Numerical investigation of deposition strategies on the residual stress and geometrical deviation in Laser Metal Deposition

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Abstract: In the current study, effect of deposition strategy on the residual stress, geometrical deviation, area change, and temperature distribution has been investigated. To do so, four different strategies namely continuous, two direction raster, inside-out contouring, outside-in contouring with the same process parameters were used. To run simulation, Simufact software was used and both powder and substrate were considered as deformable part with SS316. Having run the simulation, the most important results are as follows: maximum and minimum residual stress occurred by using continuous and outside-in contouring, respectively. The maximum and minimum total displacement (total geometrical deviation) occurred by applying inside-out contouring and outside-in contouring, respectively.

Keywords: Numerical Simulation, Laser Metal Deposition, Deposition Strategy, Residual Stress, Geometrical deviation.

1. Introduction

Direct Energy Deposition (DED) technologies have been accentuated to produce parts with complex geometry, repairing industries and modifying metallic parts [1]. These methods can be divided into different groups based on the process and power feed rate such as Laser Cladding and Laser Metal Deposition [2]. Laser metal deposition (LMD) is an advanced manufacturing technology that is widely used in various applications by adding material layer by layer. In this direct digital manufacturing process, a 3D CAD model is used to generate a material deposition strategy using CAM tools and then imported to a LMD machine for manufacturing parts. It is a challenging issue to control and assess the process layer by layer in experimental tests. So, to address this issue, numerical simulation can be highly beneficial. Numerous researches have been employed in LMD simulation to model the process both thermomechanically and numerically [3]. The additive manufacturing modelling has some sub-segments namely thermal modelling [4], thermomechanical modelling [5], CFD modelling [6], microstructural modelling [7] and nanoscale modelling [8]. Based on the process outputs, the type of simulation is...
determined. In order to have mechanical and thermal outputs, thermomechanical modelling is suitable and can be implemented using ABAQUS [9], ANSYS [10], Simufact [11], LS-DYNA [12], COMSOL [13], and Marc [14] software, etc. In order to fulfil the LMD process simulation, four steps must be run: 1) a laser heat source thermal model and its movement, 2) a temperature-dependent material model enabling heating and cooling environment, 3) a physical model of layering process, 4) a laser-material interaction model to simulate within a transient thermomechanical approach [15]. H.Liu et al [16] investigated residual stress and deformation in Laser AM of SS 304 by using a thermomechanical model with ABAQUS software. In order to model heat loss in the mentioned research, a FILM subroutine was programmed and there was a reasonable correlation between experimental and numerical results and, based on their results, the maximum deflection occurred on the side of the samples where there are no constraints. G.Turichin et al [17] studied the part distortion in LMD parts. Their results showed that if the material has low ductility, the fracture might occur near the substrate in the cylindrical part.

Y. Lee et al [18] implemented research on the cooling time, deposition strategy and constraints on the deformation of large Ti-6Al-4V components. In order to validate the simulation, temperature distribution and part distortion were measured. There was a total of 20 layers and three main strategies were used namely unidirectional, bi-directional and bi-directional with 180 degree rotation in each layer. Their results showed that the maximum deflection occur on the side or outer zones of the part. In addition, maximum stress variation occurred in the bottom layers. Miguel Zavala-Arredondo et al [19] used multi laser diode area melting for investigating thermal effect and melt pool properties. A DFLUX subroutine and modified prismatic laser heat flux (MPHF) were used to model laser movement and variation of laser intensity, respectively. To validate the simulation, temperature versus time was utilised and there was a reasonable correlation between the results. Based on their achievements, the nodal temperature decreases along the Z direction because of being in vicinity of open air which can play a key role in the cooling process.

G. Piscopo et al [20] modelled the material addition and track generation in DED process by using ABAQUS package and UEPACTIVATIONV OL and DFLUX subroutines. They claimed that, by increasing laser power, the melt pool height, width and penetration is enhanced. M. Samantaray et al [21] studied the heat transfer in laser additive manufacturing of A1Si10Mg by using FE simulation in ANSYS software. Their achievements showed that by increasing laser spot size, melt pool length and width, temperature and sintering depth are decreased. Also, increase in powder bed thickness would have inverse effect on the temperature, sintering depth, melt pool length and width.

As mentioned, most numerical studies focus on the impact of the manufacturing parameters in the results. In the current study, a thermomechanical model of laser metal deposition of multi-layer part is implemented to investigate the influence of the material deposition strategy on the process based on the numerical simulation. Four continuous deposition strategies are used to find and compare their effect on the residual stress and part’s geometrical deviation. The material, method and process parameters are elaborated in the following paragraphs. The research aims to explore different strategies for metal deposition seeking future applications in the tool making area.

2. Finite Element Modelling of LMD process
A 3D CAD model with a flat 30×30×5 mm substrate and prismatic 20×20×8 mm centred specimen were designed, partitioned, and meshed in the MSC Apex software. A cubic linear element with 8 nodes and 1 × 1 × 1 mm size was used for layers, and 2 × 2 × 2 mm was used for the substrate. The simulation is done based on a Finite Element algorithm for thermo-mechanically coupled transient modelling of moving 3D heat Source. This quiet-element method is widely known to model material deposition and melting (activate the elements) with the heat source movement during the process [11]. In the current research evaporation temperature and latent heat for evaporation were not considered.

The part was divided into 8 layers for material deposition. Having designed, meshed, and layered the parts, they are imported as BDF format into the Simufact Welding package. Both substrate and specimen were considered as isotropic SS316 material which the chemical and mechanical properties were shown in the table 1 and 2 [22]. A temperature dependent material model is used that has ability to change the
microstructure due to number of heating cycle in the process. It is worth noting that, the microstructural evolution was not modelled. To model the melt pool, low-stiffness solid approached was used. Also, to model Marangoni effect, an artificial thermal conductivity was used [23-24].

$$k_{m}(T) = \begin{cases} k(T) & T > T_{Liq} \\ 2.5 k(T) & T \leq T_{Liq} \end{cases}$$  \hspace{1cm} (1)

In the above-mentioned equation, $K_{M}(T)$ stands for modified thermal conductivity, $T_{Liq}$ stands for liquids temperature and $T$ and $K(T)$ are used to keep the previously defined values.

| Table 1. Chemical composition of SS316 [22]. |
|---------------------------------------------|
| Grade | C   | Mn | Si | P  | S  | Cr  | Mo  | Ni  | N   |
|-------|-----|----|----|----|----|-----|-----|-----|-----|
| 316L  | Min | -  | -  | -  | -  | 16.0| 2.00| 10.0| -   |
|       | Max | 0.03| 2.0| 0.75| 0.045| 18.0| 3.00| 14.0| 0.10|

| Table 2. Mechanical properties of SS316. |
|-----------------------------------------|
| Parameter                          | Value                  |
| Solidus temperature                | 1279 °C                |
| Melting temperature                | 1450 °C                |
| Density                           | 7966 Kgm$^{-3}$        |
| Latent heat for melting            | 25400 J/Kg             |
| Poison ratio                       | 0.3                    |
| Convective heat transfer for first and remaining layers | 10, 30 (W/m$^2$K) |
| Emissivity for first and remaining layers | 0.6, 0.6 |
| Elastic modulus                    | 200 GPa                |
| Ultimate Tensile Strength          | 580 MPa                |
| Yield Strength                     | 290 MPa                |
| Specific heat                      | 490 BTU/lb.F           |
| Thermal conduction                 | 13 BTU.ft/h.ft2.F      |

To apply laser parameters in this process, a Gaussian method was used and the values for process parameters are shown in the table 3. The heat flux was modelled with a 3D Gaussian distribution inside a conical heat source, with upper radius, lower radius and depth 0.70, 0.65 and 0.90 respectively figure 1.

**Figure 1.** Heat source spot compared to mesh size and hatching distance.
Table 3. Process parameters.

| Parameter                                      | Value   |
|------------------------------------------------|---------|
| Laser power                                    | 400 W   |
| Scanning speed                                 | 10 mm/s |
| Laser efficiency for first and remaining layers| 0.45, 0.6 |

The modelling contains 8 steps, which are done successively. A 60-second cooling time was assigned after each layer and Coulomb friction model was used. To model the deposition strategy, four types of strategies were used which are shown in figure 2.

![Figure 2. Material Deposition strategies: (a) Continuous. (b) Two direction raster. (c) Inside-out contouring. (d) Outside-in contouring.](image)

Having prepared the simulation, MSC Marc solver was used to run the simulation. Figure 3 shows FE model with mesh and part description of LMD process.

![Figure 3. FE model of LMD process with part description.](image)

![Figure 4. (a) Maximum temperature distribution. (b) Temperature gradient during the process with outside-in strategy.](image)
3. Results and Discussion

In this section the achieved results are explained. Firstly, the maximum temperature is analysed. Figures 4(a) and 4(b) present the maximum temperature reached in the strategies and the maximum temperature gradient inside the specimen and between the specimen and base plate.

As can be seen in figure 4(b), the temperature around the melt pool is higher than the other regions and this value decreases from top layer to base plate. The temperature distribution analysis allowed to evaluate an expected heat affected zone (HAZ) of about 0.5 mm.

The total displacement (geometrical deviation) based on various strategies is investigated. The total displacement is measured after cooling of the last layer, the 8th layer. Figure 5(b) shows the comparison of strategies and FE results of total displacement.

![Figure 5](image)

**Figure 5.** (a) Total displacement (deviation) with different deposition strategies, (b) FE illustration of total displacement with inside-out strategy.

Based on figure 5(a), inside-out contouring strategy has the highest deviation and outside-in contouring strategy has the lowest value. The reason for this trend is heat convection. Because the elements in the outside-in contouring strategy have the higher time for being in contact with the free air which can be useful for increasing cooling time. To fortify this claim, geometrical deviation along X, Y, Z direction is given in figure 6. As can be seen in this figure, the maximum and minimum deviation occurred in the previously mentioned strategies. In addition, by using inside-out countering strategy, the contact area between elements is higher than the other strategies. Because the heat concentration which was achieved from laser source is higher in these elements and more elements are in contact at a certain time. Biggest deviation on the top results from the accumulation of the strain from the base because of the induced stress [25-26].

As can be seen form from the figure 6, the highest deviation is occurred in the Z direction due to the deposition of layer and shrinkage in this direction. It is worth noting that, the absolute value of deviation was measured and considered. As the total displacement is related to the deviation in the X, Y, Z directions, if inferred that the maximum deviation is occurred in the inside-out strategy. Figure 7(a) illustrates the schematic view of area change in LMD process. Because of the material shrinkage, which is based on rapid solidification, in each layer in the X, Y, Z axis, the area change occurred. Figure 7(b) shows the area change based on the various strategies.
As shown in figure 7(b), the maximum change in the area occurred in two direction raster strategy and the lowest change was assigned to inside-out contouring strategy.

To measure the residual stress, maximum stress was measured after the cooling of last layer. Despite existence of measuring methods in the experimental tests such as destructive and non-destructive testing, in simulation, the residual stress is measured when the simulation is finished and all boundary conditions are removed. The remained stress can be measured as residual stress. Figure 8(a) shows the residual stress of the LMD process by considering the four strategies. The reason for having higher residual stress is heat conduction between elements and line of deposition. Based on the achieved results, two raster direction strategy has the highest value of residual stress that can be justified by the highest temperature in the process. In addition, the maximum residual stress occurs in the interference of baseplate and first layer which is completely aligned with literature study [27].

4. Conclusions
In the current study, different deposition strategies have been investigated to find the values of residual stress and part deflection. Minimal maximum temperatures and gradients benefit part quality. Thus, strategies that minimize stress distribution have the potential for better results. Based on the achieved results, the maximum and minimum deviation occurred by using inside-out contouring and outside-in contouring, respectively. And the maximum and minimum area change occurred by using two direction...
raster and inside-out contouring strategy, respectively. Also, the maximum and minimum residual stress occurred by using two direction raster strategy and outside-in contouring.

![Residual stress graph](image)

**Figure 8.** (a) Values of residual stress with different deposition strategies. (b) FE illustration of residual stress with outside-in strategies.

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