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Original Article

A segregation model study of suspension-based additive manufacturing

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ABSTRACT

The additive manufacturing method of direct ceramic stereolithography directly fabricate complex core and shell molds while suspensions of coarser or denser particles have undergone differential sedimentation and cause particle size segregation. In order to safely use refractory coarse ceramic powder without the segregation problem, we develop a segregation model derived from the degree of segregation parameter (β) with the relation of two time constants; the writing time and the settling time. Given the relationships of material, apparatus, and design parameters, no segregation is expected in the silica particle dispersed suspension with average particle size of 40 μm when laser powers larger than 89 mW or 60 mW is applied to build layers with layer thicknesses of 150 μm or 250 μm, respectively. The explanation and application of the segregation model provided in this article enables to easily determine optimum variables and maximize the efficiency of additive manufacturing methods, thus able to suppress segregation in a layer.

1. Introduction

Complex ceramic parts can be produced with the additive manufacturing (AM) method of direct ceramic stereolithography (CerSLA) [1,2]. CerSLA works like conventional stereolithography, a repeated layered manufacturing process where thin liquid layers are solidified by photopolymerization with a UV laser, which "writes" the design for each slice [3,4]. By replacing the liquid with a fluid photopolymerizable powder suspension, CerSLA can be used to directly produce cores and shell molds with integral cores from materials such as silica and alumina without the use of a wax pattern, which efficiently replace conventional investment casting (IC) [5–7].

Ceramic casting molds have been made from refractory grade powders (> 50 μm) to creep resistance and prevent severe dimensional change of ceramic mold from high temperature of casting metal [8,9]. On the other hand, CerSLA necessitates the use of a UV-curable liquid with fine ceramic powder sustaining a colloidal state of suspension [10,11]. Thus, to retain the benefit of the stable ceramic molds of IC, CerSLA would require suspensions prepared with coarse ceramic powders. However, suspensions of coarser or denser particles have undergone differential sedimentation, causing particle size segregation in which the population of larger or denser particles is greater near the bottom in Fig. 1 [12].

The particle segregated regions in the green body generated property degrading defects such as delamination, distortion, and excessive shrinkage after binder bun-out. Therefore, in order to prevent particle size segregations, the additive manufacturing process of CerSLA should be complied with a prerequisite that the time required to write a layer must be shorter than the time required to settle a thickness of a layer. The settling time depends on particle size, density, and monomer viscosity, and volume fraction for the case of hindered settling appropriate for concentrated suspensions, while the time required to write a layer depends on the kinetics of photopolymerization, the refractive index of the ceramic, the volume fraction, the particle size, and the details of Mei scattering [13].

In this paper, we developed the Segregation Model considering material property and apparatus to safely use refractory coarse ceramic powder without the segregation problem. The goal of the segregation model is to understand the fundamental aspects governing the AM process of CerSLA, and establish the criteria for segregation resulting from the consideration of time to write a layer in acrylate-powder mixture and settling time. Given the segregation model, it can easily select optimum variables and maximize the efficiency of CerSLA, thus able to suppress segregation in a layer.

2. Model development

2.1. Settling rate and time

The size of particles in suspension is one of the most important facts

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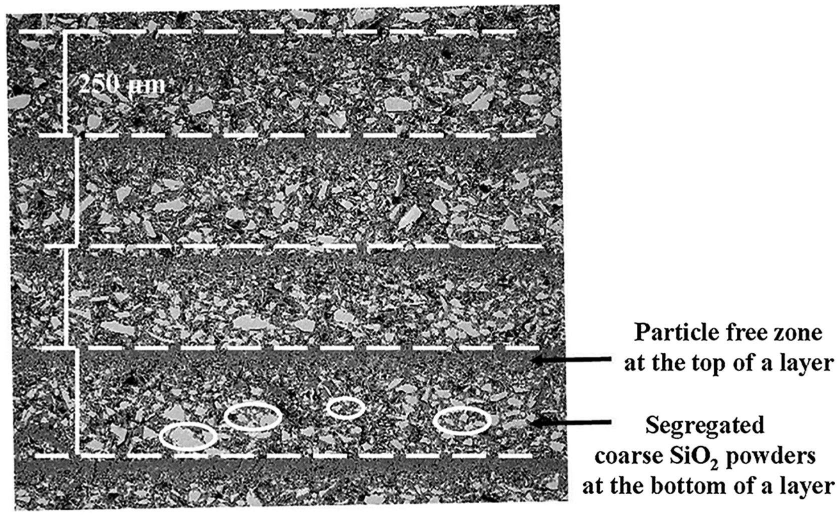

Fig. 1. Particle size segregation in a layer due to the fast sedimentation of coarse powder. Suspensions of coarser or denser particles can undergo differential sedimentation, leading to particle size segregation in which the population of larger or denser particles is greater near the bottom.

affecting the stability of suspensions. Colloidal particles will remain suspended within fluid systems even after long times, while large particles will settle quickly when suspensions are at rest and flow velocities are low. Those settling rate, a time constant related to the segregation, on the various particle sizes of silica powder as a given particle in isolation in fluid is calculated by Stokes' law [14], representing that the settling rate of a single particle is much larger by an increase in the particle size (proportional to d^2), and retarded by an increase in the liquid viscosity.

When increasing solid loading in a suspension, the rate of sedimentation is less than the velocity given by the Stokes law. Stoke's law does not apply when circumstances cause settling to be 'hindered'. One example of this is when too many particles are in suspension, and particles crowd one another. Another example is when coarse particles settle and the turbulence in their wakes drags along other particles. In the hindered region with more concentrated solid, hindered settling occur and reduce the settling velocity of a particle, and longer residence time from the interaction between a particle and its neighboring particles [15,16].

Large particle sizes of fused silica used in this work were governed by the hydrodynamic interaction forces and gravitational force. The settling rate of large particle sizes is calculated by the Richardson-Zaki (R-Z) equation. This equation is widely accepted to correlate the superficial fluidizing velocity ν and the particle volume fraction φ of fluidized beds and suspensions of non-agglomerated particles

$$\nu = \nu_{stokes}(1-\phi)^n = \frac{1}{18}\frac{(\rho_p-\rho_f)gd^2}{\eta}(1-\phi)^n \quad (1)$$

Where ρ_c and ρ_l are the density of the solid ceramic particle and the monomer liquid, g is the gravitational acceleration, d is diameter of ceramic powder, η is the fluid viscosity, φ is the concentration of solid, respectively. The exponent n, an empirical parameter value, has been 4.65 reported by Richardson and Zaki in the small particle Reynolds number (Re_t) regime, while n decreased as Re_t increased [17]. Given the Richardson-Zaki (R-Z) Eq. (1), the settling rate of silica with different particle sizes in the suspension as a function of volume faction silica is calculated, as shown in Fig. 2. Note that the exponent of 4.65 was applied due to the small particle Reynolds number. In the dilute region, coarser silica powders by rapid settling rate quickly settle. However, in the concentrated region, when the amount of silica increased from 40 to 60 vol fraction silica in the HDDA, the settling rate for silica powders with diameter of 60 μm decreased from 2.2×10^{-5} m/s to 3.3×10^{-6} m/s.

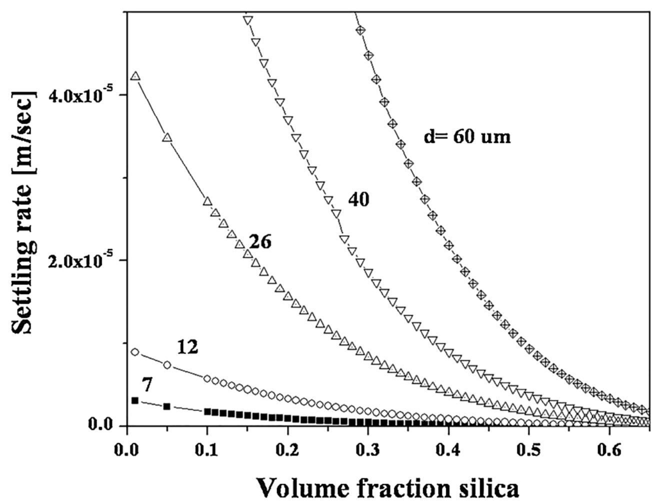

Fig. 2. Settling rate as a function of volume fraction silica.

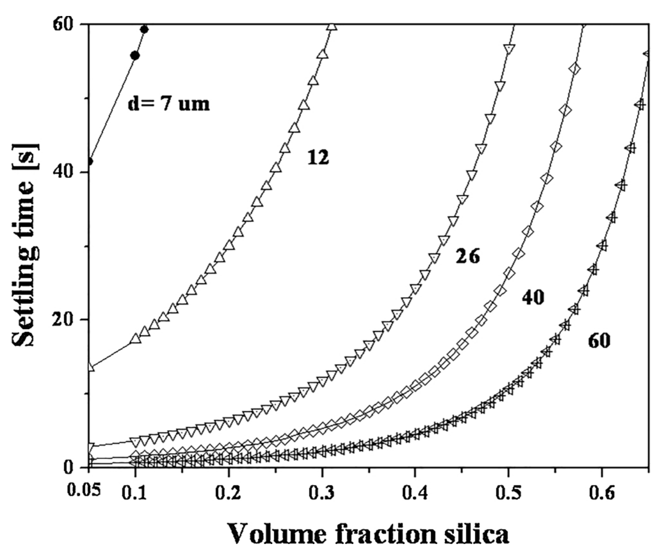

Fig. 3. Settling time for a layer thickness of 100 μm, as a function of volume fraction of silica with different particle size.