Int J Adv Manuf Technol (2014) 75:15–20
DOI 10.1007/s00170-014-6127-6

ORIGINAL ARTICLE

Study on forming mechanism of appearance defects in rotating arc narrow gap horizontal GMAW

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Received: 31 March 2014 / Accepted: 30 June 2014 / Published online: 10 July 2014

Abstract In horizontal position welding process, the key problem is the poor weld formation and weld defects induced by the downward motion of the molten metal. Base on the research results of welding process, droplet transfer, molten pool behavior, temperature field, reasons, and solutions of the typical weld appearance defects in rotating arc narrow gap horizontal GMAW are studied. The causes and mechanisms of the defects of sagging surface, under cut, and convex surface are explored. The relationship of the defects and the welding parameters is established. The main causes of the appearance defects can be classified into three categories. The first one is the excessive heat input of the welding process, the second one is unstable welding process, and the third one is the mismatch between the fusion area of base metal and filling metal. Finally, the optimum welding parameters of rotating arc narrow gap horizontal welding are determined.

Keywords Horizontal welding · Narrow gap welding · Rotating arc welding · Defect

1 Introduction

Reasons and solutions of weld formation defects have always been a concern owing to their effects on the weld quality, especially in additional position welding and manufacturing of heavy plate structure [1, 2]. The control of formation defects and elimination methods are crucial for heavy plate welding process in which the weld is filled by multiple passes and layers [3]. Each layer and pass must be precisely controlled to avoid welding defect, otherwise the high repair rate could have great effect on the economic efficiency and productivity. Especially in horizontal welding process, the control of formation defects is more difficult because the molten pool sags under the influence of gravity and the asymmetry of weld formation. Until now, the technology of solving this problem can be sorted into two kinds of control strategies: energy strategy and force strategy. The technical feature of the energy strategy is devoting to reduce the welding heat input to shorten the cooling period in order to decrease the sagging tendency of the molten pool. There are two methods of reducing the heat input. One is to use the pulse current to reduce the energy input of the welding, such as PAW-HB [4] (pulse arc welding-horizontal bead) technology. The other is to increase the instantaneous velocity of welding, such as the wire oscillating welding technology [5–8]. The principle of the force strategy is to apply the external force to counteract the gravity of molten pool. The most common technology using this strategy is the multipass welding in which the lower bead can support the upper bead. The Lorentz force was used for supporting the molten pool and preventing it from sagging by Motomi [9] and Yukio [10]. Using slag and backing plate to support the molten pool was also presented [11].

Our recent research presented that the rotating arc process could be benefit for the molten pool control of narrow gap horizontal welding, the droplet transfer characteristics, molten pool behavior and control, temperature distribution, welding process, and weld formation mechanism had been systematically studied [12–16]. This paper places the emphasis on the forming mechanism of appearance defects which is always a problem in welding process. The causes of sagging surface, undercut, and outer convex surface are explored. The relationship of the defects and the welding parameters is established.

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The technology advantages of the rotating arc process on the narrow gap horizontal welding are represented from the aspects of welding heat input and molten pool behavior. This study not only can be contributed to the better understanding of rotating arc narrow gap horizontal welding, but also provides the technique support for the developing of horizontal welding technology which is widely used in the manufacturing field.

2 Experimental apparatus and procedure

In this work, a FASTCAM SUPER10K high-frame-rate digital camera (3,000 frames s^{-1}) is used to obtain the images of the molten pool formation process in real time. A continuous xenon lamp is used as the back-lighting source. The base material is low carbon steel plates with thickness of 10 mm, which are assembled to I type groove with gap width of 10 mm for present study. H08Mn2Si welding wire of 1.6 mm diameter is used for depositing the weld beads. Weld cross-sections are removed from each weld, ground through 200–1,200-mesh grinding papers and polished through 1-μm diamond paste. The samples are etched in 2 % Nital solution. In the present work, optical examinations of sample are carried out using a MPG3 OLYMPUS microscope.

The schematic of rotating arc welding setup is shown in Fig. 1 [12]. The formation principle of the rotating arc is that the nozzle and the wire are clockwise rotated with the conductor tube which is connected with the eccentric sleeve driven by the motor. There is no relative motion between the nozzle and the wire, so it could reduce wear and prolong the service life of the nozzle. The welding power source is KEMPPI PROMIG 5000. The power source is operating in constant wire feed and constant voltage mode. The welding parameters are given in Table 1.

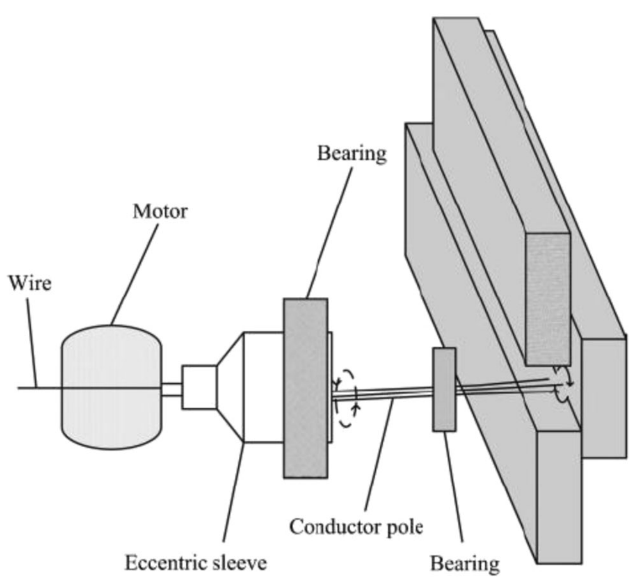

Fig. 1 Schematic of rotating arc welding setup [12]

Table 1 Welding parameters were used during the welding

Arc voltage, V	26–30
Wire feeding speed, m min^{-1}	4–8
Welding speed, m min^{-1}	0.23
Arc rotation frequency, Hz	2.5–50
Rotating radius, mm	2.0–4.0
Contents of CO_2 in shielding gas	5–50 %

3 Results and discussion

In horizontal position welding process, the key problem is the poor weld formation and weld defects induced by the downward motion of the molten metal. There are three kinds of common appearance defects, such as sagging surface, undercut, and outer convex surface.

3.1 Weld formations with different welding parameters

The cross-sections of the horizontal weld with different arc voltage are shown in Fig. 2 [16]. It should be noted that the excellent horizontal weld without sagging and convex surface defect can be obtained with the arc voltage of 27 and 28 V. The convex surface and sagging surface defect is observed in the weld with arc voltage of 26 and 29 V, respectively. Figure 3

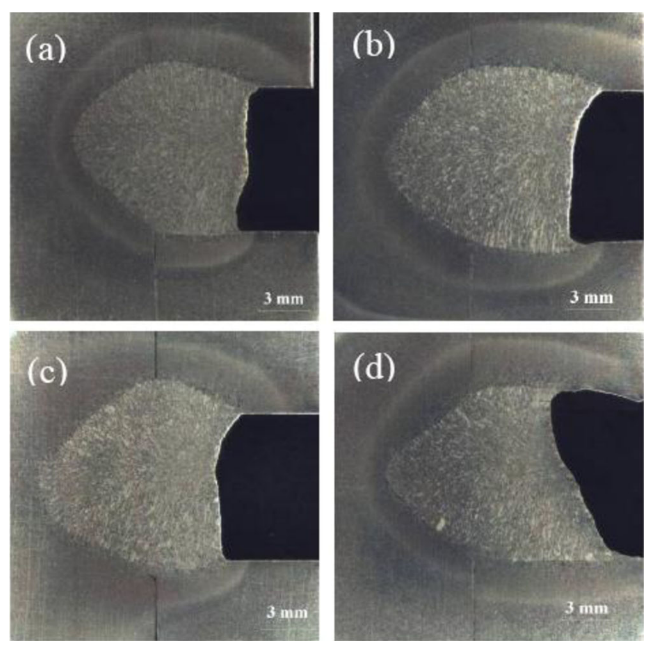

Fig. 2 Cross-sections of weld with different arc voltage: **a** 26 V; **b** 27 V; **c** 28 V; **d** 29 V [16]

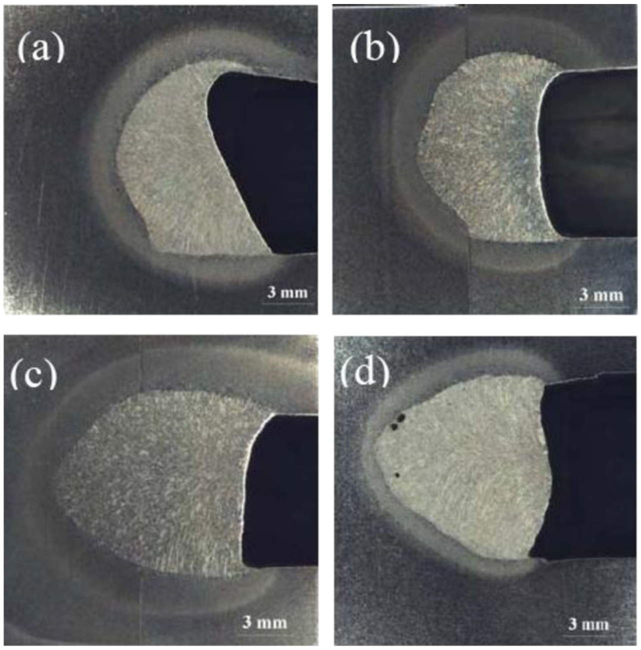

Fig. 3 Cross-sections of weld with different wire feed speed: **a** 3.5 m/min; **b** 4 m/min; **c** 5 m/min; **d** 6 m/min

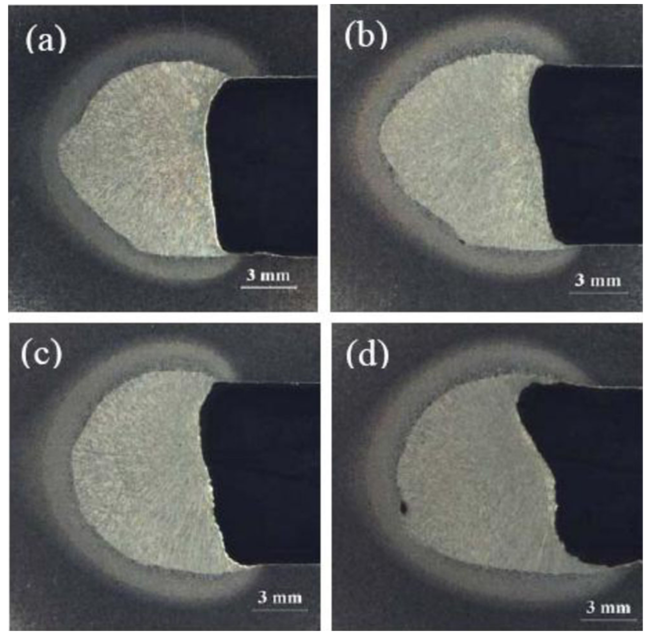

Fig. 5 Cross-sections of weld with different arc rotating radius: **a** 2 mm; **b** 2.6 mm; **d** 3.6 mm; **e** 4 mm [12]

shows the weld formation with different wire feeding speed. The serious sagging surface defect is obtained with the wire feeding speed of 3.5 m/min. The formations with wire feeding speed of 4 and 5 m/min are acceptable, whereas the weld with wire feeding speed of 6 m/min presents the convex surface defect. Our previous study results of rotating arc welding process indicated that the acceptable weld formation can be obtained with the rotating frequency of 2.5–10 Hz and the rotating radius of 2.0–3.0 mm, and the sagging surface defects are observed with the others rotating parameters, as shown in Figs. 4 and 5 [12]. An integrated weld cannot be obtained with the contents of CO_2 more than 20 % in the shielding gas. So the results mentioned above indicates that the welding parameters have great effects on the appearance defects in rotating arc narrow gap horizontal welding, and it presents certain regularity.

In this paper, we suppose that the main causes of the appearance defects should classified into three categories. The first one is the excessive heat input of the welding process, the second one is unstable welding process, and the third one is the mismatch between the fusion area of base metal and filling metal.

3.2 Sagging surface and undercut

As the most common defect in horizontal position welding process, sagging surface is the key question must be solved.

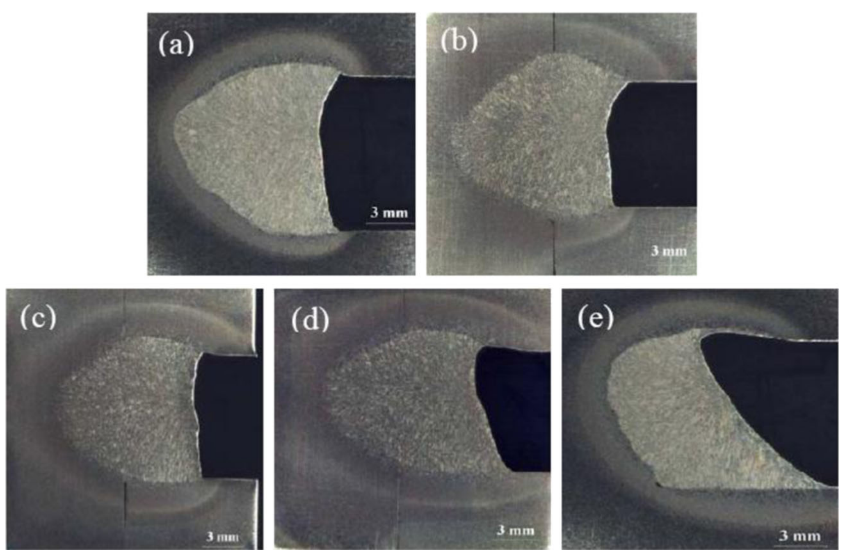

Fig. 4 Cross-sections of weld with different arc rotating speed: **a** 2.5 Hz; **b** 5 Hz; **c** 10 Hz; **d** 20 Hz; **e** 50 Hz [12]

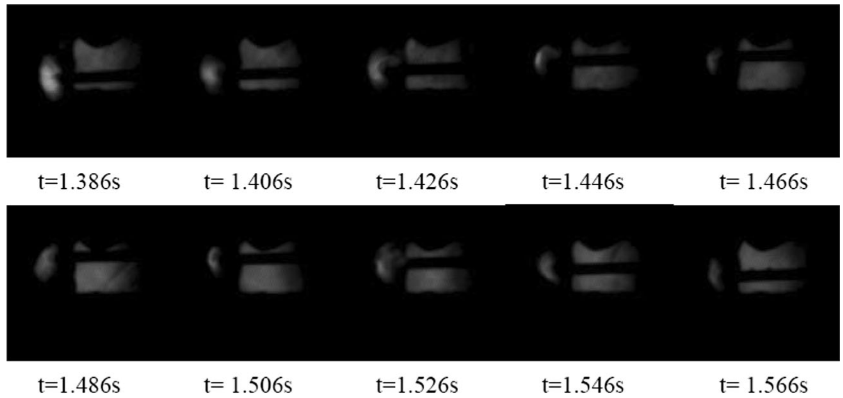

Fig. 6 Droplet transfer of rotating arc process with protective air of Ar+50%CO_2

So exploring the mechanism of the defects can promote the development of horizontal welding technology. From welding process perspective, the causes of sagging surface and undercut can be classified as follows:

1. The fusion area of base metal is greater than the filling metal

   This phenomenon is usually caused by incorrect welding conditions such as arc voltage higher than 28 V, wire feeding speed slower than 4 m/min, rotating radius larger than 3 mm, as shown in Figs. 2d, 3a, and 5d. In these conditions, either the arc heat affecting area is too large or the filling metal is too few, induces the defects of sagging surface and undercut. In horizontal welding process, the liquid molten metal accumulates on the lower sidewall due to the gravity in the beginning of molten pool formation, and then the molten pool is filled from the lower side to the upper side and solidifies to form the final weld formation. So there is an appropriate volume of filler metal to fill the fusion area of base metal for obtaining shapely horizontal weld. If the volume of filler metal is less than the volume of fusion area, it may induce the weld defect of sagging surface which is accompanied with undercut.
2. Unstable welding process

   Unstable welding process is usually induced by the instability in the droplet transfer process. This phenomenon is caused by too high rotating frequency (not less than 50 Hz) and too much content of CO_2 (not less than 20 %) in the protective gas. These two causes can result in the loss of filled metal by the large amount of spatters, which induces the unstable molten pool in the bottom of the groove and the accumulation of liquid molten metal on the lower sidewall. Then the weld collapsing is induced.

Figure 6 shows the droplet transfer of rotating arc process with protective air of Ar+50%CO_2. It can be seen that the arc length is quite short during the whole process. The metal transfer presents short circuiting transfer mode, occasionally presents repulsive transfer mode or arc extinguishing. Much spatter occurs during the whole process, which induces the unstable welding process. Figure 7 displays the droplet transfer of rotating arc process in a cycle with rotating frequency of 50 Hz. It indicates that a long liquid column is formed in the area near the lower sidewall. The metal transfer presents instability transfer mode under the centrifugal force and inertia. Subsequently, the size of liquid column decreases. When the wire crosses the centerline and continues upwards to the location near the upper sidewall, the metal transfer still presents instability transfer mode. With the downward motion of the wire, the size of liquid column increases. When the wire moves downwards to the location near the lower sidewall, the metal transfer presents instability transfer mode again.

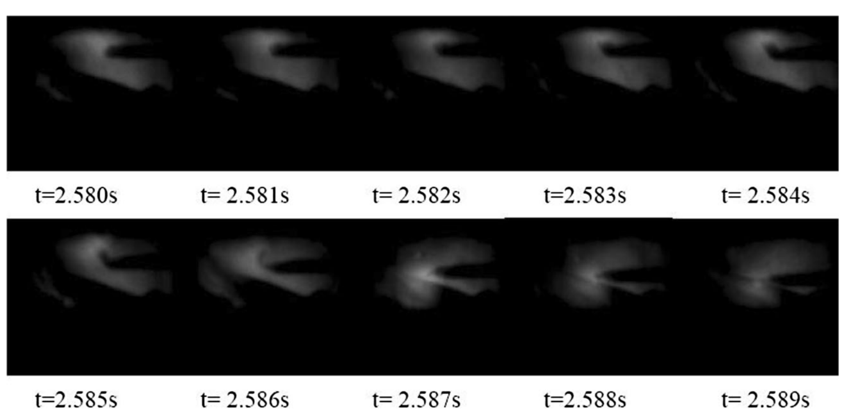

Fig. 7 Droplet transfer of rotating arc process with rotating frequency of 50 Hz

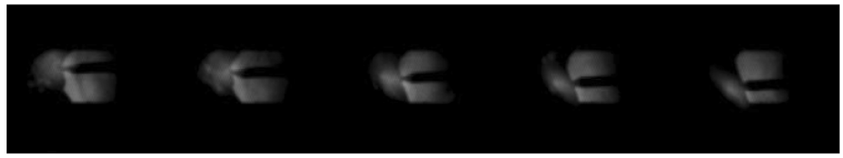

Fig. 8 Droplet transfer of rotating arc process with rotating frequency of 20 Hz

Due to the occurrence of instability transfer mode, the metal transfer location is irregular. So the welding process is very unstable at the rotating frequency of 50 Hz. The cross-section of horizontal weld is shown in Fig. 4e. It can be seen that the sagging surface which is resulted by the unstable welding process.

3. Excessive heat input of molten metal pool

In traditional narrow gap horizontal welding, it usually increases the welding specification for enough sidewall penetration. In this case, lower surface tension is caused by the long high-temperature residence time of molten pool, which results in the increasing collapsing trend of the molten metal pool. Furthermore, it also resulted in the formation of finger penetration defects. Our previous simulation studies show that in the rotating arc welding process, with the rotating frequency from 2.5 to 10 Hz, the rotating arc process distributes less heat input in the weld center. Whereas with the increasing of rotation frequency up to more than 10 Hz, the temperature of molten metal pool increases to the same level of non-rotating arc process, which also increases the collapsing trend of the pool [15]. The cross-section of horizontal weld with rotating frequency of 20 Hz is shown in Fig. 4d. It can be seen that the weld surface sags. However, the droplet transfer during the whole welding process is very stable, as shown in Fig. 8. Therefore, it can be inferred that the sagging surface is caused by the high temperature of molten metal pool. With the rotating frequency increasing, the remelting times increases. Then the temperature of molten metal and high-temperature residence time of molten pool increases. Therefore, the surface tension of molten metal pool decreases, which results in the weld surface sagging.

3.3 Causes of outer convex surface

In multiple layers welding process, outer convex surface, as a welding defect, is considered to be one of the main causes of lack of fusion between layers. Deeply understanding the causes of the defects can improve the quality of welded joints in the horizontal welding.

The main cause of outer convex surface defect is that the amount of fusion area of base metal is less than that of filling metal. This phenomenon is mainly caused by the small arc thermal effect area, which results in the formation of a relatively small fusion area of base metal. When the amount of filler metal is relatively great, the excess filler metal cannot completely break through the surface tension to expand outward overall. The solidification process of welding pool is from inside to outside and from surrounding area to the center of the welds. This phenomenon results in the excess molten filler metal only expanding outward from the middle of the weld which is the most easily deformed area. Therefore, the outer convex surface forms. The schematic of convex surface defect formation process is shown in Fig. 9. Moreover, it can be inferred that the outer convex surface defect will not sequentially increase with the increase of the amount of filler metal. When the filler metal achieves a certain amount, the molten metal breaks the surface tension to expand outward. The sagging surface defects are eventually formed.

From the perspective of welding process, outer convex surface is mainly caused by incorrect welding conditions such as arc voltage lower than 27 V, wire feeding speed higher than 5 m/min, too slow welding speed, and so on, as shown in Figs. 2a and 3d.

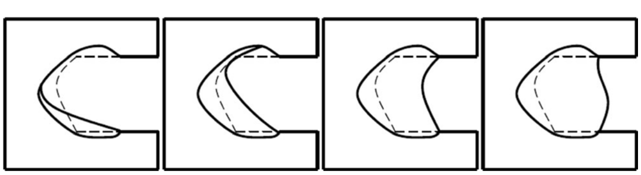

Fig. 9 Schematic of convex surface defect formation process

3.4 Determination of the optimum welding parameter

Based on the above analysis, there is an optimum welding parameter range of rotating arc narrow gap horizontal GMAW process. It results in the excellent formation horizontal weld without sagging, outer convex surface, and other defects. The optimum welding parameter range is shown in Table 2. Finally, an excellent weld formation of single layer horizontal welding can be achieved, as shown in Fig. 4a.

Table 2 Optimum welding parameter range of rotating arc narrow gap horizontal welding

Arc voltage, V	27–28
Wire feeding speed, m min^{-1}	4–5
Arc rotation frequency, Hz	2.5–10
Rotating radius, mm	2.0–3.0
Content of CO_2, %	5–20

4 Conclusions

1. The causes of the appearance defects such as sagging surface, under cut, and convex surface are explored. There are three main causes of the appearance defects. These are the mismatches of the amount of fusion area of base metal and that of filling metal, unstable welding process, and the excessive heat input of molten metal pool.
2. The rotating arc plays an important role in eliminating the weld defects caused by the improper control behavior of molten pool. The formation of molten pool can be controlled by reducing the heat input and changing the effect of arc force and droplet impact on the molten pool, which is beneficial for horizontal weld formation.
3. The optimum welding parameter range of rotating arc narrow gap horizontal GMAW process is determined. An excellent weld formation of single layer horizontal welding can be obtained.

Acknowledgements We are grateful to the National Natural Science Foundation of China (grant no. 51005141), the State Key Development Program for Basic Research of China (grant no. 2013CB035502) and Weihai Science and Technology Development Planning (grant no.2013DXGJ07) for the financial support to this study.

References

1. Ding M, Tang XH, Lu FG, Yao S (2011) Welding of quenched and tempered steels with high-spin arc narrow gap MAG system. Int J Adv Manuf Technol 55:527–533
2. Cui HC, Jiang ZD, Tang XH, Lu FG (2014) Research on narrow-gap GMAW with swing arc system in horizontal position. Int J Adv Manuf Technol. doi:10.1007/s00170-014-5984-3
3. Xu WH, Lin SB, Fan CL, Zhuo XQ, Yang CL (2014) Statistical modeling of weld bead geometry in oscillating arc narrow gap all-position GMA welding. Int J Adv Manuf Technol 72:1705–1716
4. Murakami S, Kitagawa A, Nakajima H (1986) Study on horizontal narrow gap welding for heavy plates. Hitachi Zosen Technical Review 47:33–38
5. Nakayama H (1975) Application of narrow gap automatic CO_2 arc weaving welding processes to heavy steel structures of building. The Second International Symposium of the Japan Welding Society 2–2:21
6. Yang XQ (1980) A study on weave locus in horizontal position welding. Trans China Weld Inst 1:197–204
7. Song X (2004) Analysis on application of welding gun oscillation mechanism to 3-RPS parallel platform. Weld Join 4:24–26
8. Wang G, Sha YZ, Wang B, Miao WQ, Hao JC, Lu SQ (1998) Automatic horizontal CO_2 welding procedure for blast furnace. Weld Join 9:20–22
9. Motomi K, Keiichiro H, Katsuhiko N (1980) Welding apparatus with shifting magnetic field. United States patent: 4190760
10. Yukio M, Satoru Z, Yoshinori H (2000) Method of welding in the horizontal position and welding apparatus. United States patent: 6023043.
11. Henderson I, Seifert K (1976) Investigation of different methods of protecting the molten metal pool in narrow-gap welding of a structural steel for nuclear reactor use. Weld Cutt 28:291–293
12. Yang CL, Guo N, Lin SB, Fan CL, Zhang YQ (2009) The application of a rotating arc system to horizontal narrow gap welding. Sci Technol Weld Join 14:172–177
13. Guo N, Lin SB, Gao C, Fan CL, Yang CL (2009) Study on elimination of interlayer defects in horizontal joints made by rotating arc narrow gap welding. Sci Technol Weld Join 14:584–588
14. Guo N, Yang CL, Lin SB, Fan CL et al (2009) Metal transfer characteristics of rotating arc horizontal GMAW. Sci Technol Weld Join 14:760–764
15. Guo N, Wang MR, Guo W, Yu JB et al (2014) Effect of rotating arc process on molten pool control in horizontal welding. Sci Technol Weld Join 19:385–391
16. Guo N, Lin SB, Fan CL, Zhang YQ, Yang CL (2009) Study on weld formation in a novel rotating arc horizontal GMAW. China Weld 18: 41–45