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Slurry mixing device with microchannels for gelcasting

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ABSTRACT

We developed a slurry mixing device with microchannels. Each channel has a width of 500 μm and a height of 75 μm with oblique ridges on the wall with the aim of rotating the slurry and enhancing the chaotic mixing efficiency. The effect of the oblique ridges on the slurry mixing efficiency was investigated for various ridge angles (30°, 45°, and 60°). We found that the slurry was successfully mixed by the channels with oblique ridges and that channels with a 45° ridge angle had the highest mixing efficiency.

1. Introduction

Gelcasting is a novel near-net-shape forming method for fabricating complex three-dimensional ceramic bodies that can be used with over a dozen different ceramic compositions including alumina, zirconia, hydroxyapatite and non-oxide powders [1,2]. In this process, the slurry, which is mixed with ceramic powders, organic monomers and cross-linking solutions, is poured into a mold, then cross-linking polymerization occurs and the polymer gel holds the ceramic powder particles in the desired shape. Compared with conventional ceramic forming methods, the gelcasting process has a significant advantage of greater homogeneity and higher green strength [3]. Thus, gelcasting has been studied for its use in various applications such as electrode powders and substrates for solid oxide fuel cells [4,5]. During the mixing in the gelcasting process, the mixing method strongly affects the forming time and the product quality. Rapid and homogeneous mixing enables throughput reduction and an improved yield. However, it is difficult to mix slurries rapidly and homogeneously owing to the slurry characteristics of high viscosity and thixotropy.

Meanwhile microfluidic systems have attracted a great deal of attention from scientific and industrial fields. Microchannel-based mixers have strong potential to achieve rapid and homogeneous mixing [6,7]. In general, micromixers can be categorized into passive micromixers and active micromixers. Passive micromixers have the advantages of a low cost and ease of fabrication and integration over active micromixers. As passive micromixers, chaotic micromixers using oblique grooves have been reported [8,9] and their mechanism and efficiency have been analyzed [10,11]. Although there have been many reports on mixing Newtonian fluids, there have been no reports on mixing slurries with microchannels. The micromixers may be useful for slurry as well as Newtonian fluids. In this study, we studied the effect of patterns in the microchannel on the slurry mixing efficiency for a slurry mixing device with microchannels used for gelcasting.

2. Experimental

Fig. 1 shows a schematic of our slurry mixing device with two inlets, A and B. The width and height of the channel are 500 and 75 μm, respectively. The channel has oblique ridges on the wall with a height of 15 μm and a pitch of 100 μm. The angle of the ridges is 30°, 45° or 60°. The devices were fabricated by a soft-lithographic method with polydimethylsiloxane (PDMS, Silpot184, Dow Corning Toray). The master structure was fabricated by double-layer lithography. First, we exposed the channel pattern onto SU-8 photoresist (thickness: 60 μm, SU-8 3050, Microchem), which had been spin-coated on a glass substrate. Second, the sheet-type SU-8 photoresist (thickness: 15 μm, XP FILM TRIAL-15, Microchem.) was adhered on the surface and the ridge pattern was then exposed and aligned with the channel pattern. Third, the SU-8 photoresist was developed. The PDMS channel was molded using the SU-8 structures and sealed onto the flat PDMS-coated glass substrate after plasma treatment.

We used a slurry that contained about 50 vol.% zirconia powder. The density and surface tension of the slurry were 3.3 g/cm^3 and 36 mN/m, respectively. The slurry behaved as a thixotropic fluid. As the shear rate increased, the viscosity of the slurry was reduced from about 3–1 Pa·s. The surface contact angle on the PDMS surface was 59°. We injected the slurry separately into channels having ridges with angles of 30°, 45°, and 60° and investigated the mixing effect by microscopy (IX 71, Olympus). For easy observation, a fluorescent polymer microsphere suspension (G500, Duke

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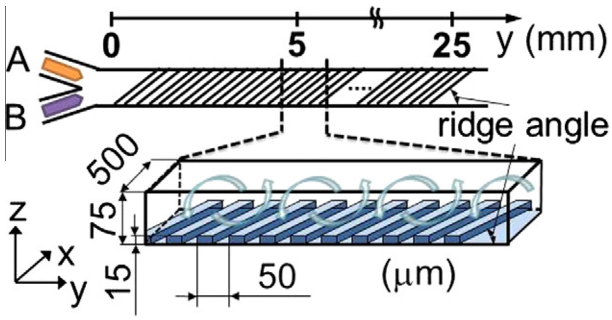
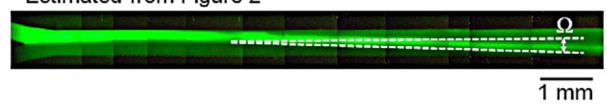


Fig. 1. Schematic of our slurry mixing device.

Table 1
Comparison of the streamline angles and rotation cycles.

	No pattern	Ridge angle (°) 30	45	60
Streamline angle* (°)	0	0.6	1.9	0.9
Rotation cycle (mm)	-	60†	20	45†

*Evaluated from the angle Ω in the following figure
†Estimated from Figure 2



Scientific) was mixed with the slurry injected into an ‘inlet A’ side of each channel. We measured the standard deviation of the intensity distribution in the microscopy images.

3. Results and discussion

Fig. 2a shows the observed slurry behavior in the channels with no structure on the walls. Fig. 2b–d shows the rotation flow behaviors of the channels with ridges having angles of 30°, 45°, and 60° on the wall, respectively. In each case, the flow speed was about 1 mm/s. A segregated flow was observed in the channels with no ridge. Flows with a rotation of a quarter turn, a turn and 1/3 turn were observed in the channels with 30°, 45°, and 60° ridges, respectively. It was demonstrated that the oblique ridges on the wall enhanced the generation of spiral flows in the slurry. Table 1 shows a comparison of the streamline angles and rotation cycles. The streamline angle, Ω, was evaluated from the dashed lines in Table 1 and the rotation cycle was measured from the image in Fig. 2. The streamline angle for a ridge angle of 45° was more than twice as high as those for ridge angles of 30° and 60°. The spiral flow efficiency was strongly improved by the use of 45° oblique ridges. The boundary of the luminesced and non-luminesced slurry was linear, and continuous, so it was found that the rotation cycle in the channel with 45° ridges was 20 mm.

Fig. 3 shows plots of the standard deviation of the intensity distribution in the microscopy images in Fig. 2 as a function of the distance along the channel, *y*. The standard deviation indicates the mixing efficiency and is 0.5 for a completely separate flow and 0 for a completely mixed flow. Because the standard deviations of the channels with the ridges were reduced with increasing distance along the channels, the oblique ridges induced the rotation of the slurry. The second spiral of the flow made the point ($y = 20$ mm) where the standard deviation for the channel with

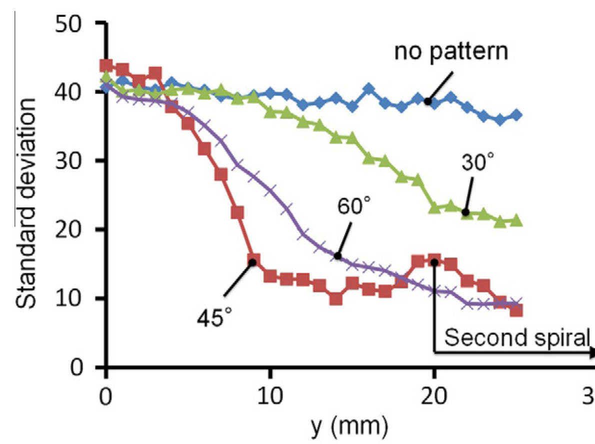


Fig. 3. Plots of the standard deviation of intensity distribution in microscopy images in Fig. 2. as a function of the distance along the channel, *y*.

45° ridges increase. The reduction in the standard deviation between the start of the first spiral and that of the second spiral indicates that the oblique ridges enhanced the mixing of the slurry in the channels. This result for the slurry exhibits the same tendency as that for a Newtonian fluid [12].

4. Conclusions

We investigated the effect of ridges on the wall of a microchannel on slurry mixing efficiency. We fabricated mixing devices that had microchannels with oblique ridges on the wall. The width and

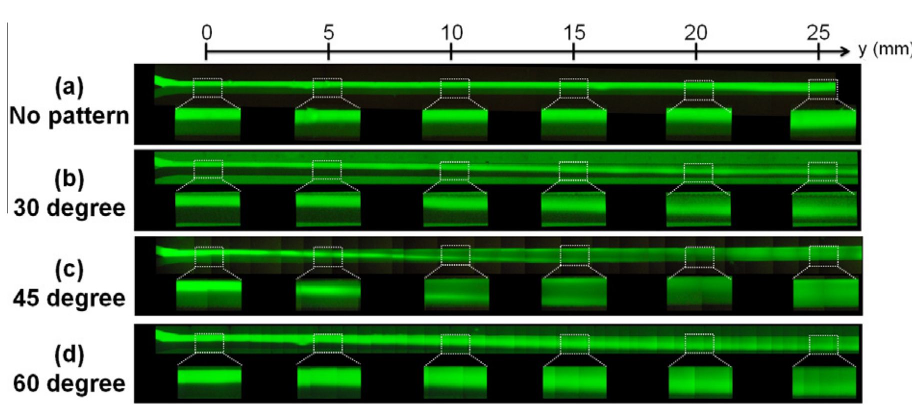


Fig. 2. Comparison of the flow behaviors. The flow speed is about 1 mm/s.

height of the channels were 500 and 75 μm and the pitch and height of the ridges were 100 and 15 μm, respectively. It was found that oblique ridges on the wall enhanced the rotation and chaotic mixing efficiency of the slurry and that the channel with a ridge angle of 45° exhibited the highest mixing efficiency of the slurry among channels with the ridge angles of 30°, 45°, and 60°. It was thus shown that channels with oblique ridges can be used as slurry mixing devices.

Acknowledgments

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