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, and 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’s simultaneous solidifying changes the stress state of printed shell from three-dimensional to two-dimensional. All the above are conductive 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 0.31 mm, and the overall forming accuracy is \(\pm 0.625\) 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.

Keywords Oscillate-WAAM · Temperature field · Dynamic strain · Forming accuracy · WAAM conical shell

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 is not only longitudinal seam, but also ring seam, which impose great stress and deformation on the shell, further affecting the 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, a large number of overlaps make 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 possesses 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 in 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 research 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 phases: 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, and 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 is 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 and offset-filling WAAM conical shell; compares the differences of the two processes in temperature field, dynamic strain, and deformation; and reveals the deformation law of oscillate-WAAM process. Finally, an oscillate-WAAM rocket motor bimetallic conical shell is manufactured; furthermore, 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 a dual-axis positioner. The deposition material used in an oscillate-WAAM conical shell is HS600 and HS900 metal-type

|         | 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|
flux-core wire with a diameter of 1.2 mm. The metal chemical composition is shown in Table 1. The chemical composition in Table 1 meets the QJ3199-2004 national standard. The schematic diagram of the cross-sectional path planning of conical shell formed by the oscillate and the offset filling process is shown in Fig. 1. Among the oscillate filling processes is triangular swing, and the offset filling offset from the outside to the inside. The oscillate-WAAM parameters in Table 2 to ensure that the accumulation of metal is well formed and the structure and mechanical properties of the components meet the requirements.

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 8 mm. The inner diameter of conical shell is 110 mm, the outer diameter is 150 mm, the wall thickness is 20 mm, and the cone angle is 21.8°. The dimensions are reduced in equal proportion to the actual components. The focal-length of the thermal imager is 18 mm, the temperature range is 0–1500 °C, and the thermal imager layout is shown in Fig. 2a.

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 30 mm is formed firstly, and then the high-temperature strain gauge is uniformly spot welded around the sample as shown in Fig. 2b. The remaining upper half was formed subsequently, in which period the dynamic strain curve was recorded. The strain gauge is 2.5 mm away from the upper part of the sample, arranged at 60° intervals in the circumferential. The sampling duration of resistance strain gauge was 10 min, the sampling frequency was 0.5 Hz, 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 30 mm is formed firstly, and then the marker points are pasted at 2.5 mm from the upper surface with a 60-degree angle interval, as shown in Fig. 2c. Then, the 3D model S1 of the current component is obtained by the 3D scanning and the coordinate Qi (Xi, Yi, Zi) of the measuring point analyzed by the Geomagic Qualify software. Next, the conical shell was formed. After forming, the 3D model S2 of the current component is measured by a 3D measuring, and the coordinate Pi (Xi', Yi', Zi') of the measuring point is analyzed by Geomagic Qualify software. Formula (1) for calculating the relative distance is L, which is the deformation of the shell in the manufacturing process:

\[ L = \sqrt{(X_i - X_i')^2 + (Y_i - Y_i')^2 + (Z_i - Z_i')^2} \]  

(1)

The conical shell was fabricated on Q235 substrate with a thickness of 20 mm. After deposition, the conical shell 3D model is overall measured; afterward, 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 –20 °C. The samples used in this paper to measure the impact toughness are sampled and processed in accordance with the GB/T229 standard. The sample is shown in Fig. 2. The sample length is 55 mm, the sample width is 10 mm, and the notch angle is 45°.
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. 4a. 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 81 °C. The temperature field of the conical shell fabricated by offset-filling path planning is shown in Fig. 4b 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 is 176 °C and 913 °C respectively, and the temperature difference is 737 °C. Oscillate-WAAM greatly reduces the temperature difference between the inner and outer walls of shell.

As shown in Fig. 4a, the width of the 1200 °C isotherm region is basically the same as the shell thickness; the area of 1200 °C isotherm is 76 mm², and the average temperature gradient is 31 °C/mm in the oscillate-WAAM forming process. As shown in Fig. 4b, c, the area of 1200 °C isotherm is 41 mm², 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 35 mm² 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. 5a, and its peak temperature, interlayer temperature, and cooling rate values are shown in Table 3. 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. 5b, 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 makes it possible to manufacture conical shell with little residual stress.
3.2 Dynamic strain and stresses of Oscillating WAAM

The distribution of dynamic strain measurement points of oscillate-WAAM conical shell is shown in Fig. 6a. The dynamic strain curves of each measurement point are shown in Fig. 6b. During the forming process, the dynamic strain curve variation of point 1 to point 6 turns to be increased positively first, decreases to 0 next, then increases negatively, after that, increases rapidly to a positive maximum, and finally decreases 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 με. When the arc moves above point 1, it can be seen from the thermal cycle curve shown in Fig. 5a 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 produces compressive stress, as is seen when the dynamic strain curve increases negatively to ~154 με. 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 moves 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 in a tensile strain of 1052με. With the overall cooling of the shell, the strain of point 1 decreases slowly and finally stabilizes at 923 με. At this time, the internal stress of point 1 is 196.9 MPa. 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 με. When the 5th and 6th layers are deposited, the strain decreases and becomes stable at 1121 με. When the 1st to 4th layers 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, 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 με; the internal stress is 230.9 MPa.

The dynamic strain stability value of conical shell formed by offset-filling WAAM is 1520 με, and the internal stress of conical shell is 313.1 MPa. The dynamic strain stability

| Table 3 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 |
value of oscillate-WAAM conical shell decreases by 35.6%, and the stress value lowers by 82.2 MPa. The blind hole drilling method is used to measure the residual stress of conical shells manufactured by oscillate-WAAM and offset-filling WAAM respectively. The measurement results are shown in Table 4. Compared with the offset-filling WAAM conical shell, the average residual stress of the oscillate-WAAM conical shell is reduced by 26%. 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 in Fig. 8a is the 3D model of the lower half of the shell with a height of 30 mm and in Fig. 8b is the 3D model of the whole shell. The coordinate deviation of the marking points is shown in Table 5. The average error of oscillate filling shell is ±0.31 mm, while the average error of offset filling shell is ±0.64 mm. The temperature field of oscillate-WAAM shell is uniform, and the temperature gradient, stress, and deformation of it are small. This technology is suitable for forming high-precision conical shell.

### 4 Conical shell oscillating WAAM forming

The bimetal conical shell of rocket motor is a two-stage structure. The lower part is a cylindrical structure formed by HS600 wire, with the outer diameter of 629 mm, inner diameter of 589 mm, and the height of 300 mm. The upper

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**Table 4** Residual stress of conical shell

| Point | Oscillate-WAAM(MPa) | Offset-filling WAAM(MPa) |
|-------|---------------------|--------------------------|
| #1    | 210.2               | 298.5                    |
| #2    | 225.3               | 287.5                    |
| #3    | 214.9               | 301.2                    |
| #4    | 232.8               | 314.4                    |
| #5    | 245.7               | 295.3                    |
| #6    | 218.6               | 324.5                    |
| #7    | 223.5               | 289.5                    |
| #8    | 213.5               | 315.6                    |
| #9    | 232.6               | 304.5                    |
| #10   | 218.9               | 291.2                    |
| Average value | 223.6 | 302.2                    |

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**Fig. 7** Continuous dynamic strain curve of point

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**Fig. 8** Oscillate-WAAM conical shell deformation: a lower half model; b complete model
part is a conical structure formed by HS950 wire, with the tapered angle of 21.8°, height of 650 mm, large diameter of 649 mm, and thickness of 20 mm. Its structure and size are shown in Fig. 9a. 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 10.0 mm, the length is 4.5 mm, the period is 0.8 s, and the height of each layer is 2.5 mm. The conical shell forming process is shown in Fig. 9b.

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. 10b. The roundness error is obtained by comparing the ring section of the printed shell with the standard round. As shown in Table 6, 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.

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

| Table 5 | 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           |
size, below 20 µm. The deposited metal form HS950 is composed of pearlite, acicular ferrite, and bainite, and the grain size is about 15 µm. When the conical shell is formed by the oscillate-WAAM, the interlayer 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 microstructure in Fig. 11a is the formed by HS600 metal wire, which is located in the cylinder area of conical shell. The microstructure of Fig. 11b is the formed by HS900 metal wire, which is located in the conical region of conical shell. The microstructure of Fig. 11c is the bonding region of HS600 and HS900 metal wire, which is located in the connecting region of the cylinder and the conical region. The two kinds of deposition metals are closely bonded, with no cracks or holes defects. The Vickers hardness distribution curve of the interface is

Table 6 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 | ±0.19 | ±0.24 | ±0.12 | ±0.16 |
shown in Fig. 11d. 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 7. The tensile strength of HS600 is 652 MPa, the yield strength is 534 Mpa, the elongation is 32%, and the impact toughness at −20 °C is 115 J. The tensile strength of HS950 is 961 MPa, the yield strength is 874 Mpa, the elongation is 19%, and the impact toughness at −20 °C is 87 J. To sum up, the oscillate-WAAM conical shell is of excellent mechanical properties.

5 Conclusions

In this paper, high-precision conical shell is fabricated by oscillate-WAAM, and the temperature distribution is measured by thermal imager, the dynamic strain curve is measured by dynamic resistance strain gauge, and the deformation is measured by 3D measuring instrument. Finally, the temperature distribution and dynamic strain variation of the oscillate-WAAM are obtained. The results show that the temperature field of oscillate-WAAM conical shell is more

Table 7  Mechanical properties of the printing conical shell

| Material | Yield strength Rp0.2/MPa | Tensile strength Rm/MPa | Elongation A/% | Impact toughness (−20°C) A_{k}/J |
|----------|--------------------------|-------------------------|----------------|----------------------------------|
| HS600    | 534                      | 652                     | 32             | 115                              |
| HS950    | 874                      | 961                     | 19             | 87                               |
uniform, and the molten pool is solidified synchronously. This makes the strain, residual stress, and deformation of the component smaller. Therefore, the oscillate-WAAM can manufacture conical shell with high roundness and forming accuracy.

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 double decreased, the interlayer temperature is above 300 °C, and 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 beneficial 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’s simultaneous solidifying changes the three-dimensional to two-dimensional stress state of the 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 0.31 mm, 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.

Author contribution All the 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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Declarations

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