MODELING AND VERIFICATION OF TEMPERATURE DISTRIBUTION AND RESIDUAL STRESS IN LASER AIDED METAL DEPOSITION PROCESS

ABSTRACT
Laser Metal Deposition is a novel, robust technique to manufacture or repair complex aerospace parts. However, as this process is very complicated and often operating at very high temperature, the resulting material behavior is hard to predict. The strain and stress induced by large thermal gradients in the fabrication process may cause parts failure such as cracking and distortion, so it is essential to make sure that the parts have sound mechanical properties after LMD. The focus of this paper is to develop a reliable model for Ti-6Al-4V laser deposition process and discuss how to reduce the residual stress. Using the commercial code ABAQUS, a 3D finite element model is developed for both thermal and mechanical analysis so temperature field generation and residual stress prediction is implemented. In addition, the impact of deposition patterns on strain and residual stress will also be studied. A set of experiments will be developed to validate the simulation results. This validated predictive model would enable the industry to control appropriate parameters during LMD process in order to fabricate or repair parts with good mechanical properties.

1. INTRODUCTION
Laser Metal Deposition (LMD) is a process which uses a laser beam to form a melt pool on a metallic substrate. Powder is fed into the melt pool to form a deposit that is fusion bonded to the substrate. The required geometry is built up layer by layer [1]. One of the advantages of LMD is the ability to add material to an existing structure for repair applications.

Residual stresses are the self-equilibrating internal stresses existing in a free body at equilibrium with no externally imposed surface tractions [2]. In this paper, the only load under consideration in mechanical analysis is from the thermal field. Due to the strong temperature gradients induced by laser beam, thermal strain will appear and eventually lead to plastic strain [3]. In analyzing the temperature and strain/residual stress field, the Finite Element method has been proven to be a powerful modeling tool to deal with this process.

The thermal process and residual stress during LMD process has been previously investigated by many scholars. Kim and Peng [4] used a 2D Finite Element model to obtain the temperature field in laser cladding process. In their case, no residual stress analysis was conducted. Experiments have been done to generate the residual stress. For example, Moat et al. [5] measured strain in three directions with neutron diffraction beam line to calculate stress in LMD manufactured Waspaloy blocks. Some research about welding whose heat sources were not laser beam was present. Using double-ellipsoid heat source, Gery et al. [6] generated the transient temperature distributions and temperature variations of the welded plates. In recent years, research about residual stress analysis using FE model have been well documented by many literatures while most of which dealt with ferritic steel. Deng [7] investigate the effects of solid-state phase transformation on welding residual stress and distortion in low carbon and medium steels. Feli et al. [8] analyzed the temperature history and the residual stress in multi-pass butt-welded stainless steel pipe. Murakawa and Deng [9] presented the temperature fields and residual stress states in multi-pass welds in SUS304 stainless steel pipe.

In this paper, the focus is to investigate the temperature field and residual stress in Ti-6Al-4V substrate during and after Laser Metal Deposition process. In addition, the factors which affect the residual stress will be discussed and the suggestions about how to control these factors in order to get good-quality parts will be given. A finite element (FE) model is developed to account for both thermal and mechanical analysis. Firstly, the temperature is calculated using heat transfer elements in ABAQUS; secondly, 3D stress elements are used to generate the stress/strain and displacement of work piece. An experiment will be conducted to validate the model.

2. MATHEMATICAL MODEL
2.1. Temperature Distribution
In the LMD process, a moving laser beam strikes on the substrate cause the powder and a portion to melt. The melted parts solidify again after cooling. By solving the three-dimensional heat conduction equation in the substrate, the transient temperature field can be obtained.

The heat conduction equation with no source term is:

$$\frac{\partial}{\partial x} (k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k \frac{\partial T}{\partial z}) = \rho c_p \left( \frac{\partial T}{\partial t} \right)$$  \hspace{1cm} (1)
Where \( k \) is the thermal conductivity, \( T \) is the temperature, \( \rho \) is the density, \( c_p \) is the specific heat and \( t \) is the time. The left term of Eq. (1) depicts the conductive heat transfer in the space while the right term of Eq. (1) refers to the imposed heat flux at a point of the clad.

The heat conduction equation must be subject to the following boundary conditions:

The imposed heat flux will correspond to the power density of the laser beam. Assuming an uniform-distributed laser beam, we have:

\[
Q(x, y, z, t) = \frac{Pa}{\pi r_0^2} \tag{2}
\]

where \( P \) is the power of laser source, \( a \) is the absorptivity of clad material and \( r_0 \) is the radius of laser beam.

The heat conduction equation must be subject to the following boundary conditions:

Convection:
\[
-k\nabla T = h(T - T_0) \tag{3}
\]

Radiation:
\[
-k\nabla T = \varepsilon\sigma(T^4 - T_0^4) \tag{4}
\]

Where \( h \) is the convective heat transfer coefficient, \( \varepsilon \) is the emissivity, \( \sigma \) is the Stephan-Boltzmann constant and \( T_0 \) is the ambient temperature.

In addition, the following initial condition should be satisfied:

\[
T(x, y, z, 0) = T_0 \quad \text{and} \quad T(x, y, z, \infty) = T_0 \tag{5}
\]

2.2 Stress Analysis

In this case, no body forces or surface tractions are applied and the only load is from the transient thermal field. The strong temperature gradients induced by laser beam causes thermal strain which lead the work piece to yield.

The total strain [10] is written as:

\[
\varepsilon_{ij} = \varepsilon_{ij}^e + \varepsilon_{ij}^p + \varepsilon_{ij}^s \tag{6}
\]

Where the components refer to elastic, plastic and thermal strain, respectively. The elastic and thermal strains are expressed as [12]:

\[
\varepsilon_{ij}^e = \frac{1 + v}{E} \sigma_{ij} - \frac{v}{E} \sigma_{kk} \delta_{ij} \tag{7}
\]

and

\[
\varepsilon_{ij}^s = \alpha(T - T_0) \delta_{ij} \tag{8}
\]

To calculate the plastic strain, kinematic hardening, together with Von Mises yield criterion is assumed. This is verified sound for the clad and substrate [2].

3. SIMULATION PROGRESS

3.1 Assumption

The simulation for LMD process in this paper is based on the assumptions as followed:

1. The initial temperature for the whole work piece is 294 K.
2. The temperature will not be influenced by strain and stress generated during LMD process.
3. Both absorptivity and emissivity of substrate are considered constant.
4. The convection coefficient is considered constant for all the surfaces of substrate and clad.
5. The speed of laser beam is considered constant and the time for laser to change direction is negligible.
6. No phase transformation is considered in this paper.
7. The melt pool dynamics and the solidification phenomenon have been neglected.
8. The powder addition onto the substrate is divided into many small time steps to simulate the quasi-steady nature of LMD process.
9. All the powder is melted to for a rectangular-shape clad.
10. No external forces are applied to work piece while the thermal field is the only load.

3.2 Thermal Run

There are two main steps during the computation conducted by ABAQUS. Firstly, a transient thermal analysis is conducted to generate the temperature history in the work piece. In this step, the temperature-dependent thermal properties such as density, conductivity, specific heat and latent heat are needed as input. DC3D8 elements (8-node linear heat transfer brick) are used for simulation and a user subroutine “DFLUX” [1] is written to simulate the moving heat source. The material addition onto the substrate is divided into many small time steps with corresponding heat flux and boundary conditions. Using the “Model Change” technique [12] in ABAQUS, in each time step, a set of elements is added onto the substrate to form cladding. The width of cladding is assumed to be the same as laser beam size, so the thickness of cladding can be calculated from the powder flow rate.

3.3 Stress Run
The second step is the strain/residual stress analysis in which the same mesh method in thermal analysis is used. C3D8R elements (8-node linear brick) are used and steps and increments are also different. The temperature-dependent thermal properties such as Young’s modulus, Poisson’s ratio, yield stress, and thermal expansion coefficient are needed as input. To simulate the real environment in which experiment is conducted, it’s also essential to set proper boundary condition. In the experiment, the substrate is clamped from the side so in the simulation, the side nodes of the substrate are fixed to prevent rigid body motion.

3.4. Model
A model for single pass LMD process is built. As shown in Fig. 1, the example under consideration has length L=50 mm, breadth W=25 mm, height H=12.7 mm. The width and height of the clad are L₁=2.5 mm and H₁=0.6 mm respectively. The traverse speed and radius of the laser beam in the LMD system are 6.25 mm/sec and 1.25 mm respectively. The power of laser source is set as 500 W and the absorptivity of the substrate is assumed to be 0.4. The powder material is also Ti-6Al-4V with a flow rate of 2 gm/min. As shown in Fig. 2, a total of 99705 nodes, and 92000 8-node linear brick elements are generated to accomplish this simulation.

The laser beam travel time for one pass is 4 seconds and it is discretized into 25 equal time steps with 0.16 second for each step. One more step with time t=200s is added after the existing 25 steps to account for the cooling after laser beam goes past the substrate. The input heat flux is calculated from Eq. (2). Temperature-dependent thermal properties such as density, conductivity, specific heat and latent heat is given by materials properties handbooks [13]. Based on a previous model by Choi and Mazumder [14], h=10 W/(m²) has been used as convection coefficient for all the surfaces.

4. SIMULATION RESULTS
4.1. Temperature Distribution
As seen in Fig. 3, the cross section of work piece is shown. The temperature fields at point “a-d” are observed.

From Fig. 4(b) we can see that at point “c” the temperature of powder is raised from room temperature to melting point by laser source in a very short time about 0.034 s. The corresponding heating rate is about 48235 K/s. After laser beam goes pass point “c”, this part cools also very rapidly. It only takes 0.1235 s for the temperature to fall from the peak temperature which is 2403.76 K to solidus temperature which is 1877 K. The corresponding cooling rate is about 4265K/s. The
Figure 4 (a) Temperature History at point “a” and “b”, (b) Temperature History at Point “c” and “d”
abrupt slopes of the curves can also depict the rapid heating and cooling rate.

Figure. 5(a) and Fig. 5(b) shows the ideal shape of melt pool and isotherms. Considering the small geometry parameters and big temperature differences, high temperature gradient which is about 1000 K/mm will surely appear in LMD process.

4.2. Strain/Residual Stress

Since the accurate temperature-dependent plastic properties are still unavailable, the strain and residual stress cannot be generated currently. Some random data has been tried as input and the simulation result is obviously unreasonable. So it is
essential to apply exact data to get correct strain and residual stress during LMD process.

5. CONCLUSIONS

A finite element model for Laser Metal Deposition process is developed with commercial code ABAQUS. High heating rate which is 48255 K/s and cooling rate which is 4265 K/s are observed. The temperature gradient which is as high as 1000 K/mm will cause thermal stress and lead to plastic strain, so residual stress will appear. These results are reasonable for LMD technology, but are unconfirmed for this particular specimen geometry. Experimental validation is the next step of this work.

6. FUTURE WORK

There is a lot of work needed to be conducted in the future.
1. Residual stress should be generated in FEA model with accurate elastic and plastic properties of Ti-6Al-4V as input.
2. To better simulate the real-world process, more accurate data about temperature-dependent materials properties will be used, including Temperature-dependent density, conductivity, specific heat, elastic property (Young’s Modulus and Poisson’s Ratio, plastic property (Yield stress and Plastic strain, density expansion coefficient, absorptivity and emittance, latent heat, solidus temperature, and liquidus temperature).
3. The forced convection caused by shielding gas should be considered so the convection coefficient for gas affected zone should be calculated.
4. In real LMD process, the powder fed is not 100% melted to form clad, so the model should be modified to take the powder loose into account.
5. The analysis about Multi-track multi-layer LMD process will be conducted in the future to better analyze the nature of LMD process.
6. To reduce the time for computation, a better mesh method will be developed.
7. An experiment will be developed and carried out to validate the simulation results.

7. ACKNOWLEDGMENTS

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8. REFERENCES