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Review

A survey of finite element analysis of temperature and thermal stress fields in powder bed fusion Additive Manufacturing

Zhibo Luo, Yaoyao Zhao*

Mechanical Engineering Department, McGill University, Canada

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ABSTRACT

This survey aims to provide a review on the application of finite element method to optimize process parameters and improve the mechanical performance of a part fabricated by powder-bed-fusion Additive Manufacturing process. The state-of-the-art finite element models in the simulation of powder bed fusion process are reviewed. Numerical modeling methodologies of the laser beam melting or electron beam melting process at the macro-level are summarized in detail. Specifically, the importance of pre-processing of the part model, process parameters, mesh scheme, and temperature-dependent material properties are clarified. Simulation techniques used to reduce the computational cost are also discussed. Then the existing finite element models in the simulation of powder-bed fusion processes are reviewed and discussed. Simulation results are classified based on the characteristics of the melt pool and the printed part. Then the simulation results are validated by the experiment results. Finally, the significance of finite element method in the connection of other Additive Manufacturing issues such as material design, in-process monitoring and control, and process optimization are explained. The drawbacks of existing finite element models are summarized. And potential new methods to optimize process parameters of PBF process are proposed.

1. Introduction

Powder bed fusion process is one of the seven Additive Manufacturing (AM) processes defined by ASTM in 2012 [1]. According to the ASTM technical committee, the seven AM processes are defined as powder bed fusion (PBF), directed energy deposition, binder jetting, material jetting, sheet lamination process, material extrusion, and Vat photopolymerization. Among these AM processes, the previous five types are able to process metal materials [2]. Readers who are interested in these AM techniques could find detail descriptions in these references [3,4]. Compared with other AM processes, PBF mainly utilizes energy source with high density such as laser beam or electron beam to selectively melt the metal powder with the desired shape on the powder bed and join the material layer by layer. Based on the difference of heat source, PBF can be further divided into Selective Laser Melting/Sintering (SLM/SLS) which utilizes laser beam as the heat source [5] and Electron Beam Melting (EBM) which utilizes electron beam as the heat source [6]. The initial SLS process is developed by the University of Texas and the company DTM Corporation [7]. The initial EBM process is developed by the Chalmers University of Technology in Sweden and is commercialized by Acram AB company [3]. Compared to the laser beam, the electron beam has higher energy density and is more efficient, and thus EBM manufacturing process is more efficient. Another difference between EBM and SLM is the resulting microstructure. In general, the laser beam scanning tracks are usually easy to distinguish, whereas the electron beam scanning tracks are not easy to identify. This difference can be attributed to the low energy density and low efficiency of the laser beam, which result in non-melting or partially melting particles among subsequent layers. In addition, a more moderate thermal stress of EBM processed part compared to the SLM processed part can be attributed to the preheating process of the powder bed in EBM process.

PBF process has numerous merits over traditional manufacturing processes [8] such as machining, forging, and casting. First, it can build a part with complex geometrical features such as lattice structures, which cannot be manufactured via conventional manufacturing methods. Second, it is cost effective for high complexity part in small batches. Third, it has the ability to build an assembled product, which results in reduced assembly need. Due to the ability to fabricate a part with complex geometries and nearly full density [9], PBF process has been widely used in automobile, aerospace, biomedical, and energy industry [10–14]. Many types of metal powders can be used in the PBF process. Stainless steel, aluminum, Ti6Al4V, nickel alloys, are materials of high interest in these industries [15–18]. Lightweight and durable

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* Corresponding author.
E-mail address: yaoyao.zhao@mcgill.ca (Y. Zhao).

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components filled with lattice structure are more desired in the aerospace industry; customized bio-implants can only be fabricated through AM techniques [19].

However, several process deficiencies such as balling effect [20,21], deteriorated surface finish [22], part shrinkage [23], pores and microcracks [24], residual stress-induced defects including warping and distortion [25], have been discovered in PBF process and remain as unsolved issues. Most of these defects are induced by the significant temperature gradient during the heating and cooling cycles. Especially for a part with overhang features, rapid heating and cooling processes will result in the deformation of overhang features, and support structures are needed to build it successfully [26,27]. On the other hand, support structures are not easy to remove and place restrictions on the design freedom for complex parts. Significant efforts have been spent to restrict the number of supports and minimize deformation of PBF processed parts. As experimental method typically takes vast amount of time and cost and cannot delineate the variation of temperature fields or thermal stress fields with respect to the time, numerical analysis of temperature and thermal stress fields development in a part with overhang feature is needed to analyze the relations between process parameters and mechanical performance of final part. Numerical modeling of temperature distribution, thermal stress and deformation occurred in the PBF process is similar to that of multi-pass welding process [28], which has been developed and modeled for four decades. However, compared to the modeling of the multi-pass welding process, modeling of PBF process introduces significant amount of computational work due to several coupled and complicated physical phenomena such as the irradiation of laser beam on the powder bed, heat transfer, fluid dynamics in the melt pool, evaporation and chemical reactions within the melt pool. Though there have existed many numerical methods to model the history of temperature fields and thermal stress fields, most of them are not easy to implement due to lack of sufficient information. In addition, only limited amount of research has studied the finite element analysis of PBF process [29–32]. The existing numerical models and reviews are not easy to understand for newcomers in the field of AM.

This review attempts to provide an overview of the finite element analysis (FEA) of PBF process for newcomers in this field who want to optimize the process parameters to achieve a better mechanical performance of final printed parts. In section 2, the detailed process of numerical modeling methodologies such as heat source, material properties, boundary conditions, and meshing strategy will be provided. In Section 3, the existing finite element models (FEMs) will be reviewed. After that, in Section 4, simulation results of the reviewed FEMs will be presented in the form of melt pool characters, temperature fields, and thermal stress/distortion fields. Then, experimental validation of the numerical results will be discussed in Section 5. Finally, the conclusions and some prospects will be summarized.

2. Numerical modeling methodology

The general flow chart for the modeling of temperature and thermal stress fields is shown in Fig. 1. The major steps in the FE formulation and analysis of a typical problem include pre-processing, processing (thermal analysis and mechanical analysis), and post-processing. Next, the main procedures and techniques used in this figure will be explained in detail.

2.1. Pre-processing

2.1.1. Part geometry

Geometric model of a part defines the domain for the generation of finite element (FE) mesh and the subsequent FE analysis. The basic idea of the FE mesh is to view a given domain as an assemblage of simple finite elements such as triangular element and rectangular element in 2D or tetrahedral elements and hexahedral element in 3D [33]. Due to a large number of cells when meshing a part and hundreds of scan tracks for a layer with complex geometry, great computational costs are needed. Therefore, most of the 3D FE models [34–37] and 2D FE models [38–40] simulate the temperature and thermal stress evolutions with a simple geometry. The dimension of deposited part varies from several millimeters [41] to several centimeters [42]. However, even for a scanning domain with 6 × 6 mm square, the simulation time for thermal and mechanical analysis could take 92 hours [43]. Therefore, the dimension of the part and substrate is the first thing needs to be considered carefully before the simulation process.

2.1.2. Process parameters for PBF simulation

The primary purpose of FE model for PBF process is to investigate the relationship between different process parameters and the (mechanical and geometrical) quality of final printed part. Unlike conventional manufacturing methods whose process parameters have been studied and optimized extensively in the past, the optimization of process parameters for PBF process is started somewhat recently. Usually, the process parameters for PBF process are optimized by experiment method [44,45], which is time-consuming with a high cost. The evolution of temperature gradient and thermal stress within the part are closely correlated with scanning speed, scanning pattern, laser power, spot size, etc. [46]. Table 1 lists the necessary process parameters used in the finite element simulation. These parameters need to be specified before the FE analysis. The laser or electron power is supposed to be a Gaussian distribution with certain spot size [36,45]. For each layer, the heat source moves along the scanning vectors defined by the scanning pattern with certain scanning speed. The distance between two adjacent and parallel scanning vectors is the hatching space, which guarantees the fully melting or re-melting of each scanning track.

Many works, either through experiment or simulation, have been done to optimize these process parameters to either maximize strength or minimize residual stress and deformation of the end part. For example, it has been reported that powder bed temperature under pulsed wave mode laser is 30% lower than powder bed temperature under continuous wave mode laser [47]. A relatively low laser power results in increased voids and about 50% decrease in the material strength for stainless steel 316 L [48], while high laser power increases the warping trend for overhanging surface [49]. A relatively lower scanning speed will improve the surface quality of a single layer while higher scanning speed will improve the surface quality of multi-layers [50]. Residual stress increases with the decrease of layer thickness [51]. Hardness and density of end part decrease with the increase of layer thickness while porosity increase with the increase of layer thickness [52]. Scanning strategy includes scanning pattern, scanning vector length, scanning direction. These process parameters have been studied widely to control the residual stress-induced deformation of end part [53,54]. Traditional scanning pattern applies “S” pattern to deliver laser energy to the whole deposited layer which would lead to large distortion due to long scanning vectors and the stress accumulation from underlying layers. Altering the scanning pattern with shorter scanning vectors can significantly reduce distortion [9,55–57] while more deposition passes and processing time are required to deposition one layer.

2.1.3. Material model

An effective material model which considers the variation of properties during the cycle of heating and cooling processes is fundamental [20]. Since the temperature varies from tens of Celsius degrees to thousands of Celsius degrees during PBF processes, most of the physical properties change drastically. For example, powder bed density of Titanium alloy decreases slowly with the increase of temperature before the melting point and then decreases sharply after reaching the melting point. Powder bed density increases irreversibly with the rise of temperature from the solidus temperature to liquidus temperature [58]. Masubuchi [59] stated that temperature dependent material property is