A Swing Arc System for Narrow Gap GMA Welding

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(Received on August 23, 2011; accepted on September 8, 2011)

A novel swing arc system was developed to realize high quality narrow gap GMA welding at low cost. This system uses a motor of hollow axis to turn directly the micro-bent conductive rod and then to weave circularly the arc around itself axis of torch, and can automatically search for the midpoint of symmetrical swing trail and detect precisely swing frequency in real time. Three mathematical models are also presented to calculate precisely key swing variables from torch structure and process parameters. Experimental results show that weld surface curvature and the penetration into groove sidewalls increase and weld sectional thickness decreases with increasing swing frequency and at-sidewall staying time of arc, while bottom shape of bead varies from single to twin peaks. This swing arc process thus improved obviously narrow gap weld formation.

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

1. Introduction

Large-scale and thick-wall welding structures have been increasingly applied in modern equipments manufacturing industry, particularly many of which must be site-welded. Some welding problems thus need to be solved for the structure plates of heavy thickness, such as narrow gap welding (NGW), horizontal welding and vertical welding.

Narrow gap gas-metal-arc (GMA) welding is a high efficiency and high quality arc welding process, primarily applied for welding thick steel plates with single pass technique of which is more attracting but more difficult. How to ensure enough penetration into NGW groove sidewalls is its key point. So, several single-wire approaches were proposed, typically such as rotation arc, wave (or snake) wire, ultra-narrow gap processes, of which the former two being successfully used in practical flat-position welding.

The traditional rotation arc system employs a motor to drive indirectly or directly a conductive rod, and then to rotate conically the arc via offset contact tip. This torch could yield good narrow gap weld, but service life of its contact tip was low due to the big wear from high speed relative motion between the specially made tip and electrode wire. Another rotating arc process using the eccentric sleeve attempted to weld horizontally narrow gap groove, but not gaining optimal weld formation at bottom sidewall of groove. The wave wire process wave (or snake) wire, ultra-narrow gap processes, of which the former two being successfully used in practical flat-position welding.

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The principle and application characteristics of the swing arc system are discussed to understand deeply the swing process of arc and to select properly swing parameters, and a number of welding experiments were then carried out to demonstrate the effectiveness of the developed process.

2. Swing Arc Welding System

The schematic diagram of swing arc narrow gap welding (SA-NGW) system is shown in Fig. 1. Motor axis and micro-bent conductive rod are respectively connected to a ring flange of copper, and an ordinary contact tip is screwed into the conductive rod. The positive and negative terminals of welding power source are respectively connected to carbon brush and groove sidewalls. The carbon brush is pressed on the ring flange surface to supply power for the arc without cable wrapping. An electrode wire is fed to pass through the hollow axis of motor, the inner hole of the micro-bent rod and ordinary contact tip. The principle and application characteristics of the swing arc system are discussed to understand deeply the swing process of arc and to select properly swing parameters, and a number of welding experiments were then carried out to demonstrate the effectiveness of the developed process.
the contact tip, and then to drive the arc on the end of wire to weave circularly. This system controls the arc to swing around itself axis of torch commonly at several hertz frequencies and utilizes only ordinary contact tip, thus compacting torch while reducing obviously operation cost due to simple fabrication and small wear of the tip.

A grating disc matches an optocoupler to constitute a photoswitch for the detection of wire swing position and arc swing frequency. To determine precisely the swing angles of arc at two sides around the central line of groove, the motor is drove to direct the transparent hole of grating disc against the optocoupler before welding, in which the conductive rod just bends to the due front of groove centre along welding direction, thus realizing the automatic search for the midpoint \( O_1 \) of wire symmetrical swing trail. In welding, the arc starts to swing always from the initial point \( O_1 \), while advancing at welding speed of \( V_w \). The combination of the micro-bent conductive rod to the above positioning control ensures regular swing of wire, good directivity of arc and thus high quality of welding.

By controlling the turning angle and direction of the motor, moreover, several weaving modes are conveniently available, such as the bilaterally symmetrical and asymmetrical swings respectively for the major or inferior arc trajectory. For each swing mode, the swing frequency, swing amplitude and at-sidewall staying time of arc are also adjustable. The appropriate selection of arc swing mode and swing parameters can meet the various demands for multi-position welding applications, so the stronger adaptability exhibits for this system.

3. Arc Motion Trajectory and Swing Parameters

3.1. Motion Trajectory

Figure 2 gives an explanation of arc motion trajectory for one whole period of swing, where the vertical projection point \( O \) of torch axis and the midpoint \( O_1 \) of arc symmetrical trail are just on the central line of groove. The electric arc swings along the inferior arc \( d-O_1-m \) with relative angle of \( \alpha \) to the torch meanwhile linearly moving at welding speed of \( V_w \), and stops weaving shortly at the points \( d \) and \( m \) to heat sufficiently groove sidewalls, as shown in Fig. 2(a). The points \( d \) and \( m \) can be described by two sets of points, that is, \( d=\{d_1, d_2\} \) and \( m=\{m_1, m_2\} \), where \( d_1 \) and \( d_2 \), and \( m_1 \) and \( m_2 \) are the start and end points of no weaving respectively in the left and right sides of groove. If relative to the work, therefore, the electric arc actually moves along the path of \( d_2-m_1-m_2-d_1-d_2 \) in Fig. 2(b) due to the existence of welding speed \( V_w \). Here, the straight line segments \( m_1-m_2 \) and \( d_1-d_2 \) indicate the pausing stages of arc swing, and the points of \( O_1 \) and \( O_1' \), and \( d_2 \) and \( d_2' \) are respectively the rear and front points of swing midpoint \( O_1 \) and at-left-sidewall staying endpoint \( d_2 \).

Owing to the swing of electric arc at a certain frequency, there must be a heating interval \( \eta \) between groove sidewalls, as shown in Fig. 2(b). If \( \eta \) were zero, in other words, there would be no swing of arc. So \( \eta \) is an important variable of this swing process. The smaller the value of \( \eta \) is, the more symmetrical the arc heating is at two sides of groove centre. The interval \( \eta \) is determined by welding speed \( V_w \) and swing frequency \( f \), and can be calculated from the below formula:

\[
\eta = \frac{1}{2} \left( \frac{V_w}{f} - 1 \right) = \frac{V_w}{2f} \quad \text{.................. (1)}
\]

which shows that the value of \( \eta \) is in direct and inverse proportions respectively to welding speed and swing frequency.

3.2. Swing Parameters

Swing parameters include the swing frequency, swing amplitude and at-sidewall staying time of arc. It can be seen from Eq. (1) that the lower the swing frequency is, the greater the heating interval is. Thus, swing frequency should be selected beyond a certain value to improve the symmetry of
arc heating as possible. To seek such an appropriate frequency of arc swing respectively for vertical-up and flat-position narrow gap welding processes, for example, Fig. 3 accordingly draws the curves of relationship between swing frequency and sidewalls heating interval at welding speeds of 1.5 and 4.0 mm s\(^{-1}\). Clearly, \(\eta\) varies considerably slowly and simultaneously becomes acceptably small beyond 1.0 and 2.0 Hz respectively at the two welding speeds. That is to say, the two frequencies may be regarded as the proper values of swing frequency for the two welding processes, because too large frequencies will not reduce rapidly the value of \(\eta\) but will increase dramatically the difficulty and cost of swing control. If the other speed of welding is used, an optimum value of swing frequency will be determined similarly from Eq. (1).

Swing amplitude of electric arc is another key parameter for this process, and is covered by swing radius \(r\) and swing angle \(\alpha\). Figure 4 gives a physical model to calculate \(r\) and \(\alpha\), where \(h\) and \(\beta\) are the standoff height of torch and the bent angle of conductive rod, the arc \(M-O_1-D\) denotes the relative path of arc scanning to the torch, and \(OM=OD=r\). Supposing \(O_1E=a, EF=b,\) and \(AM=DB=g\), which respectively represent the bent length of conductive rod, the length of contact tip, and the reserved minimum gap of arc axis from the sidewalls, the expressions of \(r\) and \(\alpha\) can be derived below:

\[
\begin{align*}
    r &= (a+b)\sin\beta + h\tan\beta \quad \text{................... (2)} \\
    \sin\frac{\alpha}{2} &= \frac{1}{2r}(G-2g) \quad \text{................... (3)}
\end{align*}
\]

where \(G\) is groove gap, and \(g\) is generally set as \(-2.0\) mm to avoid effectively shunting arc between groove sidewall and electrode wire. It can be seen that swing radius \(r\) depends on the structure and position of torch, while swing angle \(\alpha\) can be calculated according to \(G\) and \(g\) for given torch. For example, let \((a+b)=31\) mm, \(g=2.17\) mm, \(\beta=8^\circ\) and \(G=12\) mm, so \(r\) and \(\alpha\) equal respectively 6.84 mm and 68° at \(h=18\) mm. Conversely, the minimum gap of groove will be found for given angle of \(\alpha\).

The frequency, radius, angle and staying time of arc swing are practically correlated. According to the above equations and analysis, greater radius of swing \(r\) accepts smaller angle of swing, and finally such a shorter path of swing permits greater frequency of swing for given groove gap. Surely, if the staying time simply increases, the limiting frequency of swing will go to low subject to this time and the dynamic quality of motor. Figure 5 gives a few of related examples, where the maximum frequency \(f_{\text{max}}\) of swing was measured without arcing. As torch standoff height obviously extended from 18 to 25 mm, swing angle was calculated to decrease only from 68° to 59° for the normal welding of 12 mm gap groove, accordingly causing a very slight rise of \(f_{\text{max}}\), where it is thus considered that the effect of \(h\) is negligible at common standoff heights of torch. With increasing simply swing angle and staying time, on the other hand, the limiting frequency of swing becomes small. However, \(f_{\text{max}}\) still exceeded 2.0 Hz even though the arc swung with a pause of 160 ms at each sidewall of groove, which is enough to ensure satisfactory formation of weld.

4. Swing Arc Weld Formation

4.1. Experimental Conditions

In order to demonstrate the effectiveness of the developed system, a number of pulsed welding experiments were carried out at flat position. The welding parameters were: 200 Hz for pulse frequency of arc current, 50% for current pulse duty circle, peak currents of 445 and 485 A respectively for average arc currents of 280 and 300 A, 28 V for average arc voltage, 3.38 mm s\(^{-1}\) for welding speed; 18 mm for torch standoff height, 40 L min\(^{-1}\) for the flowrate of Ar-
20%CO₂ shielding gas, φ 1.2 mm for the diameter of solid wire; 0–3.5 Hz for swing frequency, 6.84 mm for swing radius, 68° for swing angle, 40–100 ms for at-each-sidewall staying time ₜₛ of arc.

Moreover, a testpiece was tacked directly from three mild steel plates of 16 mm thickness, and welding groove had a root gap of 12 mm and an angle of 2°. After welding, an observed section was obtained in the middle of 200 mm long weld to evaluate bead formation.

### 4.2. Effects of Swing Frequency and Arc Current

Figure 6 shows the effect of arc swing frequency on narrow gap weld formation, where ₜₛ=100 ms and average arc current was 280 A. For the non-swing process (i.e., ₟=0 Hz in Fig. 6(a)), the penetration into bottom plate appears to be fingerlike due to the concentration of arc heat and force on the centre of groove.4) In swing arc welding, the arc alternatively deflects to heat directly the left and right sidewalls of groove, and simultaneously the convective heat within molten pool speedups subject to arc stirring. Hence, more heat of arc is transferred towards the sidewalls, which causes the penetration into groove sidewalls to increase obviously. On the other hand, the ratio of staying time to swing period rises with increasing swing frequency, which changes the distribution of arc heat and force across groove gap, and accordingly the bottom shape of bead varies from single to twin peaks while the weld section becomes thin. In addition, note that the asymmetry of bead shape occurs clearly at swing frequency of 0.5 Hz, as shown in Fig. 6(b), because of a greater heating interval between the sidewalls.

Based on the above phenomena of weld formation, a model of bead shape is given in Fig. 6(f), where ₚₑ, ₚₑ, ₜₑ, and ₛₑ refer respectively to the penetrated depths of left and right sidewalls, and the surface curvature and sectional thickness of bead. Figure 7 shows the effect of swing frequency and average arc current on these shape parameters. Here, 阽 is average value of ₚₑ and ₚₑ, and ₜₑ and ₛₑ refer respectively to the average curvature and the average thickness as two peaks of bead bottom and two weld toes of sidewalls are asymmetrical. Obviously, the average penetrated depth of sidewalls grows to the maximum value at 2.5 Hz, and the surface curvature of weld simply increases while sectional thickness of bead decreases with increasing swing frequency. Such smaller thickness and greater curvature actually help to prevent weld porosity and interlayer slag inclusion. When average arc current was raised to 300 A, the peak current of arc accordingly rose to 485 A, in which the deposited metal increases and simultaneously the penetrating capability of arc is strengthened due to the greater stiffness and force of arc. As a result, the penetrated depth of sidewalls and the sectional thickness of bead increase, while the surface curvature of weld becomes small.

### 4.3. Effect of At-sidewall Staying Time

Figure 8 shows the effect of staying time on weld formation, where swing frequency was 2.5 Hz and average arc current was 280 A. At the staying time of 40 ms, bead shape is a little similar to that in the high speed rotation arc NGW process.3,4) With an increase in the staying time of arc at each sidewall, more heat of arc directly transfers to sidewalls and the close regions of groove bottom to the sidewalls, and consequently the penetration into sidewalls increases while the bottom shape of bead gradually appears to be twin peaks. From the quantitative relationship between staying time and weld shape parameters, as shown in Fig. 9, it can be seen also that greater curvature of weld surface...
and thinner section of bead occur at longer staying time, while the influencing law of arc current on bead shape is similar to that in Fig. 7.

The above results demonstrate that the low frequency swing of arc with an at-sidewall short pause can improve remarkably weld formation. However, an excessively great frequency of swing was not good for the growth of sidewall penetration, for example in Fig. 7(a), and an overlong staying time of arc at each sidewall practically limited to raise the swing frequency.

5. Conclusions

(1) A swing arc narrow gap welding system has been developed. This system employs a hollow axis motor to turn directly micro-bent conductive rod and ordinary contact tip and then to weave circularly the arc around itself axis of torch at several hertz frequencies, and can freely regulate swing parameters and swing mode for different applications, thus having compact torch, good controllability and low use cost.

(2) The heating interval is presented to evaluate the symmetry of arc heating at two sides of groove centre, and guides to select properly swing frequency at different welding speeds. In addition, two mathematical models are derived to calculate precisely swing radius and swing angle. It is shown that greater swing radius matches smaller swing angle, and thus permits higher swing frequency for given groove gap.

(3) The maximum frequency of swing is determined by swing angle and at-sidewall staying time of arc, actually exceeded 2.0 Hz even at staying time of 160 ms and swing angle of 180°, and is enough to ensure satisfactory formation of bead at multi-position welding. As torch standoff height varied within a commonly used range, moreover, the limiting frequency was scarcely affected due to a very small change of swing angle.

(4) With increasing swing frequency and staying time, the penetrated depth of groove sidewalls and the surface curvature of weld increase while the sectional thickness of bead decreases, and simultaneously the bottom shape of bead varies from single to twin peaks. Furthermore, the better symmetry of bead shape exhibits at higher swing frequencies. This swing arc process thus improved obviously weld formation.

Acknowledgements

This study is sponsored by the Jiangsu Provincial Key Industrial Technology Support Program (Grant No. BE2011148), the Jiangsu Six Great Talent Peak Project, and the Research Achievements Industrialization Promotion Project (Grant No. JHB06-24), the Qing Lan Project and the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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