PARAMETER ANALYSIS AND OPTIMIZATION OF THE ROTATING ARC NG-GMAW WELDING PROCESS

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Abstract

Parameters of the narrow gap gas metal arc welding (NG-GMAW) method are complex and strongly coupled, which can easily cause welding defects, such as poor sidewall fusion, overlap, gas pore and slag inclusion. So parameter optimization of NG-GMAW is very difficult. The common experimental analysis method is complex, especially take a long time and cost. In this paper, the simulation analysis method is used to analyse NG-GMAW welding process. After the analysis of the NG-GMAW welding mechanism, the dynamic simulation model of the rotating arc NG-GMAW welding process is established firstly. Then, the influence of key process parameters on the welding quality is analysed in detail, which include the rotation angular velocity, rotation angular amplitude, wire feed speed, welding speed, sidewall stay time and so on. The simulation and analysis results illustrate the role and influence of the above parameters. In short, this paper provides a flexible and efficient method for the analysis and optimization of NG-GMAW welding process parameters to discover new phenomena, improve efficiency and save cost.

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Key Words: NG-GMAW, Rotating Arc, Simulation Model, Parameters Optimization

1. INTRODUCTION

With the rapid development of modern manufacturing industry, especially the large demand of thick and ultra-thick plates in the ultra-high speed, supercritical and other extreme service environment, it is extremely urgent to research and develop high-efficient welding technology and high-performance welding equipment [1, 2]. The narrow gap welding method is known for saving time, electricity and material, which has the great application prospect in modern industrial and military fields, such as the high pressure vessels, ships, deep sea detectors and spacecrafts [3].

Compared with traditional welding methods, the narrow gap welding method has advantages of high-efficient and energy-saving especially for more than 30 mm thick plates by reducing the cross section of grooves and using medium or small energy input. Compared with the submerged arc welding (SAW), the narrow gap gas metal arc welding (NG-GMAW) method can save more than half of the welding material and increase nearly 2.5 times of the welding productivity. Moreover, the welding energy input can be controlled easily to realize all directions of welding [4, 5].

However, the factors that affect the NG-GMAW welding process are complex and strongly coupled, leading to poor fusion of the sidewalls and other welding quality problems [6-8]. The experimental analysis method to optimize the process parameters is complex, especially take a long time and cost [9-10]. The simulation analysis method is particularly suitable for the NG-GMAW, which can improve efficiency and save cost. So first, the mathematical model of the rotating arc NG-GMAW welding process is established in this paper. Then, the influence of key process parameters on the welding quality is analysed in detail. Finally, selection rules of the NG-GMAW welding process parameters are given.

2. NG-GMAW WELDING PROCESS MODELLING

2.1 Analysis of the rotating arc NG-GMAW welding process

The schematic diagram of the rotating arc NG-GMAW is shown in Fig. 1 [11], where the curved tip drives the arc back and forth rotation. In the welding process, parameters such as sidewall stay time, rotation angular velocity, and amplitude, must be matched reasonably to realize high quality sidewall fusion and weld formation. Because the radius of arc rotation is not constrained by the tip, it is theoretically possible to weld any thickness of the plate as shown in Fig. 2.



Figure 1: Schematic diagram of the rotating arc NG-GMAW.



Figure 2: Geometric diagram of the rotating arc NG-GMAW.

In Fig. 2, ω stands the rotation angular velocity of the welding gun. *r* is the rotation radius, β is the rotation angle, and *v* is the welding speed, which is a constant. When the welding gun rotates to the sidewall, it will stay for some time *t_s*. And at this time, the rotation angular velocity becomes zero, and the sidewall absorbs most of the arc heat to promote the melting of the sidewall plate and the penetration. In the welding process, the welding gun is always perpendicular to the groove bottom and points to the groove centreline like the *x*-axis in Fig.

2. While the welding gun is moving at a constant speed v, rotate at an angular velocity ω . The superposition of the two movements forms the trajectory of the arc.

2.2 NG-GMAW welding process modelling based on MATLAB

According to Fig. 2, the arc velocity v_a can be obtained by Eq. (1).

$$v_{ax} = -|\omega r \sin \theta| + v = -\omega r \sin \theta + v$$

$$v_{ay} = -|\omega r \cos \theta| = -\omega r \cos \theta$$

$$v_{a} = \sqrt{v_{ax}^{2} + v_{ay}^{2}} = \sqrt{v^{2} + \omega^{2} r^{2} - 2\omega r v \sin \theta}$$
(1)

According to the above welding method, ω shows a periodic change as shown in Fig. 3, which is positive when the welding gun rotates from right to left, negative when rotates from left to right, and zero when stays on the sidewall.



Figure 3: Waveform of ω .

Because the arc rotation angle θ and ω have the relationship in Eq. (2), the change waveform of θ can be obtained as shown in Fig. 4. It's obvious that the periodic change of θ is the same as that of ω , so whether the welding gun stays on the sidewall can be got by the value of θ .

(2)



Figure 4: Waveform of θ .

The motion trajectory model of the arc can be established according to Eq. (1) as shown in Fig. 5, where *omega* and *theta* are respectively the same with ω and θ . v_{ax} and v_{ay} are respectively the decomposition speed of v in the x-axis and the y-axis. And the motion trajectory of the arc is shown in Fig. 6.



Figure 5: The motion trajectory model of the arc.

With the welding gun reciprocating, the arc swings back and forth to strengthen the pool stirring. When the welding gun stays on the sidewall, most of the heat is distributed to the sidewall to increase the sidewall penetration and keep the sidewall well fused, and the weld bead is a straight line.



Figure 6: The motion trajectory of the arc.

Since the groove of NG-GMAW is narrow and deep, the heat loss during the welding process is ignored. And then the heat input per unit length E_m can be obtained with the welding wire rotation [12-15] as shown in Eq. (3).

$$E_m = \frac{UI}{v_a} = \frac{UI}{\sqrt{v^2 + \omega^2 r^2 - 2\omega r v \sin \theta}}$$
(3)

When the welding gun rotates to the sidewall, ω is zero and the heat input per unit length E_e can be obtained as shown in Eq. (4).

$$E_e = \frac{UI}{v_a} = \frac{UI}{\sqrt{v^2 + \omega^2 r^2 - 2\omega r v \sin \theta}} = \frac{UI}{v}$$
(4)

According to Eqs. (3) and (4), the welding heat input model can be established as shown in Fig. 7. U is the arc voltage and I is the welding current. The other parameters have the same meaning as the above ones as shown in Fig. 5.

In fact, parameters of the NG-GMAW welding process are very complex, including the groove size, the bending angle of the conductive mouth, the diameter and extension of the welding wire, the arc voltage, the welding current, the welding speed, the rotation speed and many other parameters. So in this paper, the critical parameters that are closely related to the rotating arc and directly affect the welding quality are analysed and discussed.



Figure 7: The welding heat input model.

3. EFFECT OF THE CRITICAL PARAMETERS ON WELDING OUALITY

3.1 Effect of the rotation angular velocity and angle

Assume that ω increases from 4 rad/s to 8 rad/s in 3 seconds, and the rotation amplitude is constant, the simulation result of E_m is shown in Fig. 8, and Fig. 9 shows the enlarged waveform on the y-axis of Fig. 8.



Figure 8: Waveform of E_m at different rotation angular velocities.



Figure 9: Enlarged waveform of E_m in Fig. 8.

It can be seen that E_m is vulnerable to ω , and E_e is independent of ω . When the welding wire is in the middle of the groove, the heat input obtained by the molten pool decreases and the weld reinforcement is low. As the rotation angle β increases, the stirring speed of the pool becomes larger, which will help the weld formation. According to Eq. (3), E_m is independent of β . However, if β is too small, the welding wire is in the middle of the groove during the welding gun stays on the sidewall, and the arc cannot cover the entire sidewall, easily leading

to poor sidewall fusion. Because E_e is much larger than E_m , which is distributed to the middle part of the groove, the arc energy will increase sharply to produce the controllable well weld formation.

3.2 Effect of the wire feed speed and welding speed

It can be seen from Fig. 1 that when the welding gun rotates, the distance from the wire tip to the groove bottom is constant. If the wire feed speed is constant, the melting rate is also constant. Besides the arc length and wire extension remains unchanged, then the droplet transfer of the welding process also remains stable. When the wire feed speed is 6 m/min, the change of E_m is approximately the same as the pulse waveform as shown in Fig. 10. The peak and base of the pulse are respectively the sidewall stay stage and the rotation stage of the arc.



Figure 10: Waveform of E_m when the wire feed speed is 6 m/min.

It can be seen from Fig. 10 that the difference between the peak and base is large. ω is about 3 rad/s to 9 rad/s, *r* is 8 mm to 10 mm, θ is -45° to 45°, and *v* is 2 mm/s to 4 mm/s. Then the Eqs. (5) and (6) can be obtained.

$$\omega^2 r^2 >> v^2 - 2\omega r v \sin\theta \tag{5}$$

$$\frac{E_m}{E_e} = \frac{UI}{\sqrt{v^2 + \omega^2 r^2 - 2\omega r v \sin \theta}} \div \frac{UI}{v}$$

$$= \frac{v}{\sqrt{v^2 + \omega^2 r^2 - 2\omega r v \sin \theta}} \approx \frac{v}{\omega r}$$
(6)

According to Eq. (6), E_m in the rotation stage is much smaller than E_e in the sidewall stay stage. The change of the input heat in the rotation stage can be obtained by the enlarged waveform on the y-axis of Fig. 10, which is shown in Fig. 11.



Figure 11: Enlarged waveform of E_m in Fig. 10.

Fig. 11 shows that the arc position does not change after the sidewall stay stage, but the heat input has a significant decrease. It's obvious that the signs θ and ω are opposite, which makes the denominator in Eq. (3) become larger and E_m becomes smaller. Assuming that the wire feed speed increases to 7.2 m/min in the third second, the change of E_m is shown in Fig. 12.



Figure 12: Waveform of E_m when the wire feed speed increases.

As the wire feed speed increases, the wire melting speed should also be increased to ensure the stable arc length. So the welding current need to be increased and E_m becomes larger as shown in Fig. 12. The heat input in the sidewall stay stage is significantly increased. Fig. 13 shows the enlarged waveform on the y-axis of Fig. 12, and the heat input in the rotation stage is also increased. As the deposition coefficient increases, there is more molten metal per unit weld length, which flows to the pool centre under the influence of gravity. Then the pool forms a convex after cooling under the combined effect of gravity and surface tension. So the wire feed speed should be controlled reasonable to avoid the convex weld.



Figure 13: Enlarged waveform of E_m in Fig. 12.

According to Eq. (6), when the gun walking speed, that is, the welding speed increases, E_e will decrease in the sidewall stay stage. Fig. 14 shows the change of E_e as the welding speed increases from 2 mm/s to 4 mm/s, which will results in poor sidewall fusion. Therefore, at this time the welding speed should be reduced.

Fig. 15 shows the enlarged waveform on the y-axis of Fig. 14. It is obvious that as the welding speed changes, the heat input in the rotation stage has changed little, only the amplitude of which increases. Through Figs. 14 and 15, it can be seen that the welding speed has little effect on the heat input per unit length in the rotation stage, but has large influence on that in the sidewall stay stage.



Figure 14: Waveform of E_m when the welding speed is increased.



Figure 15: Enlarged waveform of E_m in Fig. 14.

If the welding speed is very small, E_e will be too large, which means that the heat absorbed by the sidewall is too much. The parent mental will be overheated, and the overlap is produced, which will easily cause undercut and other defects. Therefore, the reasonable welding speed choice is crucial.

3.3 Effect of the stay time on the sidewall

The sidewall stay time t_s in the rotating arc NG-GMAW also has a significant effect on the welding quality. Fig. 16 shows the simulation result when the sidewall stay time changes from 50 ms to 200 ms.



Figure 16: Waveform of E_m during the sidewall stay time changes.

The increase of t_s has no effect on the heat input both in the sidewall stay stage and the rotation stage, but can increase the pulse period or frequency. When t_s is short, the frequency

is large and the arc has strong effect of pool stirring, which will help to shape the middle part of the weld bead. However, the sidewall stay time is short to lead to the unstable sidewall fusion. As t_s increases, the sidewall melting and penetration tends to be stable. If t_s continues to increase, the arc stirring effect decreases and the pool cools too fast to limit the exhaust and slag, which will easily produce welding defects of gas pore and slag inclusion.

4. CONCLUSION

Simulation and analysis results show that increased rotation angular velocity ω helps to avoid the overlap defect, but the effect of the wire feed speed change is exactly the opposite. Too large rotation angular amplitude can easily cause the arc climb on the sidewall and uneven sidewall fusion. However, too small rotation angular amplitude may cause the overlap and poor weld formation. Moreover, too large welding speed is not conductive to promote the sidewall melt and increase the sidewall penetration, which can cause poor sidewall fusion. Too large sidewall stay time can cause the incomplete fusion of the other side to produce the gas pore and slag inclusion defects.

All the results illustrate a flexible and efficient method provided for the analysis and optimization of NG-GMAW welding process parameters to discover new phenomena, improve efficiency and save cost.

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