FEM Simulation Procedure for Distortion and Residual Stress Analysis of Wire Arc Additive Manufacturing

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Abstract. This fundamental research presents an investigation of Wire Arc Additive Manufacturing (WAAM) process on distortion and residual stress using numerical simulation. Further, WAAM geometry was modeled using simplified rectangular bead shape with five layers and three strings. The thermo-mechanical numerical simulation is conducted under consideration of non-linear isotropic hardening modeled by using general purposed FEM software MSC Marc/Mentat. In this simulation, different heat source models (Goldak's double-ellipsoid and rectangular) are implemented and compared, whereby the later model was to be developed by using subroutine provided in the software. For analyzing the residual stress, separation technique between wall and substrate was introduced after the cooling down period. The outcome of this research is to develop an effective procedure to analyze the distortion and residual stress of wire arc additive manufacturing of stainless steel.

1. Introduction

In recent years, numerous studies have predicted that Additive Manufacturing (AM) plays a profound role in the manufacturing industry of the future [1]. Metal AM has become a crucial advanced-manufacturing process of custom-built metal workpieces. There are various advantages in comparison to conventional processes. For instance, AM is one method to replace conventional moulding technologies like casting and forging that often require a higher rate of material usage in machining and cannot meet the continuously demands of a sustainable, lower cost and friendly modern industry. A basic AM discipline comprises a combination of a heat source, motion strategy, and feedstock [2]. In addition, AM is a promising way-out for manufacturing parts or components fabricated of high-end materials such as titanium or aluminium alloys due to the high value of the buy-to-fly ratio [3]. Hence, metallic additive manufacturing processes are subdivided into three different categories which are powder-feed, powder-bed, and wire-feed systems [3, 4].

One of a promising breakthrough for AM techniques is Wire Arc Additive Manufacturing (WAAM) due to its high deposition rate, which enables fast and highly efficient production processes on a large-scale structural parts of medium complexity geometry with lower volume metal workpieces [6]. WAAM is made up of electrical arc heating sources with a metallic wire feeding scheme [2]. In WAAM, the building strategy allows the production of metallic structural components in a layer by layer fashion by utilizing Gas Metal Arc Welding (GMAW) welding process. A component manufactured by a wire-based additive manufacturing method can achieve the tensile strength of a casting or forging complex component [7].

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However, WAAM gives poor surface finish and low accuracy in comparison with powder-bed or beam-melting among the AM technologies so it is crucial to predict the interaction of each assigned welding process parameter with the material properties such as microstructure and residual stresses in order to produce a high quality product. An initial forecast can be made using numerical computation taking thermal-mechanical properties and different boundary conditions into consideration. The finite element modelling (FEM) simulation of WAAM process carries out the similar techniques applied in the multi-passes welding simulation by simulating the heat transfer from the arc to the molten pool of metal workpiece by means of heat source model. Thus, the heat propagation in GMAW-based additive manufacturing is profoundly non-linear transient because of the presence of solidification, multiple fusion and phase transformation [8].

In this paper, an efficient FEM procedure is to be developed in order to analyse the thermal-mechanical behaviour of WAAM process on a five layers and three strings wall structure. A numerical computation is carried out with two different type of heat source models, which are Goldak’s double ellipsoidal and rectangular heat source model by using algorithm configuration of subroutine. A comparison between these two models will be observed and discussed in terms of distortions and residual stresses.

2. Nonlinear FEM Simulation Procedure
In order to make a prediction of distortion of the WAAM structure and possible residual stresses, the general purposed FEM software MSC Marc/Mentat was utilized to conduct the coupled thermo-mechanical numerical simulations.

2.1 Geometrical and Material Modelling
A full 3D-solid FE model of WAAM structure was developed which consists of three sets of geometries as shown in Figure 1(a): a table, a base plate, and multi-layers weld beads. The base plate was modelled with dimension of 200 mm (L) x 97.5 mm (W) x 8 mm (T). Meanwhile for the multi-layered deposited walls with a rectangular-shaped weld bead of 150 mm length was modelled and consistently sketched from the first layer until a complete set of five layers with three strings.

Figure 1. Weld direction and geometrical model of WAAM

A bead geometry modelling of WAAM structure plays an important role to yield a metallic structure with a high degree of geometrical accuracy and smoothness of numerical computation process. In this research, the bead modelling strategy utilizes a much simpler rectangular shape which gives a smaller margin of relative percentage errors and shorter CPU-Time [9]. Hence, this WAAM model applied ‘element birth technique’ to simulate the weld filler material [10]. This technique works as at the initial status of analysis, all the elements of the weld bead are deactivated and then the elements are activated consecutively following the heat source movements [10, 11].
For mechanical boundary conditions, Figure 2 shows the 400N clamping force exerted on the base plate in negatively Y-directions. Furthermore, there are three basic equations that shall be considered in mechanical analysis which are the equilibrium equations, constitutive stress–strain relations and geometric compatibility equations [12]. The variations in the temperature distribution contributes to the deformation of the body via thermal strains and influences the material properties. A large strain was activated as the nonlinear procedure for analysis option which large plastic strains and large deformations are accounted for meanwhile the additive decomposition of elastic, plastic and thermal strain contributions is employed for the stress recovery process [13]. In addition, phase transformation effects in the numerical analysis are not taken into account. Thus, the modelling of the fluid flow is also not comprised because the effect of the fluid flow on the body deformation and stress field can be considered as insignificant [14].

Figure 2. The boundary conditions of the clamping force exerted on the base plate in Y-directions.

In this simulation, a low carbon steel S235 is designated as substrate material with S316L is applied as filler material. Both thermo-physical material properties are imported into FEM simulation using the existing databases from the MSC Marc/Mentat material properties library. The thermo-physical material properties are predicted equivalent with the real application, whereby C15 is assigned as the base metal with X5Crnimo18_10_1 as the filler material. Figure 3 shows the material assigned for the FE model with temperature-dependent variables.
In addition, in a way to have an accurate estimation of residual stresses after substrate removal from the weld filler material, a separation technique was introduced and applied on the WAAM model. After the cooling down period at the fifth layer, another loadcase was added to deactivate the substrate material and the table. The mechanical behaviour due to residual stresses will be discussed in the Results and Discussions section.

2.2 Heat Source Model: Rectangular and Goldak’s Double Ellipsoid

Heat source modelling is the most interesting phase in the numerical simulation procedure of generating welding process. Suitable heat source model must be chosen as the welding process accordingly. Hence, double ellipsoidal model was executed to imitate the real heat source of GMAW process. Goldak et al. defined the double ellipsoid model [15]. Nowadays, the Goldak’s double ellipsoidal model is extensively utilized as the heat source model for GMAW welding process in manufacturing background [16]. The double ellipsoidal heat source has been revealed to accurately represent the heat power density from an electric arc penetrating the surface of a flat workpiece of plate. Figure 4 presents Goldak’s double ellipsoid heat source model with the geometrical conditions but the geometrical parameters a, b and c can be modified in values for the front or rear quadrants.
The subsequent equations were applied to characterize the power density distribution inside the front and rear quadrants of the heat source along the welding path (z-axis). The power density of the heat flux in front section ($q_{vf}$) of heat source can be modelled with equation (1) and the rear section ($q_{vr}$) with equation (2) [17].

$$q_{vf}(x, y, z) = \frac{6\sqrt{3} f_{f} Q}{abc_f \pi \sqrt{\pi}} e^{-\frac{3x^2}{a^2}} e^{-\frac{3y^2}{b^2}} e^{-\frac{3z^2}{c_f^2}} \quad (1)$$

$$q_{vr}(x, y, z) = \frac{6\sqrt{3} f_{f} Q}{abc_r \pi \sqrt{\pi}} e^{-\frac{3x^2}{a^2}} e^{-\frac{3y^2}{b^2}} e^{-\frac{3z^2}{c_r^2}} \quad (2)$$

The distribution of heat fluxes in the double ellipsoid model is determined by 4 directions: Width (a), Depth (b), Rear Length ($c_r$) and Front Length ($c_f$), whereas $c_r$ and $c_f$ are the heat deposited fractional factors in the rear and front quadrant respectively and its sum is equal to 2. Detailed values for each direction are demonstrated in Table 1.

| Heat Source Dimensions (mm) | Value |
|-----------------------------|-------|
| Width                       | 7.5   |
| Depth                       | 5     |
| Rear Length, $c_r$          | 3     |
| Front Length, $c_f$         | 12    |

Furthermore, in this research the primary objective is to compare the thermo-mechanical behaviour between two different heat source models which are Goldak’s double ellipse and rectangular. Hence, the relevant thermal analysis for WAAM application begins with the solution of a moving plane heat source of appropriate shape and heat intensity distribution [18]. The moving rectangular heat source model is generated with the modified user ‘uweldflux’ subroutine in the MSC/Marc Mentat code. The heat intensity for various heat sources with uniform distribution is given by

$$Q = \int_{0}^{a} \int_{0}^{b} \int_{0}^{c} q(x, y, z) \, dx \, dy \, dz \quad (3)$$

$$Q = 4qacb \quad (4)$$

Figure 5 presents the rectangular heat source model with the geometrical conditions with the distribution of heat fluxes is determined by three directions: a, b, c which are classified as width, depth and length respectively. The power density of the heat flux of rectangular heat source can be modelled with equation (4). The values for each parameters are shown in Table 2.
Figure 5. An illustration of rectangular heat source model

Table 2. Rectangular Heat Source Parameters in FEM simulation

| Parameters   | Value |
|--------------|-------|
| Width, $a$ (mm) | 4.0   |
| Depth, $b$ (mm)  | 3.0   |
| Length, $c$ (mm)  | 6.0   |
| Power, $q$ (kW)   | 3.4   |

3.0 Results and Discussions
3.1 FE Mechanical Results
3.1.1 Distortion of WAAM Model

The distortion result produced by both models are illustrated on Figure 6 below. The predicted angular distortion along the side edge wall from the two mechanical models are compared.

Figure 6. The displacements in Y-direction displayed by heat source model (a) Rectangular (b) Goldak’s double ellipse. An angular distortion characteristic of 5Layers 3Strings WAAM model with different heat source model (c) Rectangular (d) Goldak’s double ellipse
Figure 7 shows how the distorted shape from both models is nearly identical. However, WAAM model with Goldak’s double ellipsoidal heat source shows higher distortion compared to rectangular model.

![Graphs showing distortion verification along y-direction before the separation technique applied](image)

**Figure 7.** Distortion verification along y-direction before the separation technique applied (a) Left side edge (b) Right side edge (c) Front side edge (d) Rear side edge

Furthermore, a computational time for both models is also compared. Computational time is an overall time consumed to complete the numerical simulation. Table 3 presents the comparison of total computational time between these two models.

| Heat Source Model                      | CPU-Time (Hrs) |
|----------------------------------------|----------------|
| Rectangular                            | 34.9           |
| Goldak’s Double Ellipsoidal            | 35.8           |

### 3.1.2 Residual Stress of WAAM Model

Figure 8 presents the distribution of longitudinal residual stresses on the fifth layer, the final deposited layer of WAAM model. Based on these results between the rectangular heat source and Goldak’s double ellipsoidal heat source of WAAM model, the following comprehensive observations can be made and analysed. The heat input caused by multi-passes welding process gives an effect on a tensile residual stress along the deposited weld filler as a result of the material contraction during solidification, which indirectly a balancing compressive residual stress occurs on the base plate. Based on these results, it show that the high degree of the compressive residual stress where the clamping force has been exerted and this is due to the restraint in the region locally.

In addition, around the top layer of deposited weld bead has the maximum tensile residual stress. It is shown in Figure 8 (a) and (c) that the higher tensile residual stress accumulates at the top layer after a completion of the deposition of the fifth layer. However, these stresses are relieved partially caused by the repetitive of reheating and cooling process while depositing the following upper layers [19]. After a long cooling down period, the residual stress changes from tensile to compressive at the interfaces of the successive layers, meanwhile on the base plate the longitudinal stresses go into tension as indicated in the Figure 8 (b) and (d). Thus, in WAAM, residual stresses can be as high as the yield strength of the
material, the mechanical properties can be negatively affected with leading to distortions and decreased tolerances [20]. For a better understanding of the deviations of these stresses, the residual stress was plotted along x-direction along the line shown in Figure 9 (a).

![Figure 8](image1)

**Figure 8.** The residual stresses results displayed by FEM simulations (a) A complete weld deposited of 5layers 3Strings of rectangular heat source model (b) After a cooling down period of 5layers 3Strings of rectangular heat source model (c) A complete weld deposited of 5layers 3Strings of Goldak’s double ellipsoid heat source model (d) After a cooling down period of 5layers 3Strings of Goldak’s double ellipsoid heat source model

As expected, Figure 10 (a) shows the highly non-uniform distributed of all three residual stresses components. These stresses induce repetitive expansion and contraction of the material simultaneously. As shown in Figure 10 (a), mostly compressive residual stresses occur on the longitudinal direction of the substrate due the contractions of the materials as getting farther from the heat input. The significant drop in the residual stress which is lower than the yield strength after the substrate removal which the separation technique applied, is also shown in Figure 10 (b). This is due to the residual stresses are relieved as well when the substrate is detached from the deposited weld fillers. Hence, the reducing these residual stresses give a massive impact to its mechanical behaviour in terms of distortions particularly. However, figure 9 (c) demonstrate the WAAM model applied Goldak’s double ellipsoidal heat source has higher deformations compared to the rectangular heat source model, where the residual stress at the edge deposited walls changes from compressive to tensile as getting farther to the centre of the deposited weld fillers.
Figure 9. (a) The A-A cross section on the top view of WAAM model. The residual stress distribution along longitudinal direction with contour band setting view after separation technique applied (b) rectangular heat source (c) Goldak’s double ellipsoidal heat source
Figure 10. The residual stresses along x-direction on the cross section line A-A (a) Before separation technique applied (b) After separation technique applied

In general, a highly non-uniform distributed stresses generated during WAAM process can cause big distortions on the structures after the removal of table and substrate or separation technique to be exact. The FEM models introduced in this research gives an initial estimate of the residual stresses and angular substrate distortions of WAAM process that later will be beneficial for future work in order to make comparison with experiments.

4.0 Conclusions

In this research, the numerical computation model is employed under consideration of non-linear isotropic hardening modelled by using general purposed FEM software MSC Marc/Mentat to simulate the thermo-mechanical properties of five layers and three strings WAAM structures. The numerical simulation are carried out with two different heat source models which are rectangular and Goldak’s double ellipsoidal. The thermo-mechanical analysis in terms of distortions and residual stresses is compared and discussed. As a conclusion, it can be drawn for this research as follows:

1. A comprehensive numerical study for five layers and three strings of WAAM components had been successfully executed and the simulation procedure is clear as well as structured.
2. Both heat source models namely the rectangular heat source and Goldak’s double ellipsoid can be implemented for repetitive heating and cooling cycles during WAAM process.
3. In terms of FE mechanical results, it shows that the distorted shape from both models are nearly similar. Thus, the deviations of the residual stresses depends on the transient temperature distribution during cooling phase and the application exerted on the WAAM structure after the cooling process.
4. A significant drop of the residual stresses distribution can be observed after the removal of the substrate and the table. As a result, the residual stress at the edge deposited walls changes from compressive to tensile as getting farther to the centre of the deposited weld fillers.
5. The rectangular heat source model displays a short CPU-Time which caused by a simpler rectangular shape according to the weld bead modelling geometry to be calculated. This will be a significant advantage where the WAAM process will be optimised to calculate the predicted residual stresses and distortions.
6. From the knowledge perspective, crucial information through simulation is acquired which can be utilized as a planning tool in the design phase or prior to actual experimental process.

As further research, a five layers and three strings WAAM model will be carried out by experimental work and the FE model will implement the evolved filler material instead of utilizing equivalent default material.

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