Int J Adv Manuf Technol 63(5–8):573–581
19. Li KH, Zhang YM (2008) Consumable double-electrode GMAW part I: the process. Weld J 87(1):11s–17s
20. Li KH, Zhang YM (2008) Consumable double-electrode GMAW part II: monitoring, modeling, and control. Weld J 87(2):44s–50s
21. Ma GH, Zhang YM (2012) A novel DE-GMAW method to weld steel tubes on simplified condition. Int J Adv Manuf Technol 63(14):147–153
22. Nemchinsky VA (1998) Heat transfer in an electrode during arc welding with a consumable electrode. J Phys D Appl Phys 31(6):730–736

23. Ando K, Hasegawa M (1978) Welding arc phenomena. The Machine Industrial, Beijing
24. Lowke JJ, Tanaka M (2008) The physics of non-thermionic cathodes of electric arcs. In: Proceedings of the 17th international conference on gas discharges and their applications, pp 137–140. Lindfield, NSW, Australia
25. Guile AE (1971) Arc-electrode phenomena. IEE Rev 118(9):1131–1154
26. Bingul Z (2002) Instability phenomena in the gas metal arc welding self-regulation process. Proc Inst Mech Eng B-J Eng Manuf 216(6):899–910
27. Hu B, den Ouden G (2005) Synergetic effects of hybrid laser/arc welding. Sci Technol Weld Join 10(4):427–431
28. Ribic B, Rai R, DebRoy T (2008) Numerical simulation of heat transfer and fluid flow in GTA/Laser hybrid welding. Sci Technol Weld Join 13(8):683–693