EFFECT OF SiC PARTICLES ON VISCOSITY OF 3-D PRINT PASTE
A Fractal Rheological Model and Experimental Verification

by

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Original scientific paper
https://doi.org/10.2298/TSCI200710131Z

This paper studies the effect of the rheological property of SiC-based print paste on the 3-D printability at different SiC concentrations. The viscosity depends both the size and concentration of the added particles, a fractal rheological model is suggested and verified experimentally.

Key words: *3-D printing, rheological property, fractal differential model, two-scale fractal dimension*

Introduction

The 3-D printing is a technique based on digital model files that construct objects by stacking and accumulating materials layer by layer. Compared with traditional manufacturing methods, 3-D printing technology has advantages such as reducing the processing difficulty of complex structures, reducing costs and saving space. The 3-D printing technology has been widely used in various fields to print from food to building, providing promising frontiers in food products and architectural engineering [1-4]. Though we can consider ingredient distribution, color and shape in food products, and print functional materials like hydrophilic or hydrophobic building surface for self-clean or for water collection from air like an ancient device called Fangzhu [5, 6].

The SiC has high specific strength and stiffness, and it has good wear resistance. The SiC matrix composites are widely used in military, electronics, aerospace and other fields. The SiC water-based slurry is not only environmentally friendly, but also cost-effective. The 3-D printed SiC matrix composites are conducive to the realization of many excellent properties.

The 3-D printability depends strongly on the rheological property of print paste, this paper studies the effect of the addition of SiC particles on viscosity of print paste.

Theoretical analysis

Addition of an additive in solution will greatly affect the rheological property of the solution. Figure 1(a) shows the molecule distribution in a solution, the viscosity is due to the interaction among the molecules, and the viscous force can be considered as a friction force between two molecule layers. When additives are added into the solution, the geometric mor-

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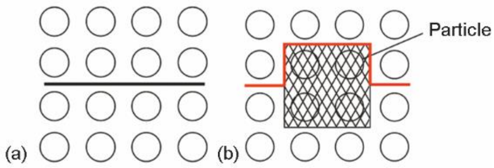

Figure 1. The solution's geometrical property; (a) without additives and (b) with a cubic additive in a controlling volume

phology of molecule distribution will be changed, see fig. 1(b), and the viscosity depends the size and concentration of the additive. According to the previous analysis, we suggest the following viscosity formulation:

$$\eta = \eta_0 \exp(kC^{\alpha}) \tag{1}$$

where η_0 is the viscosity of the solution without additive, C – the concentration of the additive, and α – the two-scale fractal dimension [7-9], it is function of the particle size and the particle concentration. For the solution without additive as shown in fig. 1(a), the contact line between two molecule layers is a line, and the two-fractal dimension is α = 1. The two-scale fractal dimension for fig. 1(b) can be calculated as α = 6/4 = 3/2.

Equation (1) can be also approximately written:

$$\eta = \eta_0 (1 + kC)^{\alpha} \tag{2}$$

The rotation speed affects greatly the viscosity of the solution when it is under a continuous stir. Due the centrifugal force, the solution moves a layered form, and the viscosity will decrease remarkably. The differential model can be expressed:

$$\frac{\mathrm{d}\eta}{\mathrm{d}\omega} + \lambda\eta = 0 \quad \eta(0) = \eta_0 \tag{3}$$

where ω is the rotation speed, λ – the constant, and $\mathrm{d}\eta/\mathrm{d}\omega$ – the effect due to the layered motion in radical direction.

The solution of eq. (3) is:

$$\eta(\omega) = \eta_0 \exp(-\lambda\omega) \tag{4}$$

This equation predicts that the viscosity reduce exponentially with the increase of the rotation speed. This is acceptable for large value of the rotation speed, but it cannot describe the sudden change of the viscosity at initial stage of $\omega \ll 1$. Any differential models can model this sudden change in viscosity, so a fractal modification has to be considered.

The rheological property can be expressed by the following fractal differential model:

$$\frac{\mathrm{d}\eta}{\mathrm{d}\omega^{\gamma}} + \lambda\eta = 0, \qquad \eta(0) = \eta_0 \tag{5}$$

where γ is the order of the fractal derivative which is defined [7]:

$$\frac{\mathrm{d}\eta}{\mathrm{d}\omega^{\gamma}}(\omega_0) = \Gamma(1+\gamma) \lim_{\substack{\omega-\omega_0 \to \Delta\omega \\ \Delta\omega \neq 0}} \frac{\eta - \eta_0}{(\omega - \omega_0)^{\alpha}} \tag{6}$$

The solution of eq. (6) is:

$$\eta(\omega) = \eta_0 \exp(-\lambda\omega^{\gamma}) \tag{7}$$

It is obvious that:

$$\frac{\mathrm{d}\eta}{\mathrm{d}\omega} = -\eta_0 \lambda\gamma\omega^{\gamma-1} \exp(-\lambda\omega^{\gamma}) \tag{8}$$

Equation (8) implies:

$$\frac{\mathrm{d}\eta}{\mathrm{d}\omega}(0)=\begin{cases}0, & \gamma>1\\ -\eta_0\lambda, & \gamma=1\\ -\infty, & \gamma<1\end{cases} \tag{9}$$

A sudden change of viscosity happens when $\gamma < 1$ at $\omega = 0$. Figure 2 shows the rheological property when $\lambda = 1$ for different values of γ.

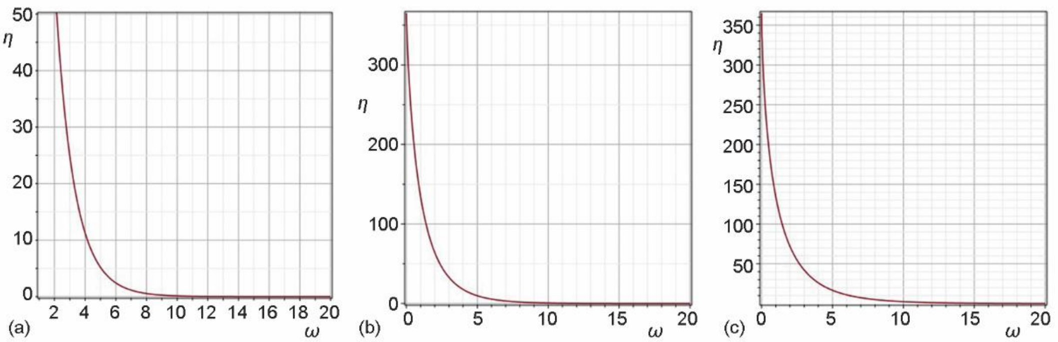

Figure 2. Theological property of solution when λ = 1 for different values of γ; (a) γ = 0.9, (b) γ = 0.8, and (c) γ = 0.7

Experimental design

In our experiment, SiC powder was manufactured by Zhengzhou Sanmo Superhard Material Co., Ltd, China, the power diameter was 1.5 μm. Other experimental chemicals, along with their manufacturers and functions, were listed in tab. 1.

Table 1. Experimental chemicals

Chemicals	Purity	Manufacturer	Function
Deionized water	–	Self-made	Solvent
Carrageen, 0.7% in water solution	–	Hainan Qionghai Changqing Agar Factory, China	Thickener
Tetramethylammonium hydroxide (TMAH), 25% in water solution	AR	Shanghai Macklin Biochemical Co., Ltd., China	Dispersant
Polyethylene Glycol 200 (PEG 200)	LR	Tianjin Damao Chemical Reagent Factory, China	Plasticizer
Glycerol	CP	Tianjin Zhiyuan Chemical Reagent Co. Ltd., China	Lubricant

Firstly, 0.7% aqueous solution of carrageenan was prepared in 95 °C water bath and cooled to room temperature. Afterwards, deionized water, carrageenan (0.7% aqueous solution), glycerol, PEG200, TMAH (25% aqueous solution) was mixed at the volume ratio of 83:16:8:2:7, thus the premixed solution was formed. Different dosage of SiC powder was added to 50 mL premixed solution, and ball milling for 2 hours to ensure thorough homogeneity, and test the viscosity of the slurry.

Carrageenan was dissolved in water bath pan, and SiC slurry was ball milled in vertical planetary mill (XQM-04, Changsha Tencan Powder Technology Co. Ltd., China), the slurry viscosity was tested by digital display viscometer (NDJ-8S, Shanghai Fangrui Instrument Co. Ltd., China), rotational speed are set as 0.6, 1.5, 3, 6, 12, 30, and 60 rpm, 5 viscosity value under each speed were recorded, then calculated the average value and took it as the measured result to analyze. The test temperature was 25 °C.

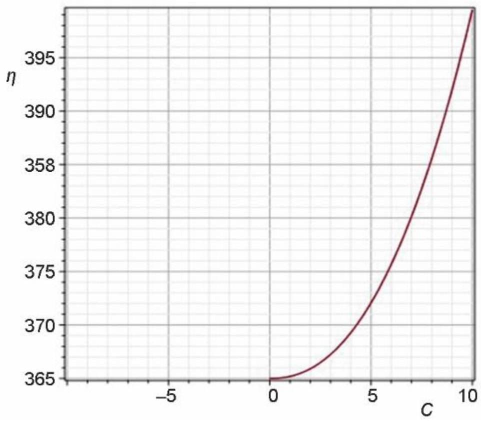

Figure 3. Effect of SiC concentration on the viscosity of the solution

Results and analysis

The viscosity of the solution without additive is η_0 =365, it becomes η = 558 and η = 1043, respectively, when C = 20 g and C = 30 g, according to eq. (1), the constants k and α can be determined as k = 0.000526920 and α = 2.23369, we obtain the following viscosity property:

$$\eta = 365\exp(0.000526920C^{2.23369}) \quad (10)$$

Figure 3 shows the effect of SiC concentration on the viscosity of the solution. Figure 4 is the rheological property, it is obvious the concentration of SiC additive affects greatly the value of γ.

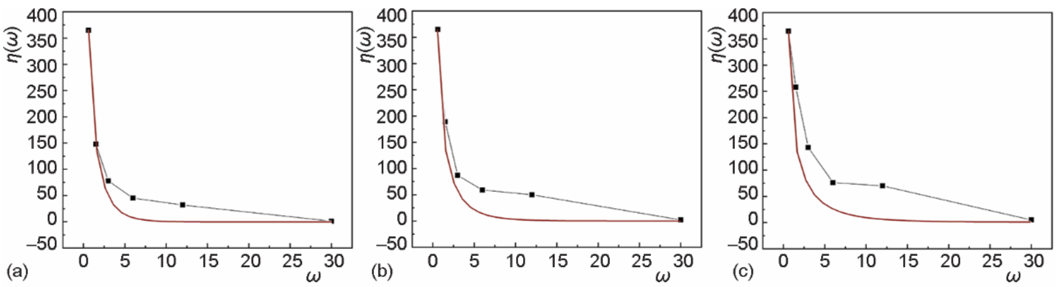

Figure 4. Rheological properties of the paste with and without SiC powers; (a) without SiC, λ = 1.0, γ = 0.8, (b) 20 g SiC, λ = 1.0, γ = 0.7, and (c) 30 g SiC, λ = 1.0, γ = 0.6

Discussion and conclusion

The rheological properties will greatly affect the 3-D printability. This paper establishes a fractal model for predicting the viscosity of the paste, see eq. (1), and a fractal rheological model, see eq. (7). The parameters in eqs. (1) and (7) can determined experimentally, and can be directly used to optimal design of the printing paste with given viscosity and given rheological property.

Our experiment shows that λ keeps unchanged for different concentration of SiC additives when SiC concentration is low, λ is the solution property, and it is not affected by the additives. On the other hand, the SiC concentration affect greatly the value of γ, this can be explained that higher centration of SiC particles implies a higher configural force, as a result, the radical layered motion is enhanced, and the friction becomes less.

Acknowledgment

The author wishes to acknowledge the financial support for this work from School of Materials Science and Engineering of Lanzhou University of Technology, and wishes to thank teachers from State Key Laboratory of Advanced Processing and Recycling of Nonferrous Metals for the technical support.

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Paper submitted: July 10, 2020
Paper revised: July 13, 2020
Paper accepted: July 13, 2020