

Development of Swing Arc Narrow Gap Vertical Welding Process

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(Received on December 1, 2014; accepted on February 18, 2015)

The present work develops a hollow axis motor driven swing arc process for narrow gap vertical GMA welding, and investigates the characteristics of swing arc force, heat and weld formation. This process uses an upwardly bending conductive rod through the established mathematical models to weave circularly the arc, and then enables arc force to resolve into three favorable components while regulating arc energy distribution in groove, finally yielding satisfied vertical welds even with concave surface. Experimental results show that the penetrated depths into groove sidewall and bottom plate grew with increasing groove gap and decreasing rod bending angle, and molten pool sagging and bottom twin peaks were suppressed by great bending angle and respectively in wide and narrow grooves.

KEY WORDS: vertical welding; narrow gap welding; swing arc; weld formation; GMA welding.

1. Introduction

With the developments of modern equipments manufacturing industry, thick-sectional welding steel structures of high strength have been growingly used in shipbuilding, offshore engineering and pressure vessels manufacturing *etc.* Some of large-size parts have to be welded in vertical position as a result of difficult positioning, so vertical welding is paid more attention.

Traditional vertical welding processes cover the big groove arc welding, electrogas welding¹⁾ and electroslog welding,²⁾ which are either of low production efficiency owing to multilayer and multipass welding, or unsuitable for high strength steels because of great welding heat input. By comparison, narrow gap gas metal arc (GMA) vertical welding can be realized by single run at every layer, and will thus lead to higher welding efficiency at lower heat input. However, this GMA process usually employs a narrow groove of small angle to zero degree, which readily causes the sagging of molten pool subject to itself gravity, as well as the incomplete fusion of groove sidewalls due to insufficient heating of common arc.

To improve groove sidewalls penetration in narrow gap GMA welding, several single-wire approaches were presented, typically such as rotation arc,^{3,4)} snake wire⁵⁾ and oscillating arc⁶⁾ processes. Noticeably, a mechanically driven swing arc^{7,8)} of circular motion trajectory recently appeared as one of oscillating arcs, and has been rapidly reported in the applications of flat-position, horizontal and all-position narrow gap welding,^{9–11)} because of its good directivity and parameters controllability. With the purpose of further expanding this attracting arc, according to the swing arc vertical welding method¹²⁾ proposed by the

authors, the present work develops a hollow axis motor driven swing arc process for narrow gap vertical-up GMA welding. The characteristics of arc force, heat distribution and weld formation are then investigated in detail to understand deeply this process and to select properly such key process parameters as arc incidence angle and groove gap.

2. Swing Arc Vertical Welding System

2.1. Operating Principle

Swing arc narrow gap vertical GMA welding system is schematically shown in **Fig. 1**. A straightened electrode wire passes through the hollow axis of motor and the inner hole of bending conductive rod, and finally feeds out from ordinary contact tip. The motor of hollow axis directly turns the upwardly bending rod to oscillate circularly the arc around itself axis of torch at ~1 hertz frequency, and permits the arc to stay shortly at groove sidewalls for sufficient heating. Arc swing parameters include swing frequency, swing angle and at-sidewall staying time of arc, and can be adjusted for various groove gaps and welding runs. Furthermore, the torch moves at vertical-up speed of V_w to obtain greater sidewall penetration.

Consequently, this system enables the torch to be fabricated more compact and the swing angle to be controlled more precisely owing to using the hollow-axis motor, as well as the arc to be well directed under terminal guidance of the bending rod for wire. In addition, the conductive rod that bends to the upward direction of groove avoids the downward blow of arc, so as to restrain the sagging of molten pool. Finally, welding formation quality will be improved while reducing cost.

2.2. Selection of Bending Conductive Rod

The bending conductive rod is the most crucial part for the swing arc process, the bending angle of which directly

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DOI: <http://dx.doi.org/10.2355/isijinternational.55.1076>

determines the swing radius r and swing angle α of arc and thus affects the results of vertical-up weld formation. So, how to select properly this bending angle is considerably important.

Figure 2 gives a geometrical model of arc swing in groove, where h and β are the standoff height of torch and the bending angle of the rod, the inferior arc $M-O_1-D$ denotes the relative path of arc swing to the torch, and $OM=OD=r$. Assuming $AM=DB=g$, $AB=G$ and $O_2O=H$, which are respectively the minimum gap of arc axis from the sidewalls, groove gap and the distance of bending point O_2 to bottom plate, the range of bending angle can be mathematically derived below.

Since

$$r = H \cdot \tan \beta \quad (1)$$

So

$$\sin \frac{\alpha}{2} = \frac{(G-2g)}{2H \cdot \tan \beta} \quad (2)$$

Equation (2) shows that the minimum value $\beta_{\min}$ of bending

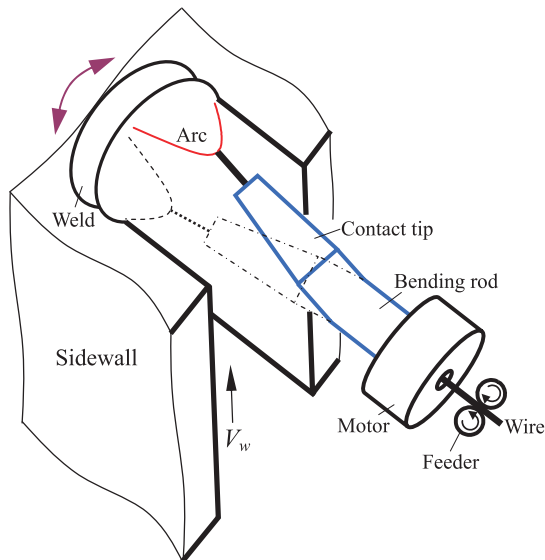


Fig. 1. Schematic diagram of swing arc narrow gap vertical welding system.

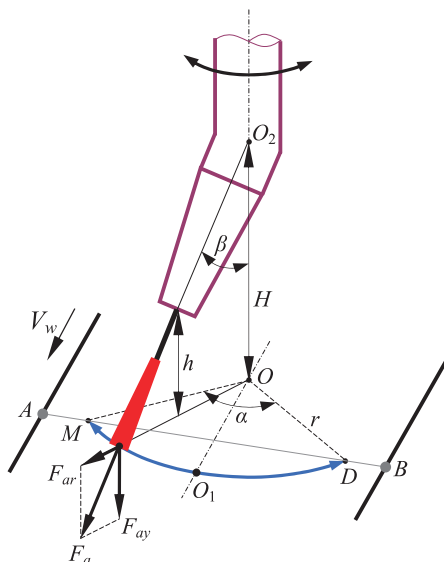


Fig. 2. Geometrical model of arc swing in groove.

angle will occur if $\alpha=180^\circ$, that is

$$\beta_{\min} = \beta \Big|_{\alpha=180} = \arctan \left[\frac{(G-2g)}{2H} \right] \quad (3)$$

To keep electrode wire in good directionality, on the other hand, the electrode wire is not allowed actually to extend without limitation. Therefore, the bending angle will not exceed its maximum value $\beta_{\max}$ that is determined by the maximum extension length $l_{\max}$ of wire before striking an arc, the relationship of which is derived from Fig. 2

$$\beta_{\max} = \arccos \left(\frac{h}{l_{\max}} \right) \quad (4)$$

Accordingly, the varying range of bending angle can be found from Eqs. (3) and (4). For example, let $G=12$ mm, $g=1$ mm, $H=60$ mm, $h=15$ mm and $l_{\max}=25$ mm, so $\beta_{\min}=4.76^\circ$ and $\beta_{\max}=53.13^\circ$. For such a range of bending angle, swing angle and swing radius are then calculated by Eqs. (1) and (2), as shown in **Fig. 3**. Obviously, swing angle falls sharply and then goes gentle with increasing the bending angle, while swing radius grows more uniformly. It suggests that the bending angle should be not too big, preferably $<20^\circ$. Otherwise, swing angle goes too small and thus affects whole effect of this swing process, in addition that too big bending angle increases the resistance to feeding wire and the difficulty of rod fabrication.

3. Arc Force and Heat Distribution

3.1. Arc Force Decomposition

Arc force together with arc heat dominates the vertical-up

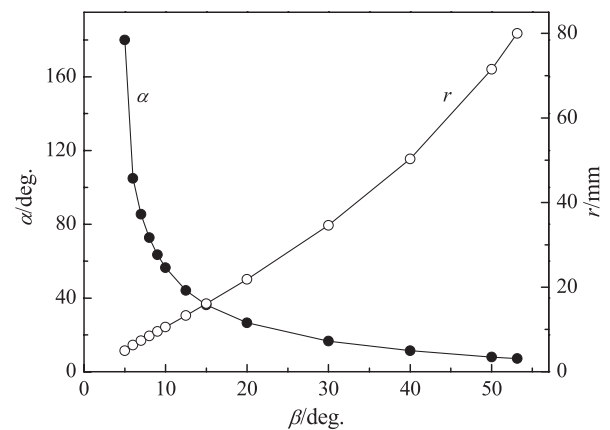


Fig. 3. Effect of bending angle on swing angle and swing radius.

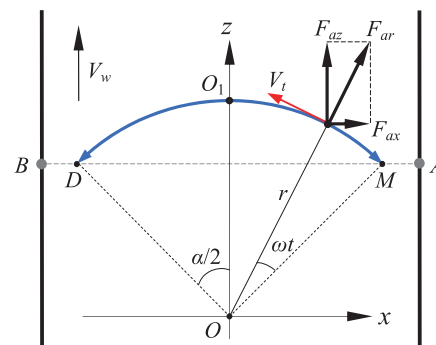


Fig. 4. Analysis of arc motion and arc force at vertical-up welding plane.

weld formation, and thus needs to be analyzed in detail. For the oscillating arc as shown in Fig. 2, its total pressure force F_a can be resolved into two components F_{ay} and F_{ar}

$$\begin{cases} F_{ay} = F_a \cos \beta \\ F_{ar} = F_a \sin \beta \end{cases} \dots\dots\dots (5)$$

where F_{ay} is perpendicular to the direction of vertical-up welding speed V_w , directing at the bottom of groove. Clearly, F_{ay} is always less than F_a subject to the existence of bending angle, which thus relieves arc pressure on bottom plate of groove and contributes to avoiding the occurrence of finger-like penetration in weld.

Actually in the x - z coordinate plane of vertical-up welding, F_{ar} can further be decomposed into the other two orthogonal vectors F_{ax} and F_{az} , the former of which always points toward groove sidewall, and the latter of which is in the direction of welding speed, as shown in Fig. 4. Suppose that ω is the mean angular velocity of arc swing from points M to D , and that swing midpoint O_1 of arc is located just in the central line O - O_1 of groove, so F_{ax} and F_{az} are

$$\begin{cases} F_{ax} = F_{ar} \sin\left(\frac{\alpha}{2} \cdot \frac{\pi}{180} - \omega t\right) \\ F_{az} = F_{ar} \cos\left(\frac{\alpha}{2} \cdot \frac{\pi}{180} - \omega t\right) \end{cases} \dots\dots\dots (6)$$

where α is swing angle in degree. Equation (6) shows that F_{ax} and F_{az} constantly vary during arc swing, and F_{az} is greater than zero (*i.e.*, being upward) if $\alpha < 180^\circ$ and thus can always play a positive role for suppressing the pool sagging.

In order to find out F_{ax} and F_{az} for given the swing frequency f and at-sidewall staying time t_s of arc, the mean angular velocity ω needs to be calculated first by formula (7)

$$\begin{cases} \omega = \frac{\alpha}{t_m} \cdot \frac{\pi}{180} \\ f = \frac{1}{2(t_m + t_s)} \end{cases} \dots\dots\dots (7)$$

where t_m is the spending time for one-way swing of arc between points M and D . Consequently, Fig. 5 gives a distribution of the two force vectors in groove, where $G=12$ mm, $g=1.0$ mm, $H=60$ mm, $f=0.8$ Hz, $t_s=0.4$ s and $\beta=6.57^\circ$. The abscissa d_{cx} represents arc position in groove, the nega-

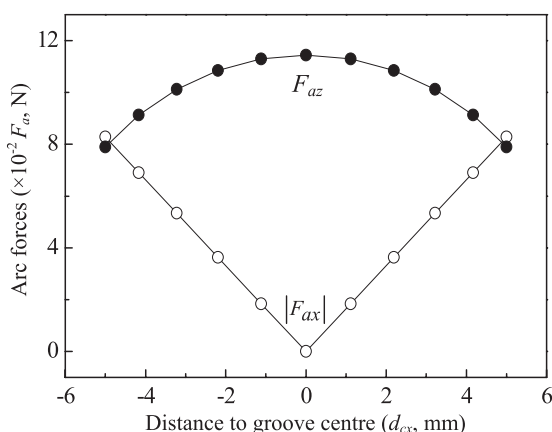


Fig. 5. Distribution of arc force in groove.

tive and positive values of which indicate the shortest distances of arc to groove center from the left and right sides, and is calculated by the below Eqs. (8) and (9), if assuming that d_{mx} and V_{tx} are the x -directional moving distance of arc from the point M and the x -directional vector of relative linear velocity V_t of arc to the torch

$$d_{cx} = \frac{1}{2}(G - 2g) - d_{mx} \dots\dots\dots (8)$$

$$\begin{aligned} d_{mx} &= \int_0^t V_{tx} \cdot dt \\ &= \int_0^t V_t \cos\left(\frac{\alpha}{2} \cdot \frac{\pi}{180} - \omega t\right) \cdot dt \\ &= r \left[\sin \frac{\alpha}{2} - \sin\left(\frac{\alpha}{2} \cdot \frac{\pi}{180} - \omega t\right) \right] \dots\dots\dots (9) \end{aligned}$$

Finally, F_{ax} and F_{az} together surround an interesting fanlike area, and the absolute value of F_{ax} increases almost linearly from groove center to any sidewall. Particularly, the maximum value F_{x1} of F_{ax} appears as the arc pauses respectively at the close points M and D to two sidewalls, which means that toward-sidewall arc force is always larger at the staying phase of arc than in the scanning course of arc, thus effectively promoting to form sidewall penetration. Accordingly, the general formula of F_{x1} can be written as

$$\begin{aligned} F_{x1} &= F_{ax} \Big|_{t=0} \\ &= F_a \sin \beta \cdot \sin \frac{\alpha}{2} \dots\dots\dots (10) \end{aligned}$$

Furthermore, the greater average value and slower changing rate of F_{az} than those of F_{ax} imply that arc force in the weaving course contributes more remarkably to weld surface formation than to groove sidewall penetration. Especially as the arc swings to the central point O_1 of groove, although the molten pool most easily sags, F_{az} exactly reaches its maximum value, which not only indicates a maximum upward relief of arc plasma stream, but also just provides a maximum support for partial liquid metal in the front of molten pool, thus helping the molten pool to keep in steady state.

It follows that the usage of bending conductive rod causes arc force to resolve into three components in favorable distributions, which respectively benefit to improve the surface convexity, sidewall penetration and bottom formation of vertical-up weld.

3.2. Mean Arc Force

To evaluate conveniently the overall effects of the constantly changing F_{ax} and F_{az} on groove sidewall penetration and weld surface formation for various process conditions, the mean values F_{x2} and F_z of the two vectors are below introduced and defined as

$$\begin{cases} F_{x2} = \frac{J_x}{t_m} \\ F_z = \frac{J_z}{t_m} \end{cases} \dots\dots\dots (11)$$

where J_x and J_z are respectively the impulses of toward-sidewall and upward arc forces F_{ax} and F_{az} , and derived as

$$\begin{aligned}
 J_x &= 2 \int_0^{\frac{\alpha}{2\omega} \cdot \frac{\pi}{180}} F_{ax} \cdot dt \\
 &= 2 \int_0^{\frac{\alpha}{2\omega} \cdot \frac{\pi}{180}} F_a \sin \beta \cdot \sin \left(\frac{\alpha}{2} \cdot \frac{\pi}{180} - \omega t \right) dt \\
 &= \frac{2F_a \sin \beta}{\omega} \cdot \left(1 - \cos \frac{\alpha}{2} \right) \quad \dots\dots (12)
 \end{aligned}$$

$$\begin{aligned}
 J_z &= 2 \int_0^{\frac{\alpha}{2\omega} \cdot \frac{\pi}{180}} F_{az} \cdot dt \\
 &= 2 \int_0^{\frac{\alpha}{2\omega} \cdot \frac{\pi}{180}} F_a \sin \beta \cdot \cos \left(\frac{\alpha}{2} \cdot \frac{\pi}{180} - \omega t \right) dt \\
 &= \frac{2F_a \sin \beta}{\omega} \cdot \sin \frac{\alpha}{2} \quad \dots\dots (13)
 \end{aligned}$$

Take ω expression in Eq. (7) into Eqs. (12) and (13), and then according to Eq. (11)

$$\begin{cases} F_{x2} = \frac{2F_a \sin \beta}{\alpha} \cdot \frac{180}{\pi} \cdot \left(1 - \cos \frac{\alpha}{2} \right) \\ F_z = \frac{2F_a \sin \beta}{\alpha} \cdot \frac{180}{\pi} \cdot \sin \frac{\alpha}{2} \end{cases} \quad \dots\dots\dots (14)$$

Clearly, the mean arc forces are governed by swing angle and bending angle. To clarify the changing laws of F_{x1} , F_{x2} and F_z , numerical calculations were performed by Eqs. (2), (10) and (14), for common examples of varying one of groove gap and bending angle.

Figure 6 shows the effect of swing angle on mean arc

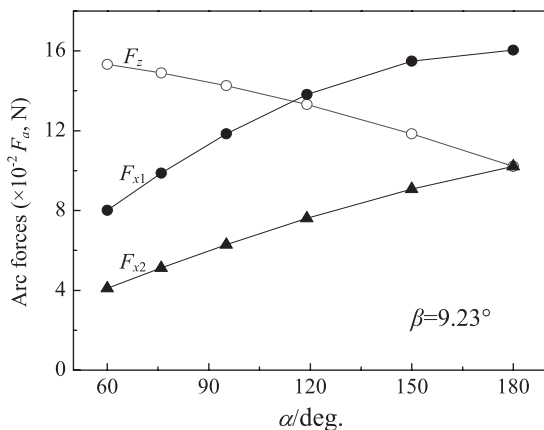


Fig. 6. Effect of swing angle on mean arc forces.

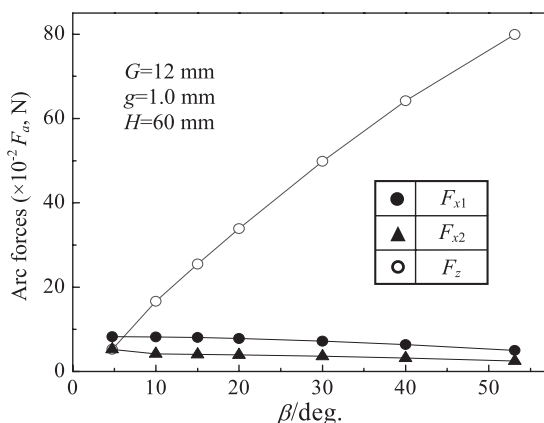


Fig. 7. Effect of bending angle on mean arc forces.

forces, where a variation of swing angle results from varying groove gap at $\beta=9.23^\circ$. As swing angle expands from 60 to 180°, which corresponds to the increase of groove gap from 10.13 to 18.25 mm according to Eq. (2) if $H=50$ mm and $g=1.0$ mm, F_{x1} and F_{x2} rise while F_z drops. The effect of bending angle on mean arc forces is given in **Fig. 7**, where $G=12$ mm, $g=1.0$ mm and $H=60$ mm. When the bending angle increases in the range determined by Eqs. (3) and (4), in which swing angle accordingly decreases subject to Eq. (2), F_{x1} and F_{x2} fall while F_z significantly grows. The calculated results suggest that increasing groove gap and decreasing the bending angle will cause sidewall penetration to increase, and the upward releasing and supporting effects of arc force are more effectively enhanced by increasing the bending angle than by narrowing groove gap.

3.3. Arc Heat Distribution

Arc heat distribution is adjusted while the arc weaves in groove, and can actually be characterized by the ratio λ of two instantaneous linear heat inputs of arc into base material

$$\lambda = \frac{q_s}{q_c} \quad \dots\dots\dots (15)$$

where q_s and q_c are the linear heat inputs of arc at staying phase and in groove center. Suppose that P_{arc} denotes total arc power that is determined by arc current and arc voltage, q_s and q_c are then expressed as

$$q_s = \frac{P_{arc}}{V_w} \quad \dots\dots\dots (16)$$

$$q_c = \frac{P_{arc}}{\sqrt{V_w^2 + V_t^2}} \quad \dots\dots\dots (17)$$

So

$$\lambda = \sqrt{1 + \left(\frac{\omega r}{V_w} \right)^2} \quad \dots\dots\dots (18)$$

which indicates that the influencing factors on angular velocity and swing radius will finally affect the ratio λ . By solving simultaneously Eq. (18) with Eqs. (1), (2) and (7), arc energy ratio can be found for various welding applications.

Figure 8 shows the effect of groove gap on arc energy ratio for bending angles of 7.96 and 9.23°, where $f=0.8$ Hz, $t_s=0.4$ s, $H=50$ mm, $g=1.0$ mm and $V_w=1.3$ mm s⁻¹. When groove gap increases from 12 to 16 mm, swing angle and thus angular velocity grow respectively according to Eqs. (2) and (7), and finally arc energy ratio rises from >36 to >57, even more quickly up to >75 for the smaller angle that corresponds to the minimum bending angle at $G=16$ mm.

Figure 9 shows the effect of bending angle on arc energy ratio for groove gaps of 12 and 14 mm, where $f=0.8$ Hz, $t_s=0.4$ s, $H=60$ mm, $g=1.0$ mm, $\beta=6\sim10.01^\circ$ and $V_w=1.52$ mm s⁻¹. With increasing the bending angle, swing angle decreases subject to an increase in swing radius by Eqs. (1) and (2). As a result, arc energy ratio slightly gets small due to a rapider rate in the decrease of angular velocity than in the increase of swing radius, more obviously for the wider groove.

It can be seen that arc energy ratio is always greater than

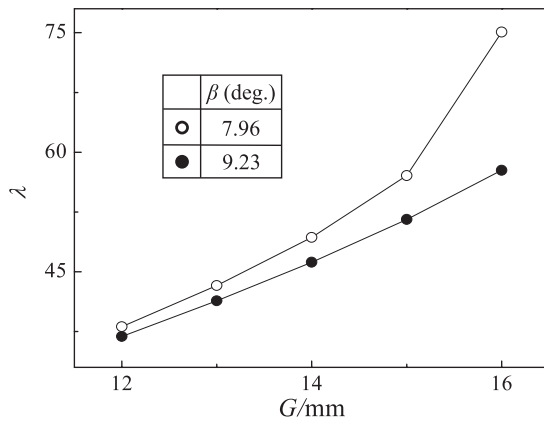


Fig. 8. Effect of groove gap on arc energy ratio.

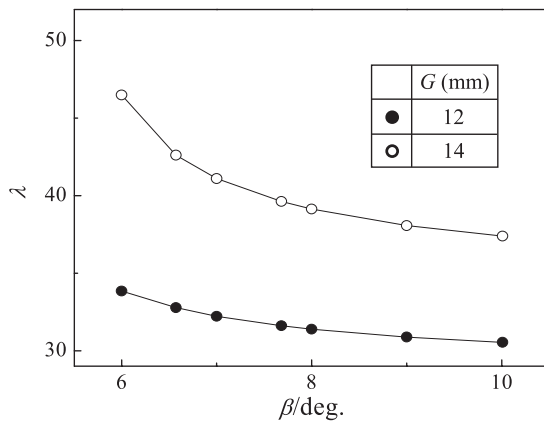


Fig. 9. Effect of bending angle on arc energy ratio.

one owing to angular velocity of arc swing, and reaches a considerably large value for common welding conditions. That is to say, the oscillating arc can put most of its energy into sidewalls and their neighboring area. Such a distribution of arc heat will finally generate as great sidewall penetration as expected, except for causing a twin-peak penetration into bottom plate.

4. Vertical-up Weld Formation

4.1. Experimental Conditions

To demonstrate the effectiveness of the developed process and to prove the validity of the above analyses, a number of narrow gap vertical-up pulsed welding experiments were carried out with solid electrode wire of 1.2 mm diameter and Ar-20%CO₂ shielding gas of 20 L min⁻¹ flowrate. Welding parameters also included: 154 and 166 A for average arc current (I_a) respectively at the current pulse duty circles of 23.9% and 26.4% with the peak current of 516 A, 20.3 and 21 V for average arc voltage (V_a) at the pulse frequency of 130 Hz, 18 mm for torch standoff height, and 1.3 and 1.52 mm s⁻¹ for welding speed; 0.8 Hz for swing frequency, 0.4 s for at-sidewall staying time, and 6.57–10.01° for the bending angle.

Moreover, a testpiece of square groove was tacked directly from three high strength steel plates of 18 mm thickness, and had a gap of 12–16 mm width. After welding, an observed section was obtained in the middle of 150 mm long weld. Weld sectional shape are then character-

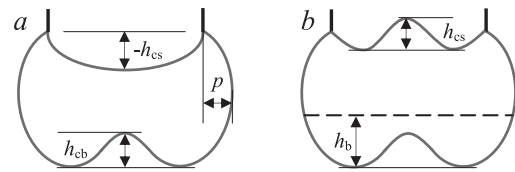


Fig. 10. Illustration of weld shape parameters. (a) Concave weld; (b) Convex weld.

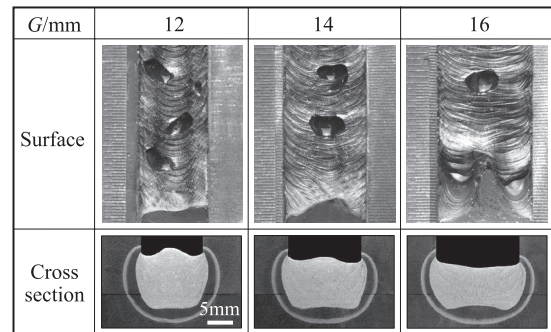


Fig. 11. Weld macrophotograph for various groove gaps.

ized by such formation parameters as sidewall penetration (p), surface curvature (h_{cs}), bottom concavity (h_{cb}) and penetration into bottom plate (h_b), as illustrated in Fig. 10, where surface curvature represents convexity and concavity respectively for convex and concave welds.

4.2. Effect of Groove Gap

Figure 11 gives the surface and sectional macrophotographs of weld for various groove gaps, where $H=50$ mm, $I_a=166$ A, $V_a=21$ V, $V_w=1.3$ mm s⁻¹ and $\beta=9.23^\circ$. With increasing groove gap, arc energy ratio rises (see Fig. 8) as swing angle expands from 76 to 119°. Correspondingly, the linear heat input q_c of arc into central groove obviously decreases while the linear heat input q_s of arc at the staying phase keeps constant. This directly led to the occurrence of twin peaks in the bottom of bead due to a decrease in the penetration into the center of bottom plate, particularly clear at $G=16$ mm. Simultaneously, surface tension of molten metal is increased in central region of groove, which caused the sagging of molten pool to be suppressed in spite of a decrease in upward mean arc force F_z (see Fig. 6), and thus weld surface to transform from convex to concave shapes. At the initial stage of welding, moreover, the molten metal difficultly attached to central region of groove subject to cooler work and lack of enough support from solidified weld, but a fillet welding pool could freely hold due to greater surface tension between the molten metal and the pool wall as the arc deflected to heat groove sidewall. Transitional fillet welds became obviously long with the above reductions of q_c and F_z for wide grooves.

Figure 12 shows the effect of groove gap on weld shape parameters. Here, sidewall penetration p is the average value of the penetrated depths into left and right sidewalls, and positive surface curvature h_{cs} , bottom concavity h_{cb} and bottom penetration h_b are also their corresponding averages to two valleys or peaks. When groove gap becomes wide, toward-sidewall mean arc forces F_{x1} and F_{x2} grow (see Fig.

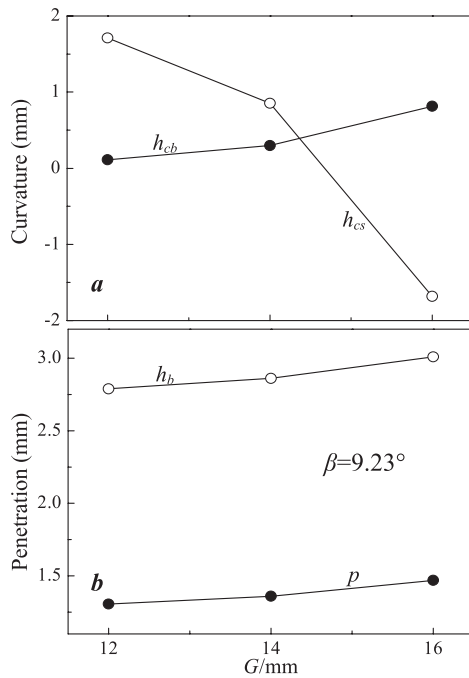


Fig. 12. Effect of groove gap on weld shape parameters. (a) Surface curvature h_{cs} and bottom concavity h_{cb} ; (b) Sidewall penetration p and bottom penetration h_b .

6), thus increasing sidewall penetration. At the same time, weld section became thin, which permitted the arc to submerge further into bottom plate once it swung to stay at any sidewall, and finally the penetration into bottom plate goes slightly great. Under the dual actions of arc energy distribution and arc submerging factors, furthermore, a great concavity exhibited in the bottom of weld for wide groove. It is also shown that surface curvature varies from positive to negative values accordingly for convex and concave welds.

The above experimental results interpret that widening appropriately groove gap is beneficial to increase sidewall penetration while preventing the pool sagging. It also implies that the amount of weld deposited metal must not only be controlled in real time to obtain a constant height of bead for a groove of varying gap, but also arc energy ratio should be adaptively reduced by lowering arc swing frequency to weaken the twin peaks for wide cross section of the groove.

4.3. Effect of Bending Angle

Figure 13 shows macro photographs of weld cross section for various bending angles and groove gaps, where $H=60$ mm, $I_a=154$ A, $V_a=20.3$ V and $V_w=1.52$ mm s⁻¹. When the bending angle increases from 6.57 to 10.01°, arc energy ratio drops from 33.8 to 30.5 at $G=12$ mm (see Fig. 9), which means that the molten pool easily sags owing to great linear heat input q_c of arc into the central groove. On the other hand, an increase of bending angle causes the upward mean arc force F_z to rise obviously (see Fig. 7), which practically helps to restrain the sagging of molten pool. Finally due to greater positive effect of F_z than the negative influence of q_c , the sagging tendency of molten pool was controlled by large bending angle, and correspondingly weld surface changed from convex to concave shapes for 12 mm gap.

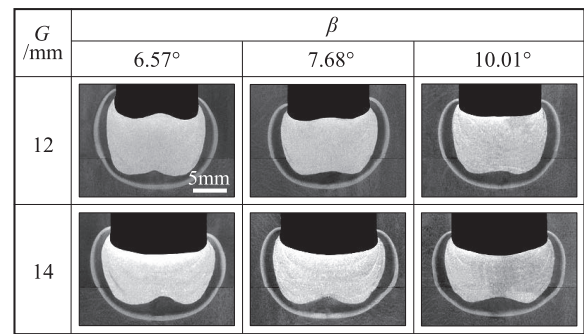


Fig. 13. Weld sectional macrophotograph for various bending angles.

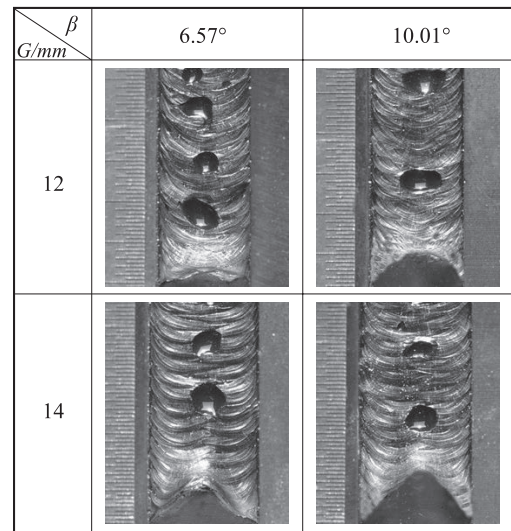


Fig. 14. Weld surface macrophotograph for various bending angles.

Figure 14 accordingly gives several macrophotograph examples for weld surface. Transitional fillet welds occurred at any bending angle, and were especially obvious for the wider groove. For great bending angle, the downward arc force component F_{ay} decreases according to Eq. (5), which is unbeneficial to the formation of molten pool in the central region of groove, thus lengthening fillet welds. Furthermore, this fact, together with the overlapping ripples that exhibit clearly on the weld surfaces at $G=14$ mm, demonstrates the existence of alternate solidification phenomena in twin molten pools.

To demonstrate distinctly the effect of bending angle on weld formation, **Fig. 15** indicates weld shape parameters. With increasing the bending angle, swing angle narrows, for example from 92.7 to 56.3° at $G=12$ mm, and thus toward-sidewall mean arc forces F_{x1} and F_{x2} go low (see Fig. 7), which reduces sidewall penetration. Simultaneously, surface curvature drops with a decrease in the sagging degree of molten pool, while the penetration h_b into bottom plate decreases slightly by ~ 0.1 mm (see Fig. 13) due to a minor decline of downward arc force component F_{ay} . This reduction of h_b , together with the increase in the penetration into the center of bottom plate that arises from a rise of q_c , finally causes bottom concavity to fall. These results demonstrate the similar influencing laws of groove gap to those as shown in Fig. 12, but also suggest that the bend-

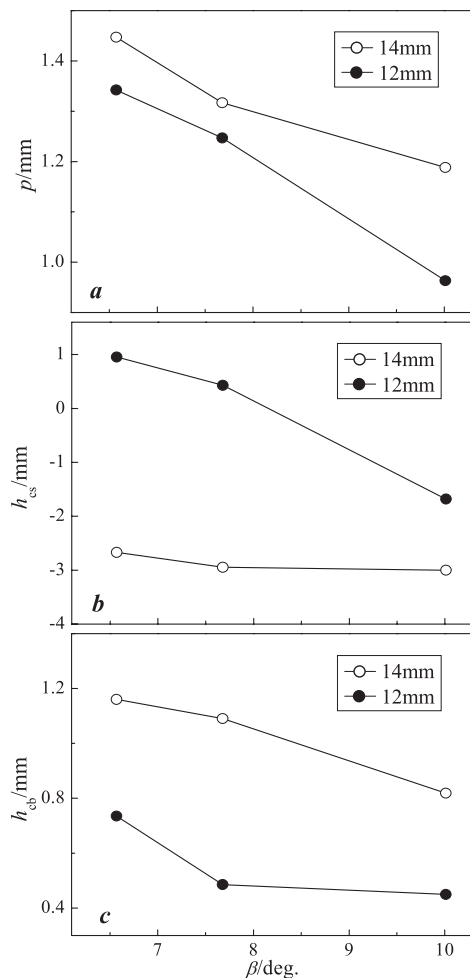


Fig. 15. Effect of bending angle on weld shape parameters. (a) Sidewall penetration; (b) Surface curvature; (c) Bottom concavity.

ing angle should be moderately selected to yield a weld of acceptable sidewall penetration and small twin peaks while not collapsing the molten pool.

5. Conclusions

(1) A hollow axis motor driven swing arc process has been developed for narrow gap vertical-up GMA welding. This process uses an upwardly bending conductive rod through the established mathematical models to weave circularly the arc, and then enables swing arc force to resolve into three favorable components while regulating effectively arc heat distribution in groove, finally yielding satisfied welds even with concave surface.

(2) Arc force vectors are overall assessed by mean arc forces that are derived from arc force impulses, while

arc energy distribution is characterized by the ratio of arc linear heat input at staying phase to that in groove center. The arc energy ratio rises with an increase in groove gap (swing angle) and a decrease in the bending angle, and accordingly the linear heat input of arc into central region of groove falls.

(3) With increasing groove gap and decreasing the bending angle, toward-sidewall mean arc forces grow as swing angle expands, and finally sidewall penetration increases. Simultaneously, the arc submerges further into wide groove while small bending angle strengthens the downward arc force, thus increasing the penetration into bottom plate.

(4) Upward arc force and arc energy ratio affect the sagging degree of molten pool, while twin peaks in the bottom of bead depend essentially on this ratio. Wide groove and great bending angle can suppress the pool sagging respectively under leading actions of this ratio and upward arc force, while narrow groove and large bending angle weaken twin peaks owing to low arc energy ratio, thus improving surface and bottom formations of weld.

(5) Fillet welding phenomena exhibit generally at initial stage of vertical-up weld free formation, and the transitional fillet welds become long obviously with increasing groove gap and bending angle. Furthermore, this fact along with weld overlapping ripples demonstrates the existence of alternate solidification in twin molten pools.

Acknowledgements

The present work is financially supported by the National Natural Science Foundation of China (Grant No. 51475218), and the Specialized Research Fund for the Doctoral Program of Higher Education (Grant No. 20133220110001).

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