Finite element analysis of clamping form in wire and arc additive manufacturing

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Abstract—A reasonable clamping form can effectively reduce the distortion and defect in wire and arc additive manufacturing. In this paper, a three-dimensional finite element model with verified weld-bead profile and heat source model is established. Using the Simufact.welding finite element analysis software, four typical clamping forms are compared in total distortion and residual stress distribution. The results demonstrate that the edge clamping form has the better performance than the corner clamping form. In edge clamping form, the transversal clamping plays the dominant role than the longitudinal clamping in guaranteeing the dimensional precision. Basing on the analysis of residual stress distribution, the clamping form with only the transversal clamping can obtain the least residual stress distribution.

Keywords—Clamping form; Finite element method; Residual stress; Additive manufacturing.

I. INTRODUCTION

In the field of additive manufacturing, wire and arc additive manufacturing (WAAM) is a kind of promising rapid manufacturing [1, 2]. WAAM uses arc as the heat source and metal wire as the raw material, which can greatly reduce the cost and increases the processing efficiency [3]. Deposition rates can even reach 10 kg/h [4].

The 2D finite element thermo-mechanical model had been presented to predict the residual stress induced deformations [5, 6]. The results shown that the residual stress distribution depended upon the sequence of deposition and the highest stresses were found at the last deposited row. The 3D finite element WAAM model had also been established [7, 8]. Zhao et al [9] studied the thermal stress evolution and the residual stress distribution in a single-pass multi-layer component. The deposition of the last layer dominated the residual stress of whole components, and depositing directions have significant influence on the residual stress distribution of components. Ding et al [10] analyzed the thermo-mechanical behavior of the multi-layer wall structure made by the WAAM process. The stress across the deposited wall is found uniform with very little influence of the preceding layers on the following layers. The clamping form is another important influence factor. Different clamping form can cause different deformation and residual stress. However, experience is the key considering method to choose the clamping form and few studies had focused on it. The large residual strain as well as residual stress caused the knotty problems of deformation and crack.

In this paper, a 3D single-pass multi-layer WAAM model with temperature dependent material properties is presented using the finite element software Simufact.welding. Four clamping forms are established and compared to analyze the different influence. The deformation and residual stress are investigated. To validate the simulation calculated results, the weld-bead profile and heat source model were verified by experiments.

Fig. 1. Wire and arc manufacturing system.
II. VERIFIED MODEL

A. Experimental setup

The wire and arc manufacturing system is shown in Fig. 1. The control cabinet controls the ABB IRB 1410 robot and also communicates with the welding system. The welding system consists of a Fronius TPS3200 CMT welding power supply. A laser vision sensor with an AVT Manta G-283B CCD camera is utilized to take pictures of the welding bead. The bead profile is analyzed by computer using MATLAB.

The wire electrode was ER5356 wire of 1.2mm diameters. The shielding gas of 99.999% Ar was used with a flow rate of 18 L/min. The welding current was set at 200 A, and the welding voltage was set at 20.6 V.

B. Weld-bead profile model

As for the single bead model, many researchers employed the arc, parabola and cosine curves to describe the bead profile [11-13]. Xiong et al [14] demonstrated that the cross section profile is related to the ratio of wire feeding rate to welding speed. Since the height and the width of a single bead are measured, the bead cross-section can be defined as a fitting curve. To model the asymmetry profile, parabola conventional mathematics function is used. The parabola model function is given by (1).

\[ y = ax^2 + h \]  

The experimental result is shown in Fig. 2(a). The value of the height is 3.13 mm and the width is 11.4 mm, which can be used to calculate the parabola model parameters, namely \( a = -0.0963 \) and \( h = 3.13 \). The modeling weld-bead profile is shown in Fig. 2(b)

\[ y = ax^2 + h \]

C. Heat source model

A moving heat source model, namely Goldak double ellipsoidal, is employed in the thermal model [15]. The heat distribution is given by (2), as shown in Fig. 3.

\[ q_r(x, y, z) = \frac{6f_r \sqrt{3Q}}{a \cdot b \cdot d} e^{-3(x/a)^2} \cdot e^{-3(y/b)^2} \cdot e^{-3(z/c)^2} \]

\[ Q = \eta V, f_r = 2 \]

where the parameters of \( a, b, c, f \) are obtained from the experimental welding pool shape, which is shown in Fig. 2(a). The simulating welding pool shape is presented as the red region of Fig. 2(b). The simulation result is suitable for the experimental result.

III. FINITE ELEMENT MODELS

The three-dimensional finite element model is composed of 9 clamping, a substrate and single-pass 6 layers component, which is shown in Fig. 4.

The sub-clamping is a rigid body which represents the workbench and is set as bearing clamping. Clamping 1, 2, 3, 4 are the corner clamping. Clamping 5, 6 are the transversal clamping and clamping 7, 8 are the longitudinal clamping. Clamping 1-8 are configured as fixing clamping. Four clamping forms are used to investigate the influence caused by clamping. The simulation models of four clamping forms are shown in Fig. 5. Clamping form 1, which contains clamping 1-4, is to get the effect of corner clamping. Clamping form 2 contains clamping 5-8, which can investigate the edge clamping. Clamping form 3 contains the clamping 5, 6 and clamping form 4 contains the clamping 7, 8. These two clamping forms are used to verify which side clamping has the more significant influence.

The component is deposited layer by layer. The depositing direction of two adjacent layer is reversely. Global mesh refinement is used to improve the calculation precision. For more obvious result, the thickness of the substrate is chosen as
6 mm, and large welding simulation parameters are used, which are the same as the experiments. The cooling time is set after each layer deposition to reduce the heat accumulation.

IV. RESULTS AND ANALYSIS

A. Comparison of different clamping forms

The simulation parameters were the same ones except the clamping forms. To compare and analyze the results, four sampling lines were chosen in the longitudinal and transversal direction, and Fig. 6 shows their distribution. Sampling line 1 and 2 are the central lines while line 3 and 4 are the offset lines. Transversal sampling line 2 and 4 contain the sampling points in each layer. Total distortion and residual stress had been investigated to analyze each clamping form.

B. Total distortion of component

Total distortion is an essential evaluation index of WAAM. It makes a strong impact on the dimensional precision. Fig. 7 plots the distortion of the substrate in four clamping forms after cooling. The results show that the effect of clamping form 1 is the worst in all sampling lines, and the distortion can reach nearly 6 mm. The clamping form 2 has the least distortion of 1 mm, which means that the edge clamping form is more effective than the corner clamping form. For further study about whether the longitudinal edge or the transversal edge takes the more important factor, clamping form 3 and 4 has been compared. Clamping form 3 has the same distortion trend with clamping form 2 in transversal direction, while the edge-near region’s distortion is more obvious along longitudinal direction due to the lack of longitudinal clamping. Clamping form 4 has little effect to reduce the distortion, and we can conclude that the transversal clamping plays the dominant role in guaranteeing the dimensional precision.

The distortion along with processing time is also been studied. Fig. 8 shows the time historical distortion of the middle points of sampling line 1. The curves contain the processing part and the cooling part. In the processing time, the distortion increases with the development of process, while the distortion decreases in the cooling time. With careful analysis of the processing time, the distortion is almost the same in all clamping forms before 3 layers deposition. Then, the distortion grows quickly in the condition of clamping form 1 and 2, which don’t have the transversal clamping. In the cooling time, the total distortion has reducing trend in each clamping form.

C. Residual stress distribution of component

Effective residual stress along the sampling lines of different clamping forms are illustrated in Fig. 9. The curves are not fully symmetrical due to that the depositing direction of two adjacent layered is reversely, while the difference is not obvious which can be neglected. From Fig. 9(a), (b) and (d), it is evident that the residual stress of clamping form 3 is much lower than other clamping forms, especially in the substrate region of the component. The residual stress of clamping form 2 has poor performance, especially in the substrate region around the component according to Fig. 9(d).
The effective stress is the resultant result, and the longitudinal (y direction) and transversal (x direction) stresses are studied respectively. Stress components of sampling line 1 and 2 of four clamping forms are plotted in Fig. 10. Here we focus on the substrate region under the component, which contains the -50 mm to 50 mm region in longitudinal length and -5.3 mm to 5.3 mm region in transversal length.

The transversal stress under the component region is in the range of -50 MPa to 50 MPa, which is smaller than the longitudinal stress in all clamping forms. The stress components of clamping form 3 has the most different characteristics. Its transversal stress is a bit higher than the others, while its longitudinal stress is evident lowest, which contributes to the least residual stress performance of clamping form 3. The other 3 clamping forms have almost the same performance in stress components. If the low stress is an important consideration and the distortion requirement is not
strict, clamping form 3 may be a great choice.

V. CONCLUSION

In this paper, a three-dimensional finite element model is established. The weld-bead profile and heat source model are verified depending on the experimental data. Four typical clamping forms are compared and the results of total distortion and residual stress distribution are analyzed. The following conclusions can be drawn from the study:

1. Built on the experimental data, the weld-bead profile is verified using a parabola model, and the Goldak double ellipsoidal heat source model is also verified to suit the experimental condition. The simulating welding pool shape is fit for the experimental result.

2. The total distortion results show that the edge clamping form has the least deformation than the corner clamping form. In the edge clamping form, the transversal clamping play the dominant role than the longitudinal clamping in guaranteeing the dimensional precision.

3. According to the analysis of residual stress distribution, the transversal stress in substrate under the component region is smaller than longitudinal stress in all clamping forms. The clamping form with only the transversal clamping can obtain the least residual stress distribution.

REFERENCES
