Ceramic Nanoparticle Ink for Direct Colloidal Assembly†

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Abstract

Y$_2$O$_3$ stabilized ZrO$_2$ (YSZ) whose equivalent spherical diameter was 77nm was used as nanoparticles, and YSZ/ethanol colloidal dispersion with a volume fraction of 30vol% was prepared using poly(ethylenimine) (PEI) as dispersant. Then, colloidal gelation was induced by adding a small amount of nonadsorbed polymer, poly (vinyl butyral) (PVB) into the colloidal dispersion. The yield stress of the colloidal dispersion increased remarkably when PVB was added at 1mass%-powder or more. The two dimensional colloidal patterns of YSZ were directly formed by extruding the colloidal gel through a micro-nozzle.

KEY WORDS: (direct ink writing), (colloidal gel), (viscoelastic), (nanoparticles)

1. Introduction

Direct writing techniques offer the ability to produce ceramic components on-demand with complex structures. These techniques can be attractive routes for advanced ceramics, sensors, composites, tissue engineering scaffolds and photonic materials 1,2). Several approaches such as robocasting 3,4), fused deposition 2,5), and micropen writing 6) have been introduced and have demonstrated solid freeforming of 2D and 3D colloidal structures via a layer-by-layer deposition of particle based inks. In each approach, ink is continuously extruded through a micro-nozzle to create a filamentary element.

Nanoparticle suspensions for the filament-based direct writing technique must satisfy two important criteria 4). First, they should exhibit a well-controlled viscoelastic response, i.e., they flow through the deposition nozzle and then set immediately to facilitate shape retention of the deposited features. Secondly, they should contain a high volume fraction of powder to minimize drying-induced shrinkage after assembly is complete, i.e., the particles network must be able to resist compressive stresses arising from capillary tension. The developed nanoparticle ink was an aqueous colloidal gel comprised of poly(acrylic acid)(PAA)-coated BaTiO$_3$ nanoparticles, whose interactions were carefully modulated by changing ionic strength through the addition of monovalent or divalent salt species 7).

Here, we report nanoparticle dispersed colloidal gels with ethanol solvent for the filament-based direct writing. In this study, the colloidal gelation was successfully induced by adding small amount of nonadsorbed polymer into the colloidal sol.

2. Experimental

Materials. Y$_2$O$_3$ stabilized ZrO$_2$ (YSZ) powders (TZ-8Y,Tosoh, Japan) were used as model particles. The specific surface area of the powder, measured by nitrogen adsorption, was approximately 13.2m$^2$/g yielding an equivalent spherical diameter of 77nm. Branched poly(ethyleneimine) (PEI, MW~10,000, Nippon Shokubai, Japan) was used as dispersant. PEI has been proved to be a good dispersant of nanosized ZrO$_2$ in aqueous systems 8). A high affinity of PEI on oxide surfaces can also promote the colloidal stabilization of oxide particles in an ethanol system 9). Poly(vinyl butyral) (PVB, #3000K, Denka, Japan) was composed of 81mol% vinyl butyral, 12mol% vinyl hydroxyl, and 7mol% vinyl acetate units, and the number average of their polymerization is ~800. Ethanol (purity 99.5%, Wako Pure Chemical, Japan) was used as solvent.

Preparation of Colloidal Gel. The solid volume fraction of YSZ in the ethanol suspension was set at 30vol%. The amount of PEI added was 1.5mass% of the solid. The suspension was milled in a laboratory scale ball mill for 24h using ZrO$_2$ milling media. Then, PVB was added using a conventional stirrer for the fluid-to-gel transition. The total amount of PVB added was 0.01,0.1,1 and 3mass% of the solid.

Rheological Measurements. The rheological measurements of the colloidal inks were conducted using a rheology meter (HAAKE Rheostress RS600, Thermo fisher scientific Inc., USA). As sensor attachments, cone-plate type sensors with 20 and 35mm diameters were employed. To avoid undesired influence from different mechanical histories, samples were
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Homogenized by shearing at an identical rate of 20 s$^{-1}$ for 10 s and left standing for an additional 10 s prior to measurement. Flow curves were automatically recorded via a built-in program. The measurements were performed with the following input conditions: the shear rate increased logarithmically from 0.1 s$^{-1}$ to 100 s$^{-1}$, over the time period of 2 min. The measurement temperature was 25°C.

**Direct Ink Writing.** A robocasting system with a micro-pen was employed. The ink of the resultant colloidal gel was housed in a syringe and pushed out as a filament through a tapered nozzle (diameter, D=200 μm) by a pneumatic system. The filament was deposited on a plate while the position of the nozzle was moving with a CAD system control. The deposition was carried out at 25°C in air.

3. Results and Discussion

Figures 1 and 2 show apparent viscosity and shear stress as a function of shear rate for the prepared colloidal inks with various contents of PVB. Each colloidal ink displayed shear thinning behavior with yield stress. In Fig. 2, the flow curves are fitted with the Herschel-Bulkley model, as described by:

$$\tau = \tau_y + K (G_p)^n$$

where $G_p$ is the shear rate, $\tau$ is the shear stress, $\tau_y$ is the yield stress, $n$ is the shear thinning exponent and $K$ is the viscosity parameter.

Yield stress is the shear stress at vanishing shear rate. It represents the minimum stress leading to deformation of the static form of the material. Here, we determined the values of yield stress from the fitting curves of the Herschel-Bulkley model. Figure 3 shows the relationship between the yield stress and PVB added. The yield stress at 3 mass% was about 70 Pa which was enough to be applicable to the direct writing technique. On the other hand, the yield stress of the suspension without PVB was less than 1 Pa. The addition of PVB promoted flocculation well, suggesting increasing interparticle attractive forces.
In this study, it was found that the small amount of 
PVB added induced strong flocculation, giving to 
fluid-to-gel transition. PVB with this amount does not 
have gelling ability. In fact, the solvent viscosity with 
dissolved PVB of 3mass% was negligibly small 
compared to those of the suspensions. In the suspension, 
PEI was fully coated on YSZ nanoparticles, whereas 
PVB existed as nonadsorbed polymer. It was noted that 
the phenomenon was not observed when the volume 
fraction of YSZ was less than 30vol%, suggesting that it 
would be probably explained by depletion interaction \(^{10}\). 
The detail of the mechanism will be discussed in a 
separate paper.

As shown in Fig. 4, various patterns of 2D structures 
assembled with YSZ nanoparticles were successfully 
obtained by direct-writing with the PVB added colloidal 
gel.

Fig. 4 Photograph of various 2D patterns by 
direct-writing

Conclusions

In this study, we propose an approach to producing 
nanoparticle colloidal gel for a direct writing technique. 
Salt species which are used in aqueous systems were not 
employed. Instead, we used PVB polymer as a gelation 
agent. Using the present colloidal gel, 2D patterns of 
YSZ nanoparticles were directly formed.

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