# Effects of Arc-Sidewall Distance on Arc Appearance in Narrow Gap MAG Welding

**Hu Lan, Hua-Jun Zhang, De-Long Zhao, A-Jing Chen and Shang-Yang Lin**

**Abstract** Arc appearance is a key factor to sidewall fusion in narrow gap MAG welding (NG-MAG). By observing arc images with high-speed video and weld cross-sections at different arc-sidewall distances in NG-MAG vertical welding, it was discovered that the arc ascended along the groove sidewalls and arc appearance changed from cone to olive when the arc-sidewall distance was relatively small, which contributed to large weld concavity and significant "bead separation" phenomenon. On the other hand, arc length and arc appearance were stable as the arc-sidewall distance was relatively large. Due to not being heated directly and effectively by the arc high temperature zone, the sidewall penetration was low and weld was convex. Only when the arc-sidewall distance was controlled in the range of 2.0 to 3.0 mm, the arc was stable and the weld appearance was concave. Also, the penetration of groove sidewalls was deep. Thus, the sidewall fusion in NG-MAG vertical welding is highly sensitive to process parameters under the low heat input conditions. The laws being discovered above will make a good preparation for the realization of thick high strength low alloy steel (HSLA) plates with NG-MAG automatic welding technology in ocean engineering.

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## 1 Introduction

In recent years, with increasing on the size of welded structures and the thickness of steel plates, high production efficiency and quality, and excellent joint mechanical properties are required, which conventional welding methods can not meet [1]. However, Narrow gap MAG welding (NG-MAG) is an energy-saving technology of welding joints of large wall thickness in a narrow gap with minimum groove dimensions. Correspondingly, such gaps should result in a decrease in the cross-section areas of the welding gap, and a decrease in the consumption of welding consumables, welding time, electric energy, deformation and stresses in welding structures [2].

NG-MAG, as a special industrial technology, needs to solve a key technical problem of improving the stability of double sidewall penetration. Studies have shown that the most direct factor, influencing sidewall fusion, is the heat effect of arc on the sidewalls [3]. Currently, the main approach to enhance this heat effect is changing the arc appearance near groove sidewalls, such as bending the wire [4–6], oscillating the electrode [7–10], moving the arc up and down in the gap [11], swing the arc transversely and periodically in groove with applied magnetic field [12], constraining the arc with flux [13] and so on. But it was discovered that sidewall fusion is sensitive to NG-MAG welding process parameters under low heat input conditions in practical applications. If the arc-sidewall distance (the distance between wire tip i.e. the center of arc and the sidewall) is not controlled properly, short arc-sidewall distance will lead to arc climbing up along the groove sidewalls and destroy the arc appearance, while long arc-sidewall distance will contribute to no effective heating to the sidewalls with arc high energy zone. Both conditions above will result in poor sidewall fusion. Therefore, controlling a reasonable arc-sidewall distance is the basic premise to maintain a desirable arc heating shape and the basic guarantee to achieve uniform sidewall fusion.

Reference [14] employed deposition experiments to research two typical visual arc appearances (conical and wispy) and the characteristics of heating on the weld pool in pulsed metal arc welding. Reference [15] adopted mathematical derivation and numerical calculation methods to analyze the heat input distributions in traditional V-shaped and U-shaped grooves in swing arc welding. Reference [3] analyzed the errors of the arc-work position in the process of narrow gap welding, and studied the influence of the arc-work position on the continuous fusion of the thick wall with corresponding experimental. Reference [16] combined the structure characteristics of small-diameter thick-walled pipe and the properties of 40CrMnMo steel, applied narrow gap pulsed MAG welding technique to the oil drill collars and investigated the gas protection, arc morphology, arc stability, and weld appearance in narrow groove. However, the influence of arc-sidewall distance on arc appearance and sidewall fusion in NG-MAG welding has not been reported. Therefore, in order to get the optimal arc-sidewall distance for heat effect of arc on the wall sidewalls, a large number of experiments about the influence of arc-sidewall distance on arc appearance in robot NG-MAG pulsed welding were conducted in this paper. This would contribute to define the adaptive ranges of welding process parameters to the errors of groove width and assembly, and provide technology support for thick plates with NG-MAG automatic welding.

## 2 Experimental Procedure

In Fig. 1 is seen the robot NG-MAG pulsed vertical welding system with 11 degrees of freedom (DOF). The whole workstation consists of 6-DOF robot system cooperated with KUKA-KR16, 3-DOF gantry HLV03-13, 2-DOF L-type positioner HDS50 and power source EWM PHOENIX 521 ForceArc. The arc-sidewall distance (described by *d*) experiments were carried out with segmented vertical up welding, and the base metal is Q345B with a groove of 20 mm in width and 12 mm in depth and 3 mm in fillet radius. Shielding gas is Ar mixed with 20 % $CO_2$ with flow rate in the range of 15–18 L/min. The other detailed welding process parameters are shown in Table 1. The processes of arc-dynamic changes are recorded by a high-speed video in different arc-sidewall distance experiments.

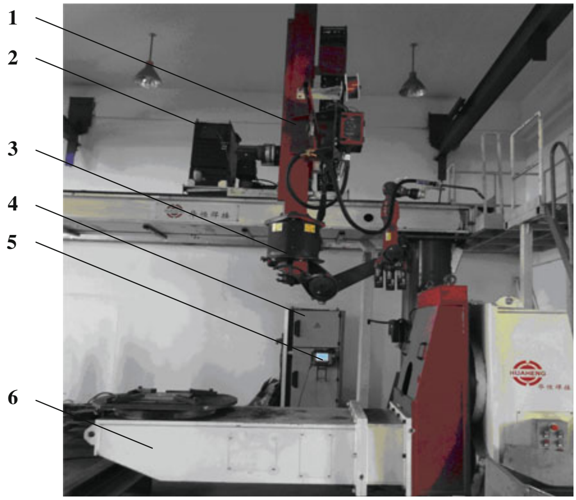



**Fig. 1** Experiment Device of Robot NG-MAG Welding. *1* 3-DOF gantry, *2* welding power, *3* robot, *4* controller, *5* teach pendant, *6* L-type 2-DOF positioner

**Table 1** Process parameters of NG-MAG welding

| Pulse current (A) | Background current (A) | Arc voltage (V) | Pulse frequency (Hz) | Welding speed (m/min) | [a]Weaving amplitude (mm) | Weaving frequency (Hz) | Dwell time (s) |
|---|---|---|---|---|---|---|---|
| 400–405 | 50 | 21.3–22.2 | 84–108 | 0.13 | 6.0–8.8 | 0.5–0.6 | 0.2–0.3 |

[a]Corresponding arc-sidewall distance $d = 1.2$–$4.0$ mm

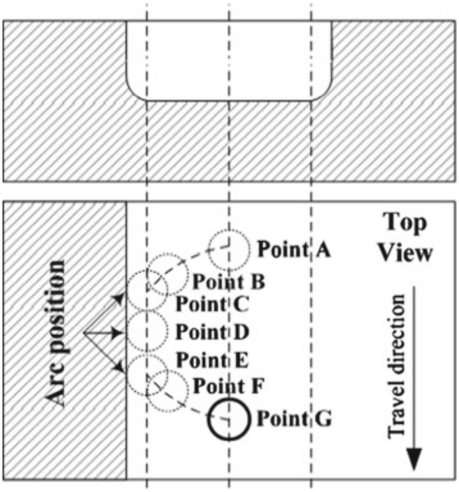



**Fig. 2** Torch oscillation positions for measuring arc images

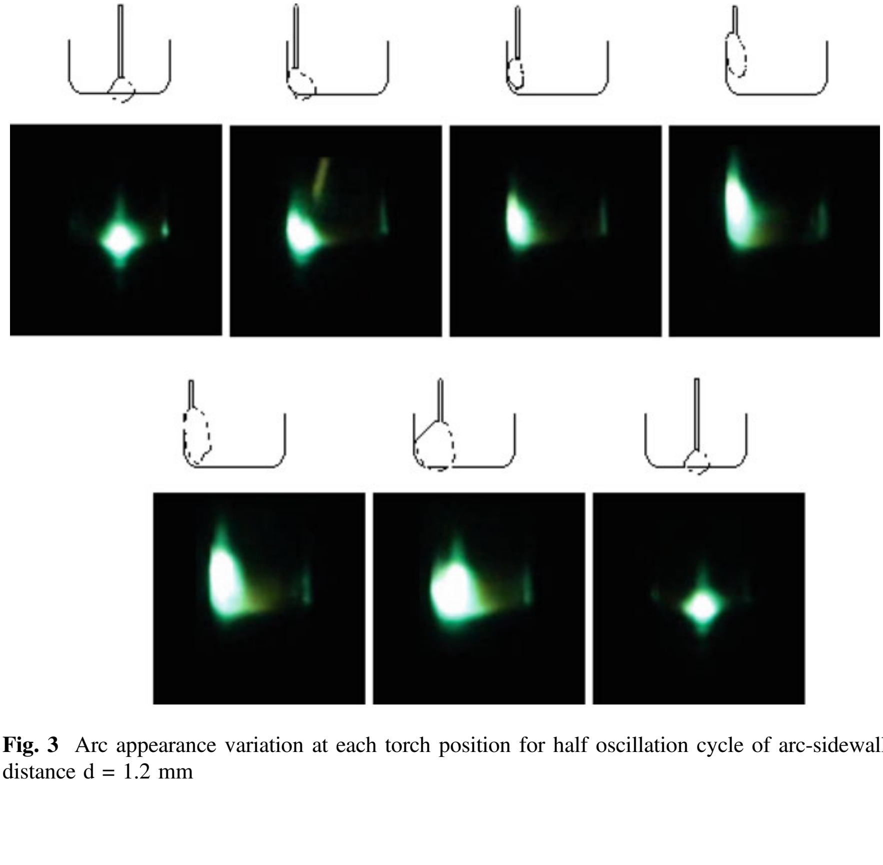


**Fig. 3** Arc appearance variation at each torch position for half oscillation cycle of arc-sidewall distance d = 1.2 mm

# 3 Results and Discussion

## *3.1 Effects of Arc-Sidewall Distance on Arc Appearance*

It can be found that the different visual arc appearances are dependent on the changing process of the instantaneous arc appearances in NG-MAG vertical pulsed welding by analyzing the photos taken by high-speed video. As illustrated in the Ref. [14], if the duration of pulse current is long enough, in the vicinity of the weld center, the bright zone of arc (arc appearance) has a dynamic process of changing from wispy to conical. Moreover, after the wispy arc appearance changing into conical, the arc appearance shall keep conical even the role of the pulse current continues until the pulse current stopped. In order to facilitate the analysis of the influence of arc-sidewall distance on the arc appearance in NG-MAG vertical welding, photographs taken in experiments were chosen in accordance with the arc positions shown in Fig. 2. Among the positions shown in Fig. 2, Point A and Point G are at the weld center. Point B and Point F are the positions where arc and sidewall are contacting and detaching with each other in a half cycle of arc swing. While Point C, Point D

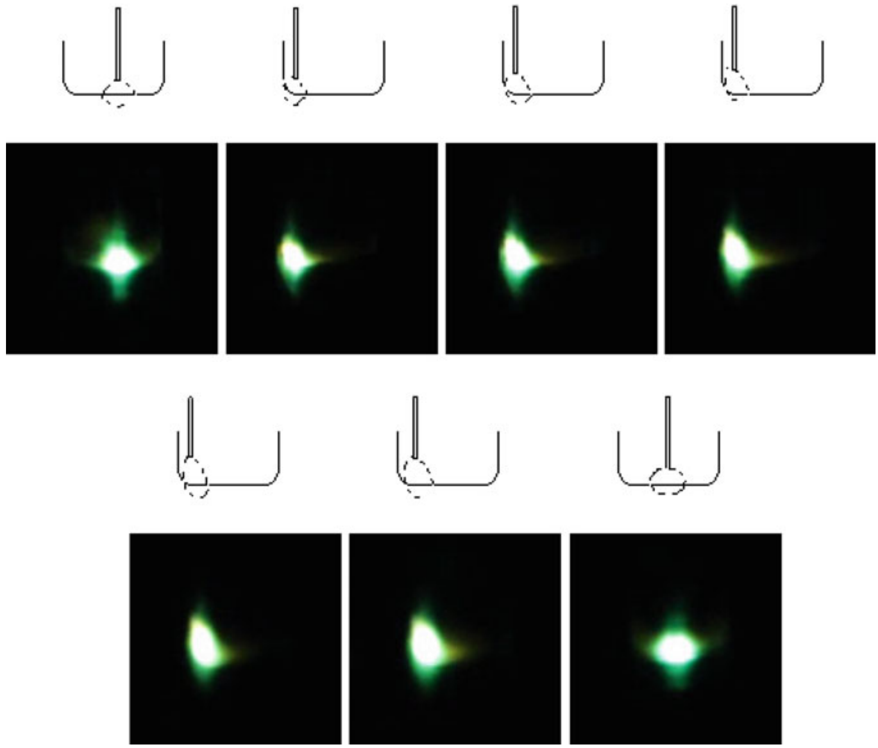


**Fig. 4** Arc appearance variation at each torch position for half oscillation cycle of arc-sidewall distance d = 1.6 mm

and Point E respectively are at the initial, middle, and end position where arc moved to the edge of weld (maximum swing point). Figures 3, 4, 5, 6, 7 and 8 show the instantaneous arc appearances when the arc is approaching to and departing from the sidewall in the range of arc-sidewall distance of $d$ = 1.2–4.0 mm.

As can be seen from Figs. 3 and 4, the phenomenon of arc climbing up was obvious when the arc-sidewall distance is small (d = 1.2 or 1.6 mm). The arc was lengthening and changing from conical to olive. Also, the wire tip was ascending with the arc approximating to the sidewall successively. While the arc length and arc appearance recovered as the arc was detaching from the sidewall. Generally speaking, the arc length can be maintained stable by inherent self-regulation with constant speed wire feeding in gas metal arc welding (GMAW). That means the arc length can be adjusted by the wire melting rate. In other words, when the arc length is shortened by some factors, the welding current will increase to accelerate the wire melting speed immediately to restore the arc length. According to the principle of minimum voltage, if the arc-sidewall distance was shorter than arc length in the process of NG-MAG welding, the arc would burn between wire and sidewall. Although welding current was increasing rapidly, the cathode spot was climbing up along the sidewall. The ability of self-regulation of arc was lost with the arc

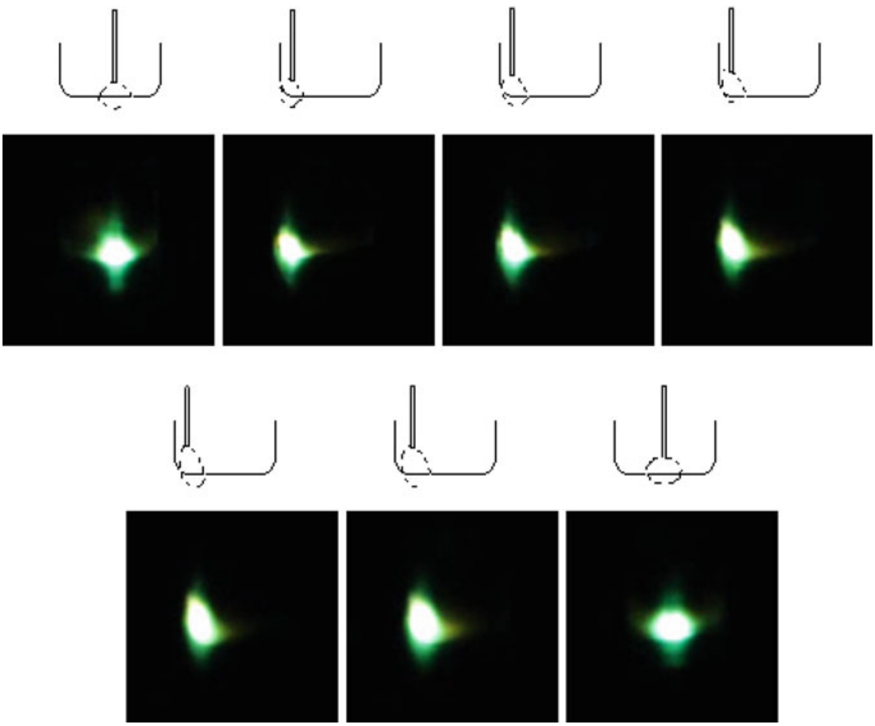


**Fig. 5** Arc appearance variation at each torch position for half oscillation cycle of arc-sidewall distance d = 2.0 mm

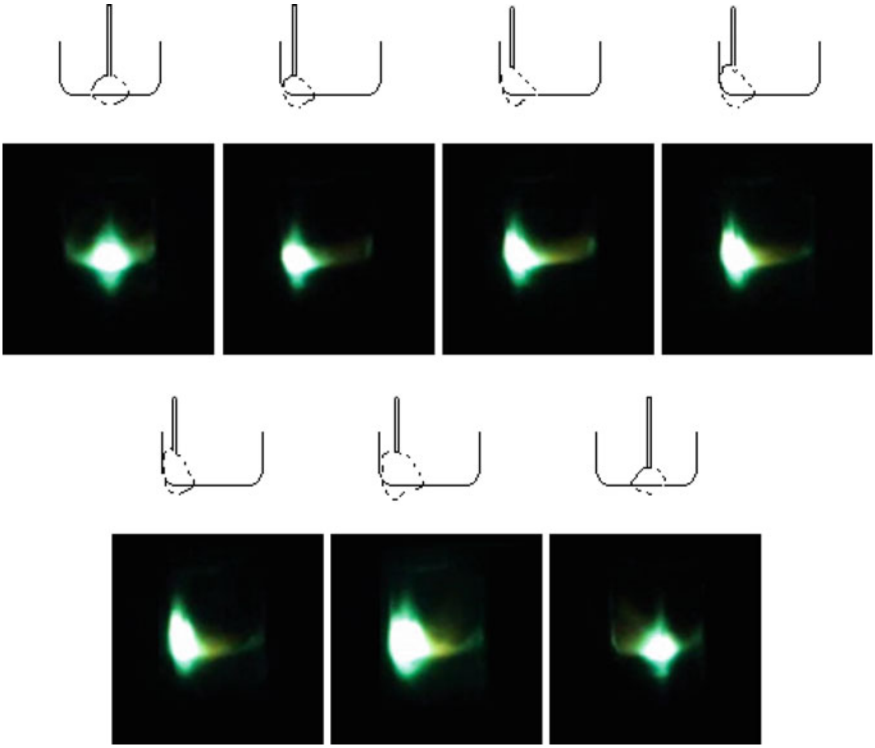


**Fig. 6** Arc appearance variation at each torch position for half oscillation cycle of arc-sidewall distance d = 2.4 mm

ascending. However, the arc length could be shortened by reducing the wire melting speed with its inherent self-regulation in the subsequent departure from the sidewall.

See Figs. 5, 6 and 7, it is clear that the arc was stable with good sidewall fusion, in the whole process of arc approaching to and departing from the sidewall successively, when the arc-sidewall distance d = 2.0–3.0 mm. And the change of wire extension, arc length and arc appearance was smaller than that of arc-sidewall distance d = 1.2 or 1.6 mm.

With increasing the arc-sidewall distance d, the arc almost remained conical shape. However, the heat effect of arc on the sidewalls was weakened. When d = 4.0 mm, as shown in Fig. 8, the arc edge could just touch the sidewall. In this case, the sidewall was mainly heated by the arc heat radiation and heat conduction of weld pool. Comparing to the occasion that the sidewall was heated by the arc directly (see Figs. 5, 6 and 7), there was a greater chance of emerging poor fusion at the sidewall due to insufficient heat. That's because when the arc-sidewall distance is becoming larger, the high energy zone can not heat the sidewall effectively under low heat input conditions.

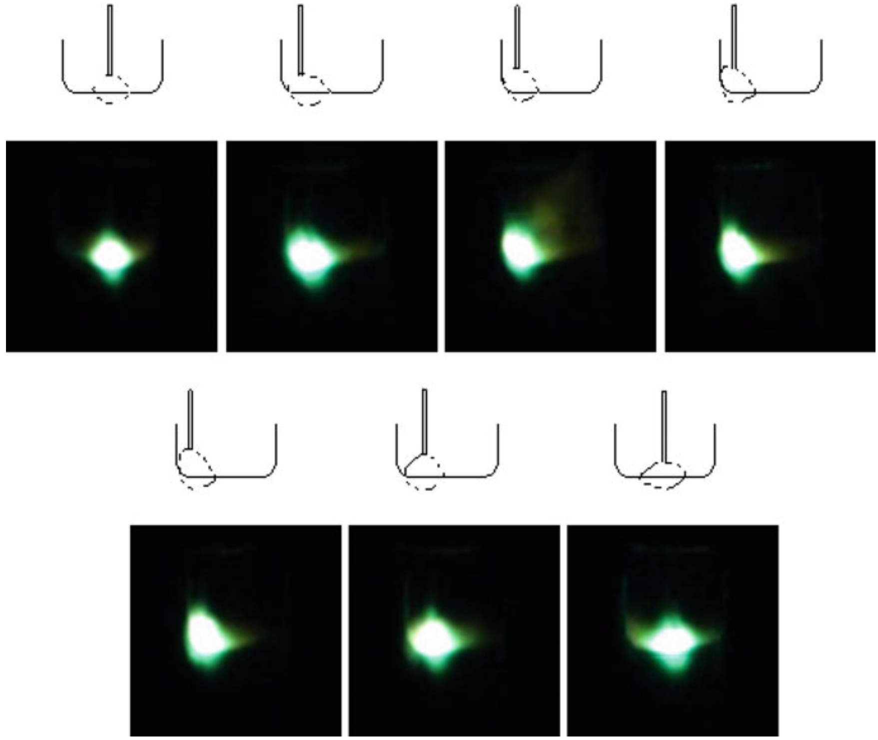


**Fig. 7** Arc appearance variation at each torch position for half oscillation cycle of arc-sidewall distance d = 3.0 mm

In short, the sidewall fusion has higher sensitivity to process parameters under low heat input conditions in NG-MAG welding, which also confirms the statements above. The arc can maintain a relatively stable shape and heat the sidewall effectively and directly when arc-sidewall distance d is controlled in the range of 2.0–3.0 mm.

## 3.2 Effects of Arc-Sidewall Distance on Weld Cross Section

By observing the cross section of specimens, see Fig. 9, it's easy to find that the arc ascended when the arc-sidewall distance was short ($d$ = 1.2 or 1.6 mm), which contributed to too much filler metal on sidewall and too little in center, and significant "bead separation" phenomenon. While heating the sidewall was limited and the welding pool could not dissipate timely with long arc-sidewall distance ($d$ = 4.0 mm), which resulted in high temperature at weld center, the liquid flowing to the center, weld raised significantly and not being conducive to the subsequent

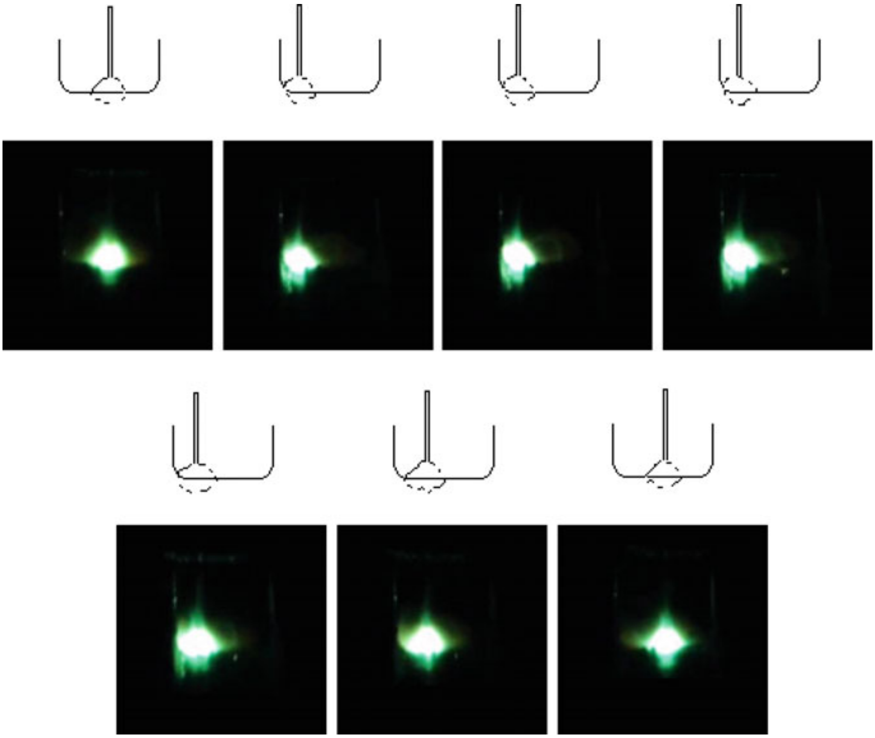


**Fig. 8** Arc appearance variation at each torch position for half oscillation cycle of arc-sidewall distance d = 4.0 mm

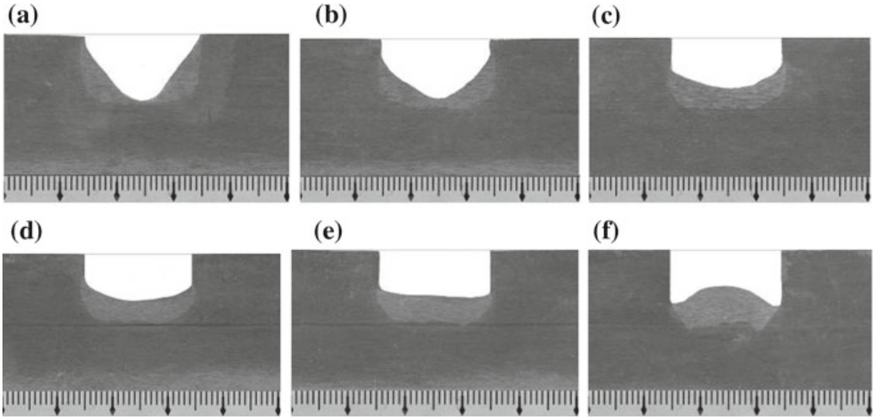
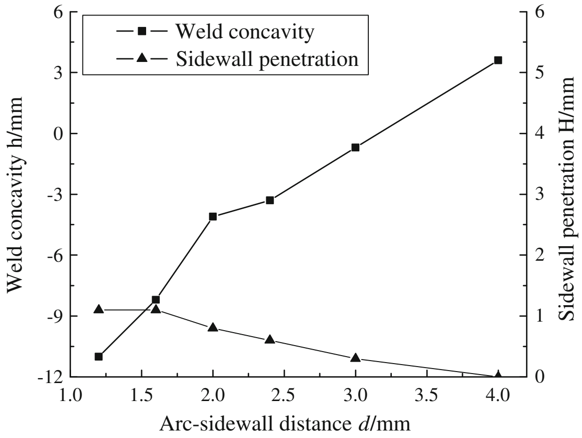



**Fig. 9** Weld cross section shape of arc-sidewall distance test: **a** d = 1.2 mm, **b** d = 1.6 mm, **c** d = 2.0 mm, **d** d = 2.4 mm, **e** d = 3.0 mm, **f** d = 4.0 mm

**Fig. 10** Curve of weld cross section shape coefficient




welding. Only when the arc-sidewall distance *d* = 2.0–3.0 mm, the weld could be of good sidewall fusion and slightly concave weld appearance.

The curve of shape coefficient of the weld cross sections is shown in Fig. 10. As shown in the figure, the concavity of weld was gradually reduced, and weld appearance finally transformed from slightly concave (d = 2.0–3.0 mm) to convex (d = 4.0 mm) with the increasing of arc-sidewall distance d. While the sidewall penetration kept decreasing with the increasing of arc-sidewall distance d. There was almost no sidewall penetration when the distance d = 4 mm. The laws are consistent with the above analysis of influence of arc-sidewall distance on arc appearance in NG-MAG welding. That is when the arc-sidewall distance d = 2.0–3.0 mm, continuous and uniform sidewall fusion can be got in NG-MAG welding under low heat input conditions.

## 4 Conclusion

1. The process of NG-MAG pulse welding has a high sensitivity to the welding process parameters under low heat input conditions.
2. The influence of arc-sidewall distance on arc appearance in NG-MAG vertical welding is significant. If arc-sidewall distance is small, arc will climb up along sidewall of the groove quickly to the surface. While the sidewall can not be heated sufficiently as the distance is large, which contributes to large probability of emerging defects.
3. With the increasing of arc-sidewall distance, the weld appearance gradually transforms from concave to slightly concave and convex finally. While the sidewall penetration always shows a tendency of decreasing until it is zero.
4. The welding process is stable and good sidewall fusion can be maintained when the arc-sidewall distance is in the range of 2.0–3.0 mm.

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