Design & Modelling of Double Cantilever structure by Stainless Steel 316L deposited using Additive Manufacturing Directed Energy Deposition Process

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Abstract. Distortion in the metal additive manufacturing due to inherent residual stress during the separation of the deposited part from the base plate is critical. Distortion gets amplified after removing it from the build platform. Internal stress in the deposited sample during the material deposition and cooling phase is crucial to estimate. Residual stress in the structure influences structural distortion. Numerical analysis of residual stress prior to deposition helps to identify inconsistent stress in the built part and helps to take required measures like optimising process parameters, base plate preheat to make it less significant. Residual stress estimation before deposition using numerical calculation plays a major role in the improvement of the built part and establishing technology for a wide application. A numerical model for thermal history and residual stress estimation has been developed for Directed Energy Deposition (DED). A standard double cantilever model was considered for physical deposition and numerical model verification. Thermal history from Finite Element (FE) Analysis was compared with the in-situ measurement. A close agreement was noticed between in situ measurement and simulation results. A double cantilever was built using austenite stainless steel 316L by the DED technique. Internal stress in the deposited part before and after a partial separation from the base plate was compared. Numerical results comparison before and after separation emphasize the impact of residual stress on distortion.

1 Introduction

Directed Energy Deposition (DED) is one branch of the metal deposition technique under the Additive Manufacturing (AM) process. A 3D object has been built using a laser/electron beam energy source from a feedstock powder/wire. DED employs a powder blown technique (in the case of powder as feedstock) to supply feedstock directly to the melt pool generated by the concentric heat source. Localized heating and complex thermal cycle during the deposition of solid structure generate residual stress in the built part. Distortion of the built structure after separation from the build platform results in redistribution of internal stress and strain which may lead to dimensional inaccuracy. Internal stress before separation and after separation in the built structure is important to estimate distortion. The residual internal stress calculation provides the information to take measures (such as process parameter optimization, scanning strategy) required to hinder distortion in the built structure.

A numerical calculation for distortion before a deposition can prevent a failure of the part by adopting required design modification or process parameters optimization. Several studies on the process
parameters, distortion, residual stress numerical modeling, and experimental validation have been reported for the Selective Laser Melting (SLM) and DED AM process [1,2,3,4].

The main goal of this work is to develop a Finite Element (FE) model for the DED process simulation to calculate thermal and internal stress in the built part. An FE model was built using 3DEXperience Finite Element (FE) Analysis software with an Additive Manufacturing scenario. A double cantilever structure is a popular model for distortion, residual stress, and inherent strain estimation in SLM [5]. The cantilever shape which exhibits distortion at the arms represents the magnitude of residual stress in the built structure. The double cantilever structure can be classified as two simple cantilevers. Distortion/stress measurement for two simple cantilevers can be compared to experimental measurement validation. Thus cantilever distortion measurement is reliable for the numerical model calibration. The double cantilever calibration for the DED numerical model has not been reported to the author's knowledge. The reason to select a double cantilever model is the ease of internal stress estimation, easiness to measure distortion directly and efficiently. In the presented work, thermal validation for FE numerical model was carried out to ensure the efficiency of structural calculation for thermo-mechanical FE simulation. Residual stress in the structure before and after separation from the base plate was evaluated using numerical results. The calibrated numerical model is planned to study different process parameters, material behavior, scanning strategy and, a part design for the DED structure.

1.1 Materials

Austenite stainless steel 316L (Sandvik Osprey LTD, Neath, UK) powder with a 50-150 µm particle size range was used. The base plate 316L steel was heat-treated at 400°C for four hours to remove potential residual stress before deposition. The chemical properties of steel 316L are listed in table 1.

| Powder (316L) | Fe  | Cr  | Ni  | Mo  | Mn  | Si  |
|---------------|-----|-----|-----|-----|-----|-----|
| Bal.          | 17.2| 10.4| 2.3 | 1.3 | 0.8 |
| Base Plate (316L) | Bal. | 16.24 | 10.49 | 2.14 | 1.12 | 0.44 |

Table 1. Powder and base plate steel 316L chemical composition (wt. %).

The temperature-dependent thermal material properties for numerical calculation were derived from the literature [6].

1.2 Experimental setup

The base plate dimension and thermocouple positions are shown in figure 1 (a). Thermocouples are welded approximately at a distance of 2 mm away from the contour path of the cantilever structure. The thermocouple (TC0) is in the center along the length of the double cantilever. TC1 and TC2 are at a distance of 17 mm from the extreme ends of the double cantilever.
Double cantilever structural dimensions are depicted in figure 1 (b) and designed as per the DED process parameter taking the minimum thickness of the columns, external support for top bar deposition, etc. into account. The double cantilever consists of five columns on either side of the center pillar. The Center column is 5mm thick and the remaining side columns are 3.25mm. Each column is separated at a distance of 4.75mm. All columns are built to the height of 8mm and the top bar is 3mm thick.

InssTek MX-600 metallic deposition system (InssTek, Daejeon, South Korea) is equipped with a DED process technology that was used for the deposition of a double cantilever. The deposition using InssTek MX-600 during the top bar is shown in figure 3. Process parameters are listed in table 2.

| Parameter               | Value       |
|-------------------------|-------------|
| Laser power             | 500 W       |
| Laser beam diameter     | 0.8 mm      |
| Scanning speed          | 14 mm/sec   |
| Hatching distance       | 0.5 mm      |
| Powder feed rate        | 3 g/min     |
| Deposition duration     | 130 mins    |

The top bar of the double cantilever deposition was supported by placing a 1mm thick 316L sheet cut into a cross-section of 4.75×10mm. The support structure material was the same as the deposition powder to avoid thermal expansion mismatch. Thin supporting sheets were placed between the columns in such a way to provide a continuous flat surface to deposit the top bar. The top bar of the double cantilever measures 3mm thickness and consists of 12 layers. Thin steel 316L sheets were selected to ensure negligible resistance for residual stress redistribution in the top bar and distortion after cutting at the bottom of the columns.

A thermal field during the deposition process was measured on the base plate using the thermocouple type ‘K’ [6]. Thermocouple positions are marked in figure 1. The deposited double cantilever before cutting is shown in Figure 4 (a). Columns of double cantilever were cut using a wire electric discharge machine (diameter of the wire 0.25 mm). The distorted double cantilever model after the cut is shown in figure 4 (b).
1.3 Finite Element (FE) Model
A Finite Element (FE) model was designed using the 3DExperience (Dassault Systèmes, Vélizy-Villacoublay, France) software. A Thermo-Mechanical approach was implemented [1]. The FE model of double cantilever consists of 43800 elements (0.5mm mesh size) and 53298 nodes. The base plate consists of 28800 elements (1mm mesh size) and 39188 nodes. A hexa dominant with linear order elements were selected. A thermo-mechanical DED process was simulated as two-stage, (1) Thermal simulation with Heat Transfer Coefficient (HTC) of 18 W/m².K and emissivity of 0.1 was set to the model [6]. A laser power of 500W was set as per the experimental data with an absorption coefficient of 0.12. A concentrated energy method was adopted for laser energy distribution. The initial temperature of 27°C was allotted to the structure. Linear heat transfer elements (DC3D8) were selected for the thermal simulation. (2) The mechanical simulation for distortion calculation was driven by thermal output. Linear elements (C3D8) from the 3DExperience library were used for mechanical analysis. The bottom plane of the base plate was clamped and the cutting plane at 2 mm above from the upper surface of the base plate defined in the static step. The meshed model and the cutting plane are shown in figure 5.

Figure 5. FE model and cutting plane.

2 Results and Discussion

2.1 Thermal history
The nodal temperature was attained from the thermal numerical result. The nodal temperature corresponding to the thermocouple position from thermal analysis closely agrees to the in situ measurement. The average temperature in the structure increases during the deposition of the top bar as shown in figure 6 (a). Whereas an average temperature during the deposition of the columns is below
100 °C. A thermal source interaction with the structure during the deposition of the columns was for a short duration. Dwell time as per the scanning strategy and idle time during shifting laser source from one column to another is the reason for the low average temperature. Long and continuous laser energy interaction during the deposition of the top bar develops a higher average temperature on the base plate.

![Thermal history comparison between nodal temperature from the numerical calculation and thermocouple data from the experiment.](image1)

**Figure 6.** Thermal history comparison between nodal temperature from the numerical calculation and thermocouple data from the experiment. (a) Thermocouple TC0 (b) Thermocouple TC1 (b) Thermocouple TC2

2.1 Residual Stress

The structural simulation was derived from thermal results. The structural calculation reveals Von Mises stress in the double cantilever structure distributed uniformly. A stress concentration at the edge of the column in contact with the base plate can be noticed in the before cut model shown in figure 7(a). The structural simulation was conducted until 9000sec. The internal stress development during rapid cooling after the thermal source disconnected from the structure was considered.
Figure 7(a). Contour map of the Von Mises stress distribution in the before cut sample. (b) After the cut sample. (c) After cut the sample normal view

Stress relaxation around the cut plane in the column of the double cantilever is depicted in figure 7(b). Stress relaxation on the top surface on the double cantilever forced for the contraction of the top bar. This could be the reason for the two ends of the double cantilever distortion in the positive Z-axis and negative X-axis direction shown in figure 7(c). Distortion can be noticed in the deposited sample shown in figure 4(b).

3 Conclusion

The numerical model was built for the Thermo-Mechanical DED simulation to estimate internal stress in the structure. The Double Cantilever structural dimension was designed and succeed in deposition using a DED process condition for 316L. Thermal results from the numerical calculation were validated with experimental results which closely agree. Thermal simulation accuracy is important for reliable structural calculation in Thermo-Mechanical DED simulation. The residual stress calculation illustrates the importance of internal stress on the distortion of the structure. The second stage of the work will be (1) numerical modeling for distortion and validation with the experimental result (2) Evaluating preheating temperature on the base plate to hinder residual stress and distortion.

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