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Finite element simulations of temperature distribution and of densification of a titanium powder during metal laser sintering

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ABSTRACT

Metal Laser Sintering (LS) is a powder bed fusion process that can be used to produce manufactured parts of complex shapes directly from metallic powders. One of the major problems of such powder bed fusion processes is that during the continuous movement of the laser beam, temperature distribution becomes inhomogeneous and instable in the powder. It leads to greater residual stresses in the solidified layer. Thus, temperature analyses must be performed to better understand the heating-cooling process of the powder bed as well as the interactions of different laser scanning paths within a sintering pattern. A transient 3D Finite Element (FE) model of the LS process has been developed with the commercial FE code ABAQUS. The model takes into account the different physical phenomena involved in this powder bed fusion technology (including thermal conduction, radiation and convection). A moving thermal source, modeling the laser scan, is implemented with the user scripting subroutine DFLUX in this FE code. The material's thermal behavior is also defined via the subroutine UMATHT. As the material properties change due to the powder bed fusion process, the model takes it into account. In this way, the calculation of a temperature-dependent behavior is undertaken for the packed powder bed, within its effective thermal conductivity and specific heat. Furthermore, the model accounts for the latent heat due to phase change of the metal powder. Finally, a time- and temperature-dependent formulation for the material's density is also computed, which is then integrated along with the other thermal properties in the heat equation. FE simulations have been applied to the case of titanium powder and show predictions in good agreement with experimental results. The effects of process parameters on the temperature and on the density distribution are also presented.

1. Introduction

Additive manufacturing (AM) is driving emerging technologies from the industry that have been developed to create three-dimensional solid parts, of complex shapes, directly from Computer-Aided Design geometries. The common feature of these new technologies is that the final part is built by cumulative deposition of material, layer by layer, with no need for further heavy machining. Such processes made a breakthrough in the prototyping practices since they allow to shorten development time and to decrease the costs [1]. Laser Sintering (LS) that belongs to the powder bed fusion technology is an important branch of AM for potential application such cost-saving practices. It was invented by C.R. Deckard at the University of Texas, U.S.A., in 1986 [2]. In such powder bed fusion technology, a thin layer of powder is spread and is then selectively sintered with a laser beam. This process is repeated until the whole 3D part is fabricated. The powder bed fusion process was initially developed to produce polymer-based components. Nowadays, a wide range of powdered materials can be employed, for further details see the overview of this technology by Kumar [3]. LS of metal powders is also referred as Metal Laser Sintering (MLS). Metal components can be fabricated by different powder bed fusion sub-technologies, such as single- or double-component metal powders processes. The present work is focused on the LS for powder bed fusion process of single metallic powders.

Titanium powders are very interesting since different functional such as aeronautical parts [4] and medical implants parts can be fabricated by LS processes. For example, titanium powders have been used to fabricate dental implants using powder bed fusion processes in Ref. [5]. One advantage of using powder bed fusion

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technology in this case is that it is possible to fabricate implants with controlled porosity using appropriate processing parameters. Laoui et al. [5] built dental implants with a porous surface layer surrounding a dense core. Their dental implants then possessed a good osseointegration in the body (due to their porous surface) and also good mechanical properties such as tensile and fatigue strength (due to their dense core). As reported in the work of Kruth et al. [6], the basic binding mechanisms of a single metallic powder that can occur in powder bed fusion processes are solid state sintering and/or liquid phase sintering (also called partial melting in Ref. [6]). Moreover both mechanisms can also run simultaneously in agreement with the work of Tolochko et al. [7]. As presented in Ref. [7], the binding mechanisms acting in powder bed fusion processes depend on the laser technology, on components of metallic powders and most importantly on processing parameters. However Tolochko et al. [7] pointed out that it is difficult to realize this process in practice because of the occurrence of “balling” (formation of large spherical liquid droplets at the surface).

Furthermore, the high intensity of laser beam used in LS processes leads to a rapid heating of a small region of powder layer, which results in great changes of the distribution of temperatures and then large temperature gradients. It causes residual stresses that affect part quality (such as curling defect). Consequently, LS of titanium powder remains a complicated process. In order to prevent such defects and to ensure the achievement of the desired quality of the product, the processing parameters of the powder bed fusion technology must be carefully selected. Classically, the choice of processing parameters can be determined empirically with many tests and failures. This can be replaced by less costly numerical studies, which are more and more feasible, to improve LS processes.

Numerical simulations were previously employed to determine the temperature field under LS of polymer powder bed fusion processes. The commonly used numerical methods for solving LS thermal problems are the Finite Difference (FD) and Finite Element (FE) methods. To save computation time, a one-dimensional numerical model can be developed. For example, Nelson et al. [8] estimated the distribution of temperature and of density by using one-dimensional (1D) FD and FE methods for polycarbonate powders. However 1D models are not always enough to understand the details of thermal and sintering phenomena occurring during powder bed fusion processes. Consequently, two-dimensional (2D) numerical models have been developed both for amorphous [9] and semi-crystalline [10] polymers. In order to better simulate the LS process and to provide accurate information about thermal gradient and densification in the powder bed, three-dimensional (3D) models were developed. Papadatos et al. [11,12] predicted the density and temperature variations in the built parts of amorphous polymer by using a 3D FD method. A 3D FE model for LS of polymer powders was developed by Bugeda et al. [13]. In their work, both thermal and sintering phenomena were taken into account by rewriting the thermal and sintering equations for a steady state problem. As for amorphous and semi-crystalline polymer powders, Dong et al. [14–16] developed more recently a 3D transient FE model to predict temperature and density distribution under LS. In the model they presented [14–16], the preheating temperature and different laser process parameters are considered, such as its beam velocity, power, and diameter. Moreover, this model is fully capable of taking into account the powder density and specific heat as a function of temperature, with the thermal conductivity and latent heat also considered here [14–16].

In contrast to polymer powders, only some numerical studies on sintering of metal powders are available in the literature. As there is no translational or planar symmetry in real sintering processes, Kolossov et al. [17] developed a 3D FE model to predict temperature evolution during the sintering of titanium powders. The temperature dependent thermal conductivity and the specific heat are taken into account in Ref. [17]. However, the density of the material was assumed to be constant in the FE predictions reported there. Xiao and Zhang [18] developed a 3D Finite Volume model of sintering of single-component powder by partial melting. They assumed that melting and resolidification phenomena occur and affect significantly the temperature distribution during sintering. In their work [18], a moving laser beam was considered and a parametric study was carried out using AISI 304 powder. Patil and Yadava [19] developed a 2D FE thermal model to determine transient temperature distributions in a single-component powder layer. The effects of the following process parameters were also investigated [19]: laser power, laser beam diameter, laser on-time, laser off-time and hatch spacing. However, their thermal conductivity of metal powder and their specific heat were assumed to be constant. It should be noted that the hatch spacing is a process parameter specifying the distance between two parallel scanning paths by the laser beam (the scanning being in the two different directions). Recently, Liu et al. [20] proposed a micro-scale approach to analyze the temperature field within the porous powder bed during the sintering of metal powders. Their micro-scale approach is based on a 3D FE thermal analysis of three layers of powder. To study the mechanism of laser sintering, two cases were simulated by Liu et al. [20]: the laser beam struck the last but one top layer of the powder, or the top layer. The temperature variations throughout the powder layer thickness were then predicted. However, predicted temperature distributions were inhomogeneous owing to their discretely distributed particles.

In the present paper, the powder bed fusion process 3D FE model proposed by Dong et al. [14–16] is extended to study the LS of titanium powders. The numerical model is developed with the commercial FE code ABAQUS where was implemented the thermal and sintering sub-models for this metal powder bed fusion process. The simulation is operated by first resolving the density, thermal conductivity, specific heat and latent heat, in accordance with Refs. [14–16]. All these properties are indeed function of temperature, or even temperature and time. Secondly, all the updated values are used as materials properties for solving the heat equation. The material properties and the processing parameters, which can affect the sintering quality, will be further studied to find out the optimal sintering parameters. The results for the titanium powder are presented thereafter in terms of temperature and density distributions. We also compare these predicted results to the experimental ones from the literature [17,19].

2. Modeling approach

The modeling approach developed in the work of Dong and his co-workers [14–16] is briefly reviewed in the following section. In the LS process, the powder bed is pre-heated and we assumed an initial temperature which is lower than the melting temperature of powder material. The laser beam scans the top surface of powder bed following a prescribed direction with a constant velocity. Under the laser beam, heat is transferred to powder material and then a sintering region is formed. After the laser beam moves away, the sintering region cools, thus forming a zone of larger density. Consequently, the numerical model of this powder bed fusion process must include: optical, thermal and sintering sub-models. The optical sub-model refers to the photon-matter interactions, i.e. between the laser and the powder surface (facing the laser beam). The thermal sub-model refers to the heat transfer mechanisms occurring in the material due to the laser penetration within the powder bed, and heat dissipation at surface. The sintering sub-model refers to the sintering process, i.e. the densification phenomenon of the powder towards the fully dense solid material.