

Numerical study of heat transfer characteristics in positional wire and arc additive manufacturing

Dongqing Yang

School of Materials Science and Engineering, Nanjing University of Science and Technology, Nanjing, China, and

Jun Xiong and Rong Li

Key Laboratory of Advanced Technologies of Materials, Ministry of Education,
School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu, China

Abstract

Purpose – This paper aims to fabricate inclined thin-walled components using positional wire and arc additive manufacturing (WAAM) and investigate the heat transfer characteristics of inclined thin-walled parts via finite element analysis method.

Design/methodology/approach – An inclined thin-walled part is fabricated in gas metal arc (GMA)-based additive manufacturing using a positional deposition approach in which the torch is set to be inclined with respect to the substrate surface. A three-dimensional finite element model is established to simulate the thermal process of the inclined component based on a general Goldak double ellipsoidal heat source and a combined heat dissipation model. Verification tests are performed based on thermal cycles of locations on the substrate and the molten pool size.

Findings – The simulated results are in agreement with experimental tests. It is shown that the dwell time between two adjacent layers greatly influences the number of the re-melting layers. The temperature distribution on both sides of the substrate is asymmetric, and the temperature peaks and temperature gradients of points in the same distance from the first deposition layer are different. Along the deposition path, the temperature distribution of the previous layer has a significant influence on the heat dissipation condition of the next layer.

Originality/value – The established finite element model is helpful to simulate and understand the heat transfer process of geometrical thin-walled components in WAAM.

Keywords Numerical simulation, Additive manufacturing, Heat transfer, GMA, Inclined thin-walled part

Paper type Research paper

1. Introduction

With the increasing emphasis on a sustainable industry, additive manufacturing (AM) has received substantial attention because of its ability to fabricate fully functional metal components with complex shapes (Williams *et al.*, 2016). In general, AM processes can be powered by laser, electron beam and arc (Ding *et al.*, 2014). Compared with the other two kinds of power sources, arc-based AM has predominant advantages in terms of reducing production costs and manufacturing time (Busachi *et al.*, 2015; Brandl *et al.*, 2012). Therefore, arc-based AM has a potential application in manufacturing medium-scale and large-scale parts with variable weldable materials, such as carbon steel, Al alloy, Ti alloys and Ni alloys (Frazier, 2014).

Arc-based AM can be mainly categorized into three types: gas metal arc (GMA) (Spencer *et al.*, 1998), gas tungsten arc

(GTA) (Geng *et al.*, 2017) and plasma arc (PA) (Martina *et al.*, 2012). To obtain a higher deposition rate, the AM process using GMA as the heat source is gaining increasingly popularity in recent decades. During GMA-based AM, the filler material in the form of wire is fed at a predefined rate and melted by the GMA arc established between the wire electrode and the previous layers. As the arc moves away, the melted materials solidify rapidly and then form a continuous line structure on the substrate. A three-dimensional structure with desired geometries can be built layer by layer and undergoes a complex thermal process due to the repeated non-uniform heating and cooling cycles. As introduced by Zhao *et al.* (2011), during the GMA-based AM process, the complex thermal history is prone to producing the thermal stress and residual stress, which may lead to the occurrence of distortions and cracks in deposited parts. Thus, a better understanding and quantitative

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Rapid Prototyping Journal
26/9 (2020) 1627–1635
© Emerald Publishing Limited [ISSN 1355-2546]
[DOI 10.1108/RPJ-01-2020-0016]

Funding: This work was funded by National Natural Science Foundation of China, no. 51975491 and no. 51805266, Sichuan Science and Technology Program, no. 2020YFG0197 and no. 2019YFG0354, and the Fundamental Research Funds for the Central Universities, no. 30919011411.

Received 22 January 2020

Revised 14 May 2020

Accepted 30 June 2020

knowledge of the thermal behavior in GMA-based AM is extremely essential for mitigating the residual stress and distortions of fabricated components.

Currently, reported researches on the thermal behavior have usually been conducted through experimental and finite element methods. As the GMA process involves localized heating, high temperature distributions and fast cooling rates, accurate measurements of thermal cycles are deemed to be difficult. Yang *et al.* (2017) investigated the thermal behavior and the effect of inter-layer cooling time on the thermal propagation of thin-walled components built in GMA-based AM by means of an infrared camera. To reduce the experimentation and observe dynamic thermal and stress histories, many researchers chose the finite element modeling to study the thermomechanical behavior of parts deposited in arc-based AM. Ding *et al.* (2011) developed a steady-state finite element model to study the residual stresses of large-scale components fabricated by GMA-based AM, reporting that the calculated results were in good agreement with experimental tests and the computational time could be saved by 80% compared to conventional transient models. A three-dimensional finite element model was established by Mughal *et al.* (2006) to investigate residual stress-induced deformations in multi-pass single-layer weld-based rapid prototyping. It was found that the unexpected deformations during the deposition were mainly caused by the complicated thermal cycling. As reported in Mughal *et al.* (2005), a two-dimensional finite element thermo-mechanical model was presented to study the effect of deposition sequence on residual stresses and deformations of metallic parts in layered manufacturing using GMA. Their results showed that the depositing sequence, from edges to center, minimized the residual stresses of the deposition. Bai *et al.* (2013) conducted the thermal analysis of multi-layer single-pass depositions by weld-based AM with calibrated model input parameters, finding that the prediction error of temperature calculations could be less than 30°C. Based on the same calibration technique, Bai *et al.* (2015)

simulated the temperature distribution and residual stresses of a thin-walled component in induction-assisted weld-based AM. Their results revealed that both induction preheating and postheating led to a more homogeneous heat input and reduced temperature gradients.

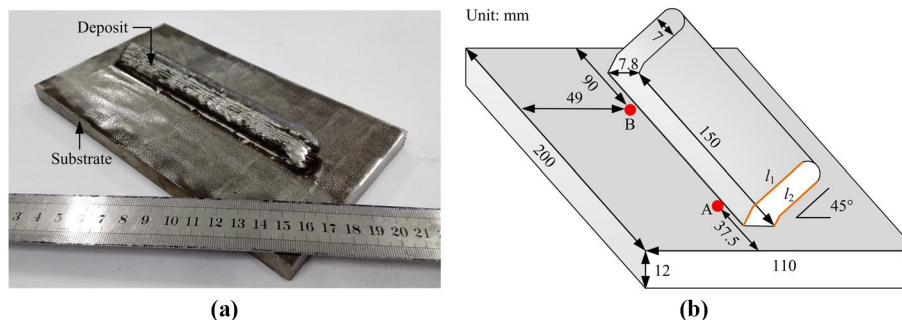
As discussed above, most publications have been focused on the thermal behavior of simple thin-walled parts in which the growth directions of deposition layers are vertical to the substrate surface, and little has been paid to inclined thin-walled parts with complex geometric features. However, inclined thin-walled parts show more valuable applications in the empirical industrial field. In comparison to vertical parts, the heat behavior of inclined thin-walled parts during the fabrication process must exhibit different characteristics. In a previous publication of authors (Li and Xiong, 2019), the residual stress of components with geometrical features was investigated via a coupled thermo-mechanical analysis. It was found that the residual stress distribution in the substrate was asymmetrical and large residual stresses occurred at the substrate–component interfaces.

This paper develops a three-dimensional finite element model of an inclined thin-walled part in GMA-based AM. The heat evolution, thermal cycle characters and temperature gradient on the substrate and the deposited component are investigated in the following. The calculated results are verified by measuring the thermal cycle curves of points on the substrate and the size of molten pool.

2. Experiments

As shown in Figure 1(a), an inclined thin-walled component was manufactured on a mild steel substrate (material grade Q235B) using a wire feed GMA-based AM experiment system. The wire electrode was made of H08Mn2Si with 1.2-mm diameter. The chemical compositions of the substrate and wire are listed in Table 1. Figure 1(b) displays the schematic and dimensions of the component. The substrate is 200 mm in

Figure 1 The inclined thin-walled component fabricated by GMA-based AM



Notes: (a) Real part; (b) dimensions and thermocouple locations

Table 1 Chemical compositions of experiment materials (Wt. %)

Materials	C	Si	Mn	P	S	Cr	Ni	Fe
Substrate	0.12–0.20	≤0.3	0.3–0.7	≤0.045	≤0.045	≤0.3	≤0.3	Remainder
Wire	0.06–0.15	0.65–0.95	1.8–2.1	≤0.025	≤0.025	≤0.2	≤0.3	Remainder

length, 110 mm in width and 12 mm in height. The inclined wall has a wall length 150 mm and a wall thickness varying between 7 and 7.8 mm. Except the bottom part, the component is tilted at 45° with the horizontal substrate.

During the fabrication process, a positional deposition method shown in Figure 2 is adopted, in which the torch axis is set to be parallel to the *XY* plane with an angle to the *y*-axis of 45°. This positional fabrication technique can greatly reduce the movement of components and get rid of the dependence on the positioner. The main process parameters used in the experiment were as follows. The arc voltage was 19 V and the deposition current was 150 A, and the torch travel speed was 5 mm/s. 95% Ar + 5% CO₂ at a flow rate of 18 L/min was used as the shielding gas. After each layer was deposited, an interval time of 42 s was applied to obtain a proper inter-layer temperature. The deposition directions of two consecutive layers were reverse. Temperature cycle curves of points A and B on the top surface of the substrate were acquired by using K type thermocouples (nickel-chromium/nickel-silicon wire) attached on the measured points. The temperature measuring of the K type thermocouple ranged from 0 to 1300°C with an error ±0.8% and the sampling rate was 10 HZ. A MER-125-30UM-L digital camera maintained to be vertical to the torch axis was used to obtain the images of the molten pool. The optical center of the camera was perpendicular to the deposition direction. The images captured by the camera were 8-bit gray scale with a resolution of 1292 × 964 pixels. The molten pool images could be acquired with a sampling frequency of 30 fps/s. For removing disturbances from arc lights, a narrow-band filter having a center wavelength of 685 nm with a width at half maximum of 10 nm was fixed in front of the camera.

3. Finite element model

The commercial finite element software package MSC. Marc is used to perform the heat analysis of a GMA-processed inclined thin-walled part. Figure 3 shows the meshing of the finite element model. *X*-axis is the substrate width direction, *y*-axis is the substrate height direction and *z*-axis is torch travel direction. The eight-node hexahedron element is used for the model. It can be seen that the simulation model consists of ten deposition layers.

Figure 2 Schematic diagram of GMA-based AM process for the inclined component

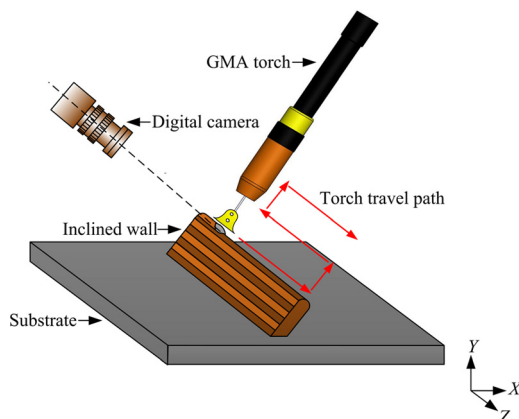
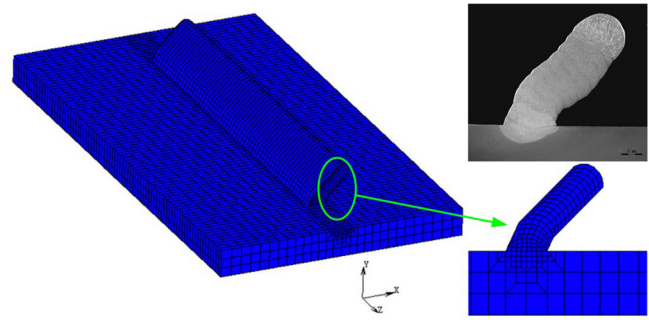


Figure 3 Finite element meshing of the model

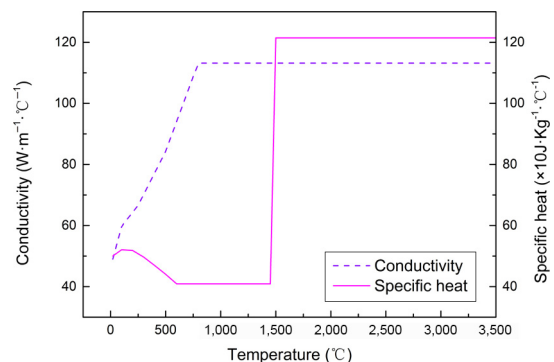


Totally, there are 18,100 elements and 22334 nodes in the model. The elements in deposition layers are activated gradually with the moving of heat source. The material properties of the substrate are assumed to be the same with the adding materials. At room temperature, the melting point is 1425°C, the density is 7.8×10^{-3} g/mm³ and the Poisson's ratio is 0.29. Material properties dependent on the temperature are given in Figure 4. The values of the thermal conductivity are purposely increased due to the stirring effect in the molten pool for temperatures above the melting point (Lindgren, 2001). The latent heat of melting is taken into account by setting the solidus and liquidus temperatures in the interface of the MSC Marc software. The latent heat about 300 kJ/kg will be uniformly released between the solidus and liquidus temperatures. The initial temperatures of all nodes on the model are set at the ambient temperature 25°C. The effects of radiation and convection between the component surface and ambient environment are combined according to Abid and Siddique (2005).

The most commonly used heat source model for GMA-based AM is the double-ellipsoidal volumetric one presented by Goldak *et al.* (1984). Considering the inclination of torch, the general double ellipsoid heat source modified from the Goldak model is applied as the heat source model of GMA-based AM. The power density distributions of the front and rear quadrants are stated as:

$$q_1(x, y, z) = \frac{6\sqrt{3}f_1 Q \sin\beta \sin\theta}{abc_1 \pi \sqrt{\pi \cos\gamma}} \exp \left(-\frac{3x^2}{(a/\sin\beta)^2} - \frac{3y^2}{(bc_0 \gamma)^2} - \frac{3z^2}{(c_1/\sin\theta)^2} \right) \quad (1)$$

Figure 4 Material temperature-dependent properties



$$q_2(x, y, z) = \frac{6\sqrt{3}f_2 Q \sin\beta \sin\theta}{abc_2 \pi \sqrt{\pi} \cos\gamma} \exp \left(-\frac{3x^2}{(a/\sin\beta)^2} - \frac{3y^2}{(bc\cos\gamma)^2} - \frac{3z^2}{(c_2/\sin\theta)^2} \right) \quad (2)$$

The illustration and values of heat source parameters in equations (1) and (2) are given in Li and Xiong (2019). Here, x , y and z refer to the point coordinates in the moving local coordinate systems as presented in Figure 5. There are two coordinate systems involved during the deposition process of the ten layers. One is the global coordinate system fixed in the MSC. Marc software, and another, is the local coordinate system varied with the locations of the moving heat source. In addition, the local coordinate system is divided into two types, as the deposition directions are dissimilar between successive layers. If the deposition direction of the current layer is identical with the Z direction of the globe coordinate systems, the transformation connecting the global and local frames of reference is:

$$\begin{cases} x_{1t} = X - X_0 \\ y_{1t} = Y - Y_0 \\ z_{1t} = (Z - Z_0) - vt \end{cases} \quad (3)$$

Contrarily, the transformation is:

$$\begin{cases} x_{2t} = -(X - X_0) \\ y_{2t} = Y - Y_0 \\ z_{2t} = -(Z - Z_0) - vt \end{cases} \quad (4)$$

where X_0 , Y_0 , Z_0 is the coordinate values of the arc starting point on each deposition layer; v is the deposition velocity; t is the deposition time of the current layer.

4. Results and discussion

4.1 Verification with experimental results

The main purpose of this work is to simulate the heat transfer characteristics of the inclined thin-walled part fabricated in GMA-based AM. Figure 6 shows comparisons between the simulated and related measured thermal cycles of points A and B shown in Figure 1(b). There exist ten peaks and nine valleys in both the simulated and measured curves. The variation trends of the predicted and experimentally determined thermal cycle curves are reasonably similar. After analysis, the calculated temperatures are in agreement with the experimental results. However, it is obvious that temperature errors exist between the solid and dash lines due to various influence factors. The temperature measuring error of the K type thermocouple is less than 1%. The heat conduction between the substrate and the platform is ignored in the course of modeling. What is more, the distribution parameters of the heat source are unchangeable during the whole modeling process. Nevertheless, these parameters are variable in the actual experiment. It can be concluded that the calculated thermal cycle curves coincide with the measured data, validating the accuracy of the proposed simulation model.

Figure 7 shows the molten pool size as the heat source is located at the midpoint of the third layer. As represented in Figure 7(a), the molten pool captured by the digital camera shown in Figure 2 has a length of 14.8 mm. Here, the molten pool length in front of the electrode is ignored because it is difficult to measure and only accounts for a very small proportion of the whole length. The actual dimensions of the molten pool are used to adjust the distribution parameters of the heat source used in the simulation process. Figure 7(b) gives the simulated results, in which the molten pool length is

Figure 5 The coordinate transformation used in the loading of the general heat source model

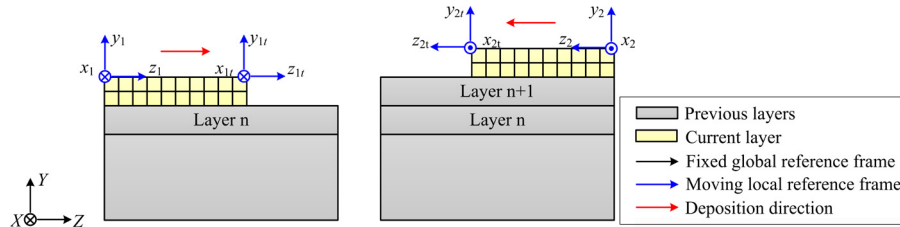


Figure 6 Comparison between experimental and simulated thermal cycles of points A and B

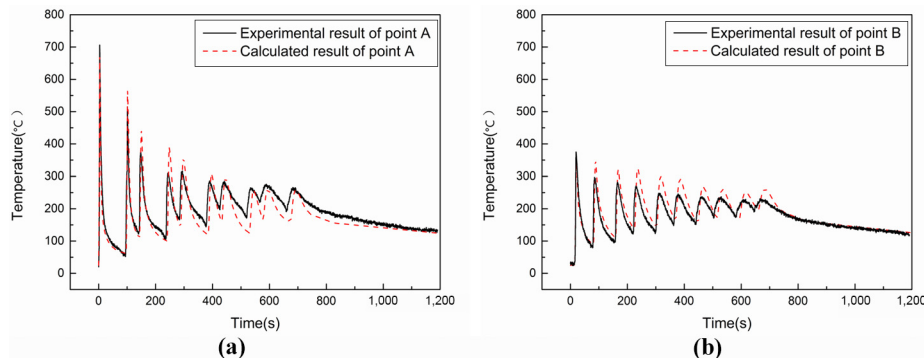
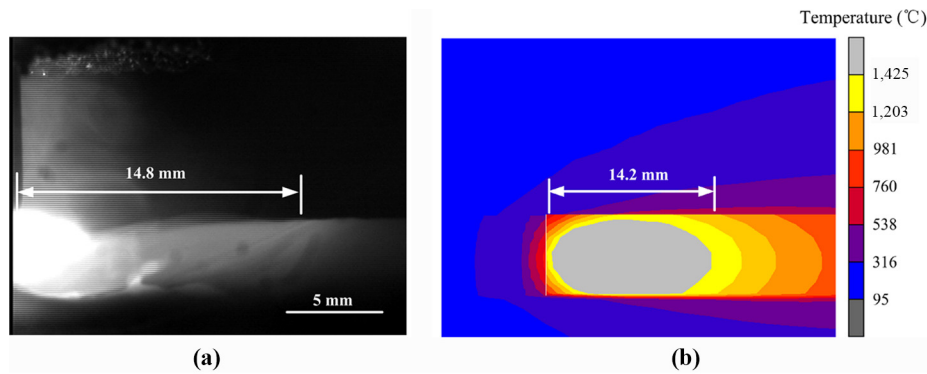


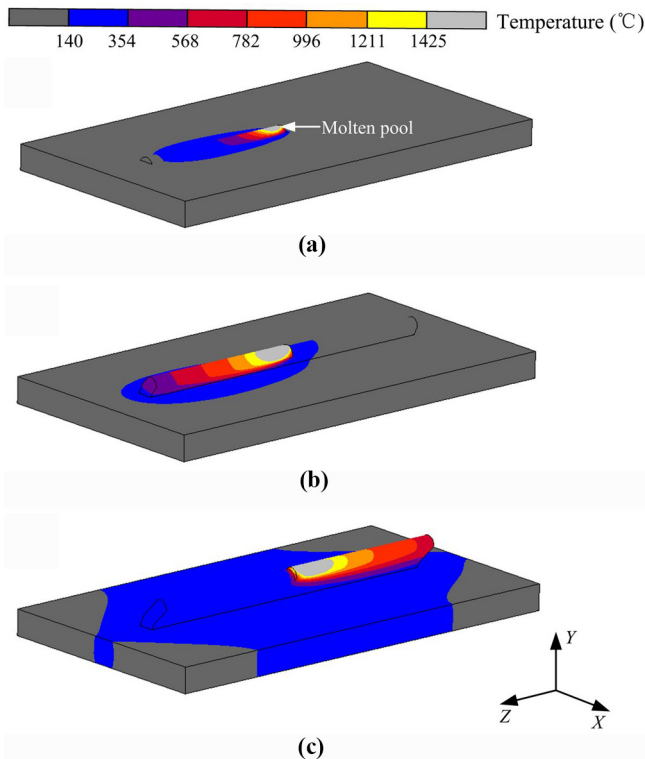
Figure 7 Molten pool shape and size when the heat source moves to the midpoint of the third layer

Notes: (a) Experimental results; (b) computed results

14.2 mm with a 4% error compared to the experimental value. The agreement in the length of the molten pool also indicates that the established model can be used for the further investigations on the temperature field.

4.2 Heat evolution

The temperature field evolution of the fabricated component can be observed intuitively by analyzing the temperature contour maps, as depicted in Figure 8, where (a), (b) and (c) are the temperature distributions as the moving heat source is

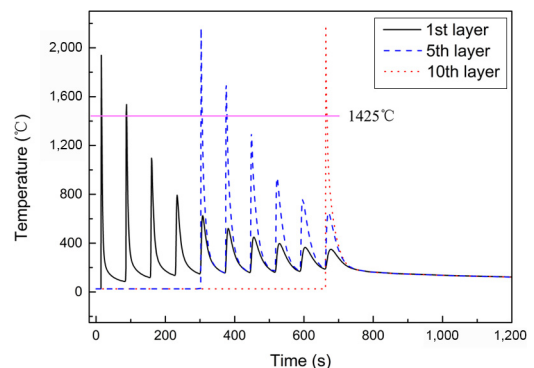
Figure 8 Temperature contours of the established model when the heat source moves to midpoints of different layers

Notes: (a) The 1st layer; (b) the 5th layer; (c) the 10th layer

located at the midpoints of the first, fifth and tenth deposition layers, respectively. As shown in Figure 8, the maximum value of the temperature scale is set at 1425°C, the melting point of the adding material. In this manner, the morphology of the molten pool can be seen clearly from the grey part. With the motion of the heat source along the deposition path, elements making up each layer appear sequentially, forming the deposition layers. It can be seen in Figure 8(a) that as the first layer is deposited, the substrate temperature goes up quickly owing to the significant temperature difference between the newly deposited materials and the substrate. When depositing the subsequent layers [Figure 8(b) and (c)], the high-temperature area of the substrate enlarges and an obvious trailing can be observed in the molten pool.

During the fabrication process, energy inputting into the part is divided into two parts through three basic heat transfer ways: saved in the solidified metals and the substrate by means of the heat conduction or lost to the surrounding environment via convection and radiation. Based on the previous knowledge, the energy input provided by the heat source for ten layers is identical. Since, it can be concluded from the trailing of the molten pool tail that with the increasing of the deposition height, there exists a heat accumulation phenomenon in the molten pool thanks to the heat loss less than the heat input.

As shown in Figure 9, three representative thermal cycle curves of the midpoints in the first, fifth and tenth layers are extracted to analyze the thermal process. It can be observed that the thermal

Figure 9 Calculated thermal cycles of midpoints in different layers

cycles of midpoints in different layers show similar variation trends. The midpoint in the n th layer experiences $10 - n + 1$ decreasing temperature peaks during the whole deposition process. Taking the first layer as an example, the first temperature peak (1764°C) appears when the GMA torch is positioned directly at the midpoint of the first layer. As the heat source leaves away, the temperature of the midpoint decreases quickly due to the heat conduction between the deposited materials and the substrate. The second peak is obtained when the heat source passes by the midpoint of the second layer. It is worth noting that the second temperature peak also exceeds the melting point. Therefore, the midpoint of the first layer is re-melted when the arc moves to the midpoint of the second layer, resulting in a satisfactory metallurgy bonding between the first layer and the second layer. In the fifth layer, there are two peak values exceeding the melting point as well.

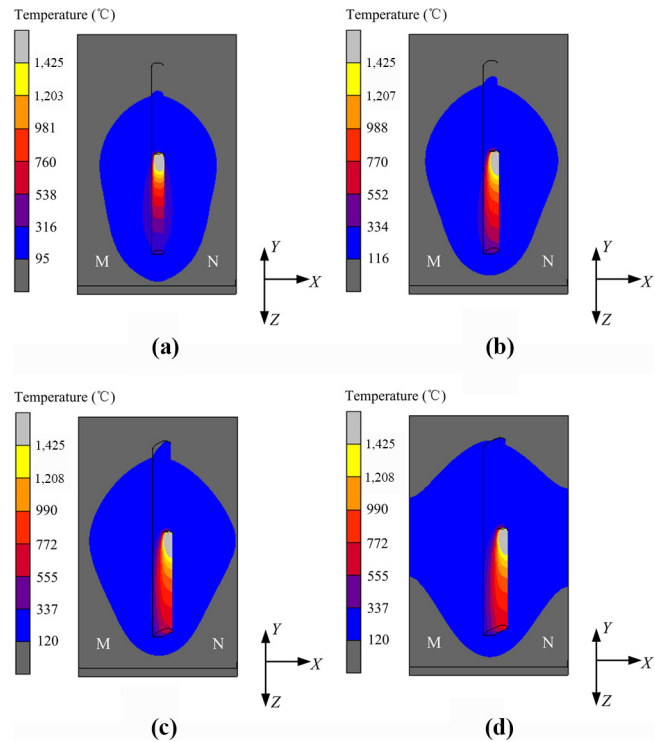
However, the GMA heat source re-melts previous two layers during the deposition of single-pass multi-layer components in Zhao *et al.* (2011). The most possible reason is that the inter-layer dwell time in the current study is 42 s, longer than the 33 s used by Zhao *et al.* (2011). During the inter-layer dwell time, the deposited component cools down by dissipating cumulative heat to the environment. It can be inferred that a longer inter-layer dwell time can avoid excessive re-melting of deposited layers by keeping other process parameters consistent. In addition, the temperature peak values of each layers decrease gradually during the deposition process. This is because the effect of the heat source on the previous solidified layers becomes less with the increasing height.

4.3 Asymmetric temperature field on the substrate

Figure 10 depicts the temperature distributions of the substrate as the heat source moves to the midpoints of the third, fifth, seventh and ninth layers. The whole substrate can be divided into two parts along the longer middle line of the substrate. The region on the left side of the middle line is defined as side M and the region on the right side is side N. As shown in Figure 10(a)-(d), the temperature field on the substrate presents an asymmetric distribution. The high-temperature zone on side N is slightly larger than that on side M, and the difference becomes more obvious with the increase of deposition height. To illustrate this issue further, Figure 11 gives the simulated thermal cycle curves of points C, D, E and F on both sides of the substrate. Points C and F are 14 mm away from the substrate center, and points D and E are 7 mm away from the substrate center. The temperature peaks of points on side N are larger than those of points on side M, and the trough values are almost the same. It can be deduced that more heats are transferred to side N compared with side M. As shown in Figure 1(b), lines l_1 and l_2 are the heat conduction paths between the component and substrate. Lengths of lines l_1 and l_2 are different due to the inclined geometric feature. Obviously, heats are conveyed to side N at a faster rate because line l_2 intersected with side N at the top surface of the substrate is shorter than line l_1 intersected with side M. Ultimately, the sizes of high-temperature region on side M and side N are different, and the temperature peaks of points on side N are larger.

Figure 12 shows the temperature gradients of points D and E when the heat source is located at the midpoints of different

Figure 10 Temperature distributions of the substrate as the heat source is located at the midpoints of various layers

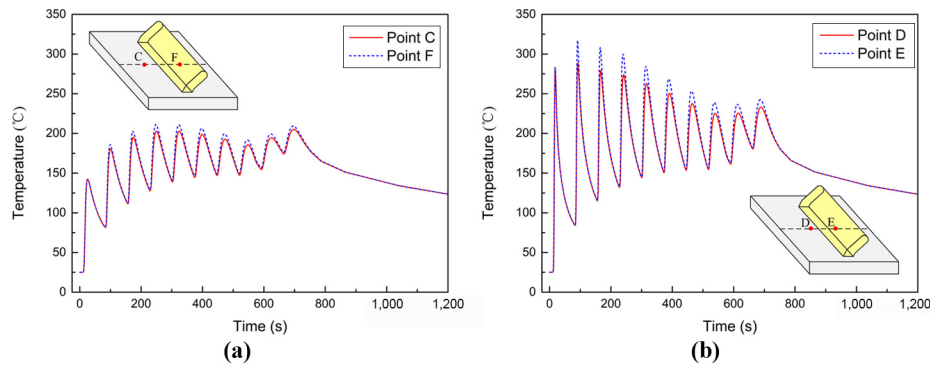


Notes: (a) The 3rd layer; (b) the 5th layer; (c) the 7th layer; (d) the 9th layer

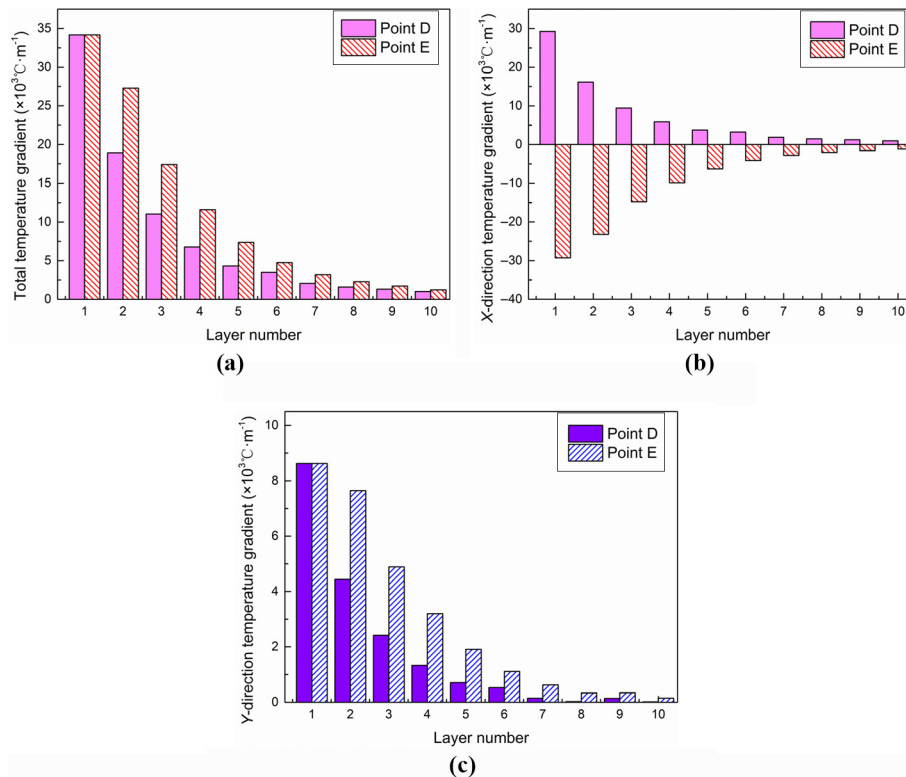
layers. The total temperature gradients of points D and E decline with the increase of deposition layer numbers, indicating a deterioration of the heat dissipation condition. Except for the first layer, the total temperature gradients of point E are larger than those of point D, which implies that point E has a better heat dissipation condition and a higher cooling rate. Thus, although the temperature peaks of point E are larger than those of point D, the trough values are almost the same, as shown in Figure 11(b). The X -direction temperature gradients are positive at point D, while they show negative values at point E. This is because the heat conduction directions along the x -axis at points D and E are contrary. In addition, the absolute values of X -direction temperature gradients at both points are close to those of total temperature gradients. It indicates that the X direction is the main heat dissipation orientation for the substrate. The Y -direction temperature gradients on points D and E present a similar variation tendency with the total temperature gradients. In comparison with point D, point E presents larger Y -direction temperature gradients. From what has been discussed above, the temperature gradients of points in the same distance from the first layer show a significant difference when the heat source is moved to the midpoints of deposition layers.

4.4 Temperature gradient along the deposition path

Figure 13 gives the maximum temperature gradients in the molten pool along the deposition paths of the first, fifth and tenth layers. The temperature gradients in the first layer are

Figure 11 Calculated thermal cycle curves of four points on the top surface of the substrate

Notes: (a) Points C and F; (b) points D and E

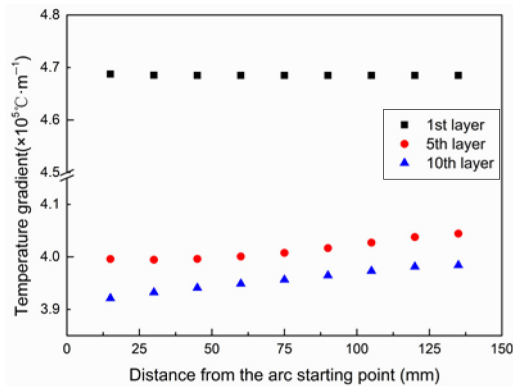
Figure 12 Temperature gradients of points D and E when the heat source is located at the midpoints of different layers

Notes: (a) Total temperature gradient; (b) X-direction temperature gradient; (c) Y-direction temperature gradient

apparently larger than those in the fifth and tenth layers, demonstrating that the heat dissipation condition in the first layer is the best. As shown in Figure 13, the temperature gradient in the molten pool of the first layer experiences a slight decrease along the deposition path. However, the temperature gradients in the fifth and tenth layers show an increasing trend. When depositing the first layer, the melting metals are directly deposited on the substrate. The temperature of the substrate is

first at the room temperature and then increases gradually due to the successive heat input. Therefore, the heat dissipation condition of the first layer gets worse along the deposition path. The fifth layer is deposited on the fourth layer in a reverse deposition direction. The arc starting point of the fifth layer is located at the arc ending point of the fourth layer. On the contrary, the arc ending point of the fifth layer is on the side of the arc starting point of the fourth layer. Consequently, the heat

Figure 13 Calculated maximum temperature gradients in the molten pool along the deposition paths of various layers



dissipation condition gets better from the arc starting point to the arc ending point in the fifth layer. It can be inferred that the temperature distribution of the previous layer shows a significant influence on the heat dissipation state of the next layer.

5. Conclusions

A comprehensive analysis of the thermal history of the inclined thin-walled part fabricated by GMA-based AM has been carried out by experimental and numerical methods. The main findings are listed below:

- The general Goldak double ellipsoidal heat source is used to simulate the inclined GMA torch in software MSC Marc. The calculated results agree with experimental data. Except for the tenth layer, there are two temperature peaks above the melting point in the thermal cycle curves of deposition layers, resulting in a satisfactory metallurgy bonding. The re-melting effect of the heat source on the previously deposited layers decreases with the prolongation of the inter-layer idle time.
- The temperature field on both sides of the substrate is asymmetric during the deposition process. The temperatures of the region with an obtuse angle to the inclined thin-walled part are higher than those of the region with an acute angle to the part. Moreover, the region with higher temperature presents higher temperature gradients and faster cooling rates.
- In the first layer, the maximum temperature gradient in the molten pool gradually decreases along the deposition path, while it shows an increasing trend along the deposition paths of the fifth and tenth layers. The result shows that the temperature distribution of the previous layer has a significant influence on the heat dissipation condition of the next layer.

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Corresponding author

Jun Xiong can be contacted at: xiongjun@home.swjtu.edu.cn