Modeling and Multiphysics Simulation of the Directed Energy Deposition Additive Manufacturing

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Abstract
In this paper, we present a study of the simulation of Directed Energy Deposition (DED) Additive Manufacturing (AM) using a multiphysics approach. We use a combination of Heat Transfer in Fluids, Solid Mechanics and Laminar Flow physics to accurately simulate the DED process. The simulation provides detailed information about the temperature of the melt pool while using various process parameters for each layer of material deposited. Results demonstrate the importance of a multiphysics approach for gaining insights into the complex interplay between various physical phenomena during DED AM. The findings of the study have important implications for the optimization of the DED AM process.

Keywords: Additive Manufacturing, Direct Energy Deposition, Mathematical Modeling, Simulation, Comsol, Temperature

Introduction

Additive manufacturing (AM) has become increasingly popular due to its ability to produce complex geometries with a high degree of customization. Among the various AM techniques, Directed Energy Deposition (DED) is a popular method for manufacturing large and complex components. DED entails the injection of a continuous flow of metallic powder, which is then liquefied using a laser beam, enabling the gradual deposition of material layer by layer onto a building platform [1]. To optimize the manufacturing process and ensure the quality of the final product, it is essential to understand the underlying physical phenomena occurring during the process. Multiphysics simulations can provide valuable insights into the complex interplay between various physical phenomena during DED AM.

A straightforward and partially analytical thermal analysis of directed energy deposition (DED) is shown by [1], which aims to achieve simulations of the entire process that are computationally efficient. The analysis considers solidification and phase transitions that occur in the solid state. F. Caiazzo and V. Alfieri [2] develop a thorough numerical model for laser-assisted deposition. Specifically, the study examines the shape of the metal that will be deposited beforehand, in order to identify the most efficient reference shape that can be used to feed the simulation, taking into account the

factors that govern both single-track and multi-track, multi-layer deposition. The paper also presents a non-stationary thermal model and discusses the underlying assumptions used to simulate the addition of metal in a step-by-step manner. A. Kiran et al. [3] established a computational cost effective thermo-mechanical weld model that utilizes the Directed Energy Deposition (DED) process on 316L stainless steel. This model is designed to support residual stress calculations for large additive manufacturing (AM) components. In order to integrate the weld model into the DED simulation, they conducted single and multi-track thermal simulations.

In this paper, we present a detailed study of the simulation of DED AM using a multiphysics approach. Specifically, we focus on the coupling of Heat Transfer in Fluids, Solid Mechanics and Laminar Flow physics to accurately simulate the process. We extract temperature results while using various process parameters for each layer of material deposited as part of our simulation.

Governing Equations of DED Process

A mathematical model was established for simulating the interaction between laser beam and powder. In the developed model, the energy equation is used to depict temperature and temperature gradient employing the Heat Transfer in Fluids physics, and it is solved

numerically as part of the simulation process for DED.

$$\rho C_p^* \frac{\partial T}{\partial t} + \rho C_p^* u.\nabla T$$
$$= \nabla.(k\nabla T) + AQ_{Laser} + Q_{Rad} + Q_{ev} \qquad (1)$$

where ρ, C_p^*, T, t, u, k, A, Q_{Laser}, Q_{Rad}, and Q_{ev} are density (kg/m^3), modified specific heat capacity ($J/kg.K$), temperature (K), time (s), velocity (m/s), thermal conductivity ($W/(m.K)$), absorption coefficient (-), input laser energy source (W/m^3), radiated energy source (W/m^2) and evaporation heat loss (W/m^3) respectively. The laser beam is modeled as a moving Gaussian distributed heat source on the powders. Shadowing effect, multi-reflection, and beam angle effect on the absorption of the laser are neglected [4].

The Navier-Stokes equation and continuity equation is used to describe the mechanics of the fluid in the model using the Laminar Flow physics, as follows:

$$\rho \left(\frac{\partial u}{\partial t} + u(\nabla.u) \right)$$
$$= \nabla.[-pI + \mu(\nabla u + (\nabla u)^T)] + \rho g + F_s \qquad (2)$$

$$\nabla.u = Q_s \qquad (3)$$

where p, I, μ, $(.)^T$, g, F_s and Q_s are pressure (N/m^2), identity matrix, viscosity ($Pa.s$), transposed matrix, gravity (m/s^2), surface tension volume force (N/m^3) and source term ($1/s$) respectively [5].

The Solid Mechanics physics was added to the model to simulate the material deposition:

$$\epsilon = \alpha(T - T_{ref}) \qquad (6)$$

where ϵ, α and T_{ref} are strain (-), coefficient of thermal expansion ($1/K$) and reference temperature (K).

Simulation

A symmetric model composing a fixed base plate and three bulk powder layers was designed as shown in Figure 1. The moving heat source melts the powders sequentially and the next powder metals and layers deposit simultaneously.

The boundary conditions were applied as explained in the modeling formulation. The heat sources and also source terms were added as boundary condition to the model. Also, the base plate was fixed from bottom as a fixed boundary condition in solid mechanics physics.
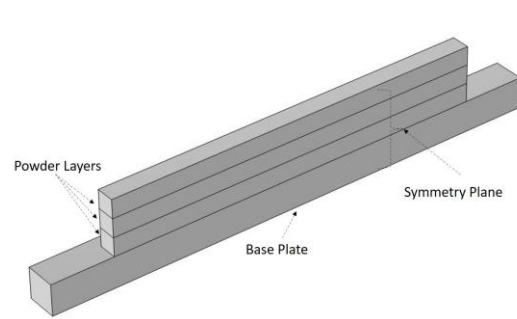

Figure 1. Symmetric model design to simulate the DED process.

During the simulations a tetrahedral mesh of 10 μm was used for domains and corner refinement is employed as well. A dual CPU Intel Xeon Gold 6230 CPU workstation simulated the model in 9 hours. Steel AISI 4340 alloy was selected as the medium metal material in the interaction process between energy source and material. Thermal material properties are listed in Table 1.

Table 1: *Material properties of Steel AISI 4340 metal alloy powder* [6].

Material Property	Symbol	Value	Unit
Melting Temperature	T_m	1793	K
Latent Heat of Melting	H_m	$2.5 \times 10e5$	J/kg
Density	ρ	7850	kg/m^3
Specific Heat Capacity	C_p	475	$J/(kg.K)$
Thermal Conductivity	k	44.5	$W/(m.K)$
Absorption Coefficient	A	0.6	-
Young's Modulus	E	205	GPa

Simulation Result

The temperature distribution of the simulated DED process is shown in Figure 2. A preheat of 300 K was considered for the base plate. The process parameters were changed during each layer as the former melted layer's heat provides a preheat for the deposited powder on it. Each

layer of printing shown in Figure owes different laser power, laser spot diameter and scanning velocity value. Also, Figure 3 shows the melt pool schematic during the scanning of each layer.
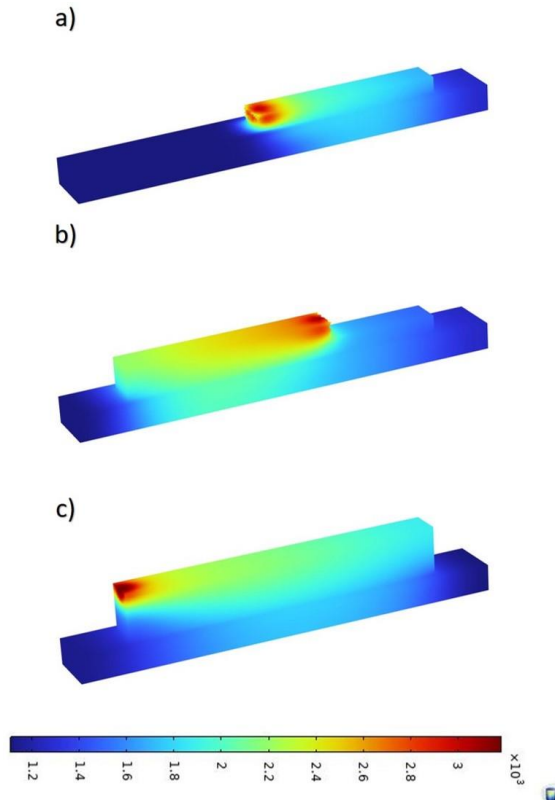

Figure 2. The temperature distribution of the simulated DED process. a) The first layer, b) the second layer and c) the third layer of printing.
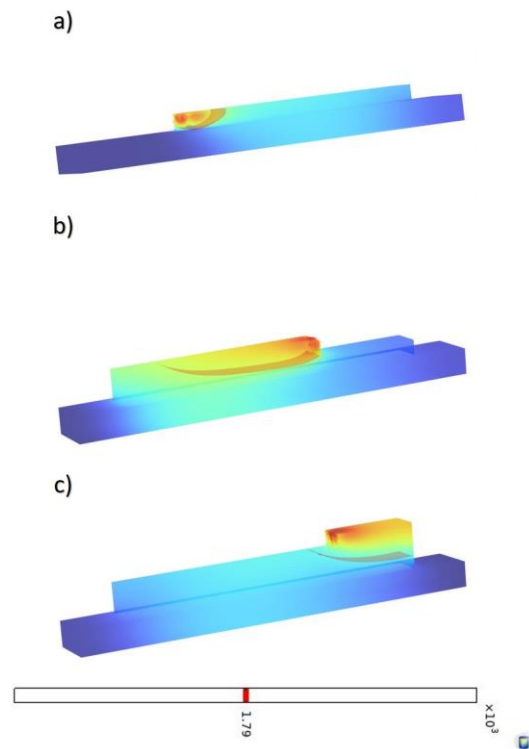

Figure 2. Melt pool iso-surface schematic of the melt pool in the a) first layer, b) the second layer and c) the third layer.

Conclusions

The paper presents a multiphysics simulation of the DED additive manufacturing method. Regarding the simulation, the melt pool temperature, melt pool geometry and thermal gradients can be calculated.

It helps us to estimate the suitable process parameters for a full dense DED printing of parts.

References

[1]   D. Weisz-Patrault, "Fast simulation of temperature and phase transitions in directed energy deposition additive manufacturing," *Addit. Manuf.*, vol. 31, no. December 2019, p. 100990, 2020, doi: 10.1016/j.addma.2019.100990.

[2]   Caiazzo F, Alfieri V.,"Simulation of laser-assisted directed energy deposition of aluminum powder: Prediction of geometry and temperature evolution," *Materials (Basel).*, vol. 12, no. 13, 2019, doi: 10.3390/ma12132100.

[3]   Kiran A, Hodek J, Vavřík J, Urbánek M, Džugan J., "Numerical Simulation Development and Computational Optimization for Directed Energy Deposition Additive Manufacturing

Process," *Materials (Basel).*, 2020.

[4]   Ansari P, Rehman AU, Pitir F, Veziroglu S, Mishra YK, Aktas OC, Salamci MU., "Selective Laser Melting of 316L Austenitic Stainless Steel: Detailed Process Understanding Using Multiphysics Simulation and Experimentation," *Metals (Basel).*, vol. 11, no. 7, p. 1076, 2021, [Online]. Available: https://doi.org/10.3390/met11071076.

[5]   Ansari P, Salamci MU., "On the selective laser melting based additive manufacturing of AlSi10Mg: The process parameter investigation through multiphysics simulation and experimental validation," *J. Alloys Compd.*, vol. 890, p. 161873, 2022, doi: 10.1016/j.jallcom.2021.161873.

[6]   "COMSOL Multiphysics® v. 6.1." COMSOL AB, Stockholm, [Online]. Available: www.comsol.com.