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Pore filling during selective laser melting - assisted additive manufacturing of composites

Andrey L. Maximenko, Eugene A. Olevsky *

San Diego State University, 5500 Campanile Dr., San Diego, CA 92182-1323, United States

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ABSTRACT

Numerical assessment of pore-filling time during Selective Laser Melting (SLM) of metal matrix composites is conducted based on the theory of liquid-phase sintering. Modeling of 3D bi-modal packings of spherical metal and ceramic particles indicates the existence of clusters of ceramic reinforcements with various volume concentrations. During SLM the pores between ceramic particles have to be filled with liquid metal, and the pore-filling duration can be considered to be the minimum necessary time of the successful pore-free SLM processing. Based on the results of the modeling an analytical criterion for the pore-free additive manufacturing of composites utilizing SLM is developed.

One of the most widespread direct approaches in Additive Manufacturing (AM) is the Selective Laser Melting (SLM). During the SLM process a thin (100–250μm) powder layer is deposited and then fused by a laser scanning with a rate of 0.1–1 m/s. Under these processing conditions the material consolidates and solidifies after the laser beam moves away [1,2]. As a result of melting it is expected that the processed powder transforms into a solid pore-free material.

In principle, SLM approach can be applied for any types of materials: polymers, metals, ceramics or any combinations of those. Metal-matrix composites with ceramic inclusions are a class of materials which combines high strength and stiffness of ceramics with the damage tolerance and toughness provided by a metal matrix. In particular, unique properties of metal-matrix composites made WC-Co cemented carbides to be the ones of the most commercially successful products in the history of powder metallurgy [3].

As a rule, SLM processing of composite materials involves melting of a mixture of two or more different powders with the low melting point powder acting as the matrix material and all other powders acting as the reinforcement. Modern laser equipment can provide high enough temperatures during scanning to melt both metallic and ceramic particles in the powder mixture [4], but severe localized heating often leads to high thermal stresses and damage development. It still seems promising to melt during SLM only one (metallic) component of the ceramic-metal powder mixture, without using extremely high temperatures for ceramic melting. This SLM approach has been employed by many authors for the fabrication of different metal matrix composites [5–15]. The common problem persisting through these attempts is the high residual porosity of the obtained components. For SLM of composites with non-melted or partially melted ceramic particles the mechanism of porosity elimination is similar to the mechanism of liquid-phase sintering: pore filling with the molten metal. Residual porosity can result from the insufficient time for pore filling because of the highly transient liquid phase formation during SLM. The time of the liquid phase existence can be less than 1 ms [16]. The present study is dedicated to the numerical analysis of this phenomenon.

The additive step in SLM process starts from spreading a very thin layer of a powder across the surface to be printed. The size of pores during consolidation and, therefore, the time of the pore filling depend on the details of the powder packing. In the case of composites it is a packing of several powders.

Powder packing of two types of spherical particles has been modeled by the “rain drop” method similar to the ones proposed in Refs [17,18]. The particles have been deposited consecutively under the action of gravity. The coordinates of the starting points have been identified by a random number generator. The selection of the size of the next falling sphere corresponded to the pre-set size distribution of the particles and the volume concentrations of the different powder fractions in the mixture. After collision of a falling spherical particle with a powder layer, the particle continued the movement along or inside the powder layer up to the stable rest position. This modeling procedure generates a loose powder packing with the average porosity of about 0.5, which corresponds to the packing during powder spreading. In SLM-assisted manufacturing, a roller or a blade usually smoothes the powder layer surface after the deposition. As a result, the powder layer has a uniform thickness that was considered to be a constant during modeling. Therefore, if during the “virtual deposition” a particle sticks out from the layer, it is being removed, and the deposition attempt is repeated.

* Corresponding author.
E-mail address: eolevsky@mail.sdsu.edu (E.A. Olevsky).

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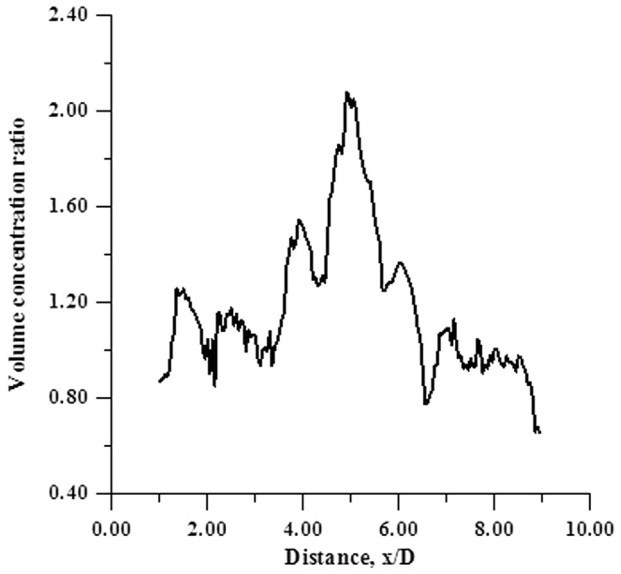

Fig. 1. Concentration ratio of large and small particles along the central section of powder packing in 10 × 10 × 3 box.

In the case of the SLM of metal matrix composites it seems reasonable to use comparatively more fusible metal particles to be smaller than ceramic particles to improve the homogeneity of the metal distribution in the composite. In the numerical examples described below the diameters of metal particles are three times smaller than the diameters of ceramic particles.

The theory of liquid phase sintering predicts that approximately 30 vol% of the melted powder is necessary for complete vitrification of the powder mixture and filling of all the voids between ceramic particles [19]. Because of the short sintering time, the vitrification has to be the main consolidation mechanism during SLM. The modeling of powder packings shows what types of pores should be filled during vitrification. The detailed numerical analysis of the obtained powders packings reveals the substantial volume nonuniformity of the concentrations of both small and large particles even in the considered case of their completely random deposition.

Fig. 1 shows the volume concentration ratio of large and small particles as a function of the chosen position in the powder packing with their equal average volume concentrations in the box 10 × 10 × 3, where the diameter of the larger particles is taken as 1. The coordinate X in Fig. 1 corresponds to the centre of the 2 × 2 × 2 small test box sliding on the large box bottom along the centerline of the packing. Parameter D is the large particle diameter. Both small and large particle concentrations for any coordinates in Fig. 1 are calculated as average values throughout this test box.

Peak at the curve in Fig. 1 indicates that packing has a local zone with prevalent large particles. Indeed, the images of the powder packing confirm this conclusion. Fig. 2-left shows the general top view of the packing with the volume concentration of the large particles in the solid phase equal to 0.35, and Fig. 2-right shows the respective distribution of the large particles. It is clear that, even for such a low volume concentration as 0.35, large particles form clusters with low concentrations of metal particles. This situation is aggravated with an increase of the volume concentration of large particles. Fig. 3 show the packing of the large particles in a powder layer with their volume concentrations of 0.5 and 0.65, respectively.

According to the well-known geometric considerations, the diameter of the tetrahedral pores in the packing of spheres is equal to 0.225D, and the diameter of octahedral pores is equal to 0.414D, where D is the diameter of particles [20]. The pores between large ceramic particles are larger than the pores between small metallic particles. Therefore during SLM the capillarity drives the liquid to preferentially fill smaller pores between metal particles and only after that it fills large pores between ceramic particles. Consequently, the time for the filling of large pores can be used for the estimation of the consolidation time during SLM.

The relationship describing the dynamic pore collapse in viscous liquid has been used for a long time in the theory of cavitation [21].The Reileigh-Plesset equation describes the evolution of the pore radius R under the influence of external pressure and surface tension at the pore surface:

$$\rho\left(R\frac{d^2R}{dt^2}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2\right)=P_g-P_\infty-\frac{2\gamma}{R}-4\frac{\mu}{R}\frac{dR}{dt} \quad (1)$$

Here ρ is the density of liquid; P_g and P_∞ are the gas pressure in the pore and the liquid pressure at infinity, respectively; γ is the specific surface energy of the pore. Liquid around the pore is assumed to be incompressible with viscosity equal to μ. The effective viscosity of liquid around the pore is a function of the volume concentration of the unmelted ceramic particles. According to Ref. [22] this viscosity can be estimated as:

$$\mu=\frac{\mu_0}{\left(1-\frac{\varphi}{\varphi_c}\right)^2} \quad (2)$$

where μ_0 is the viscosity of liquid, φ is the volume concentration of ceramic particles, and φ_c is the maximum volume concentration of spherical particles in the melt equal to 0.74 in the considered case.

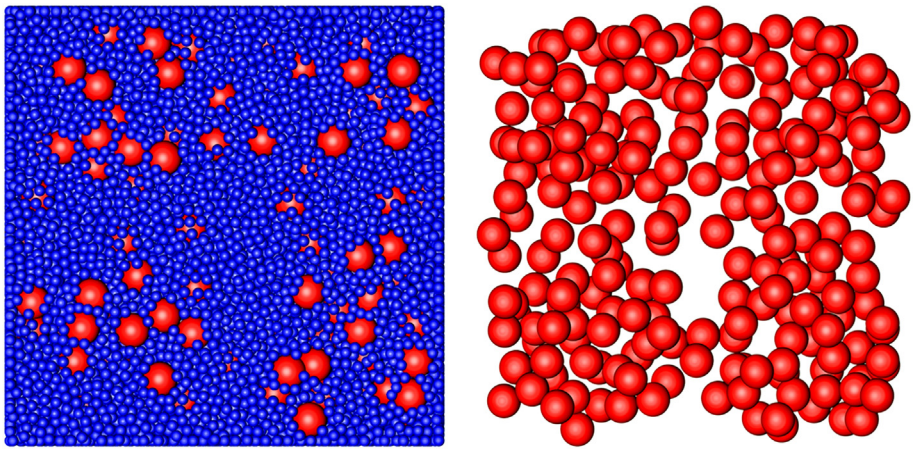

Fig. 2. (Left) Top view of powder packing for volume concentration of large particles equal to 0.35, (right) Respective packing of large particles.