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PARTICLE ACCUMULATION IN MICROCHANNEL AND ITS REDUCTION BY SURFACE ACOUSTIC WAVE (SAW)

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ABSTRACT: Printing highly viscous ink through small nozzle(s) is limited because of the clogging problem. Particle accumulation along the nozzle wall makes the channel gradually narrower and finally obstructs the upstream flow. In order to understand this phenomenon the accumulation of micro-particles in a 100-µm microfluidic channel was observed under a microscope. Concentration of sodium alginate and micro-particles, flow rate were varied, and the accumulation rate was used to characterize the clogging problem. It is found that increasing the particle concentration and decreasing the flow rate would expedite the accumulation rate. At the flow rate of 10 µl/min and particle concentration of 1% and 1.4% the accumulation rate was 2.8 and 3.1 %/min, respectively. The corresponding values decreased to 0.006 and 0.010 min⁻¹ at the flow rate of 2 µl/min. Increasing the particle concentration from 0.2%, 0.6%, 1.0% to 1.4% shows gradual increase of accumulation rate from 1.5, 2.1, 2.8 to 3.1 %/min, respectively. With 1% micro-particles and 1%, 3% and 5% alginate the accumulation rate was 4.6, 5.9 and 4.1 %/min, respectively. However, above 4% alginate concentration, the micro-particles would agglomerate into a bridge structure for partial obstruction. In order to reduce the particle accumulation, the standing SAW was generated in the microfluidic channel using a pair of interdigitated transducer (IDT) at the optimum frequency and power to move the accumulated particles away from the wall and, therefore, reduce the chance of clogging. The accumulation rate dropped from 3.14 %/min to 0.21 %/min at the flow rate of 2 µl/min and 1.4% particle in water. In summary, the dependence of particle accumulation on the hydrodynamic parameters was found. Applying standing SAW could effectively reduce the particle accumulation, which may enhance the accuracy and reliability in 3D printing.

KEYWORDS: Microchannel, Clogging, Particle Accumulation, Printing, Surface acoustic wave

1 INTRODUCTION

Printing homogeneous but highly viscous fluid or dense micro-particles mixture through small nozzle(s) is limited because of the clogging problem. The clogging can occur in every nozzle based system, such as bioprinting for tissue engineering, food manufacture, and manufacture of conducting polymer circuits. Clogging microchannel is a progressive phenomenon which obstructs the upstream flow temporarily or permanently. The surface tension of homogeneous viscous fluid for printing is generally above 28 mN/m and viscosity is limited to below 40 mN·s/m². For reference, the viscosity and surface tension of pure water are approximately 1 mN·s/m² and 73 mN/m, respectively, at room temperature and ambient air pressure (Meacham et al., 2010) For dense micro-particles mixture, the duration of accurate and reliable continuous flow or droplet output before clogging is highly dependent on characteristics of hydrodynamics in the nozzle. Viscosity of medium, concentration of micro-particles and solute, flow rate, microchannel shape are main influencing factors for particle accumulation and clogging phenomenon (Agbangla et al., 2012; Bacchin et al., 2014; Bacchin et al., 2011).

The mechanism of obstruction has been classified into three types; complete blocking, bridging formation and clogging (Dersoir, 2015). Complete blocking occurs when the particle size is larger than the channel size, which has been commonly found in filtration or sieving process.
membrane. Bridging or arch formation has been found only at the entrance of the microchannel under the condition of high concentration of micro-particles. Adrian and Sharp observed the bridging formations of 50 μm particles flown into microtubes when the nominal particle-to-tube diameter ratios are approximately 0.3-0.4 (Sharp and Adrian, 2005). The standard clogging is a result from gradual accumulation of particles along the microchannel wall mostly near the constriction area, making the channel gradually narrower and finally obstructing the upstream flow. Retardation effect was used to explained particle accumulation by Wyss et al.(2006). They proposed that particle tends to continue its trajectory along the straight streamlines. Nevertheless, the streamlines bend near a constriction, and then particle trajectory would be deflected, leading particle to get captured on the wall irreversibly and ending up with clogging.

In this paper, we measured the behavior of particle accumulation in a microfluidic channel and reduced the particle accumulation by using surface acoustic wave (SAW). To visualize layer of particle accumulation, Polydimethylsiloxane (PDMS) was used to fabricate microchannel by using soft-lithography due to its optical transparency and dimensional accuracy in the manufacture. Concentration of sodium alginate and micro-particles, flow rate were varied, and the accumulation rate was used to characterize the clogging problem. In order to reduce the particle accumulation, the standing SAW was generated in the microfluidic channel using a pair of interdigitated transducers (IDTs) at the optimum frequency and power to move the accumulated particles away from the wall and, therefore, reduce the chance of clogging.

2 MATERIALS AND METHODOLOGY

Microchannel was fabricated by soft-lithography techniques (SU8 as a negative photoresist). PDMS (Sylgard 184, Dow Corning, Auburn, MI) was mixed with elastomer base to curing agent ratio of 10:1. The mixture was degassed and poured on silicon wafer with SU-8 pattern on the top. After that, it was degassed again and heated at 70°C for 3 hour in the incubator. The channel length, width and height are 1 cm, 100 μm and 100 μm, respectively. A 4” double-sided polished Y-128° propagating LiNbO₃ wafer (University Wafer, Boston, MA) was used as a substrate to deposit the Cr-Al electrode. The IDT was patterned on plastic mask for photolithography with the strip width of 50 μm which corresponds to the acoustic wavelength of 200 μm. AZ9260 was spun coated on the LiNbO₃ wafer. 20 nm of Cr and 400 nm of Al were deposited on the substrate. Eventually, the Cr-Al layer on non-exposed area was removed by acetone. To bond and align PDMS on LiNbO₃, oxygen plasma (Harrick Plasma, Ithaca, NY) was used to treat the PDMS and LiNbO₃ surface. The printed grid was inserted under LiNbO₃ wafer and treated PDMS was sprayed by 99% ethanol. After that, PDMS was carefully aligned on LiNbO₃ surface and heated at 80°C in a vacuum chamber. The 1 mm inner diameter of polyethylene tubing was used to supply the solution into microchannel. Because the cross-sectional area of tubing has an enormous difference to that of microchannel, the hydrodynamic resistance from the tubing can be neglected. Deionized (DI) water was used as solvent. 4-8 μm micro-particles (Cospheric, Santa Barbara, CA) and sodium alginate (Sigma-Aldrich, St. Louis, MO) were used as colloidal particles and solute. The concentration of micro-particles and alginate varied from 0.2-1.4% and 1.0-5.0% by weight, respectively. At the beginning of the experiment, the solution was spun by vortex and put in ultrasound sonicator to separate any agglomeration. As shown in Fig. 1a, the solution was flown from the inlet reservoir (Zone A) at the flow rat of 2 μm/min or 10 μm/min set by a syringe pump in this experiment. Light microscope with 40× magnification was used to observe the dynamic behavior of micro-particles in 100 μm microchannel. The area near constriction (Zone B) and center of the channel (Zone C) were recorded.

Two main parameters, accumulation rate and agglomeration area, were used to quantitatively describe the behavior of micro-particles in the obstruction process, and calculated by Matlab (Mathworks, Natick, MA) and ImageJ (National Institute of Health, Bethesda, MD). The accumulation rate is defined as the percentage of the area of deposited particles over that of the total microchannel in a unit time, which expresses the amount of accumulated or deposited
others nearby, mostly in Zone A. Therefore, the chance of blocking of the arch or bulk at the entrance is higher. Unlike the standard clogging, the arch or bulk blocking may not be a progressive process. Sinusoidal wave at the frequency of 19.95 MHz and power of 1-3 watts was generated by function generator (AF3021B, Tektronics, Beaverton, OR) and power amplifier (25A250A, Amplifier Research, Souderton, PA) was applied to the IDTs to generate SAW.

![Figure 1](image1.png)

Figure 1. The photo of microchannel structure (left): Zone A is the inlet reservoir, Zone B and C are the two consideration areas, and micro-particles accumulation (right).

3 RESULTS AND DISCUSSION

3.1 Effect of flow rate and concentration of micro-particles

Initially, the flow rate was fixed as 2 μl/min or 10 μl/min, and the concentration of micro-particles in the DI water was increased from 0.2%, 0.6%, 1.0% to 1.4%, respectively, with no sodium alginate. As a result, there is a gradual increase of the accumulation rate from 1.5, 2.1, 2.8 to 3.1 %/min at flow rate of 2 μl/min. The corresponding value at flow rate of 10 μl/min is 0.05, 0.29, 0.60 to 1.03 %/min, respectively. At both flow rates, the relation between the accumulation rate and particle concentration could be fit quite well in a linear model. Because the accumulation occurs randomly along the microchannel wall, the standard deviation is large at low flow rate (i.e., 2 μl/min). In comparison, the microparticles are hard to accumulate at the wall at high flow rate (i.e., 10 μl/min). Sometimes the accumulated particles could even strip from the wall by the inside flow according to the microscopic observation. However, whether the stripped parts has high propensity of another accumulation in the downstream was unknown due to the limited viewing range. The experimental observation may also illustrate the mechanism of plaque formation in the vascular wall and blood circulation obstruction in the lower extremity for chronic arterial insufficiency or in the middle cerebral artery (MCA) for stroke.

![Figure 2](image2.png)

Figure 2. The effect of particle concentration on the accumulation rate at flow rate of 2 μl/min and 10 μl/min, respectively (n = 40).
In contrast, there was no monotonic relationship between particle accumulation and the concentration of sodium alginate. At micro-particles concentration of 1% and flow rate of 2 µl/min the sodium alginate concentration was varied 1-10% which covers the range of alginate concentration used in bioprinting application (Cohen et al., 2010; Khalil and Sun, 2009; Schuurman et al., 2011; Song et al., 2011; Wüst et al., 2014). Below the alginate concentration of 4%, the accumulation rate increased rapidly from 2.09 to 5.90 %/min at 0% and 3% alginate concentration. On the other hand, the accumulation rate dropped significant at above 4% alginate concentration in Zone B and Z, which is because that the micro-particles and alginate agglomerated into a bulk or a bridge structure in Zone A (see Fig. 4).

![Figure 3](image)

**Figure 3.** The effect of sodium alginate concentration on the accumulation rate at micro-particles concentration of 1% and flow rate of 2 µl/min.

### 3.3 Agglomeration area

A group of micro-particles and alginate agglomerating and blocking mostly at the entrance of the microfluidic channel (Zone A) as shown in Fig. 4 is considered as the second mechanism of obstruction. It is found that the agglomeration area increased from 96.4±57.3 µm² to 215.3±146.4 µm² by the increasing alginate concentration from 1% to 10% at flow rate of 2 µl/min and particle concentration of 1.0%, respectively (see Fig. 5). There is no turning point found in this range of concentration.

![Figure 4](image)

**Figure 4.** Agglomeration of particles and alginate at the entrance of the microchannel.

![Figure 5](image)

**Figure 5.** The effect of sodium alginate concentration on the agglomeration area.
3.4 Surface acoustics wave (SAW)

SAW was generated from interdigitated transducer (IDT) from Cr-Al electrode along the LiNbO\(_3\) substrate. A pair of IDT was used to form standing wave at the center of the microfluidic channel. Continuous sinusoidal wave at the driving frequency of 19.95 MHz was generated by function generator and amplified to the power of 1-3 watts by the power amplifier before being delivered to both IDTs. The surface wave was produced by IDT, and propagates along the LiNbO\(_3\) surface. Eventually, the guided wave (Lamb wave) leaked into PDMS channel and reflected at the wall of PDMS microchannel; hence the standing wave is formed in the fluid (Yeo and Friend, 2014). The application of SAW showed significant reduction of particle accumulation rate. For 1.2% micro-particles concentration at flow rate of 2 \(\mu\)l/min in water the accumulation rate dropped 5-10 times with actuation of SAW (from 0.05\(\pm\)0.01%/min at 0.2% particle to 0.22\(\pm\)0.08%/min at 1.% particle, see Fig. 6). Moreover, the average agglomeration area also dropped moderately from 253.6\(\pm\)48.9 \(\mu\)m\(^2\) to 149.0\(\pm\)32.1 \(\mu\)m\(^2\) (\(p<0.05\), see Fig. 7). With optimal ultrasound parameters or actuation mode in the future study the reduction on the agglomeration area could be even more significant.

![Graph 1](image1.png)

Figure 6. Comparison of the accumulation rate of particle in normal condition and under SAW actuation.

![Graph 2](image2.png)

Figure 7. Comparison of the agglomerate area of particles in normal condition and under SAW actuation.

4 CONCLUSIONS

In this work, the PDMS microchannel was used to imitate the nozzle. To characterize and quantify the obstruction process (clogging and bridge formation), the accumulation rate and agglomerate area were calculated from the recorded particle behaviors under an optical microscope. Concentration of sodium alginate and micro-particles, flow rate were varied. It is found that increasing the particle concentration and decreasing the flow rate would expedite the accumulation rate. Increasing of alginate concentration, if below 4%, speeds up accumulation rate. However, further increase of alginate concentration (> 4%) would lead to the significant reduction of accumulation rate, but a bulk or bridge formation in the microchannel and sharp increase of agglomeration size. Besides, manipulation of particle to the center by standing wave of SAW was proved to be an effective and non-invasive method to reduce the micro-particle accumulation.

In the near future, the effect of microchannel structure (i.e., converging angle and shape) on the clogging would be studied both numerically and experimentally to optimize the design. Moreover, the optimal operation parameters of SAW will be found, and the interaction between SAW and accumulated microparticles will be investigated to understand the mechanism. Finally, the accuracy and reliability of nozzle in 3D printing together with the standing SAW will be evaluated, and the performance will be compared with the standard setup.
5 REFERENCES


