3D Finite Element Modeling of Micro Rolling assisted Direct Laser Deposition

WCMNM 2021

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Abstract

In the Direct Laser Deposition process, continuous melting and solidification induce residual stresses, thermal distortion, and columnar grain growth due to directional cooling. Further, the columnar grains induce anisotropy in mechanical properties. Experimental investigations on adding a micro-roller behind the deposition nozzle show the deformation caused by rolling has significant effects on flattening of bead, microstructural evolution, and subsequently on mechanical properties. The columnar grains are found to be converted into equiaxed grains with smaller sizes and hence reduce an-isotropy. So, the investigation of the deformation of the bead becomes a precursor to microstructural and mechanical studies. There is a need for a thermo-mechanical model to predict the deformation caused by the rolling and the temperature field history on which microstructure is heavily dependent. This work attempts to develop a thermo-mechanical model for the DLD process coupled with the rolling dynamics with the consideration of laser heating of a single bead. The study found the 1600W as an optimized power value for the model at a 4 mm gap between the roller and the deposition nozzle. This model can be extended to the multi-layered three-dimensional deposition.

Keywords: Hybrid micro rolling, FEM simulation, Thermo-mechanical modeling, Strain Field

1. Introduction

Direct Laser Deposition (DLD), a disruptive but easy and economical technique of Metal Additive Manufacturing (MAM), requires rigorous research to find direct industrial applications. DLD lacks in generating fully functional parts in a single step as it requires further postprocessing such as heat treatment [4-5] to get the necessary functionality. One of the attempts to reduce the postprocessing in DLD is including a hybrid approach by adding milling [6] or rolling [2]. In comparison, the integrated milling process chips off the excess material to maintain the profile, incorporating an in-situ roller just after the deposition nozzle plastically deforms the material to maintain the profile. The Hybrid Micro Rolling of DLD (HMRDLD) parts is preferred to keep the basic principle of additive manufacturing, i.e., manufacturing by adding material.

In literature, experimental investigation of rolling of Wire and Arc Additive Manufacturing (WAAM), a deposition process with arc as the power source, has been significantly reported [1,3]. The research area for HMRDLD, where a laser is used as the power source, is still new, and very few experimental research works have been reported [2]. These experimental investigations on rolling have shown promising effects to tackle deposition's critical limitation with improved strength (even surpassing the wrought counterpart), ductility, toughness, and fatigue life, with reduced porosity and hardness. There is a significant change in microstructure observed, i.e., from columnar to equiaxed. This change reduces anisotropy due to deformation caused by rolling. To investigate these improvements, knowledge of thermal history and strain field is imperative. While temperature history decides microstructural evolution, rolling gives strain to the deposited beads and alters the microstructure. The mechanical properties with the residual stresses and thermal distortion are also dependent on temperature history. The experimental measurement process of the temperature field is cumbersome and also not feasible with HMRDLD. Modeling with analytical equations is also tricky as it involves solving partial differential equations. So, a coupled thermo-mechanical numerical simulation becomes the crucial way to model the HMRDLD process.

The coupled thermo-mechanical and thermo-metallurgical modeling of the DLD process is widely reported in the literature to predict mechanical aspects such as thermal distortion and residual stress [10-12] and metallurgical aspects such as grain morphology evolution [13-14], respectively. However, to the Author's best knowledge, no literature on the modeling of HMRDLD has been reported. Nevertheless, few research papers were found on simulation of rolling of other deposition-based manufacturing. Abbaszadeh et al. [9] developed a Finite Element (FE) model with symmetry conditions for WAAM to study the effect of roller profile radius on residual stress. However, the effect of temperature field due to molten pool during deposition has not been done. Zhou et al. [8] developed two-dimensional cellular automata (CA) and Finite Volume (FV) coupled model to simulate dynamic recrystallization and microstructure evolution for Hybrid deposition and micro-rolling (HDMR) using GMAW torch. The model showed the effect of rolling on dynamic recrystallization area and recrystallized grain size. However, thermo-mechanical aspects such as residual stress and thermal distortion are not investigated.

As thermo-mechanical modeling of HMRDLD is still untouched, there is a need to find an initial temperature and strain field. The model can then be utilized to predict mechanical responses such as residual stresses and thermal distortion. The approach to the problem is to find the temperature field just before the roller during material addition due to laser deposition and then study the dynamic thermo-mechanical effects of rolling and its process parameters.

DLD involves making objects by adding overlapping beads to form a layer and then adding multiple layers to create a three-dimensional object. So, instead of going directly to study a complex three-dimensional multilayered deposition process, there should be a model that tells the physical phenomenon happening at a single line of the deposited bead. The primary effect of rolling on a single bead is the flattened cross-sectional due to compressive stresses given by the loaded roller. Further, from the experimental investigation in literature, the deformation caused by rolling has a significant effect on microstructure change (i.e. recrystallization) and subsequently on mechanical properties. Also, the microstructure evolution is dependent on the thermal history. This study attempts to investigate the temperature profile and the geometrical effects of rolling on a single line bead through a Finite Element thermo-mechanical model using ABAQUS software with the intent to expand the model in three dimensions by progressively adding complexity to it.

2. Model Description

During the deposition process, the material is added in molten form to the substrate. It creates a molten pool on the substrate, which is cooled to form a solid in the subsequent process before hybrid rolling the solidified bead. The dynamic process of material addition creates a variable temperature field on the newly deposited bead on the substrate just before rolling. In this study, the complex material addition process is simplified with laser heating on a preformed bead. The laser beam follows a Gaussian profile within its spot diameter. Here, the variable temperature field is considered to form by a moving laser flux with Gaussian distribution, as shown in equation 1.

$$I = \frac{2\alpha P}{\pi R_0^2} . \exp\left(-\frac{2r^2}{R_0^2}\right) \quad (1)$$

Where, $r = \sqrt{X^2 + y^2}$, and R_0 is spot radius of laser flux and to consider the moving heat source the 'X' is modified as in equation 2.

$$X = x - vt \quad (2)$$

Where, 'x' is the location and 'v' is velocity of moving heat source. 't' is the time taken by heat source to arrive at that location.

Metal forging in hot conditions makes material flow plastically with minimal strain hardening. In-situ rolling just after deposition takes advantage of this idea. Newly deposited material, even though solidified, remains at an elevated temperature. The rolling at an elevated temperature makes the material deform plastically and changes the microstructural evolution during the cooling cycle. For this work, Ti-6Al-4V is taken as a material of consideration because of its popularity in DLD. A phase change occurs at the beta-transus temperature (982 ^oC) for this alloy, above which $\alpha + \beta$ Phase of microstructure changes completely to β phase. This work attempts to model the rolling process above beta-transus temperature.

The temperature profile due to the moving heat source is first studied to find the gap between the roller center and the heat source center, i.e., the location of the deposition nozzle. Finding this gap is to locate the roller where the temperature is above the beta transus temperature. For this, a substrate with a semi-circular bead profile is generated in ABAQUS software, and the moving heat source is applied on the bead surface through a user-defined Fortran code using the VDFLUX sub-routine of the software. Initially, the substrate is considered at room temperature (298K), and during heating, convective heat transfer to the environment is considered at free surfaces. The substrate is considered a semi-infinite plate with the bottom temperature fixed at 298K. Figure 2 shows the temperature profile on the substrate with a single bead due to the moving heat source. The bead is 30 mm in length with a semi-circular cross-section with a radius of 1mm.

The thermal model, as mentioned above, gives the idea of the temperature profile and the range of location between which the roller should be placed, i.e., the location where the temperature is in between the Melting point and before beta transus temperature. Here, the roller radius and deposition nozzle size are also important considerations to avoid fouling between them. Once the location of the roller is defined, the physics of rolling is considered as mentioned below.

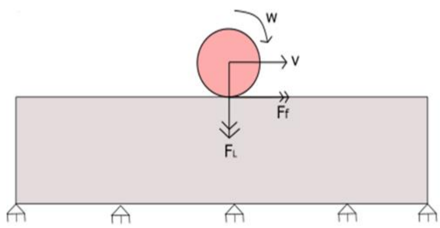

Figure 1: The compressive Load along roller's axis and its motion

The material flow stress due to rolling is defined using Johnson's Cook's (JC) constitutive model to study the effect of high plastic deformation due to loaded roller. This model provides the plastic flow behavior of the material at elevated temperature with variation in the amount of plastic strain and strain rate. Equation 3 shows the flow stress dependence on the Elasto-plastic term, Viscosity terms, and thermal softening term [15].

$$\bar{\sigma} = \underbrace{[A + B\bar{\varepsilon}^n]}_{\text{Elasto-plastic term}} \underbrace{\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]}_{\text{Viscosity term}} \underbrace{\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right]}_{\text{Thermal softening term}} \quad (3)$$

Where, $\bar{\sigma}$ is the equivalent stress, $\bar{\varepsilon}$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}$ is the equivalent strain rate, and $\dot{\bar{\varepsilon}}_0$ is the reference strain rate (taken as 1/s) respectively. T, T_m, and T_r represent current temperature, melting temperature (1878K) of workpiece material, and room temperature (298K). A,B,C,n and m are JC constants and their values are taken as 862 Mpa, 331Mpa, 0.012, 0.34, and 0.8 respectively[15].

The roller is loaded with 3kN force (F_L), as shown in Figure 1 for the semi-circular bead with a radius of 1 mm. The roller is loaded linearly using the step module of Abaqus during the duration of 0.1 s, with the roller being static at one end of the bead. The same displacement is propagated in the next step with the motion of the roller towards another end with rolling. During this step, the motion of the bottom portion of the substrate is fixed in the software. This fixing is done because the substrate is considered to be kept intact and does not move during the rolling process. The friction (F_f) is considered with the coefficient of 0.3 using the penalty contact method in FE analysis in Abaqus during rolling. To solve for the temperature and displacement field simultaneously with the dynamic effects of roller's motion, 'an 8-node thermally coupled brick, trilinear displacement, and temperature' explicit mesh elements are chosen.

3. Results and Discussions

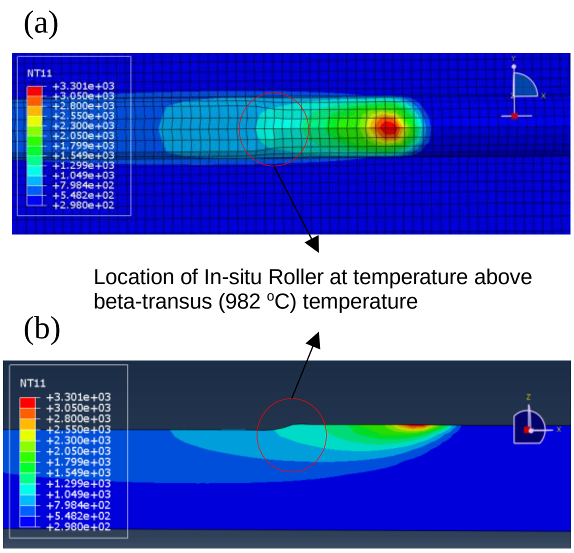

Figure 2: Temperature profile in substrate with single bead due to moving laser flux (1600W). (a) top view, (b) cross-sectional view

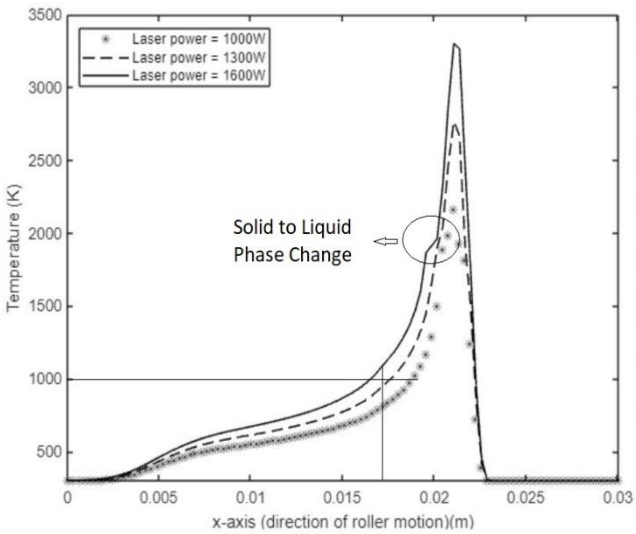

Figure 3: Temperature variation along the direction of the motion of the roller at three different laser powers.

The moving heat source has gaussian distribution throughout the spot. However, due to its motion temperature field tends to elongated. Figure 2 shows the temperature distribution with a laser spot placed at 21 mm from the start in the direction of the motion. The temperature is maximum at 21mm and non-uniformly decays on both sides. This asymmetry is because of the motion of the heat flux where the previous portion of the bead has already been heated due to interaction with the flux and the next portion is yet to be heated.

The temperature distributions at three different laser power are shown in Figure 3. The gap between the nozzle and the roller is chosen as 4 mm. This gap ensures the accommodation of the roller and the nozzle without fouling. For this fixed gap, the optimized temperature was found with Laser power 1600 W. Above this power, the peak temperature at 21mm will be above the boiling temperature, and below this power, the temperature at 17mm is below the recrystallization temperature. Figure 3 also shows the phase change at 1878 K with energy absorbed as latent heat.

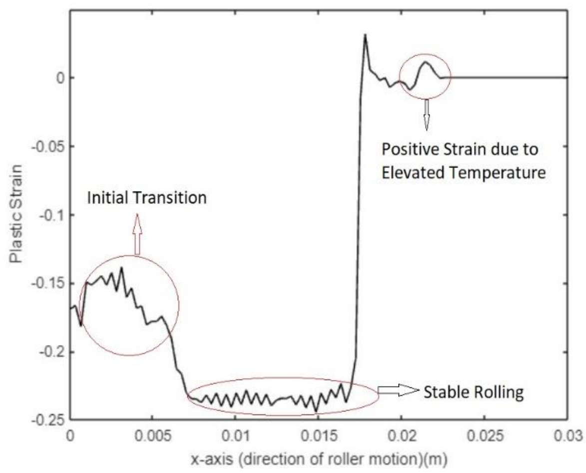

Figure 4: Plastic Strain Variation in the deposited bead along the direction of the motion of the roller with roller placed at a distance of 17 mm and heat source at 21mm.

After the selection of the power for rolling above the recrystallization temperature, Figure 4 considers the plastic strain variation at this power. The roller is gradually loaded initially, and the transition can be seen in terms of plastic strain in the loading direction variations from -15% to -24% within nearly the 6 mm in the rolling direction. The negative sign signifies the compressive strains. From 6mm to 17 mm, even though there are minor variations in strains due to roller dynamics, an overall stable Plastic strain is observed in this region after the rolling process. At 17 mm, where the roller interacts with the bead surface, the drastic change in Plastic strain can be seen, which depicts the change in the rolled region and the unrolled region. A slight positive strain is observed just before the roller in the unrolled region due to the material pushed by the roller. The expansion due to elevated temperature by the laser flux can also be seen at 21 mm with positive strains.

The geometrical changes in the bead due to the loaded roller are shown in Figure 5. This Figure depicts the story of the thermo-mechanical model with rolling. It starts with (a) the placement of the roller behind the heat source, then it shows (b) the stresses in the bead due to the roller and the high temperature due to laser flux, and finally (c) and (d) show the undeformed and deformed bead profile, respectively.

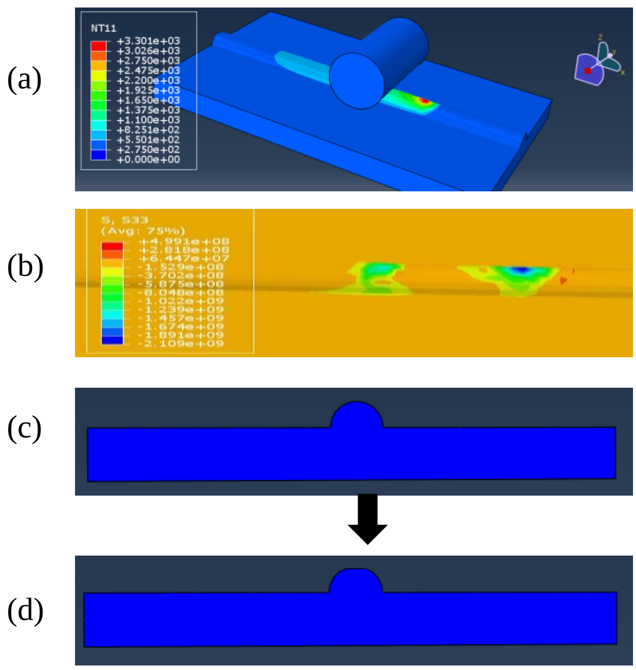

Figure 5: (a) The thermo-mechanical model with insitu-rolling behind heat source, (b) Stresses due to roller and the temperature field, (c) Cross-section of substrate with single bead undeformed and (d) deformed due to rolling

4. **Conclusion**

The study shows an initial attempt to the dynamic thermo-mechanical model of the micro-rolled DLD process. This attempt is made for the single-line deposited bead with simplified laser heating consideration to show the temperature distribution during material deposition on the preformed bead. The model shows the temperature distribution due to the moving heat source on the single bead. Further, it covers the thermomechanical coupling with the considerations of the effects of the temperature field during rolling by using JC plasticity. It identifies the required laser power for a constrained gap between the deposition nozzle and the roller center considering recrystallization temperature and solid to liquid phase change. Finally, the model gives the compressive plastic strain and shows the flattening of the bead caused by the motion of the loaded roller. The model can be extended with material addition modeling for multiple beads and multiple layers deposition.

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