Finite Element Modeling (FEM) of the thermal behavior of 3D printed parts during Directed Energy Deposition (DED)

Modélisation par éléments finis (FEM) du comportement thermique des pièces imprimées en 3D lors du dépôt d’énergie dirigée (DED)

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ABSTRACT. Additive manufacturing (AM) is an innovative and promising technology that can create complex geometries with great precision. However, parts manufactured using this technology exhibit residual stresses and distortions, which hinder widespread adoption. Directed energy deposition (DED) stands out as a promising AM technique, offering a high deposition rate compared to other AM processes. DED uses a focused energy source, such as a laser or electron beam, to melt material as it is deposited, enabling the creation and repair of complex geometries. The flexibility in material usage and the ability to control the microstructure during the process makes DED suitable for high-performance applications in aerospace, automotive, and biomedical industries. Finite element modeling (FEM) of the DED process can predict the melt pool, and temperature profile without extensive experimentation, saving considerable time, material, and money. In the current study, the FEM of a high-layer thickness DED process is developed using the Gaussian heat source model to investigate the effect of different process parameters. The model aims to enhance understanding of the thermomechanical behavior during the DED process and to optimize process parameters for improved part quality and performance.

RÉSUMÉ. La fabrication additive (FA) est une technologie innovante et prometteuse qui permet de créer des géométries complexes avec une grande précision. Cependant, les pièces fabriquées à l'aide de cette technologie présentent des contraintes résiduelles et des déformations, ce qui entrave son adoption à grande échelle. Le dépôt sous énergie dirigée (DED) se distingue comme une technique de FA prometteuse, offrant un taux de dépôt élevé par rapport à d'autres procédés de FA. Le DED utilise une source d'énergie focalisée, telle qu'un laser ou un faisceau d'électrons, pour faire fondre le matériau au fur et à mesure de son dépôt, permettant ainsi la création et la réparation de géométries complexes. La flexibilité dans l'utilisation des matériaux et la capacité à contrôler la microstructure pendant le processus rendent le DED plus adapté aux applications de haute performance dans les industries aérospatiale, automobile et biomédicale. La modélisation par éléments finis (FEM) du processus de DED peut prédire le bain de fusion et le profil de température sans avoir besoin d'expérimentations extensives, ce qui permet d'économiser considérablement du temps, des matériaux et de l'argent. Dans la présente étude, la FEM d'un processus de DED à grande épaisseur de couche est développée en utilisant le modèle de source de chaleur gaussienne pour étudier l'effet de différents paramètres de processus. Le modèle vise à améliorer la compréhension du comportement thermomécanique pendant le processus de DED et à optimiser les paramètres du processus pour améliorer la qualité et la performance des pièces.

KEYWORDS. Additive manufacturing, Directed energy deposition, Finite element method, Heat transfer, Heat source model.

MOTS-CLÉS. Fabrication additive, Dépôt d’énergie dirigée, Méthode des éléments finis, Transfert de chaleur, Modèle de source de chaleur.

1. Introduction

Additive manufacturing (AM) has gained significant traction in industrial applications over the past two decades, driven by the demand for high-performance systems. AM is the process of building components layer by layer using an incremental approach. Various AM techniques have been developed, including Directed Energy Deposition (DED). During the DED process, material in the form of powder or wire is deposited and fused using a focused energy source such as a laser, electron beam, or electric arc. This method allows for the fabrication, repair, and coating of metal parts with complex geometries that would be difficult to achieve with traditional manufacturing methods. DED has been particularly effective for high-performance alloys such as nickel and titanium, which cannot be economically manufactured by conventional methods.

However, despite its potential, several challenges need to be addressed to achieve wider acceptance in modern industrial applications. One of the key challenges is the presence of thermally induced residual stresses and distortions in manufactured parts, which can affect their mechanical performance and dimensional accuracy. To address these challenges, numerical modeling, particularly finite element modeling (FEM), plays a crucial role. By modeling the DED process, the heat transfer, material deposition, and resulting stresses and distortions can be simulated, allowing for the optimization of process parameters such as laser power and scanning speed. Previous studies have demonstrated the effectiveness of FEM in predicting the thermal behavior and residual stresses in DED processes. For instance, Mukherjee et al. (2018) investigated residual stresses and distortion in additively manufactured components, while Yang et al. (2016) validated the thermomechanical behavior of Ti-6Al-4V in DED using FEM [MUK 1] [YAN 2]. The heat source model in FEM describes the shape and mathematical formulation of the heat source, enabling an accurate simulation of its interaction with the material. This provides insights into the residual stress, tensile behavior, and fatigue performance of the manufactured parts. The application of existing computational welding mechanics to model heat energy input and material deposition in AM processes further enhances the understanding and optimization of these processes [LOR 3].

2. Finite Element Modeling

A finite element model of the DED process was developed in ANSYS Mechanical to simulate the DED printing process of a racetrack-shaped geometry shown in Figure 1. The geometry is sliced such that there are four layers through the height of the track.

Gaussian distributed heat flux model is commonly used to simulate the energy input from the laser during the DED process [LUO 4]. A Gaussian distributed disk heat source model is adopted in the current study, and it can be expressed by:

$$q = \frac{3\eta P}{\pi R^2} e^{-3\left(\frac{r^2}{R^2}\right)} \qquad [1]$$

where η is the coefficient of laser absorption, P is the laser power, R is the laser spot radius, and r is the effective radius.

Nickel-chromium alloy Inconel 718 was used in this study since it is suitable for high-temperature applications due to its weldability and oxidation resistance [SIN 5]. Boundary conditions accounted for heat loss through convection and radiation, with the preheated build plate at 80°C and room temperature set at 23°C. The model captures the transient thermal and mechanical behavior during the DED process using the element birth and death technique, accurately representing material addition. The DED process simulation involves sequential weld track solidification, starting with thermal phenomena followed by structural simulation for distortions and stresses (weak coupling). The part is meshed with Cartesian elements, and clusters were used to optimize calculation time. Each cluster, representing a portion of the weld track, is activated to simulate sequential material deposition.

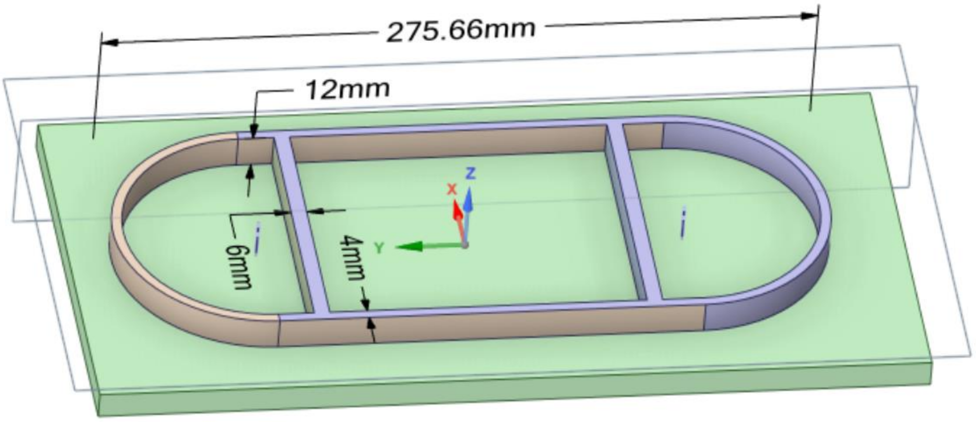
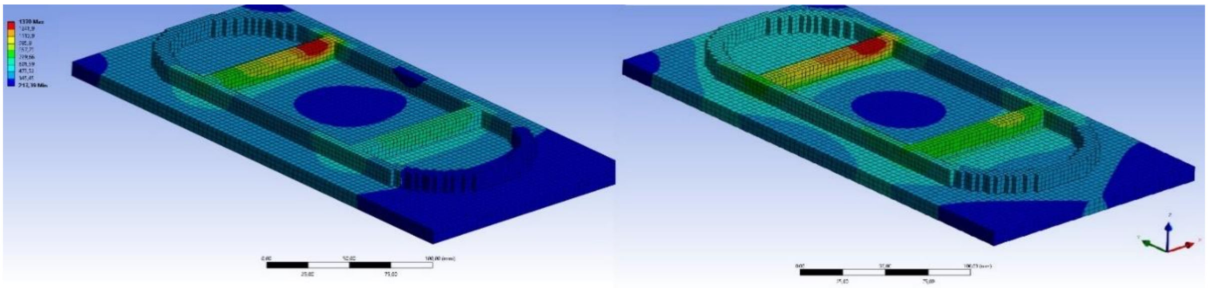


Figure 1. *Printed part and baseplate used to simulate the DED process*

3. Results and Discussion

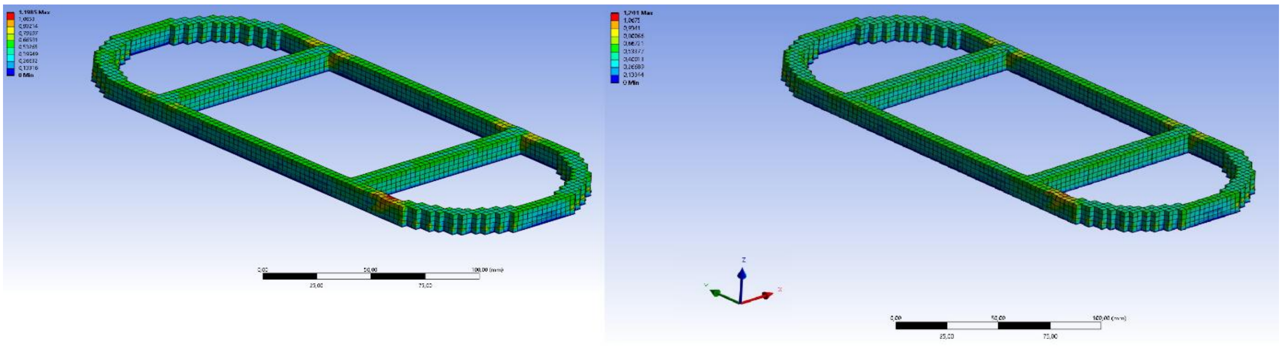
The current model was used to predict the temperature distribution (Figure 2) and distortion (Figure 3) for two different sets of parameters: (a) low feed rate and (b) high feed rate. As the laser melts the alloy to form the solid parts, the temperature increases until it reaches the process temperature before it cools down. This cycle repeats until the entire part is formed. The melt pool at the very start of the process is small, and it gradually increases as the process continues, being larger for higher feed rates. If proper temperature control is not maintained, overheating may occur. Optimizing the feed rate parameter helps ensure the proper fusion of all the layers within an optimal time frame.



(a) (b)

Figure 2. *Temperature (°C) map at the end of the deposition. Comparison between parameters (a) and (b)*

The temperature distribution shows how different feed rates affect the melt pool size and overall thermal profile of the part. Higher feed rates lead to larger melt pools, which can impact the cooling rate and solidification process, influencing the final properties of the printed part.



(a) (b)

Figure 3. *Distribution of distortion (mm) for parameters (a) and (b)*

4. Conclusions

The developed numerical model demonstrates its capability to predict the temperature distribution, melt pool dynamics, and distortions in the Directed Energy Deposition (DED) process. The simulation results provide insights into the impact of different parameter settings, explaining the thermomechanical behavior of parts fabricated by this technique and optimizing the quality and performance of manufactured parts. However, further validation and refinement of the model are necessary to ensure its accuracy and reliability for practical applications. In future work, we aim to validate the numerical model using an experimental setup, studying the impact of different parameters and finding optimal settings. Additionally, we plan to study the computing time to enhance the efficiency of the model. These efforts will contribute to a more robust and accurate simulation of the DED process, enabling better understanding and control of this technique.

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