Wire and arc additive manufacturing of 4043 Al-alloy using a CMT method

Zhi-qiang Liu\(^1,2\), Pei-lei Zhang\(^1,2\), Shao-wei Li\(^1,2\), Di Wu\(^1,2\), and Zhi-shui Yu\(^1,2\)

1) School of Materials Engineering, Shanghai University of Engineering Science, Shanghai 201620, China
2) Shanghai Collaborative Innovation Center of Laser Advanced Manufacturing Technology, Shanghai 201620, China

Abstract

A CMT+PULSE(C+P) arc was applied in the additive manufacturing of 4043 Al-alloy parts. Parameters for making parts were investigated. The properties and microstructure of the parts were researched. Experimental results showed that welding a speed of 0.008 m/s and a wire feeding speed of 0.067 m/s was suitable to manufacture thin-walled parts, and the reciprocating scanning method could be adopted to manufacture thick-walled parts. The thin-walled part of the C+P mode has fewer pores than the CMT mode. The tensile strength of C+P thin-wall parts ranges up to 172 MPa. Thick-walled parts have a maximum tensile strength of 178 MPa. Hardness decreases at the interface and in the coarse dendrite and increases in the refined grain area.

Keywords: Wire arc additive manufacturing; Aluminum alloy; Cold metal transfer; Microstructure; Layer deposition

1. Introduction

Nowadays, metal additive manufacturing has been studied extensively. Compared with the traditional manufacturing process, metal additive manufacturing is more efficient, the geometry of the parts being manufactured is more complex [1]. After years of development, more and more types of metal additive...
manufacturing technologies have emerged, such as selective laser melting (SLM), electron beam selective melting (EBSM), direct deposition of metal (DMD) [2]. For the manufacture of large components, arc additive technology is more efficient, lower production costs and the process easier. Wire and arc Additive Manufacturing (WAAM), in which the wire is melted by a strongly discharged arc and deposited along the planned path to a layer-by-layer fashion [3]. The essence of arc additive manufacturing is a buildup welding process essentially. Due to their excellent mechanical properties of aluminum alloy, large aluminum alloy components have been widely used in aviation, automobile, railway and other fields [4]. WAAM is considered the most promising way of production to manufacture of large aluminum components [5].

In the welding process, there may be a variety of welding defects in an aluminum-alloy welding seam, such as pores, hot cracks, and oxidation [6]. To ensure that large aluminum-alloy components, produced by arc-additive manufacturing, have good properties, a maintenance process must be adopted. Cold metal transfer (CMT), a further development of the Gas Metal Arc Welding (GMAW) short arc process, which relies on a controlled dip-transfer mode mechanism, should deliver beads with excellent quality, and lower heat input, nearly without spatter [7]. CMT technology has four droplet-transfer modes, CMT, CMT advanced (C+A), CMT advanced pulse (C+P+A) and CMT Pulse (C+P) [8]. There are many studies on additive manufacturing using CMT technology and CMT soldering. Cong [6] researched weld-bead geometry and the porosity of AA2219-T851 aluminum alloy welds with different arc modes. The study concluded that using the C+P mode can reduce the porosity in the weld bead. Jie [9] investigated the arc characteristics and metal transfer behavior of the C+P welding process, and analyzed the characteristics of welding aluminum alloy. This study found that the C+P mode could provide greater heat input than the CMT mode; thus the C+P mode had greater penetration, and the contact angle of the weld bead was smaller.
Gu [10] found that the grains of Al-Mg4.5-Mn alloy parts made using CMT WAAM technology were more refined, and the plasticity of the parts was better than that of forged Al-Mg alloy parts. To sum up, CMT technology’s many advantages confer great prospect in the application of WAAM. There is almost no research of the use of C+P mode to manufacture 4043 aluminum-alloy thin and thick-walled parts.

In this paper, two different arc modes were applied to WAAM-CMT and C+P. The C+P arc mode was the research focus. The scan path for manufacturing thick-walled parts is discussed. Metallurgical defects, microstructures, and mechanical properties of the parts being manufactured are analyzed. The anisotropy of mechanical properties is also discussed.

2. Experimental procedure

2.1 Experimental material and equipment

The experiments were conducted on 6061 Al-alloy substrates. ER4043 with 1.2×10⁻³ m diameter was used as the research material. The wire composition is shown in Table 1 [11].

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WAAM of the 4043 Al-alloy was carried out using the CMT WAAM system, as shown in Fig. 1. In this system, a CMT power source was used with a VR 7000-CMT 4R/G/W/F++ wire feeder, and an ABB IRB 4600 robot to provided processing movement. Robotstudio software from ABB was used to plan the path of additive manufacturing in the experiment.

2.2 Experimental method

C+P arc was developed based on CMT arc. It was a combination of the pulse arc and the conventional CMT arc. As shown in Fig. 2, C+P arc has several more pulse currents than CMT arc during a welding
cycle. Pulse arc will increase the heat input and stir the molten pool. CMT and C+P modes were used in WAAM. The substrates were dried and mechanically cleaned with acetone before the experiment. The 4043-Al alloy wire was also dried. The form path of the thin-walled part is shown in Fig. 3. Thick-wall parts of the 4043 aluminum alloy were made by the welding gun in different paths with the C+P mode.

The cross-section of the cut specimens was ground and polished. Then the internal formation and defects of the samples were observed. Interlaminar tissue of the middle portion of the cross-section of the thin-walled microstructure was analyzed, as was interlayer microstructure of the middle part of the thick-wall part. The samples to be analyzed were sanded, polished and etched. The etching solution was 0.5% hydrofluoric acid solution. Optical microscopes were used to observe the microstructure of the treated specimen.
Tensile specimens were obtained from parts made using different modes. The cut mode, sample morphology, and of the tensile specimen was shown in Fig. 4. The obtained tensile specimen was polished to remove surface scratches. The tensile test was carried out using a Zwick/Reoll Z020 lifter manufactured by Zwick/Roell, Germany, with a stretch rate of $3.33 \times 10^{-5}$ m/s. The S-3400N scanning electron microscope was used to observe the fracture morphology. The hardness test used was a HXD-1000TMC microhardness tester.

3. Results and Discussion

3.1 Forming of parts.

3.1.1 Forming of thin-walled parts.

Two arc modes, CMT and C+P, were used to manufacture thin-walled aluminum-alloy parts. Test parameters are shown in Table 2. The thin-walled parts were manufactured as shown in Fig. 5. Difference
existed in the manufacture of thin-walled parts due to various parameters.

When the welding speed was constant, the wall thickness of parts 1#-3# increased with the wire-feed speed, and the effective width increased from $6.75 \times 10^{-3}$ m to $9.3 \times 10^{-3}$ m. As can be observed in Fig. 5, at the beginning and stopping of welding, the weld pool has a significant downward flow trend, so the upper surface of thin-walled parts is not parallel to the substrates. There is an angle $\theta$ (Fig. 5 (a)) between the upper surface of the thin-walled part and the substrates. The collapse of parts is analyzed by formula 1.

There were serious collapses on both sides of parts 1#-3#, and the collapse rate ($C$) is from 13%-20%. From parts 2#, 4#, and 5#, it can be seen that when the wire feeding speed was constant, the effective width decreased from $8 \times 10^{-3}$ m to $7.4 \times 10^{-3}$ m as the welding speed increased. In addition, with welding speed increases, the collapse rate on both sides of the part was decreased from 16% to 3.5%. Therefore, the shape of part 5# was satisfactory.

$$C = \frac{2\theta}{\pi} \times 100\% \quad (1)$$

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<th>Specimens No.</th>
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<th>Wire feeding speed (m/s)</th>
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The CMT welding machine uses synergic welding, and the current and voltage changed with the wire feeding speed. The line energy increased with the wire feeding speed. Heat was mostly conducted on both sides of the component, conducting heat to the substrate. When the number of weld beads was large and
parts were quite high, heat dissipation becomes heat conduction on both sides of the parts. Therefore, excessive heat input combined with a single heat-dissipation method resulted in serious collapse of 1-3 sides of thin walled parts. Reducing the wire feeding speed can reduce the heat input. The thickness of thin-walled parts became non-uniform when the wire feeding speed is reduced. Parts 1-3 had the same number of weld beads. From Fig. 5, it can be seen that the height of the part decreased with the increasing of wire feeding speed, which is inconsistent with the theoretical result. The analysis shows that the increase of heat input led to a smaller wetting angle, and good wetting ability of a weld bead will cause molten liquid metal to flow to the side wall of the part and reduce the height of the new weld bead. The welding speed gradually increased. When the welding line energy was constant, sample 5# gets the minimum heat input. The appearance of parts 6 was good; the stratified streaks were uniform, there was no collapse on either sides, and the wall thickness was even. We analyzed properties of thin-walled pieces 5# and 6# for this paper.

![Fabricated thin-walled parts](image)

Fig. 5 Fabricated thin-walled parts: (a) 1#; (b) 2#; (c) 3#; (d) 4#; (e) 5#; (f) 6#.

3.1.2 The forming of a thick-walled part.
The process parameters for making thick-walled parts were: welding speed $6 \times 10^{-3}$ m/s, wire feeding speed $8.33 \times 10^{-2}$ m/s, and C+P mode. Bai [12] proposed an effective method to calculate the distance between adjacent weld beads. The spacing between weld beads is:

$$D = D_s = \frac{V_s n D_s}{4V_w H^2}$$  \hspace{1cm} (2)

where $V_s$ and $D_s$ are the wire feeding speed and wire diameter, respectively; $V_w$ is the welding speed; $D$ is the spacing between adjacent beads and $H$ is the height of a single bead. In this experiment, $H$ was $3.1 \times 10^{-3}$ m. So, in this study, $D$ was $5 \times 10^{-3}$ m. Based on the C+P mode, three scanning paths were used to fabricate the thick-walled aluminum-alloy structure. The path is shown in Fig. 6(a)-(c). Fig. 6(d)-(e) show the thick-walled parts made with three scanning paths. It can be seen from Fig. 6(e), that shape of a thick-walled part manufactured by using the reciprocating arc scanning method was good. The parts manufactured by the method of Fig. 6(a) are shown in Fig. 6(d). A hump appeared in the thick-walled part of the arc ignition position. Collapse occurred in parts of the arc-closing position. It can be seen that collapse occurred around the thick-walled part in Fig. 6(f). So welding torches were scanned perpendicular to each other between each layer. It is just not suitable for making thick-walled parts. The surface of the bead was not uniform and there were some distinct ripples in the front and tail of the bead [13]. These corrugations can affect the formation of thick-walled parts. The reciprocating scanning method can eliminate the ripple effect.
Fig. 6  The scan path used to make thin-walled parts and the formation of thick-walled parts: (a) unidirectional scanning; (b) reciprocating arc scanning; (c) vertical scan; (d) result of unidirectional scan; (e) result of reciprocating scan; (f) result of vertical scan.

3.2 Microstructures

Fig. 7 (a) shows the cross-section of the thin-walled part 5#, from which it can be seen that the cross section is well-formed and there are no obvious defects such as blowholes. This has two reasons: (1) When the heat input increases, the surface area of the weld bead increases and the solidification time is prolonged, which facilitates blowhole overflows. (2) The agitation of the liquid metal with the pulse mode promotes the rate of pore overflow. The bonds between beads are perfect, and no cracks appear between the beads. There are blurry, streaked stripes. Fig. 7(b) shows the microstructure of a single bead of part 5, from which it can be seen from that the microstructure of a single bead can be divided into fine and coarse grained regions. And the width of dendrite arms in fine and coarse grain regions are 10.93 um and 18.09 um, respectively. In addition, it can be seen that there are a small number of pores in the coarse grained regions. The relative content of pores is 0.57%. Wire and Arc additive manufacturing is a layer-by-layer accumulation process. The welding arc will re-melt part of the metal of the previous weld beads to form a molten pool. And the pulse arc will stir the pool, and then the pore in the pool was more likely to overflow. Then coarse grained region was not remelted, and the pores were left. The appearance of the fine grained region is related to the C+P arc characteristics. In the short-circuit transition phase of the C+P pulsed arc-welding process, a sudden decrease in the heat inputs will cause supercooling of the liquid metal, resulting in surface nucleation and grain refinement. In addition, Wang [14] believes that the high arc pressure caused by the pulsed arc mode can generate enough oscillations to cause the dendrite arms to split, thereby providing more heterogeneous nucleation sites, and refining the grain size. Due to the high heat
input of C+P, coarsening of the microstructure occurs in the lower half of a single bead. It can be seen from Fig. 7(c) that the fine grained region is mainly composed of fine columnar crystals, with a rich dendritic structure. There is a small number of equiaxed crystals between the columnar crystals. The coarse-grained regions are mainly coarse columnar crystals, and the columnar crystals grow vertically. Epitaxial growth of dendrites is observed in the bonding zone, which improves the mechanical properties of thin-walled parts.

Fig. 8 is a cross-section of thin walled part 6, from which it can be seen that the interface of the thin-walled part has many macroscopic and microscopic pores. The relative content of pores was 1.29%. Fracture of thin-walled parts usually occurs at these air-hole locations. The microstructure of a thin-walled part produced in the CMT mode is similar to that of the fine-grained area of the thin-walled part produced in the C+P mode, and the microstructure is coarsened at the stratified fringes.

![Fig. 7 Thin-walled part 5#: (a) thin-walled part cross-section; (b) partial enlarged view of cross section; (c) fine crystal area; (d) coarse-grained region.](image)

Fig. 9 shows the forming and microstructure of the cross section of a thick-walled part, from which that can be seen that the bonding between layers of the thick-walled structure and each bead are tight and
not fused. There are bright stripes between beads. In addition, there are significant pores, mainly hydrogen pores at the boundary of the weld bead. The bead of the previous layer is oxidized and contaminated, which is the main reason for the generation of pores. As can be seen in Fig. 9(c), the microstructure of a single bead has four forms. There are two coarse areas of microstructure on both sides of the weld bead. Microscopically coarsened areas also exist at the upper and lower interface of the weld. At the lower interface, there is an abnormal increase in some coarse-grained regions, which is related to the superposition of two weld beads. The coarse area of these microstructures corresponds to the fusion zone (FZ) of the welded joint. The microstructure of a single bead is mainly divided into two parts, the upper fine grained area and the lower coarse grained area. This is similar to the result of thin-walled parts made in C+P mode.

Fig. 8  Thin-walled part 6#: (a) Thin-walled part cross- section; (b) Partial enlarged view of cross section; (c) Microstructure at stratified fringes; (d) Microstructure in middle of weld bead.
Fig. 9  Cross-sections and microstructures of thick-walled parts: (a) thick-walled part cross-section; (b) part of the cross section; (c) cross section of a single bead; (d) microstructure of FZ on left; (e) microstructure of FZ at lower side; (f) fine crystal area; (g) coarse-grained region.

3.3 Mechanical properties

3.3.1 Tensile properties

The percentage of anisotropy of the tensile strength was calculated from the tensile test data as

$$\alpha = \frac{\sigma_B - \sigma_b}{\sigma_B} \times 100\%$$

where $\alpha$ represents the percentage of anisotropy, $\sigma_B$ is the maximum value of the tensile strength of the tensile sample, and $\sigma_b$ is the minimum value. Fig. 10 shows the tensile strength and anisotropy of thin and thick-walled parts.

As can be seen from Fig. 10, all transverse tensile specimens have lower tensile strength than in the longitudinal direction. For manufactured thin-walled parts, there is an FZ between beads. In the FZ region, the transverse mechanical tensile strength of the manufactured thin-walled member decreases due to the
coarsening of crystal grains and pores near the FZ. In addition, the tensile strength of part 5# is greater than that of part 6#. As discussed in section 3.2, there are many macroscopic pores inside thin-walled part 6#. Thin-walled part 5# lacks many pores. According to Kobayashi et al. [15], pores have a negative effect on the strength of aluminum alloys. This is because the porous area diminishes the properties of the metal. The tensile load-bearing capacity of the material is reduced, stress concentration occurs near the void, and premature fracture may occur.

![Graph showing tensile strength and percentage anisotropy](image)

**Fig. 10** Tensile strengths in different stretching directions and their percent anisotropy.

The difference in tensile strength between the longitudinal and transverse directions of the thin-walled parts 6 and 5 is 9 MPa and 7 MPa. And the percentage of anisotropy was only 4% and 5%, respectively. According to Qi [3], it can be considered that there is no anisotropy in the manufactured thin-walled parts, which is important for mechanical parts.

For manufactured thick-walled parts, the longitudinal tensile strength was 18 MPa greater than the transverse tensile strength, and the anisotropy was 10%. It can be considered that there is anisotropy in the mechanical properties of the thick-walled parts of the manufactured aluminum alloy. A large number of coarsened grains in the interface region of the transversely stretched weld beads cause anisotropy.

SEM images of the fracture appearance of tensile samples are shown in Fig. 11. Longitudinal fractures have fewer pores than transverse fractures. Obviously, more pores lead to lower tensile strength of
transverse tensile specimens. Stratified stripes can be clearly seen from the transverse stretch-like fracture, which proves that the tensile sample was fractured in the interface FZ. Stratified striations are another major reason for the reduction of the mechanical properties of transverse stretched specimens. As can be seen from Fig. 11, for thin walled part 6#, the size of fractured pores was larger, and their quantity was greater than in the others. In Figs. 11(c)-(d), a small number of dimples can be seen on the surface of the tensile fracture surface, but the fracture surface is characterized by cleavage fracture as a whole. The fracture may first occur in the coarse-grained region where pores exist. It can be seen that the tensile fractures of Fig. 11(a)-(b) and (e)-(f) have a large number of dimples, which are considered indicative of ductile fracture.

Fig. 11  SEM images of tensile sample fractures: (a) longitudinal of CMT; (b) transverse of CMT; (c) longitudinal of thin-walled parts manufactured with C+P; (d) transverse of thin-walled parts manufactured with C+P; (e) longitudinal of thick-walled parts; (f) transverse of thick-walled parts.

3.3.2 Microhardness
As can be seen from Fig. 12(a), the microhardness of thin walled part 5# was between 45 HV-57 HV, and the fluctuation of the microhardness was relatively large. The microhardness of thin walled part 6# was between 44 HV-50 HV. The microhardness test results of the thin-walled parts are related to their microstructure. Thin-walled part , had a relatively uniform microstructure, so its microhardness was relatively uniform and its fluctuation was small. The drop in the microhardness of thin-walled parts only occurs in grain coarsening FZ. As can be seen in Fig. 12(a), the microhardness of FZ only accounts for a small percentage. The cross-sectional microstructure of thin walled part 5 alternated between coarsened and refined grains. Thus the microhardness value between two indentations of a thin-walled part can differ greatly. Moreover, due to the presence of FZ, it can be seen from Fig. 12(a) that the microhardness of some indentations is much reduced.

Fig. 12(b) shows the microhardness of a thick-walled part at different locations, from which it can be seen that the microhardness value of the longitudinal interface was between 43 HV and 55 HV. The two adjacent microhardness values fluctuated greatly. The longitudinal microhardness value was between 49 HV and 58 HV, with variation similar to that of thin-walled parts. Its value is affected by the microstructure. The test results of horizontal and longitudinal microhardness are similar. Microhardness is lower at the
interface, The microhardness value at the non-interface is greater.

4. Conclusion

In this study, the influence of process parameters on additive manufacturing of thin-walled parts and scanning paths on additive-manufactured thick-walled parts was investigated. The microstructure and mechanical properties of the manufactured parts were studied. The following conclusions can be drawn:

(1) The process parameters included a welding speed of 0.008 m/s, a wire feeding speed of 0.067 m/s and a C+P pattern, which can produce well-formed thin-walled parts. With reciprocating scanning, good thick-walled parts can be obtained.

(2) In the thin-walled part of the C+P process, the microstructure consisted of thick and fine dendrites, and there were few pores in the cross-section. In the thin-walled part of the CMT process, the microstructure is dendritic and there are many pores in the cross section. The microstructure of a thick-walled part was similar to that of a C+P thin-walled part, but the interface had more pores.

(3) The longitudinal tensile strength of the manufactured thin-walled parts was greater than the transverse tensile strength. The difference in pores is the main cause of the difference in tensile strength. Thin-walled parts do not have anisotropy in tensile strength. However, it exists in thick-walled parts. The microhardness of the fabricated parts varied from 44 HV to 57 HV. The microhardness of a part is reduced at the interface area of the weld bead. The microhardness in the fine grained zone is the greatest.

Acknowledgements

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References


CLC number: TG 444

Secondary discipline: Material Processing Engineering (080503)
Fig. 1  The system of WAAM.

Fig. 2  The current and voltage waveforms of the welding: (a) C+P arc; (b) CMT arc.

Fig. 3  Scanning path to manufacture thin-walled parts.

Fig. 4  Tensile sample dimension and sampling positions: (a) thin-walled; (b) thick-walled; (c) geometry
Fig. 5  Fabricated thin-walled parts: (a) 1#; (b) 2#; (c) 3#; (d) 4#; (e) 5#; (f) 6#.

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Fig. 10  Tensile strengths in different stretching directions and their percent anisotropy.
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Fig. 12  Microhardness of parts being manufactured: (a) thin-walled parts; (b) thick-walled parts.
Table 1. Chemical composition of ER4043 wire (mass fraction, %)

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