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## Process of selective laser sintering of polymer powders: Modeling, simulation, and validation

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## ARTICLE INFO

*Article history:*

Received 25 June 2018

Accepted 12 July 2018

Available online xxxx

*Keywords:*

Additive manufacturing

Laser sintering

Polymer

Heat transfers

Multiphysics modeling

Numerical simulation

## ABSTRACT

Selective laser sintering (SLS) of polymer powders involves multiphysical transient phenomena. A numerical tool for simulating such a process is developed on the basis of the reliable modeling of the corresponding thermo-physical transient phenomena and appropriate numerical methods. The present paper addresses modeling, simulation, and validation aspects that are indispensable for studying and optimizing SLS process. The coupled multiphysical models are detailed, and the numerical tool based on the finite volume method is presented, with validations in terms of numerical and physical accuracy, by considering the shrinkage involved in the process and the successive layers deposition. A parametric analysis is finally proposed in order to test the reliability of the model in terms of representing real physical phenomena and thermal history experienced by the material during the process.

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### 1. Introduction

The Selective Laser Sintering (SLS) is a promising additive manufacturing technique for modern material processing. It is drawing more and more attention from scientific communities and industries. Although recent technology improvements made it move from rapid prototyping to production, SLS is not yet a reliable process for thermoplastics, because of limited quality of the resultant parts compared to those from classical processes [1].

So that the SLS becomes reliable for thermoplastic materials, more efforts are still needed to understand the physical phenomena involved in the process, model them conveniently, implement the corresponding models in a numerical tool for simulating the different steps of the process, validate the tool and perform relevant studies so as to improve the quality of the final parts. New knowledge and academic developments are therefore needed to perform studies on SLS process and make a link between process, material structure, and parts' final properties.

Despite the apparent simplicity of the SLS concept, the involved physical phenomena are numerous and complex: interaction between laser and powder bed, melting, coalescence of melted grains and air diffusion versus densification, solidification versus crystallization, volume shrinkage, and layers deposition. Furthermore, these phenomena spread over different scales of time and space.

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<https://doi.org/10.1016/j.crme.2018.08.002>

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Moreover, the quality of SLS parts depends on a large number of process and material parameters: type of polymer, grain size, layer thickness, laser power, diameter of laser beam, scanning velocity, spacing between laser scans, powder spreading speed, preheat temperature, etc.

Considering the melting step, for example, the first modeling necessary to be done concerns how laser beam interacts with powder bed, how the powder melts, how porosity of the powder layer changes and how the thermo-physical properties of the melting zones evolve in time. As evolution of the thermo-physical properties of the melt controls the density and the micro-structure of the final part, faithful models are indispensable. In other words, the corresponding models must be validated.

The models, either validated or not, should be then used in a numerical tool to simulate the whole process. As no commercial software is available, the development of a numerical code is necessary in order to study the SLS of a polymer powder. There arise questions on the approach, the mathematical formulation, and the numerical method to be used. Again, the numerical tool developed needs to be validated before any use for understanding and optimization of the SLS process. This leads to the conclusion that polymers SLS process simulation is a very complex multi-disciplinary work and that tremendous research efforts on the topic are needed to face the challenge. The present paper aims at addressing various needs in the simulation of an SLS process in order to give a global view and presenting some work we realized.

The paper is organized as follows: after detailing the main steps of an SLS process and the modeling aspects of the involved physical phenomena, simulation aspects will be discussed, before presenting the mathematical formulation and numerical methods used and the results obtained in terms of validation; finally, concluding remarks, with discussions of the capabilities of the developed tool, and perspectives for the SLS modeling are given.

## 2. SLS process and modeling aspects

In an SLS process, both the production and supply zones are preheated to homogenize and reduce the temperature gradient. The preheating temperatures could be different, but they remain slightly below the onset melting point and above the crystallization point [2]. For convenience, it can be considered that both zones are preheated at the same temperature and that preheating does not need to be modeled.

A laser placed above the production zone or the powder bed can be used to merge polymer grains on the surface of the powder bed by means of a scanning mirror. As is mentioned in the introduction, the laser beam interacts with the powder bed, which is a granular material, and the interaction depends on the laser wavelength, the powder distribution size, and the chemical composition of the polymer. The supplied energy in the material is usually represented in the depth direction by an exponential law named Beer–Lambert law, which is also suitable for UV and IR radiation [3]. Many studies simplify the problem and consider only surface interaction [4], but it was widely known and physically proven that it is a volumetric interaction [5,2], involving x-ray diffraction (Mie theory) and the behavior of semi-transparent materials due to the materials' nature [3] and the granular state [6,7]. As the interaction between the laser beam and the polymer powder bed is the starting point of an SLS process, we investigated it in previous works [8,7] by considering absorption, transmission, and diffusion with multiple scattering of the laser beam in a granular material. In fact, most of polymer grains are semi-transparent to laser beam, and their size is close to the laser wavelength. This suggests application of Mie theory. A modified Monte Carlo ray tracing method coupled with Mie theory was then developed and implemented, as in our previous work [7]. The results were validated by a case of both metallic and polymer powders. The application of the method to a polymer powder bed showed important influences of multiple scattering. As observed experimentally, the model predicts a larger heating zone near the bed surface in comparison with the diameter of the laser beam and the heating zone decreases or shrinks with increasing depth [7].

Laser power, provided to polymer grains, heats and melts them. The melted grains coalesce, and this tends to densify the bed and make air between grains escape through open pores to the bed surface. When pores are fully closed, gas diffusion starts, and the densification of the bed continues. Both coalescence and air diffusion induce bed densification and evolution of the bed porosity. They need to be taken into account when modeling the SLS process. There are many works in the literature on coalescence [9,10] and on air diffusion [11,12]. Note that polymer viscosity and surface tension are two important factors for coalescence, but also viscoelasticity and relaxation time (reptation time) play important roles in the densification process compared to metallic materials.

The melting of polymer grains results in an evolution of the powder thermo-physical properties that need to be modeled for accurate simulation of the SLS process. Unfortunately, semi-crystalline polymer grains do not have a fixed melting point: they melt in a range of temperature. In fact, polymers are not pure molecular materials, but are constituted by a statistical distribution of macromolecules, leading to different melting temperatures, as they interact by different Van der Waals forces. During this step, all the evolutions of the thermophysical properties need to be accurately described, and a fusion model is required to link the solid and fully melted states. In terms of energy balance, a heat sink representing latent heat, the amount of energy needed for melting, should appear in the energy equation. As the fusion model proposed by Voller et al. [13] is based on the volume fraction of liquid, we suggest also a similar approach to define the evolutions of the thermo-physical properties during melting.

Another consequence of the bed densification and air exhaust is the volume shrinkage, which should be also considered in simulation of the process. As volume shrinkage is closely related to the evolution of bed porosity, convenient modeling of coalescence and air diffusion is indispensable, and its accuracy is crucial for the predictions of the final part's behavior and

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