Characteristics of Arc and Metal Transfer in Pulsed Ultrasonic-Assisted GMAW

Compared to conventional GMAW, PU-GMAW of aluminum alloy is found to reduce droplet size and increase droplet frequency

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ABSTRACT

Pulsed ultrasonic-assisted gas metal arc welding (PU-GMAW) is a newly developed welding method. Pulsed frequency is one of the most important parameters in the PU-GMAW process. In this paper, the influence of pulsed frequency on the GMAW of aluminum alloy was studied. The results showed that the conventional GMAW process was improved significantly by adding different pulsed frequencies. The pulsed arc length, which was the change of arc length with the change of pulsed frequency, was obtained when the pulsed frequency ranged from 1 to 10 Hz. The stable compression arc length was obtained when the pulsed frequency exceeded 20 Hz. The metal transfer frequency in PU-GMAW increased compared to conventional GMAW. The increase of burning arc space pressure in PU-GMAW was mainly the reason for the change of the arc length. The increase in electromagnetic force and acoustic radiation force was the fundamental reason for the increase in droplet frequency.

KEYWORDS

- Pulsed Frequency • Arc Length • Metal Transfer
- Pulsed Ultrasonic-Assisted Gas Metal Arc Welding (PU-GMAW)

Introduction

Gas metal arc welding (GMAW) is widely used in automobile manufacturing, rail transit, and aerospace fields due to its high efficiency and low cost (Refs. 1, 2). However, there are many insufficiencies during the conventional GMAW process, such as more welding spatter and lower arc energy. Many hybrid welding methods have been presented to improve the GMAW process, including adding a magnetic field, a pulsing laser, and an ultrasonic field (Refs. 3–5).

By adding an external magnetic field, the arc behavior, droplet transfer, and weld pool flow were improved (Refs. 6–8), but the magnetic field was easily disturbed by the welding environment. Jia et al. (Ref. 4) reported enhanced metal transfer of aluminum alloy in GMAW with a pulsed

laser. Although the introduction of laser improves droplet transfer, the cost of equipment increases significantly.

The ultrasonic-assisted GMAW process is a new development of the hybrid welding method, and it has shown improvement of the welding process and welded joint (Ref. 5). Fan et al. (Refs. 5, 9) studied the effects of continuous ultrasound on the droplet transfer behaviors in GMAW. The authors found that continuous ultrasonic-assisted GMAW (CU-GMAW) can compress the arc and increase the droplet frequency. The welding process stability was also enhanced. Additionally, the effects of ultrasound parameters on arc behavior during the GMAW process were reported by Xie et al. (Refs. 10, 11). The geometrical parameters of acoustic radiator were also optimized by analysis of the sound field distribution. However, CU-GMAW has the disadvantage of low ultrasound utilization.

Pulsed ultrasonic-assisted GMAW (PU-GMAW) was shown to enhance ultrasound utilization. Chen et al. (Ref. 12) confirmed the feasibility of pulsed ultrasound for controlling the GMAW process. The effects of pulsed ultrasound on short-circuiting transfer has been discussed in detail (Refs. 13, 14). The short-circuiting transfer process improved under the action of the pulsed ultrasound, which included an increase in droplet frequency.

The GMAW process is commonly employed in the welding of aluminum (Refs. 15–18). A commonly used transfer mode is globular transfer. However, there has been little research on the effect of ultrasonic-assisted pulsing parameters on metal transfer behavior during GMAW.

In this work, the influence of pulsed frequency on the characteristics of arc shape and globular transfer were analyzed during the PU-GMAW of aluminum alloy. The arc shape and droplet dimension were obtained with images from a high-speed camera.

Experimental Materials and Methods

Materials

2A14 aluminum alloy plate with a thickness of 5 mm was used as the base metal. ER2319 welding wire in a diameter of

Fig. 1 — Schematic diagram of the PU-GMAW process.

Fig. 2 — Images of arc shape in different welding processes.

Table 1 — The Chemical Compositions of 2A14 Alloy and ER2319 (wt-%)

Elements	Cu	Mg	Si	Zr	Mn	Fe	V	Ti	Zn	Al
2A14	4.48	1.68	1.24	0.81	0.59	0.43	0.29	0.15	—	Bal.
ER2319	4.33	0.91	0.62	0.29	0.70	—	0.33	0.55	0.26	Bal.

1.2 mm was employed. The chemical compositions of the base metal and the welding wire are given in Table 1.

Methods

Figure 1 shows the equipment of pulsed ultrasound-assisted GMAW. The working principle of the PU-GMAW process has been given in literature (Ref. 14). The ultrasonic power source can produce the maximum power of 2000 W. The ultrasonic wave frequency was 20 kHz. The welding power source was Fusion Pro™ 450 GMAW, which was produced by the Kenbey Co. of Finland. The welding parameters are given in Table 2.

During welding, 99.99% argon was employed as the shielding gas. The contact tip-to-workpiece distance was 12 mm. Previous research (Ref. 19) indicated the compression degree of the arc shape could be altered by changing the transmitting height. When the transmitting height of 16 mm was employed, the arc length was compressed. When the transmitting height of 20 mm was employed, the arc length could be further compressed compared with that of the transmitting height of 16 mm.

In this work, the shorter arc length was useful to observe the effect of pulsed frequency on the arc shape, and the longer arc length was useful to analyze the effect of pulsed frequency on the metal transfer. Therefore, the transmitting height of 20

Fig. 3 — Change of arc length.

Fig. 4 — Change of arc area.

Table 2 — The Parameters of Welding

Welding voltage	Welding speed	Shielding gas flow	Wire feeding speed
20 V	7 mm/s	20 L/min	4.5 m/min

mm was used to study the effect of pulsed frequency on the arc shape. The transmitting height of 16 mm was used to study the effect of pulsed frequency on the metal transfer. The pulsing frequency was changed from 1 to 140 Hz. Images of the metal transfer were captured by a high-speed camera with a frame of 2000 fps. The exposure time was 30 ms during the capture of the arc shape. During the capture of the droplet transfer, the exposure time was 1.99 ms.

Results and Discussions

Arc Characteristics

Figure 2 shows arc shape images during different processes. Compared with conventional GMAW, the arc length during PU-GMAW was reduced. This result was also found in CU-GMAW (Ref. 9). Compared to GMAW, the arc energy in PU-GMAW increased due to the arc shape compression, which enhanced welding efficiency (e.g., increased weld penetration). The arc length was stabilized and compressed during CU-GMAW. However, during PU-GMAW, the arc length of the pulsed background time was greater than that of the pulsed peak time when the pulsed frequency was changed from 1 to 10 Hz. A pulsed arc length could be obtained by PU-GMAW with a lower pulsed frequency. When the pulsed frequency was increased to 20 Hz, the stabilized compression arc length was obtained.

The GMAW arc length was defined as a normalized arc length. The influence of pulsed frequencies on the arc length is shown in Fig. 3, which was obtained by Equation 1. The P-peak time expresses the arc length during the pulsed peak time. The P-background time expresses the arc length during the pulsed background time. Compared with GMAW, the arc length during the P-background time was decreased to around 0.7. The arc length during the pulsed peak time

was decreased to around 0.55. The arc length of the P-background time was greater than that of the P-peak time. The normalized arc lengths during PU-GMAW were approximately 0.5, which were similar to the arc length during P-peak time when the pulsed frequency was increased to 20 Hz. At a higher pulsed frequency (~20 Hz), the arc lengths were the same as that of the P-peak time. As shown in Fig. 4, the influence of pulsed frequencies on the arc area was obtained by Equation 2. It could be said that with the change of process parameters, the length and area of the arc had the same change tendency.

$$P_L = \frac{L_0 - L_U}{L_0} \quad (1)$$

where P_L is the change rate of the arc length, L_0 is the arc length during GMAW, and L_U is the arc length during PU-GMAW.

$$P_A = \frac{A_0 - A_U}{A_0} \quad (2)$$

where P_A is the change rate of the arc, A_0 is the arc area during GMAW, and A_U is the arc area during PU-GMAW.

Droplet Transfer Characteristics

This section mainly studies the characteristics of droplet transfer during the stable compression of arc length. Images of droplet transfer with the different processes are given in Table 3. The droplet transfer mode was the typical globular transfer. The metal transfer frequency and droplet size was always used to describe the droplet transfer behavior (Refs. 20, 21), as shown in Table 3.

Fig. 5 — Droplet frequency and droplet dimension during the different processes: A — Droplet frequency; B — droplet dimension.

Figure 5 shows the high-speed imagery of the effect of ultrasonic and pulsed ultrasonic-assisted droplet behavior. The droplet frequency is illustrated in Fig. 5A. The droplet transfer frequency of 22.5 Hz was obtained using conventional GMAW. Figure 5A indicates the droplet frequency remained relatively constant above a 20-Hz pulsed frequency. Under the action of a higher pulsed frequency, the droplet frequency during PU-GMAW was increased by about two times compared to conventional GMAW. Similar results were found during CU-GMAW, and it is believed the acoustic radiation force increased the droplet frequency (Ref. 9). Figure 5B shows the height and width of the droplet. The droplet dimensions during PU-GMAW were less than that of GMAW. There was a slight decreasing trend in the droplet dimensions as the pulse frequency increased. During PU-GMAW, the droplet frequency and the droplet dimensions had a similar variation tendency with the change of pulsed frequency.

Discussions

Mechanisms of Arc Compression

A standing wave sound field was formed between the ultrasound radiator and base metal face. The standing wave sound field was employed in the arc-burning space, which increased the space pressure and improved the arc shape. Previous research indicated the arc would be compressed under the action of the standing wave sound field (Ref. 11). It is well known that sound intensity is proportional to sound pressure. The standing wave sound field intensity (I) can be described by Equation 3.

$$I = c^2 \times f^2 \times A^2 \quad (3)$$

where c is the acoustic speed, f is the ultrasonic frequency, and A is the amplitude of the ultrasound.

In this work, the pulsed ultrasonic power was a square wave output, where there was a peak ultrasonic output and a background ultrasonic output, as shown in Fig. 6A. The ul-

Table 3 — Images of Droplet Transfer with the Different Welding Processes

	0ms	0.5ms	3ms	5.5ms	44ms	44.5ms
GMAW						
20 Hz						
50 Hz						
80 Hz						
110 Hz						
140 Hz						

trasonic transducer's output had a 50% duty cycle. The ultrasound amplitude was increased with the increase of ultrasonic power. Therefore, during PU-GMAW, the standing wave sound field intensity had a periodic change due to the change of ultrasonic power. During the lower pulsed frequency, the arc length oscillated and contained the peak time arc length and the background time arc length, as shown in Fig. 2. However, the obtained compression arc shape required a certain amount of time during PU-GMAW so the pulsed waveform of the arc length could be different from that of the pulsed ultrasonic power.

Figure 6A and B shows the relationship between the change of arc length and the pulsed ultrasonic power. The peak time arc length was obtained after the time of t_{p1} during the pulsing peak time of t_{p2} . The t_{p1} was the rise time of the pulse front. Af-

Fig. 6 — Relationship between the change of arc length and the pulsed ultrasonic power.

ter the time of t_{p2} , the arc length was changed from P-arc to B-arc length, which needed the time of t_{b1} during the pulsed background time. The t_{b1} was the falling time of the pulsed back edge. When the pulsing frequency was increased to a constant value (the pulsed width was small enough), the arc length could not respond quickly enough to the pulse change from background to peak amplitude. Therefore, a stable compression arc shape could be obtained, which could be the B-arc, T-arc, and P-arc, as shown in Fig. 6C. (Note: “C-arc” expresses the conventional arc shape, “B-arc” expresses the arc shape during the background time, “T-arc” expresses the arc shape in the time of t_{b1} or t_{p1} , and “P-arc” expresses the arc shape during the peak time.)

According to the Arc Characteristics section in this work, the stable compression arc shape was the same as the P-arc during the higher pulsed frequency. Therefore, it could be concluded that t_{p1} should be much less than t_{b1} , which means the P-arc was quickly obtained. During the pulsed peak to the pulsed background, the P-arc didn’t instantaneously change to B-arc due to thermal inertia, which kept a time (t) and then changed to B-arc gradually. During the higher pulsed frequency, the pulsed width could be less than the time of t , so the arc shape kept the P-arc.

Mechanisms of Acceleration Droplet Transfer

In conventional GMAW, the droplet transfer was affected by the surface tension, friction force, electromagnetic force, and gravity effect, as shown in Fig. 7. The surface tension had a hindrance effect on droplet transfer, which is given in Equation 4 (Ref. 22). The welding wire diameter and the surface tension coefficient were constant. The surface tension was constant. The electromagnetic force (P_r) is defined by Equation 5 (Ref. 22). Through observation of the arc shape, it could be found that the arc width (R) during PU-GMAW was reduced compared with that of GMAW. When r was zero, P_r was given as shown in Equation 6. Therefore, P_r during PU-GMAW increased compared to GMAW. The compression arc shape during PU-GMAW could promote droplet transfer.

$$F_s = 2\pi R_w \sigma \quad (4)$$

Fig. 7 — Schematic diagram of the droplet transfer during the different processes.

where F_s is the surface tension, R_w is the diameter of the welding wire, and σ is the coefficient of the surface tension.

$$P_r = K \frac{I^2}{\pi R^4} (R^2 - r^2) \quad (5)$$

$$P_r = K \frac{I^2}{\pi R^2} \quad (6)$$

where I is the welding current, R is the arc radius, and r is any radius.

As shown in Fig. 5, the droplet dimension during PU-GMAW was less than that of GMAW. Accordingly, the gravity force of PU-GMAW was less than that of GMAW. The acoustic radiation force (F_a) acted on the droplet under the action of ultrasound, which could enhance the droplet transfer, as shown in Fig. 7. The F_a was expressed by the time-averaged potential (U_0), as follows (Ref. 23):

$$F_a = -\text{grad}U_0 \quad (7)$$

U_0 is defined as follows (Ref. 23):

$$U_0 = 2\pi R_s^3 \left[\frac{\bar{P}_{in}^2}{3\rho_0 c^2} f_1 - \frac{\rho_0 \bar{U}_{in}^2}{2} f_2 \right] \quad (8)$$

where R_s is the droplet dimension; $\bar{P}_{in}^2$ is the mean square deviation of the acoustic pressure; ρ_0 is the density of the shielding gas; c is the sound velocity in the shielding gas; $\bar{U}_{in}^2$ is the mean square deviation of the vibration speed; $f_1 = 1 - \rho c^2 / \rho_s c_s^2$; $f_2 = 2(\rho_s - \rho) / (2\rho_s + \rho)$; ρ_s is the ultrasonic radiator density; and c_s is the sound velocity in the ultrasonic radiator.

Normally, U_0 is increased with the increase of the acoustic pressure. The acoustic pressure is increased with the increase of the ultrasonic power. The acoustic radiation force is in direct proportion to the ultrasonic power. Therefore, the acoustic radiation force was pulsed during PU-GMAW. Under the action of the higher pulsed ultrasound, the

droplet frequency was increased — Fig. 5. It can be concluded that PU-GMAW increases the electromagnetic force and introduces a pulsed acoustic radiation force that reduces the droplet size and increases the droplet frequency.

Conclusions

1) A pulsed arc length can be obtained during PU-GMAW with a lower pulsed frequency. When the pulsed frequency was increased to 20 Hz, the stabilized compression arc length was obtained.

2) Under the action of higher pulsed frequency, the droplet frequency during PU-GMAW was increased by about two times compared to conventional GMAW. The droplet size during PU-GMAW also decreased.

3) The changed ultrasonic power, which led to the change in the sound field intensity, was the main cause for the formation of the pulsed arc length.

4) The increase in electromagnetic force and the introduction of the pulsed acoustic radiation force was the main reason for the increase in the droplet frequency during PU-GMAW.

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