Oscillating Wire Arc Additive Manufacture of Rocket Motor Bimetallic Conical Shell

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Abstract

This paper studies the temperature field, dynamic strain and forming accuracy of the Oscillate-WAAM conical shell in the forming process and manufactures the WAAM conical shell part. The results show that compared with the offset filling WAAM, the oscillate-WAAM conical shell shows the following characteristics: the temperature difference value between the inner and outer walls of the shell is significantly reduced, the cooling rate doubled decreased, the interlayer temperature is above 300°C, as well as the average temperature gradient, the dynamic strain stability value and deformation are reduced by about 50%. Under the same process parameters, the travel speed of Oscillate-WAAM is low, which increased the heat input large and the interlayer temperature high. Meanwhile, the molten pool of Oscillate-WAAM is in consistent with the width of the shell. The molten pool simultaneous solidifying changes the stress state of printed shell form three-dimensional to two-dimensional. All above are conducive to stress release, and reduce the strain and deformation of components. The bimetallic rocket motor shell composed of HS600 and HS950 is manufactured by oscillate-WAAM. The section roundness of the shell is 0.31mm and the overall forming accuracy is $\pm 0.625\text{mm}$. The deposited metal in HS600 part of conical shell is composed of pearlite and pro-eutectoid ferrite. While the deposited metal of HS950 is composed of pearlite, acicular ferrite and bainite. The forming accuracy and mechanical properties of conical shell formed by Oscillate-WAAM meet the requirements.

1 Introduction

The conical shells are widely used in aerospace field, serving under severe environment of high temperature and high pressure. It needs to possess high forming accuracy because its section roundness will affect the motion performance of the aerospace craft [1–2]. At present, the conical shells are formed by rolling the plates into cylindrical shape, then utilizing butt-welding connecting longitudinal seam, and finally rolling to a taper shell member. During the butt-welding process, there is huge welding stress in the longitudinal seam, which reduced the roundness of section and the overall forming accuracy of the component [3]. For multi-material conical shell, there are not only longitudinal seam, but also ring seam, which impose great stress and deformation on the shell, further affecting shell's forming accuracy and mechanical properties.

Wire arc additive manufacture (WAAM) uses arc as heat source to melt down the metal wires; the component is formed layer by layer [4]. WAAM can realize the near-net forming of conical shell, which can effectively avoid the deformation of shells in the forming process [5]. WAAM is prone to form multi-material components, which can reduce the stress and deformation during the forming process of multi-material shell [6–7].

The path planning determines the movement of heat source in WAAM, which changes the temperature field and strain curve of the shell, a key factor affecting its overall forming accuracy and mechanical properties [8–10]. The common path planning methods of WAAM are divided into scan filling and offset filling. Ding et al. proposed a novel scan-filling path planning method, effectively decreasing the

probability of non-fusion defects in WAAM components [8]. Dai et al. used WAAM to form multi-directional pipe of high-buildings. During the path planning, the inner and outer contours of the pipe were first formed, and then the contours were filled by offset-filling method [9]. He et al. planned the printing path of the propeller by surface-slice method, the axial and circumferential scanning filling methods were adopted while manufacturing the blades [10]. Both two methods used multi-layer multi-pass overlapping methods to form large metal parts. The accumulated overlap error between single-pass will reduce the forming accuracy of members. In addition, large number of overlaps makes the parts be prone to produce defects, which reduces its properties.

In order to improve the forming accuracy and mechanical properties of WAAM parts, Ma et al. studied the oscillating arc additive manufacturing process in the formation of aluminum alloy components, founding that this technology could improve the surface quality of the components [11]. Xu et al. introduced the influence of oscillating arc on the surface quality, non-fused defects and microstructure of WAAM components. The oscillating deposition layer possess smaller wetting angle and larger width to height ratio, which is beneficial to the fusion between the deposition layers and can improve the forming accuracy of components [12]. Armando et al. did research on the influence of WAAM path planning of martensitic stainless steel on the microstructure and mechanical properties of parts, resulting that the swing path planning method can improve the hardness and mechanical properties of components [13]. Drisu et al employed oscillating CMT arc additive to manufacture low-alloy high-strength steel members, discovering that the oscillating arc changed the temperature field and thermal cycle curve of the members [14]. Aldalur et al. respectively used offset and swing path planning to form straight wall components, and found that the latter one can effectively improve manufacturing efficiency [15]. The existing research results show that the oscillate-WAAM can not only improve the forming accuracy and mechanical properties of components, but also reduce the number of overlaps formed by a single layer, as well as avoiding overlap accumulated errors and defects.

The temperature field and stress field of the WAAM component determine its mechanical properties and forming accuracy. Zhao et al. established a three-dimensional transient heat transfer model in the WAAM to researched the temperature field and thermal cycle curve of a single-pass multi-layer straight-wall, and found that the temperature gradient of the molten pool decreases with the deposition height increasing [16]. Bai et al. applied numerical simulation methods to study the evolution of the temperature field of WAAM components. A thermal imager was used to calibrate the parameters of the heat source for improving the accuracy of WAAM numerical simulation [17]. Mughal et al. used finite element analysis to analyze the residual stress and deformation of multi-channel single-layer WAAM members, resulting that the complicated thermal cycle of the components was the main cause of deformation [18]. Zhao et al. spotted that the temperature and stress field of the component can vary with the printing path by establishing thermo-mechanical model [19]. However, most of these research focused on the straight wall, whose temperature field is quite different from the actual temperature field of WAAM parts. Zhao et al. analyzed the temperature field distribution of the rotary body and divided it into three phase: the heating phase, quasi-steady-state phase and steady-state phase. The result showed that controlling the interlayer temperature can effectively improve the forming accuracy of the component [20]. Xiong et al.

analyzed the temperature distribution of the ring members, the results showed that with the height increasing, the temperature gradient decreases and the direction of heat dissipation changes from circumferential to axial direction [21]. At present, the research of WAAM temperature field and stress field are focused on the straight-walled or circular ring components formed by multi-layer multi-pass overlapping methods. There are few research on the temperature field and dynamic strain in the forming process of oscillate-WAAM components, which is not conducive to manufacture high-precision and performance oscillate-WAAM components.

This paper studies the temperature field, dynamic strain and deformation of the oscillate-WAAM conical shell, reveals the deformation law of oscillate-WAAM process. Finally, an oscillate-WAAM rocket motor bimetallic conical shell is manufactured, further its forming accuracy and mechanical properties are evaluated.

2 Experimental Materials And Methods

The forming system consists of a KUKA KR30HA robot, a cold metal transfer (CMT) welding machine and dual-axis positioner. The deposition material used in an oscillate-WAAM conical shell is a metal-type flux-core wire with a diameter of 1.2 mm, whose metal chemical composition are shown in Table 1. The schematic diagram of the cross-sectional path planning of conical shell formed by the oscillate and the offset filling process is shown in Figure 1. Among the oscillate filling process is triangular swing, and the offset filling offset from the outside to the inside.

Table 1 Flux-core Wire Chemical Composition (wt / %)

	C	Mn	Si	S	P	Mo	Cu	Ti	Ni	Cr
HS600	0.07	1.75	0.70	0.012	0.013	0.38	0.21	0.015	0.03	0.03
HS950	0.075	1.98	0.46	0.001	0.006	0.73	0.21	0.024	3.44	0.24

The FLIR A655sc thermal imager is used to measure the oscillate-WAAM conical shell forming process. A conical shell sample was manufactured on a Q235 substrate with a thickness of 8mm. The outer diameter of the bottom surface of the sample is 150mm, the inner diameter is 110mm, the wall thickness is 20mm, the height is 60mm, and the taper angle is 21.8°. The focal-length of the thermal imager is 18mm, the temperature range is 0-1500°C, and the thermal imager layout is shown in Figure 2(a).

The dynamic strain in WAAM process is measured by XL2101B5G resistance strain gauge. The sample is divided into two parts. The lower part with a height of 30mm is formed firstly, and then the high-temperature strain gauge is uniformly spot welded around the sample as shown in Fig. 2 (b). The remaining upper half was formed subsequently, in which period the dynamic strain curve was recorded. The strain gauge is 2.5mm away from the upper of sample, arranged at 60° intervals in the circumferential. The sampling duration of resistance strain gauge was 10min, the sampling frequency was 0.5Hz and each measuring point collected 1200 samples.

The deformation of sample is measured by Powerscan surface structured light 3D scanner. The sample is divided into two parts. The lower part with a height of 30mm is formed firstly, and then the marker points are pasted at 2.5mm from the upper surface with a 60-degree angle interval, as shown in Fig. 2 (c). The 3D model of the part is obtained by scanner, and the current coordinate Q_i of the mark point center is recorded. Subsequently, the 3D model of the specimen with a height of 60 mm and the center coordinate P_i of the marker point were measured after forming. Finally, the model is imported into Geomagic Qualify software for packaging and 3D comparison, and the relative distance between Q_i and P_i is analyzed, which is the deformation of the shell in the manufacturing process.

The conical shell was fabricated on Q235 substrate with a thickness of 20mm. After deposition, the conical shell 3D model is overall measured, afterwards the measured point cloud data is packaged and 3D compared using Geomagic Qualify software. Meanwhile, the overall forming error is analyzed. Samples were taken on the conical shell to test the mechanical properties, including tensile strength, yield strength and impact test at the -20°C. The microstructure of forming parts is analyzed by optical microscopy, the sample distribution is shown in Fig. 3.

3 Temperature Field, Dynamic Strain And Deformation Of Oscillating Waam

3.1 Temperature field and thermal cycle of Oscillating WAAM

The temperature field of the conical shell formed by Oscillate-WAAM is shown in Fig. 4 (a). The temperature of the inner wall is 1107°C and the temperature of the outer wall is 1026°C, making the temperature difference between the inner and outer sides is 81°C. The temperature field of the conical shell fabricated by offset-filling path planning is shown in Fig. 4 (b) and (c). When the arc is located on the outer wall of the conical shell, the temperature of the inner and outer wall is 957°C and 182°C respectively, and the temperature difference is 775°C. When the arc is located on the inner wall of the conical shell, the temperature of the inner and outer walls are 176°C and 913°C respectively, and the temperature difference is 737°C. Oscillate-WAAM greatly reduces the temperature difference between inner and outer walls of shell.

As shown in Fig. 4 (a), the width of 1200°C isotherm region is basically as same as the shell thickness, the area of 1200°C isotherm is 76mm² and the average temperature gradient is 31°C/mm in the Oscillate-WAAM forming process. As shown in Fig. 4 (b) and (c), the area of 1200°C isotherm is 41mm² and the average temperature gradient is 65°C/mm in the offset-filling forming process. The oscillate-WAAM increases the area of 1200°C isotherm by 35mm² and decreases the average temperature gradient by 34°C/mm. In the forming process of Oscillate-WAAM, the heat only transfers along the axis direction of the formed shell. However, the heat of the offset-filling conical shell not only transfers downward along the shell axis, but also transmits along the thickness direction. Therefore, the Oscillate-

WAAM conical shell forms a temperature field with small temperature gradient and uniform temperature distribution.

The thermal cycle curve in Oscillate-WAAM forming process is shown in Fig. 5(a), and its peak temperature, interlayer temperature and cooling rate values are shown in Table 2. The interlayer temperature gradually increases and then stabilizes at about 300°C. The cooling rate gradually decreases and then stabilizes at about 2°C/s. Nevertheless, the thermal cycle curve in offset-filling forming process is shown in Fig. 5(b), and its peak temperature, interlayer temperature and cooling rate values are shown in Table 2. The interlayer temperature gradually increases and then stabilizes at about 150°C. The cooling rate gradually decreases and then stabilizes at about 4°C/s. The interlayer temperature increases 146.7°C, cooling rate decreases 1.86°C /s in oscillate-WAAM forming process. Hence, the heat diffusion time of the shell is longer, which makes the shell form a uniform temperature field with small temperature gradient.

The arc swings in the thickness direction of the shell, the inside and outside of which are heated uniformly, so that the temperature difference is small. In the case of the same process parameters, the travel speed of Oscillate-WAAM is low, making the heat input large and the interlayer temperature high, which is conducive to the stress release. The width of molten pool formed by Oscillate-WAAM technology is consistent with that of component. The synchronous solidification of molten pool reduces restraint stress between single deposition. It makes the three-dimensional stress state of the shell composed of the axial, circumferential and thickness directions change into two-dimensional stress state composed of the axial and circumferential directions, which reduces the stress of the shell component. Therefore, Oscillate-WAAM technology makes it possible to manufacture conical shell with little residual stress.

Table 2
Characteristic data of thermal cycle curve

	Deposition number	Peak temperature(°C)	Interlayer temperature(°C)	cooling rate (°C/s)
Oscillate filling	1	1231	212	2.52
	2	1092	289	2.34
	3	952	324	2.11
Offset-filling	1	1031	112	4.15
	2	894	134	4.21
	3	795	139	4.35

3.2 Dynamic Strain of Oscillating WAAM

The distribution of dynamic strain measurement points of oscillate-WAAM conical shell is shown in Fig. 6(a). The dynamic strain curves of each measurement point are shown in Fig. 6(b). During the

forming process, the dynamic strain curves variation of Point 1 to Point 6 turn to be increase positively first, decrease to 0 next, then increase negatively, after that increase rapidly to a positive maximum, and finally decrease slowly to a stable value.

When the manufacture starts, the arc thermal conduction makes the dynamic strain curve of Point 1 rise slowly, and its value is about $121\mu\epsilon$. When the arc moves above Point 1, it can be seen from the thermal cycle curve shown in Fig. 5(a) that the temperature can reach 1231°C , at which temperature the shell is in a fully plastic state, and the yield strength is close to 0. Therefore, the dynamic strain curve rapidly decreases to 0. As the arc continues to move away, the molten pool above Point 1 shrinks and produce compressive stress, as is seen when the dynamic strain curve increases negatively to $-154\mu\epsilon$. In the above period, the temperature at Point 1 reaches above 800°C , at which temperature the shell is in a plastic state, and the yield strength is low. The strain and stress of the component are low. As the arc further away from Point 1, the molten pool is completely solidified, and the temperature of the solidified metal and Point 1 uniformity. The shrinkage of solidified metal and Point 1 is constrained by the formed part, resulting a tensile strain of $1052\mu\epsilon$. With the overall cooling of the shell, the strain of Point 1 decreases slowly and finally stabilizes at $923\mu\epsilon$. At this time, the internal stress of Point 1 is 196.9MPa . Point 2 to Point 6 undergo the same thermal process as that of Point 1, so the variation and eigenvalues of dynamic strain curves of Point 2 to Point 6 are basically the same as that of Point 1.

As shown in Fig. 7, the continuous dynamic strain curve of Point 1 shows the same trend as the single-layer strain curve in Fig. 6. In addition, the cumulative effect of strain is observed during the 1st layer to the 4th layer, and the strain stability value gradually increases to $1200\mu\epsilon$. When the 5th and 6th layers are deposited, the strain decreases and becomes stable at $1121\mu\epsilon$. When the 1st to 4th layer are formed, Point 1 is close to the molten pool, and the tensile strain produced by solidification shrinkage gradually superimposed. When the 5th and 6th layers are formed, the Point 1 is more than 10 mm away from the molten pool, out of the heat affected zone of molten pool, and the dynamic strain curve will only fluctuate due to temperature variation. Moreover, the dynamic strain stability value does not change and maintains at about $1121\mu\epsilon$, the internal stress is 230.9MPa .

The dynamic strain stability value of conical shell formed by offset-filling WAAM is $1520\mu\epsilon$, and the internal stress of conical shell is 313.1MPa . The dynamic strain stability value of oscillate-WAAM conical shell decreases by 35.6%, and the stress value lowers by 82.2MPa . Therefore, Oscillate-WAAM technology can reduce the strain and stress of conical shell.

3.3 Deformation of Oscillating WAAM

The 3D measurement model of the oscillate-WAAM conical shell is shown in Fig. 8, where shown in Fig. 8(a) is 3D model of the lower half of the shell with a height of 30mm and shown in Fig. 8(b) is 3D model of the whole shell. The coordinate deviation of the marking points is shown in Table 3. The average error of Oscillate filling shell is $\pm 0.31\text{mm}$, while the average error of offset filling shell is $\pm 0.64\text{mm}$. The temperature field of Oscillate-WAAM shell is uniform, and the temperature gradient, stress and deformation of it are small. This technology suitable for forming high-precision conical shell.

Table 3
Coordinate deviation of marking point of Oscillate-WAAM conical shell

No.	X-axis deviation /mm	Y-axis deviation /mm	Z-axis deviation /mm	Mean deviation /mm
1	0.3048	-0.0814	-0.0912	-0.3408
2	-0.1039	0.2856	-0.1332	0.3318
3	0.1263	0.1309	-0.1784	0.2548
4	-0.2012	0.0457	0.0503	-0.2124
5	-0.0894	0.3056	-0.0290	-0.3197
6	0.0848	0.2570	+ 0.0919	-0.2858

4 Conical Shell Oscillating Waam Forming

The bimetal conical shell of rocket motor is a two-stage structure. The lower part is cylindrical structure formed by HS600 wire, with the outer diameter of 629mm, inner diameter of 589mm and the height of 300mm. The upper part is conical structure formed by HS950 wire, with the tapered angle of 21.8°, height of 650mm, large diameter of 649mm and thickness of 20mm. Its structure and size are shown in Fig. 9(a). The conical shell is fabricated on a Q235 steel plate by oscillate-WAAM. The printing path is obtained by plane slicing process. The oscillate amplitude is 10.0mm, the length is 4.5mm, the period is 0.8s, and the height of each layer is 2.5mm. The conical shell forming process is shown in Fig. 9(b) and (c).

To import the point cloud file into the Geomagic qualify software after measuring conical shell by a 3D scanner is shown in Fig. 10. The overall dimensional error of printed shell was analyzed by 3D comparison. The deviation chromatogram of the overall error is 80% distributed within ± 0.8 mm with an average deviation of ± 0.625 mm. The comparison diagram of the 2D section of the printed conical shell is shown in Fig. 10(b). The roundness error is obtained by comparing the ring section of the printed shell with the standard round. As shown in Table 4, the maximum roundness error is ± 0.31 mm, and the minimum is ± 0.12 mm. The oscillate-WAAM can effectively improve the section roundness and accuracy of the WAAM shell.

Table 4
Section roundness error of conical shell member

Height (mm)	100	200	300	400	500	600	700	800	900
Section roundness error(mm)	± 0.18	± 0.24	± 0.27	± 0.31	± 0.23	± 0.19	± 0.24	± 0.12	± 0.16

The microstructure of the conical shell is shown in Fig. 11. The deposited metal form HS600 is composed of pearlite and pro-eutectoid ferrite with fine and uniform grain size, below 20um. The deposited metal

form HS950 is composed of pearlite, acicular ferrite and bainite, and the grain size is about 15 μ m. When the conical shell is formed by the Oscillate-WAAM, the interlayers temperature is high, the cooling rate is slow, and the temperature field is uniform. Therefore, the conical shell is more likely to possess fine and uniform microstructure. The interface microstructure of HS600 and HS950 is shown in Fig. 11(c). The two kinds of deposition metals are closely bonded, with no cracks or holes defects. The Vickers hardness distribution curve of the interface is shown in Fig. 11(d). The micro-hardness of HS600 part is low, which is 170–190HV. The micro-hardness of HS950 part is high, about 280–300HV, and the hardness transition of the bonding interface is smooth. The mechanical properties of conical shell are shown in Table 5. The tensile strength of HS600 is 652MPa, the yield strength is 534Mpa, the elongation is 32% and the impact toughness at -20°C is 115J. The tensile strength of HS950 is 961MPa, the yield strength is 874Mpa, the elongation is 19% and the impact toughness at -20°C is 87J. To sum up, the oscillate-WAAM conical shell is of excellent mechanical properties.

Table 5
Mechanical properties of the printing conical shell

Material	Yield strength Rp0.2/MPa	Tensile strength Rm/MPa	Elongation A/%	Impact toughness (-20°C)AK/J
HS600	534	652	32	115
HS950	874	961	19	87

5 Conclusions

1. Compared with offset-filling WAAM, the oscillate-WAAM conical shell shows the following characteristics: the temperature difference between the inner and outer is significantly reduced, the cooling rate is doubled decreased, the interlayer temperature is above 300°C, as well as the average temperature gradient, the dynamic strain stability value and deformation are reduced by about 50%.
2. The temperature difference between the inner and outer walls of the shell formed by Oscillate-WAAM is small, which reduces the uneven deformation of the inner and outer sides of the conical shell. The slow cooling rate is conducive to the formation of uniform temperature field, and the high interlayer temperature is benefit to release stress and reduce the strain and deformation of conical shell. Oscillate-WAAM forms a molten pool consistent with the width of the shell. The molten pool simultaneous solidifying changes the three-dimensional to two-dimensional stress state of printed shell.
3. The bimetallic rocket motor conical shell of HS600 and HS950 is formed by oscillate-WAAM. The section roundness of the shell is 0.31mm and the overall forming accuracy is ± 0.625 mm. The deposited metal in HS600 part of conical shell is composed of pearlite and pro-eutectoid ferrite. The deposited metal of HS950 part is composed of pearlite, acicular ferrite and bainite. The forming accuracy and mechanical properties of conical shell formed by Oscillate-WAAM process meet the requirements.

Declarations

Ethical Approval

There are no ethical issues in this paper.

Consent to Participate

Written informed consent for publication was obtained from all participants.

Consent to Publish

No conflict of interest exists in the submission of this manuscript, and manuscript is approved by all authors for publication.

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Authors Contributions

All authors have contributed to the development of the research and in the elaboration of this paper.

Tianying He: Investigation, formal analysis, data curation, write and edit original draft.

Shengfu Yu: writing-review and editing, supervision and funding acquisition.

Runzhen Yu and Bo Zheng: resources and data curation.

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Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

Availability of data and materials

The data can be provided by the corresponding author under reasonable requirements.

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Figures

Figure 1

Path planning schematic (a) Oscillate filling (b) offset filling

Figure 2

Schematic diagram of experimental device (a) temperature field measurement (b) Dynamic strain measurement (c) deformation measurement

Figure 3

Sample drawing (a) block sample position (b) tensile sample size (c) sample distribution

Figure 4

Temperature field of conical shell component (a) Temperature field of Oscillate-WAAM component (b) Offset filling temperature field of arc outside (c) Offset filling temperature field of arc inside

Figure 5

Thermal cycle curve of conical shell (a) Oscillate filling (b) offset filling

Figure 6

Oscillate-WAAM dynamic strain curve (a) Measuring point position diagram (b) Dynamic strain curve

Figure 7

Continuous dynamic strain curve of Piont

Figure 8

Oscillate-WAAM Conical Shell Deformation (a) Lower Half Model (b) Complete Model

(a)

(b)

Figure 9

Oscillate-WAAM conical shell (a) Conical shell model (b) WAAM conical shell

Figure 10

3D measurement model of the conical shell

(a)

(b)

(c)

(d)

Figure 11

Microstructure of WAAM conical shell (a) Optical microstructure of HS600 (b) Optical microstructure of HS950 (c) Optical microstructure of interface (d) Vickers hardness curve