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Three-dimensional finite element thermomechanical modeling of additive manufacturing by selective laser melting for ceramic materials

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ABSTRACT

A model for additive manufacturing by selective laser melting of a powder bed with application to alumina ceramic is presented. Based on Beer–Lambert law, a volume heat source model taking into account the material absorption is derived. The level set method is used to track the shape of deposed bead. An energy solver is coupled with thermodynamic database to calculate the melting-solidification path. Shrinkage during consolidation from powder to liquid and compact medium is modeled by a compressible Newtonian constitutive law. A semi-implicit formulation of surface tension is used, which permits a stable resolution to capture the liquid/gas interface. The influence of different process parameters on temperature distribution, melt pool profiles and bead shapes is discussed. The effects of liquid viscosity and surface tension on melt pool dynamics are investigated. Three dimensional simulations of several passes are also presented to study the influence of the scanning strategy.

1. Introduction

In recent years, additive manufacturing (AM) has met a growing interest from various industrial sectors because of its advantages compared with conventional forming techniques. AM is often referred to as "3D printing" and gives the possibility to design parts with complex geometry. AM offers the opportunity to manufacture a large variety of objects for a wide range of practical applications. Prototypes for testing can be printed right after the design rather than waiting for a long time, thus providing a more efficient strategy than usual industrial practice based on casting, machining or other forming processes. Among other advantages, assemblies can be directly printed into a single final product. Moreover, redesign of part shape with equivalent mechanical performance can be also proposed. However, most of AM processes are much slower than conventional technologies, specific defects such as cracks often exist and poor surface quality is usually encountered, all resulting in poor control of the mechanical properties [1]. As a consequence, considerable efforts must be made on the setting of AM parameters in order to manage the quality and in-service properties of AM parts.

Different AM processes have been exploited with application to various materials. Among them, Selective Laser Melting (SLM) has drawn peoples' attention, especially in the fields of aerospace and medical orthopedic for metallic alloys hard to shape with conventional technologies. Applications in aluminum [1], stainless steel [2], titanium [3,4], cobalt chromium [5] and nickel [6] are of particular interest. A typical working cycle for SLM is shown in Fig. 1 [7]. At first, a vertical build piston moves downward an upper shelf by a layer thickness. The layer thickness varies from 20 μm to 100 μm, considering a balance between fine resolution and good powder flowability [8]. The feed piston alternatively moves powder upward more than a layer thickness. A roller then shoves the powder horizontally into the build chamber with downward vertical press. A laser beam with focused spot diameter is employed to selectively melt powder, according to predefined trajectories generated from a three-dimensional CAD model. The molten layer is solidified and bonded to the previous one in order to progressively build a compact part. The whole process is usually conducted under a protective atmosphere in order to avoid oxidation. Full melting of the powder is targeted for SLM, making a difference with selective laser sintering (SLS) [9] which binds powder without totally melting the material. As a consequence, fully dense and near net

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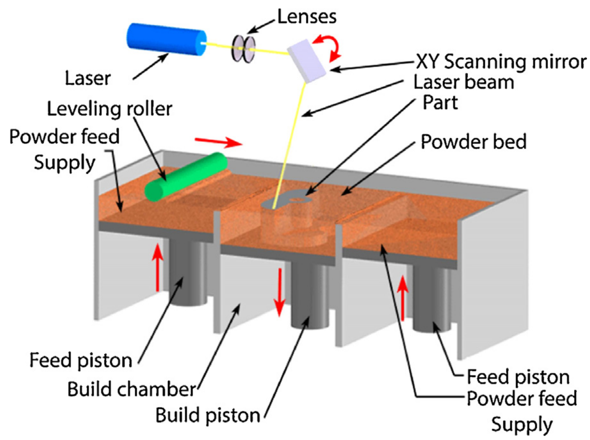

Fig. 1. Schematics of additive manufacturing (AM) by selective laser melting (SLM) [7].

shape components can be obtained by SLM, resulting into better mechanical properties [10].

Alumina (Al_2O_3) and zirconia (ZrO_2) ceramics are widely used due to their outstanding mechanical strength and excellent thermal and wear resistances [10], which is especially attractive to aeronautic industry. Traditional manufacturing processes often suffer from high cost, high tool wear (machining), shrinkage (sintering) and constraints of part geometry. SLM could open a door to a larger application of ceramics. Compared with metals, some special attention should be paid to ceramics in SLM. Ceramics have an absorption coefficient for long infrared laser wavelength which is several orders of magnitude lower than that of metals [11]. This leads to totally different temperature distribution and shape of melt pool as laser radiation can penetrate deeper into the material. Another important aspect is cracking due to thermal stresses. However, Hagedorn et al. [10] could totally eliminate cracks by high-temperature preheating just below the melting point of material and thus, in principle, offer a practical solution to this issue.

The mechanical properties of final parts are tightly related to thermal evolution during manufacturing. Large heating and cooling rates happen locally around the laser spot in a small region, leading to phase transformation in a high thermal gradient difficult to tailor by experimental studies. In order to optimize process parameters, numerical models are currently proposed for AM processes. Considering the generality of the modeling approaches, the literature study has not to be limited to SLM. Two categories can be distinguished, corresponding to the macro-scale of the parts and to the meso-scale of the bead. For large scale modeling, Hodge et al. [12] chose a complex heat source model described by Gusarov et al. [13]. The temperature field was predicted, as well as the shape of the melt pool, for 316L stainless steel. Configuration with a melt pool propagated above unconsolidated powder was predicted, caused by the insulating behavior of the powder bed. King et al. [14] pursued the work of Hodge et al. [12] to predict the temperature and stress in a 6 cm tall prism part of 316L stainless steel. Residual stresses were found to compare favorably with experiments. Li and Gu [15] predicted the temperature field in a titanium powder bed, with a Gaussian heat source model and temperature dependent thermal properties. They found that most heat was eliminated through conduction in the cold substrate and that the material experienced a rapid quenching process. Roberts et al. [16] used a heat source model considering the absorption of laser energy described in [17] and employed the method of element birth and death to simulate the addition of multiple layers, for Ti-6Al-4V material. The same method was used by Marion et al. [18] for Direct Metal Deposition.

Modeling at scale of bead helps to understand the complex temperature distribution and the shape of the melt pool. By varying process parameters, one can predict a working region in which stable bead shape can be obtained. King et al. [14] simulated the bead formation with and without surface tension, by using a powder model. They found that surface tension has a tendency to smooth melt pool and improve heat transfer to substrate. Körner et al. [19] provided a two-dimensional numerical approach based on the lattice Boltzmann model to predict melting and solidification of the powder. Stochastic spatial distribution of the powder particles and capillarity force were investigated. Results showed that the packing density of the powder bed has the most significant effect on the melt pool characteristics. Zhou et al. [20] firstly generated a 3D random packing of spherical particles with same or different size. A ray tracing algorithm based on a Monte Carlo method was then used to simulate radiation heat transfer in bimodal structures.

A numerical Finite Element (FE) model for AM by SLM is presented hereafter. It aims at studying thermomechanical phenomena at the scale of the bead, during unitary and successive multiple passes deposition of ceramic material. The model focuses on heat transfer and fluid flow during melting of the powder bed, resulting in the prediction of the shape of the bead. A 3D application for material deposition in SLM with alumina ceramics is proposed. Considering the relative transparency of this material with respect to laser radiation, a volume heat source model based on the Beer–Lambert law is derived, taking into account the local absorption coefficient. The Level Set (LS) method is used to track the material/gas interface and hence the bead shape. Shrinkage due to transformation of powder particles into a compact medium is taken into account by a compressible Newtonian constitutive law. A stable semi-implicit formulation is employed for the surface tension term in the momentum conservation. The solidification stage is modeled considering a prescribed evolution of the phase fraction with temperature. The influence of different process parameters on melt pool profiles and bead shapes is discussed, such as laser power and scanning velocity, or layer thickness of the powder bed. Sensitivity tests are also done regarding material properties, such as absorption, surface tension and viscosity.

2. Modeling

The system is made of a material domain and a gas domain, as shown in Fig. 2a. The material domain hereafter considered is pure alumina. In its initial state, it consists of a powder bed with a certain porosity, located on top of consolidated layers acting as a substrate. This powder material is melted during laser heating and cooled down to form a compact deposition, or consolidated region. During this one-way transformation, densification takes place and is modeled through the variation of the apparent density of the material from powder state to liquid and solid states. Possible states for the compact medium are liquid and solid, only depending on temperature. The surface shape of the melt pool, *i.e.* the interface between the two domains, material and gas, results from combined effects of forces acting on the liquid. They depend on properties such as liquid viscosity and surface tension at the liquid/gas interface. The evolution of the gas/material interface is tracked by a LS method and mesh adaptation. All conservation equations are established in this two-domain system considering a continuous evolution of the materials properties. The main assumptions of the proposed approach are summarized as follows (additional hypotheses will be introduced and discussed directly in the text):

- The powder is assimilated to a continuum;
- No powder projection (*i.e.* no powder loss);