Investigation of Residual Stress in Multi Arc-based Cooperative Metal Additive Manufacturing *

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The multi arc-based cooperative metal additive manufacturing, which consists of two or three wire and arc systems, is more suitable for larger components because of higher deposition rates compared with wire arc additive manufacturing (WAAM). These wire and arc systems can work cooperatively in a concurrent manner in the process of manufacturing the components. In this paper, the residual stress of multi arc-based cooperative metal additive manufacturing is investigated with finite element (FE) simulations. Firstly, on the basis of considering the temperature-dependent thermal-physical properties, the double ellipsoid heat source model is used to establish the calculation model of the molten pool heat transfer in the multi arc-based cooperative metal additive manufacturing. Temperature field distribution of this process is firstly calculated and analyzed. These results are fed into the thermal elastic-plastic FE models and then the stress can be calculated. The analysis of stress evolution in different positions of the deposition layer indicate that the residual stress in the inter-bead is higher than that inside the welding bead.

Key Words: Residual stress, Multi arc-based cooperative metal additive manufacturing, FEM

1. Introduction

In the past two or three decades, wire and arc additive manufacturing (WAAM) has gained more attentions for the fabrication of metal components due to its advantages. Compared with traditional subtractive manufacturing, WAAM is a promising alternative to for fabricating large metal components, such as titanium alloy [1], aluminum alloy [2] and nickel alloy [3]. The multi arc-based cooperative metal additive manufacturing, which consists of two or three wire and arc systems, is more suitable for larger components because of higher deposition rates compared with wire arc additive manufacturing (WAAM). These wire and arc systems can work cooperatively in a concurrent manner in the process of manufacturing the components. This process owns the advantages of WAAM including low-cost equipment, high deposition rate, and high material usage efficiency. Moreover, the deposition rate doubled or tripled.

However, there are some unsolved challenges associated with WAAM. Deformation and residual stress which affect the appearance and fatigue strength significantly are inevitable results in WAAM. The magnitudes of residual stress are usually as large as the yield stresses of raw material. Therefore, it is essential to decrease the stress in the manufacturing process. Long et al. [4] investigated the residual stress in the Metal Insert Gas welding.

The FE simulations with thermo-elastic-plastic methods were used to evaluated the effects of the welding parameters on the residual stress and distortion in butt weld of thin plate. Nishu Ma investigated the welding deformation under a free condition and a jig constraint condition, and the results showed that the jig constraint could reduce the deformation apparently [5]. F. Martina et al. [1] used high-pressure rolling to each layer of a linear Ti-6Al-4V WAAM component in between deposition passes and found that the distortion and residual stress were more than halved.

In this paper, the residual stress of multi arc-based cooperative metal additive manufacturing is investigated with finite element (FE) simulations. Firstly, temperature field is firstly calculated and analyzed. These results are fed into the thermal elastic-plastic FE models and then the stress can be calculated.

2. Finite Element Modelling

2.1 Heat source and thermal analysis

In this section, a 3D thermo-elastic-plastic numerical FE model was developed to obtain the temperature field and subsequently the residual stress during the multi arc-based cooperative metal additive manufacturing process. There were three wire and arc systems which could work cooperatively in a concurrent manner.

According to the experimental results of the specimen, FEM of single layer was built. The shape and sizes of the layer in the FE model were determined by experimental measurement. The width and height of the left and right side are 4mm and 2mm, respectively. And the width and height in the middle are 8mm and 2mm. The arc heat source was represented by a Goldak’s double ellipsoidal heat source model [6]. The method of element birth and death was

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applied to simulate the additive manufacturing process.

The aluminum alloy of ER2319 was employed in this paper. The temperature dependent thermal physical properties and mechanical properties used in the thermal conduction simulation are shown in Fig. 1(a) and (b) respectively. The properties of ER2319 alloy were calculated by Jmatpro software [7]. It was assumed that the material properties of the deposit layer were the same with substrate.

2.2 Thermal-mechanical Model

The multi arc-based cooperative metal additive manufacturing process is a highly coupled thermal-mechanical process. The transient temperature field is obtained from a non-linear thermal analysis. In an isotropic material, the transient temperature \( T(x, y, z, t) \) as a function of time \( t \) and the spatial coordinates \( (x, y, z) \) are governed by the following equation:

\[
k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q = \rho c \frac{\partial T}{\partial t}
\]  

(1)

Where \( q, \rho, c \) and \( k \) are the internal heat source, material density, specific heat capacity and thermal conductivity, respectively.

The boundary conditions were considered in the current investigation, including the convection and radiation from all exposed surfaces. Heat loss due to convection was assumed as shown in Eq. (2). The heat loss on the surface due to radiation to the surrounding was governed by Eq. (3), following the Stefan-Boltzmann law [8]:

\[
q_c = -h(T - T_0)
\]

(2)

\[
q_r = e\varepsilon[(T + 273.15)^4 - (T_0 + 273.15)^4]
\]

(3)

In the following stress and deformation analysis, the temperature distribution obtained in the thermal analysis were used as input data in conjunction with the thermo-mechanical properties and mechanical boundary conditions. The same finite element meshes associated with a 3D stress element were employed in this mechanical analysis.

The total strain increment \( \{d\varepsilon\} \) at the integration point as a function of elastic strain, plastic strain and thermal strain is governed by Eq. (4) below:

\[
d\varepsilon = d\varepsilon^e + d\varepsilon^p + d\varepsilon^th
\]

(4)

Where \( d\varepsilon^e, d\varepsilon^p \) and \( d\varepsilon^th \) are the elastic, plastic and thermal strain increments, respectively [9].

3. Result and discussion

The temperature distribution in the forming process was calculated firstly and then the thermal stresses were obtained on the basis of temperature field. Fig. 2 illustrates the transient temperature at 0.2s, 1s and 2.2s of the multi arc-based cooperative metal additive manufacturing. Element birth and death method was employed in the FEM simulations, and the additive manufacturing process was carried out by element activating step by step. Therefore, the dark blue part in the front of heat source in Fig. 2 is the killed elements whose temperature maintains 300K. In the deposition process, the arcs on the left and right side were applied ahead of the middle one, which is twice in power of the left/right arc (also called leading arc). The main purpose of the leading arcs was to construct the boundaries of the deposition layer. Consequently, the middle arc was applied to fill the material between the boundaries on both sides. These three arcs worked cooperatively in this way and the deposition layer with broader width could be formed.
In order to investigate the evolution of temperature field, three points on each deposition layer were selected as A, B, C. The temperature change curves of each point are shown in Fig.3. The point A and C have the same pattern of temperature evolution that was determined by the model’s symmetry. As for point B, there was a delay compared with the other two points. Because of the sequence of applying the heat source, the temperature at point B reached peak 0.5s later than the points of A and C.

The residual stress can be calculated incrementally on the basis of temperature field at different time of all elements. The simulated von Mises stress of the specimen was shown in Fig.4(a). Four corners of the substrate were fixed by jigs so as to constraint the displacement in X, Y, Z directions. It can be found from Fig.4(a) that the residual stress in the deposition layer was higher than the substrate. The maximum stress distributed in the overlap area of the deposition bead in which cracks tend to be formed. In order to study the stress distribution quantitatively at different positions, two straight lines (line AB and CD) are selected through the center of the upper surface of the deposition layer along the forming direction and perpendicular to the forming direction. The calculated von Mises stresses along AB and CD are shown in Fig.4(b), Fig.4(c).
Fig. 4 (a) von Mises stress distribution (b) von Mises stress along CD (c) von Mises stress along AB

In forming direction, the residual stress ascended sharply to 250 MPa from 30 MPa at the starting point. In the middle part of the deposition layer, the stress fluctuated at about 200 MPa and then decrease to zero in which elements are inactive. The reason why the stress in the beginning and end sections was obviously less than that in the middle section was that there were fewer constraints on the surrounding materials and more free surfaces, so the stress values were low. Perpendicular to the forming direction, the residual stress was higher in the overlap area than that of deposition layer, while it remained relatively stable far away from the overlap.

4. Conclusions

Based on the thermal elastic-plastic FE models of multi arc-based cooperative metal additive manufacturing, the transient temperature distribution during the forming process was investigated firstly. And consequently, the temperature data was input to the thermal-mechanical model to calculate the residual stress. The residual stress in the deposition layer was higher than the substrate. The maximum stress distributed in the overlap area of the deposition bead in which cracks tend to be formed. In the middle part of the deposition layer, the stress remained stable and fluctuated at about 200 MPa.

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