Deposition geometrical characteristics of wire arc additive-manufactured AA2219 aluminium alloy with cold metal transfer pulse advance arc mode

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Abstract
A cold metal transfer pulse advance (CMT-PA) arc mode was employed in this paper for the wire arc additive manufacturing of Al alloy. The effects of process parameters on deposition surface morphologies and geometrical characteristics were investigated. And a deposition width model was built by the multiple linear regressions. Based on the principle that the volume of the sample is equal to that of filler wire, a deposition height model was simultaneously derived. The results indicate that the disparity between two trends of droplet spreading in horizontal and molten pool tangential direction determines directly the final deposition geometrical characteristics. And two trends would be mainly affected by the heat input and arc force closely related to process parameters. The influences of three factors on the effective width percentage show a trend of first increasing and then decreasing. So, it provides an optimal process window for good deposition forming. The effective width percentage reaches 83% and the machining allowance is only 0.71 mm, which significantly improves material utilization and reduces manufacturing costs. Besides, the error rates of deposition width and height models are less than 4% and 6%, respectively. Two models can facilitate fabricating different size complex parts and make a profit for the actual production.

Keywords Aluminium alloy · Wire arc additive manufacturing · Cold metal transfer pulse advance arc mode · Deposition geometrical characteristic · Dimension model

1 Introduction
Wire and arc additive manufacturing (WAAM) is an additive manufacturing technique that an electric arc was used as the heat source and metal wire as the feed material [1–3]. It can directly fabricate large three-dimensional (3D) parts and has fulfilled near net shape to a great extent, which just needs a small amount of machining to meet the target dimension and accuracy requirements [4, 5]. Recently, WAAM has attracted much attention for manufacturing large, meter-scale aluminium alloy parts both at home and abroad [6, 7]. This technique not only saves many raw materials compared with the traditional machining process but also greatly shortens the manufacturing cycle and reduces the cost [8]. In particular, a variable polarity arc can provide effective oxide cleaning of the filler wire and previous deposition layer alternately which helps to reduce porosity defects and improve density [9]. So, it can meet the increasingly stringent requirements on the property, accuracy, manufacturing cost, and production cycle for large aerospace aluminium alloy parts [10, 11].
WAAM technique itself indicates that the arc characteristic plays a key role in the forming process, so it is crucial to choose an excellent arc mode [12]. Cold metal transfer (CMT), developed by Fronius, provides a coupling between the filler wire feeding/retraction motion and metal droplet detachment through a special digital control system, which can complete the droplet transfer under an extremely low short circuit current smoothly. It can reduce the heat input and create a spatter-free material-filling process [13–15]. In order to realize the hybrid droplet transfer, Fronius further developed CMT Advance (CMT-A) and CMT Pulse Advance (CMT-PA) hybrid arc modes [16–18]. In recent years, many scholars have tried to conduct additive manufacturing of aluminium alloys based on CMT technology. Jiang et al. [19] studied the effects of cooling time and deposition strategy on the forming performance of 5356 aluminium alloy with CMT arc mode. The study showed that suitable cooling time between the interlayers can improve the shaping accuracy and that the reciprocating deposition strategy can reduce the defects of arc starting and ending. Cong et al. [20] investigated the effect of four CMT arc modes on the porosity characteristic of additive-manufactured Al-6.3Cu alloy. They found that the pure CMT process produced a large amount of gas pores, and CMT-PA proved to be the most suitable process for depositing aluminium alloy. Zhang et al. [21] conducted Al-6 Mg alloy parts under CMT-PA arc mode. Uniform equiaxed grains in the size of 20.6–28.5 µm were obtained, and the tensile strength with a maximum of 333 MPa was higher than that of forging Al-6 Mg alloys. Due to its excellent performance in controlling the heat input and effective cathode cleaning, the CMT-PA arc mode has demonstrated superiorities over other arc modes in eliminating porosities and generating fine equiaxed grain structures. However, it can be seen that the current research mainly focused on the improvement of metallurgical defects, micro-structures, and mechanical properties by employing the variable polarity arc mode.

As we all know, forming accuracy and geometrical characteristic of WAAMed parts directly determine the subsequent machining allowance, further affecting material utilization and manufacturing costs. However, there was no comprehensive and systematic study of the process stability and geometrical characteristics of WAAM with CMT technology. In particular, few special studies were conducted on the forming characteristic of the excellent CMT-PA arc mode.

In view of this, this paper focuses on the deposition geometrical characteristics of WAAMed AA2219 alloy with CMT-PA arc mode. First, the manufacturability and typical surface morphology of the arc modes were studied. Then, the effective width percentage was taken as an index to optimize the process parameters and improve forming stabilities. Finally, a multiple linear regression method was employed to construct the deposition width model. This study will provide the technical support and scientific principle for fabricating large-scale and complex Al alloys parts for aeronautic and astronautic applications.

2 Experimental

Experiments were carried out using the arc additive manufacturing setup consisting of a Fronius CMT-Advanced power source and an M-710iC/50 industrial robot. A stagger deposition strategy was employed to manufacture thin-wall samples, as shown in Fig. 1. ER2319 alloy wire with a diameter of 1.2 mm was used as the filler material after being dried at 100 °C for 2 h; 20-mm-thickness 2A12-T6 Al plate was applied as the forming substrate on which the oxide film and greasy dirt were cleaned with a stainless steel brush and acetone, respectively, before using. The chemical compositions of the substrate and filler wire were presented in Table 1. A high-speed camera system was employed to observe the arc shape and droplet transfer behavior in real time.

In order to compare the manufacturability characteristics of different arc modes, CMT, CMT-A, and CMT-PA were employed in additive manufacturing AA2219 alloy thin-wall samples, respectively. Their specific arc waveforms are shown in Fig. 2. CMT-A arc mode consists of an
electrode-positive CMT (EP-CMT) phase and an electrode-
negative CMT (EN-CMT) phase, while CMT-PA arc mode
is made up of an electrode-positive pulse (EP-Pulse) phase
and an EN-CMT phase. The process parameters of the three
modes were shown in Table 2. The wire feeding speed was
set at 6.5 m/min, and the current and voltage would match

Table 1 Chemical constituents of welding wire and substrate (wt.%)

| Elements | Cu (wt.%) | Mn (wt.%) | Si (wt.%) | Mg (wt.%) | Fe (wt.%) | Zn (wt.%) | Ti (wt.%) | Al (wt.%) |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| ER2319   | 5.8–6.8   | 0.2–0.4   | 0.2       | 0.02      | 0.3       | 0.1       | 0.1–0.2   | Bal       |
| 2A12     | 3.8–4.9   | 0.3–0.9   | 0.5       | 1.2–1.8   | 0–0.5     | 0.3       | 0.15      | Bal       |

Fig. 2 Arc current waveforms of (a) CMT, (b) CMT-A, and (c) CMT-PA arc modes

Table 2 Processing parameters using different arc modes

| Sample number | Arc mode | Wire feeding speed, $v_{wire}$ (m min$^{-1}$) | Arc current, $I$ (A) | Arc voltage, $U$ (V) | Scanning speed, $v$ (mm s$^{-1}$) | Heat input, $HI$ (J mm$^{-1}$) |
|---------------|----------|---------------------------------------------|----------------------|---------------------|----------------------------------|-------------------------------|
| 1             | CMT      | 6.5                                         | 144                  | 16.4                | 7                                | 269.9                         |
| 2             | CMT-A    | 6.5                                         | 131                  | 14.6                | 7                                | 218.6                         |
| 3             | CMT-PA   | 6.5                                         | 100                  | 11.7                | 7                                | 133.7                         |
automatically according to different arc modes. The heat input ($HI$) can be calculated by Formula (1):

$$HI = \varphi Ui/v$$  \hspace{1cm} (1)$$

where $U$ is the arc voltage, $I$ is the arc current, $v$ is the scanning speed, and $\varphi$ is the arc thermal efficiency of CMT and normally is set to 0.8 [22].

CMT-PA was selected as the research object among the three arc modes because it can get better microstructures and properties [20, 21]. Ten groups of the experiment were designed and shown in Table 3, including three factors, i.e., arc current ($I$), scanning speed ($v$), and ratio of EP to EN ($r$). The ratio of EP to EN represents the time ratio of EP-Pulse phase to EN-CMT phase overall the whole cycle of the CMT-PA arc mode; 70-layer thin-wall samples were produced to analyze the effects of process parameters on the deposition geometrical characteristics of WAAMed Al alloy. In order to eliminate heat accumulation, the next layer would not be conducted until the temperature of the deposition surface is below 50 °C.

After the thin-wall sample is completed, three areas were selected along the deposition direction to measure their heights respectively, as shown in Fig. 1. The average of three values was taken as the final height of the thin-wall sample. Then, the cross-sections of three areas were chosen to measure their effective width $W_e$ and total width $W$. The effective width percentage of every cross-section was calculated using the formula $\eta = \frac{W_e}{W} \times 100\%$. The mean of three results was taken as the final effective width percentage of the thin-wall sample. The laser displacement sensor was adopted to measure the side profile fluctuation of thin-wall samples.

### 3 Results

#### 3.1 Deposition process characteristics of different arc modes

The samples deposited by CMT, CMT-A, and CMT-PA arc modes are shown in Fig. 3, from which it can be found that all these samples show bright metallic luster and have no any oxidative blackening on the surface. However, larger weld overlap defects are observed on the side surface of the CMT sample. And for the CMT-A sample, a serious necking phenomenon appears near the arc starting region. This defect becomes more and more serious with the increase of deposited layers, which finally leads to poor flatness on the upper surface. Besides, a slight crater occurs on the side surface. While as for the CMT-PA sample, we can see a uniform and fish scale-shaped weld bead.

Looking at the cross-section morphology in Fig. 3, it can be seen that the cross-sections of three samples have similar subarea characteristics, which all contain three regions, i.e., the broadening bottom area, middle area with stable size, and arched top area. Therefore, a broadening forming section is required before obtaining the stable section. As for the three arc modes, the broadening bottom section of CMT-PA is the maximal and reaches 6.0 mm in height. A gradual increase in the deposition width can reduce the stress concentration and avoid cracking between the thin wall and substrate. Besides, the sample with this arc mode grows in the vertical direction. While the samples under CMT and CMT-A modes tilt at the angle of 12 degrees and 5 degrees, respectively, which easily leads to serious collapse of subsequent depositions. Comparing the three arc modes, it can be found that the CMT-PA mode is able to obtain more stable forming and beautiful morphology than the other two. Good manufacturability characteristics demonstrate that it will be very suitable for fabricating large-sized Al alloy parts.

### 3.2 Deposition geometrical characteristics with CMT-PA arc mode

#### 3.2.1 Deposition morphology

According to the process parameters in Table 3, #1–#10 thin-wall samples were deposited under CMT-PA arc mode. Three typical samples are shown in Fig. 4. We can see under the larger scanning speed of 9 mm/s, such as #7, that it is

| Sample number | Arc current, $I$ (A) | Scanning speed, $v$ (mm s$^{-1}$) | Ratio of EP to EN, $r$ | Arc voltage, $U$ (V) | Heat input, $HI$ (J mm$^{-1}$) |
|---------------|---------------------|---------------------------------|-----------------------|-------------------|--------------------------|
| #1            | 85                  | 7                               | 0.9                   | 11.3              | 109.8                    |
| #2            | 95                  | 7                               | 0.9                   | 11.5              | 124.9                    |
| #3            | 105                 | 7                               | 0.9                   | 11.7              | 140.4                    |
| #4            | 115                 | 7                               | 0.9                   | 11.9              | 156.4                    |
| #5            | 95                  | 3                               | 0.9                   | 11.5              | 291.3                    |
| #6            | 95                  | 5                               | 0.9                   | 11.5              | 174.8                    |
| #7            | 95                  | 9                               | 0.9                   | 11.5              | 97.1                     |
| #8            | 95                  | 7                               | 0.8                   | 11.5              | 124.9                    |
| #9            | 95                  | 7                               | 1.0                   | 11.5              | 124.9                    |
| #10           | 95                  | 7                               | 1.1                   | 11.5              | 124.9                    |
easy to produce poor fusion and even discontinuous formation defects. What is more, these defects are not filled and improved in the subsequent additive manufacturing process and finally lead to the hump-like surface appearances on the thin wall (see Fig. 4a). Whereas using a lower scanning speed of 3 mm/s or 5 mm/s, for example, #6, the deposition bulges outward and the transition area collapses inward (see Fig. 4b). In this case, a zigzag side surface appears and the deposition quality is seriously deteriorated. When the current and scanning speed match properly, such as #2, we can get a uniform thin wall with a well-flat side surface (see Fig. 4c).

Figure 5 shows the side surface fluctuation characteristics of three thin-wall samples. It is clear that the fluctuation degree of #2 is much smaller than #6 and #7. In the meantime, its machining allowance ($Z$) is also the smallest and only 1.0 mm, which is 52.4% and 28.6% lower than that of #6 and #7, respectively. As a result, this will greatly save filler materials and shorten the manufacturing cycle.

3.2.2 Effective width percentage

The effective width percentage of cross-sections can be regarded as the material utilization rate to some extent. This is because the larger the ratio is, the smaller the machining allowance is and the higher the material utilization rate is. Accordingly, this paper takes the ratio as the index to optimize process parameters and studies the influence of process factors on the index results. The effective width percentages of 10 thin-wall samples are shown in Fig. 6. As can be seen, the range is from 56.1 to 79.7%.

Figure 7 shows the influence of various process factors on the effective width percentage of thin walls. Note that the effective width percentage first increases, then decreases with the increase of arc current, and achieves the maximum value when the arc current reaches 95 A. When the scanning speed varies from 3 to 7 mm/s, the effective width percentage will increase from 56.1 to 79.7%, which indicates deposition forming is obviously improved. However, the effective width percentage will begin to decrease if the scanning speed continues to increase. The thin walls have a better effective width percentage when the ratio of EP to EN is in the range from 0.9 to 1.0. Besides, the range value R of each factor in Fig. 7 represents its influence degree on index results. By comparing the range value, it can be seen that the scanning speed has the greatest impact on the effective width percentage, followed by the arc current and ratio of EP to EN.

The analysis above shows that the influences of three factors on the effective width percentage all increase first and then decrease. This suggests that the process window can be obtained for good deposition forming, namely, arc current...
of 92–101 A, scanning speed of 6.3–7.5 mm/s, and ratio of EP to EN of 0.86–1.01. Using process parameters in the window, the effective width percentage reaches the range from 75 to 79.7%.

To verify the effectiveness of the process window, three thin-wall components were fabricated. Figure 8 shows the surface and cross-section morphology of the thin wall with the optimal process parameter. It can be found that the side surface appears smooth and flat due to the obvious elimination of zigzag concave and convex defects. And its effective width percentage and machining allowance reach as high as 83% and only 0.71 mm, respectively. This demonstrates that the process window is effective and reliable, which can greatly improve the deposition morphology, increase material utilization, and reduce manufacturing costs.

### 3.2.3 Deposition dimension and model

There is a strong requirement for enterprises to be able to manufacture different size parts. As described in “Deposition morphology” and “Effective width percentage,” the process parameters have noteworthy effects on the deposition geometrical characteristics. Therefore, establishing models to predict the deposition dimension is of great significance for the actual production of WAAMed Al alloy.

The deposition width (W) and height (H) of #1–#10 thin-wall samples are displayed in Table 4. It shows that the deposition width and height vary greatly depending on different process parameters. The differences in deposition width and height between #1 and #5 reach 3.9 mm and 42.3 mm, respectively.

According to the above deposition width, the regression coefficient of each process factor was calculated by the multiple linear regression method, and the multiple regression equation of the deposition width was obtained as follows:

$$W = 1.824 + 0.082I - 0.744v + 3.381r$$

(2)
where \( I \) is the arc current, \( v \) is the scanning speed, and \( r \) is the ratio of EP to EN.

Then, the test of goodness for the fit of the regression equation was conducted. The correlation coefficient \( R^2 \) is 0.954. And the significance levels \( p(I), p(v), \) and \( p(r) \) of the \( F \)-test are 0.001, 0.001, and 0.038, respectively, which are all less than 0.05. The results are able to demonstrate convincingly that three process factors have a significant influence effect on the deposition width and the regression model is valid.

However, there is no significant correlation between the deposition height and the process parameters, so the linear regression method is not suitable for the prediction analysis of deposition height. Given this situation, the calculation model of deposition height was deduced according to the principle that the volume of the sample was equal to that of filler wire in the WAAM process. Since the middle region of the sample is stable in process and shape, we can assume that the deposition shape is a cuboid. And the deposition volume of each layer \( (V_d) \) is as below:

\[
V_d = Whvt
\]  

(3)

In the formula, \( W \) is the deposition width, \( h \) is the deposition height of each layer, \( v \) is the scanning speed, and \( t \) is the depositing time of each layer.

### Table 4  Deposition width and height of #1–#10 thin walls

| Sample number | #1  | #2  | #3  | #4  | #5  | #6  | #7  | #8  | #9  | #10 |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \( W \) (mm)  | 6.6 | 7.3 | 8.2 | 9.1 | 10.5| 9.3 | 6.5 | 6.8 | 7.5 | 8.1 |
| \( H \) (mm)  | 142.2|155.8|163.7|172.3|184.5|157.9|148.3|158.9|156.4|143.8|
When the wire feeding speed is $v_{\text{wire}}$ and the wire diameter is $D$, the molten wire volume of each layer ($V_{\text{wire}}$) is as follows:

$$V_{\text{wire}} = \frac{\pi D^2 v_{\text{wire}} t}{4} \tag{4}$$

On the basis of that, the deposition volume ($V_d$) and the molten wire volume ($V_{\text{wire}}$) are equal, the deposition height ($H$) of $n$-layers sample can be derived as follows:

$$H = nh = \frac{n \pi D^2 v_{\text{wire}}}{4 v W} \tag{5}$$

For the sake of verifying the accuracy of deposition width and height models, new process parameters were designed and substituted into the regression Eqs. (2) and (5) to obtain the corresponding predicted values of deposition width and height. Then, samples (T1 ~ T5) were produced to measure the actual size. The error rates between the actual values and the predicted values were calculated and illustrated in Fig. 9. The results indicate that the error rates of deposition width $E_{\text{width}}$ are all within 4% and that of deposition height $E_{\text{height}}$ are less than 6%. It is further proven that the two models are reliable and can be applied to predict the deposition size of WAAMed Al alloy parts.

4 Discussions

The spreading behavior of droplets and the solidification of the molten pool play a vital role in the forming stability and quality in the WAAM process. The force analysis of droplets in CMT-PA arc mode is shown in Fig. 10, including gravity ($G$), surface tension ($\sigma$), arc force ($F_a$), and the buoyancy of liquid metal ($F_b$). Among them, surface tension exists on the surface of the droplet and has a negative correlation with the temperature of the molten droplet. It will promote the transfer and spread of droplets when the contact angle is less than $\pi/2$, which can be calculated by the formula as follows [23, 24]:

$$\sigma = \frac{2\pi k R (T_0 - T - \tau)}{A_m} \tag{6}$$

where $k$ is a constant related to materials, $R$ is the surface radius, $T_0$ is the critical temperature when surface tension is zero, $T$ is the liquid temperature, $\tau$ is a temperature constant, and $A_m$ is the surface area of one-mole atoms.

In general, the arc force ($F_a$) includes electromagnetic force ($F_e$), plasma stream force ($F_f$), spot pressure ($P_s$), and short-circuit explosive force ($F_p$) in arc welding. For the droplets of completing the transfer, however, electromagnetic force in the axial direction ($F_{e_a}$) and plasma stream force ($F_f$) are the most important factors that affect the metal spread and are calculated by the formula as follows [25–27]:

$$F_a = F_{ez} + F_f = kI^2 \ln \frac{r_1}{r_0} + \frac{\pi}{2} (r_2^2 - r_0^2) C_d \rho_j v_f^2 \tag{7}$$

where $K$ is a constant, $I$ is the arc current, $r_0$ is the upper surface radius of the arc column, $r_1$ is the lower surface radius of the arc column, $C_d$ is the arc damping coefficient, $\rho_j$ is the plasma density, and $v_f$ is the plasma density flowing velocity having a positive correlation with arc current.

Under the combined action of the above forces, the liquid metal inside the droplet flows downward along the curved inner wall. It will generate two kinds of droplet spreading trends. First, the droplet spreads in the horizontal direction and becomes flat. Second, the droplet flows along the tangential direction at the junction of molten pool, droplet, and air. The disparity between the two trends directly determines the surface morphology and effective width percentage after the solidification of liquid metal.

According to formula (1), scanning speed can directly affect the heat input and then obviously change the temperature of droplet and molten pool in the WAAM process. When the scanning speed is 9 mm/s, such as #7 with a heat input of only 97.1 J/mm, the temperature of the liquid droplet is lower. And the strong surface tension helps the droplet metal flow along the tangential direction of the molten pool (see Fig. 10a). However, the shortening of solidification time will be likely to lead to poor spreading or even discontinuous formation of liquid metal on the deposition surface. The uneven depositions easily result in fluctuations of arc length and voltage, which can destroy the forming stability of the next layer. As a result, many crater defects are introduced into the surface of thin walls. As the decrease of scanning speed, such as #2 with a scanning speed of 7 mm/s and heat input of 124.9 J/mm, the temperature of the molten droplet rises and surface tension reduces. This helps to improve liquid metal flowabilities and increase the trend of droplet spreading in a horizontal

Fig. 9 Error rates between the actual value and predicted value of deposition width and height
Simultaneously, it is also accessible that small surface tension weakens the trend of droplets flowing along the tangential direction of the molten pool. Surface craters will be eliminated, and deposition appearance will be dramatically improved when two trends reach a dynamic equilibrium state to some extent (see Fig. 10b). In this case, the effective width percentage can be effectively increased to as high as 79.7% (#2), which reduces the machining allowance greatly. But if the scanning speed decreases continuously to below 5 mm/s, i.e., once the heat input exceeds 150 J/mm (such as #5, #6), both the droplet and molten pool will be overheating. Due to poor surface tension, the liquid metal inside the droplet flows close to the curved inner wall, as shown in Fig. 10c. The trend of the droplet spreading in a horizontal direction and becoming flat is much stronger than that flowing along the tangential direction of the molten pool. This will easily cause the deposition to bulge outwards and transition area to dent inward. Finally, the effective width percentage declines obviously; for instance, the effective width percentage of #5 thin wall has dropped to 56.1%.

It is known that arc current has an important influence on the heat input and arc force by formulas (1) and (7). Besides, the ratio of EP to EN will also affect the heat input and arc force in the CMT-PA process to some extent [10]. Figure 11 shows the arc shapes and droplet transfer process in the EP-Pulse and EN-CMT phases. As you can see in the figures, the EP-Pulse phase produces a strong bell shape arc with a maximum diameter of 6.2 mm, which could produce a deep weld penetration. However, the arc in the EN-CMT phase is elongated and only 2.2 mm in the maximum diameter, which is about one-third of that in the EP-Pulse phase. At the same time, the arc energy is transferred from the workpiece to the welding wire and is mainly used to melt filler materials. As a consequence, the heat input in the EP-Pulse phase will be much larger than that in the EN-CMT phase.

In order to further analyze quantitatively the physical characteristics of the two phases, the arc current and voltage values were collected in real time by the electric signal sensors, as shown in Fig. 12 and Table 5.

The heat input in the EP-Pulse and EN-CMT phases can be calculated by the formula as follows [28]:

\[ Q_{\text{pulse}} = I_{\text{pulse}} V_{\text{pulse}} \]

\[ Q_{\text{cmt}} = I_{\text{cmt}} V_{\text{cmt}} \]
\[ H_{EE}(H_{EN}) = \frac{\varphi \int_{t_1}^{t_2} U_i I_i dt}{v(t_2 - t_1)} = \frac{\varphi \sum_{i=1}^{n} U_i I_i \Delta t}{v(t_2 - t_1)} \]  

(8)

where \( \varphi \) is the arc thermal efficiency of CMT and normally is set to 0.8, \( t_1 \) is the start time of EP-Pulse or EN-CMT phase, \( t_2 \) is the end time of EP-Pulse or EN-CMT phase, \( U_i \) is the instantaneous voltage (V), \( I_i \) is the instantaneous current (A), \( \Delta t \) is the interval time, which is 0.02 ms in this paper, and \( v \) is the scanning speed (mm/s). According to formula (8), the heat inputs in the EP-Pulse and EN-CMT phases are 164.8 J/mm and 83.6 J/mm, respectively, which indicates that the HI of the EP-Pulse phase is twice as much as that of the EN-CMT phase.

Furthermore, by observing the droplet transfer in Fig. 11, it can be found that the droplet in the EP-Pulse phase appears in an approximately elliptical shape, and an arc crater occurs on the molten pool surface. This indicates that the arc force in the EP-Pulse phase points to the molten pool and is much greater than that in the EN-CMT phase. Therefore, with the increase of the ratio of EP to EN, the duration of the EP-Pulse phase will approach or even exceed that of the EN-CMT phase. As a consequence, both the heat input and arc force in a whole cycle will gradually increase simultaneously.

It can be summarized from the above analysis that both the arc current and ratio of EP to EN will affect forming stabilities and deposition geometrical characteristics by the heat input and arc force. When the current is more than 105 A or the ratio of EP to EN exceeds 1.0, such as #4 and #10, strong arc force going with poor surface tension will easily cause the liquid metal to spread in a horizontal direction, even flow out of control. In the meantime, strong droplet impact force in the EP-Pulse phase will also lead to drastic oscillation and serious instability in the molten pool. It will make it difficult to accurately control the shape of metals

| Phases    | Peak current, A | Peak time, ms | Basic current, A | Basic time, ms | Short circuit current, A | Short circuit time, ms | Cycle, ms |
|-----------|-----------------|---------------|------------------|----------------|------------------------|-----------------------|-----------|
| EP-Pulse  | 231.7           | 2.1           | 64.1             | 3.5            | -                      | -                     | 5.6       |
| EN-CMT    | 172.4           | 2.5           | 62.8             | 3.2            | 47.4/62.5              | 4.0                   | 9.7       |

Fig. 11 High-speed photographs of droplet transfer and molten pool: (a–d) EP-Pulse phase and (e–h) EN-CMT phase

Fig. 12 Arc current and voltage waveforms during EP-Pulse and EN-CMT phases (95 A, 7 mm/s, 0.9)
after solidification, thereby seriously lowering the forming quality of the deposition side surface.

In summary, two kinds of arcs with opposite polarities and a great disparity in temperature are constantly alternated in the CMT-PA mode. So, it can not only make the heat input level be controlled accurately but also provide a wide adjustable range of heat input and excellent gap bridging capacity. This can guarantee that the CMT-PA mode is superior to other modes for controlling deposition forming quality. However, proper process parameters are still necessary to obtain well-formed Al alloy parts, even using the excellent arc mode.

5 Conclusions

AA2219 alloy thin-wall components were fabricated by arc wire additive manufacturing using a variable polarity CMT-PA arc mode. Based on the effective width percentage index, the process parameters were optimized. And the influential mechanisms of process parameters on the deposition morphology characteristics were analyzed. Besides, dimensional models of deposition width and height were finally established. The following conclusions can be drawn.

(1) The effects of three factors on the effective width percentage show a trend of first increasing and then decreasing. This provides a process window of good deposition forming, namely arc current of 92~101 A, scanning speed of 6.3~7.5 mm/s, and ratio of EP to EN of 0.86~1.01. Using the optimal parameter in the window, the effective width percentage reaches to 83% and the machining allowance is only 0.71 mm, which significantly improves materials utilization and reduces manufacturing costs.

(2) The process parameters affect the spreading behaviors of liquid droplets and the solidification process of the molten pool via changing the heat input and arc force. With insufficient heat input, poor fusion and discontinuous formation will easily cause uneven deposition. When the arc current is above 101 A, the ratio of EP to EN in excess of 1.01 or the scanning speed less than 6.3 mm/s, strong arc force going with poor surface tension will result in a much larger trend of droplets spreading in a horizontal direction than that along the tangential direction of the molten pool. This can lead to liquid metals flowing out of control and seriously lower the forming quality. Only using the process parameters in the window can two trends reach a dynamic equilibrium state and excellent deposition appearances be obtained.

(3) The error rates of deposition width and height models are less than 4% and 6%, respectively. This proves that the two models are effective for predicting forming dimensions and convenient to manufacture different size Al alloy parts.

Author contribution Yanzhou Zhang designed and conducted the experiments, organized all the data, and wrote the manuscript. Ming Gao evaluated the obtained data and supervised all research. Yang Lu and Wenbo Du completed the auxiliary data analysis work. All authors read and approved the final manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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