Numerical Analysis of Drop Dynamics of Acrylate Resin in Piezoelectric Inkjet Three Dimensional Printers

Kun Joong Park, Ohyun Baek, Yongtaek Hong, Changbae Park, and Keon Kuk; Digital Media and Communications R&D Center, Samsung Electronics; Suwon, Gyeonggi-do 443-742, Korea

Abstract

The photopolymerized acrylate products, fabricated using piezoelectric inkjet three dimensional printers, can be deformed under some printing process conditions. To understand and solve this deformation problem, we focus on the drop dynamics of the acrylate resin ink before being cured by the ultraviolet light. We numerically solve the full Navier-Stokes equation with the Volume-of-fluid (VOF) method to investigate the impact, spreading, and recoiling behavior of the resin ink droplet to show how the resin ink flow characteristics result in the shape change of the products. We have successfully developed the numerical models for the analysis of the drop dynamics of the resin ink in piezoelectric inkjet three dimensional printers.

Introduction

The products fabricated from the piezoelectric inkjet three dimensional printers, in which the polymer resin ink is ejected from the piezoelectric inkjet head, are deformed after being cured by the ultraviolet (UV) light, and this phenomenon occurs also in general inkjet printing [1]. Specifically, the upper surfaces of the products, which should be plain, becomes concave, and the edges are changed from being straight to being curved. This deformation problem is probably due to the change in the distribution and magnitude of the internal stresses of the products, and the stresses are known to be determined by the liquid resin ink flow characteristics before being cured. In order to quantitatively understand the physics underlying this deformation and solve the problem, we tried to find out the flow characteristics before the resin ink is cured by the UV light by use of a numerical analysis.

In this work, the full transient Navier-Stokes equation is solved not only for the liquid resin ink but also the air surrounding the liquid by use of the Volume of Fluid (VOF) method [2]. We develop a model for the numerical analysis on the drop dynamics of the resin ink in the piezoelectric inkjet three dimensional printers. We employ a commercial computational fluid dynamics (CFD) code, the ANSYS-CFX, to simulate the dynamics of the resin ink droplet which impacts, spreads and recoils on the substrate [3,4]. We try to find how the drop dynamics determines the product deformation, and to find the optimized printing process conditions from the numerical simulation results.

Numerical Analysis and Results

We first defined the initial state of a numerical model for the impact and spreading of a single droplet of the acrylate resin ink as shown in Fig. 1. The droplet is assumed to be spherical at the time t = 0 s at the analysis. Although the computational domain may include the inkjet head from which the resin ink is ejected, we focused on the compact domain where the falling ink is close to the substrate. The distance between the droplet and the substrate is half the diameter of the droplet. This compact model has advantages of reducing computation time and power resources. The domain has five open rectangular boundaries and one substrate wall boundary, where the liquid contact angle is designated. The contact angle was 70° and this angle was assumed to be the same for both the static and dynamic conditions. The length of each edge of the cubic computational domain is two times the droplet diameter. The initial falling velocity was 0.5 m/s.

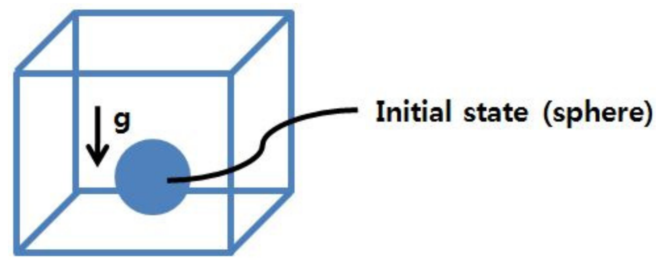

***Figure 1**. Schematic of the initial state of the numerical model for the impact and spreading of a single droplet of the acrylate resin ink in piezoelectric inkjet three dimensional printers. The initial droplet is assumed to be spherical.*

The number of the computational mesh elements is 357443 and the elements are tetrahedral. The computation of all numerical analysis in this work was performed at the supercomputer in Samsung Advanced Institute of Technology (SAIT) in Korea. We utilized the parallel computing method using 16 central processing units.

Test of the Numerical Model

Before proceeding with the numerical analysis for the ink drop dynamics in the piezoelectric inkjet three dimensional printers, we tested the numerical model applying for various sizes of the ink droplets.

Fig. 2 shows the numerical results for the dynamics of a single resin droplet having the diameter of 2 mm. We calculated the non-dimensional parameters related to the analysis conditions. For example, the Ohnesorge number Oh = 0.054, the Reynolds number Re = 83, and the Weber number We = 20. The time step was 1 ms in the numerical analysis. We checked from the results the drop dynamics, i.e. impact, spreading, and recoiling, of a single ink droplet.

In addition, we predicted in a semi-analytical way whether the ink droplet is deposited or splashed on the substrate using the experimental correlation formula developed by Mundo et al. [5]

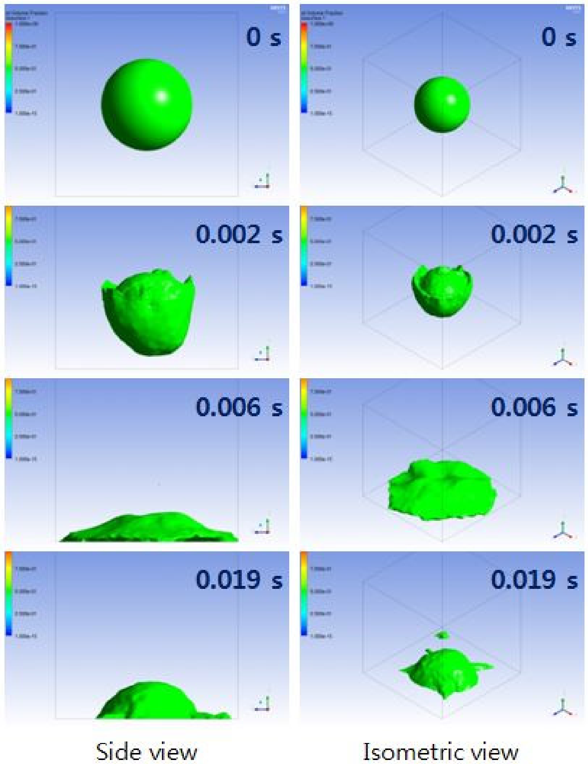

Figure 2. *Impact, spreading, and recoiling of a single ink droplet of 2 mm in diameter (Oh = 0.054, Re = 83, and We = 20).*

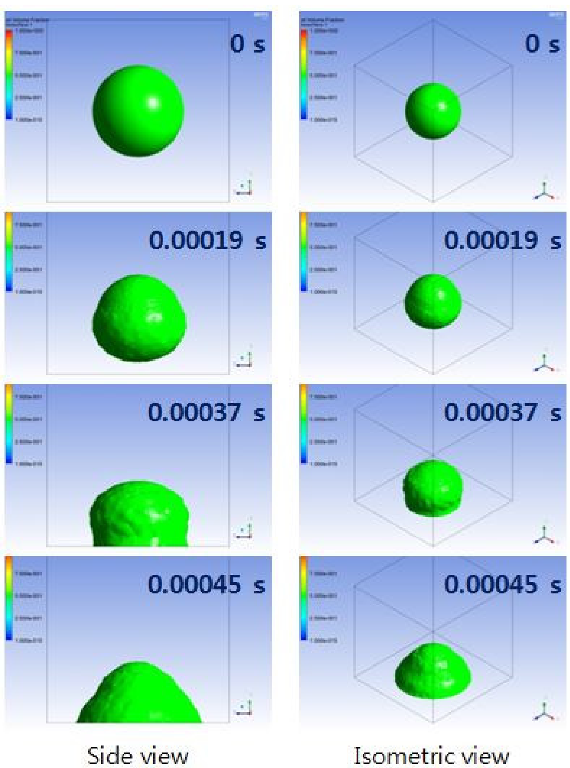

Figure 3. *Impact and spreading of a single ink droplet of 200 μm in diameter (Oh = 0.17, Re = 8.3, and We = 2). The time step of the numerical analysis is* 10^{-5} *s.*

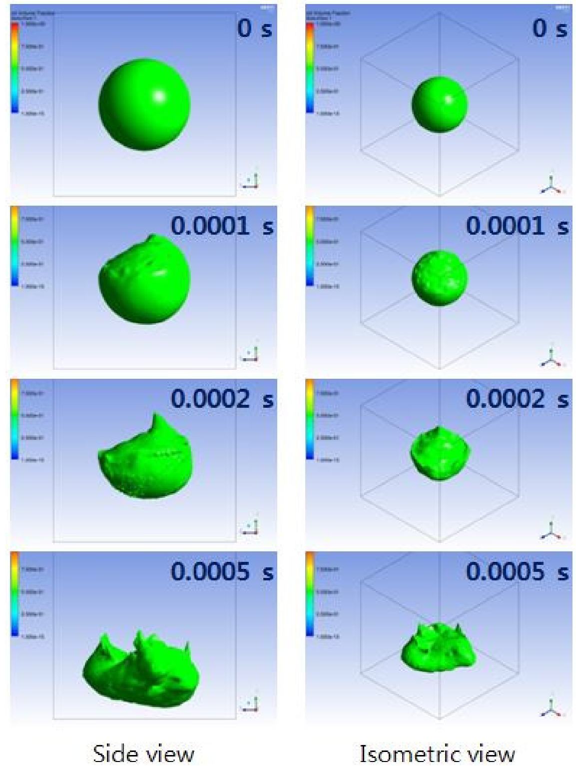

Figure 4. *Test of the time step of the numerical analysis for the impact and spreading of a single ink droplet of 200 μm in diameter. The time step is* 10^{-4} *s.*

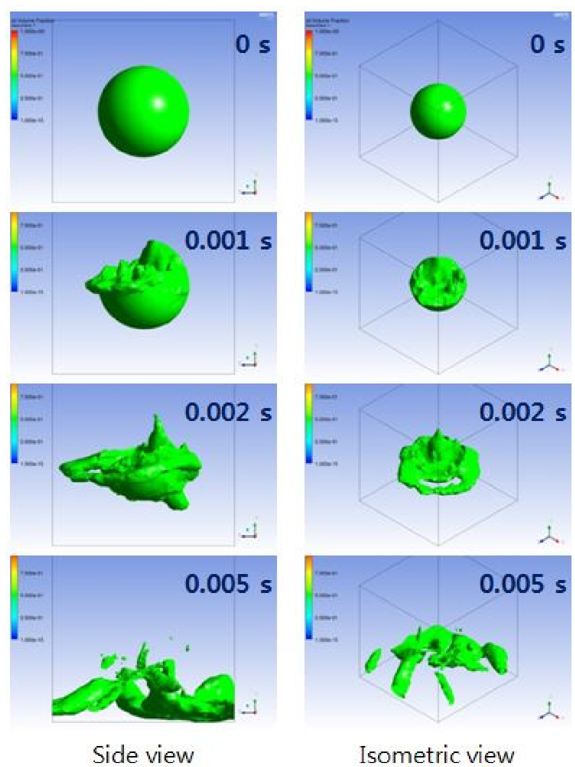

Figure 5. *Test of the time step of the numerical analysis for the impact and spreading of a single ink droplet of 200 μm in diameter. The time step is* 10^{-3} *s.*

$$K = Oh \cdot Re^{1.25} \quad (1)$$

where Oh and Re are the Ohnesorge number and the Reynolds number, respectively. The value K = 14, and this value was smaller than the critical value of 57.7 over which the splashing phenomena take place. Therefore, our numerical results, which showed that the ink droplet was deposited without splashing, were partly and qualitatively confirmed from the previous experimental results.

The numerical results for the dynamics of a single resin droplet having the diameter of 200 μm are shown in Fig. 3. The values of the calculated non-dimensional parameters are as follows. The Ohnesorge number Oh = 0.17, the Reynolds number Re = 8.3, and the Weber number We = 2. The time step was 10 μs in the analysis. We found the smooth deposition of the ink droplet under these conditions.

We additionally obtained the value of the parameter K as in (1), which is 2.4, and very smaller than the critical value of 57.7. This indicates the deposition of the droplet without splashing, which was checked in the figure of the numerical results.

We tested the time step of the numerical model for the dynamics of a droplet of 200 μm in diameter. Fig. 4 and Fig. 5 show the numerical results under the same analysis conditions as in Fig. 3 except the time step. The values of the time step were 100 μs and 1 ms in Fig. 4 and Fig. 5, respectively. In the analysis in Fig. 3, the time step was 10 μs. Although we used in the numerical model the implicit scheme for transient analysis, we found that the time step is a significant parameter in the numerical analysis.

Ink Drop Dynamics in the Piezoelectric Inkjet Three Dimensional Printers

We performed the numerical analysis for the ink drop dynamics in the piezoelectric inkjet three dimensional printers after testing the numerical model applying for various sizes of the ink droplets and time steps in the numerical analysis scheme. The diameters of the considered droplets in the analysis for the piezoelectric inkjet three dimensional printers are 40 μm and 20 μm, and these values correspond to the droplet volume of 40 pL and 4 pL, respectively.

First, the numerical results for an ink droplet having the diameter of 40 μm are shown in Fig. 6. We obtained the values of the non-dimensional parameters related to the numerical analysis, which are the Ohnesorge number Oh = 0.38, the Reynolds number Re = 1.7, and the Weber number We = 0.4. The time step was 1 μs in the numerical analysis and the total simulation time was 500 μs. We see in the figure that the ink droplet is smoothly deposited without splashing, which is also checked in the same method used for the results in Fig. 2 and Fig. 3 as follows. The value of the parameter K was 0.74, which is very smaller than the reference value of 57.7. We found from the results that the impact, spreading, and recoiling of the droplet, and it took about 157 μs for the ink droplet to enter the steady-state in the deposition process.

Fig. 7 shows the numerical results for the dynamics of a single resin droplet having the diameter of 20 μm. The time step and the total simulation time were 1 μs and 500 μs, respectively. The calculated non-dimensional parameters are Oh = 0.54, Re = 0.83, and We = 0.2, and the value of K in (1) was 0.43, which represents the deposition without splashing. We see in the figure

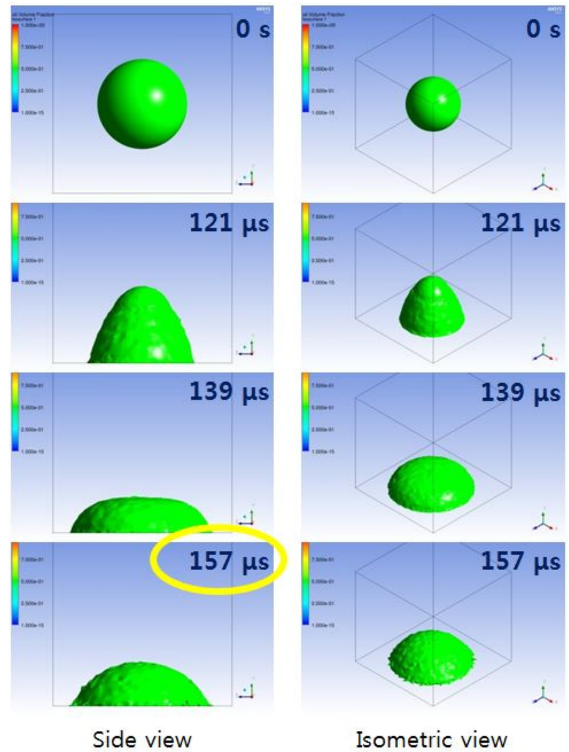

***Figure 6**. Impact, spreading, and recoiling of a single droplet of the acrylate resin ink in piezoelectric inkjet three dimensional printers. The diameter of the droplet is 40 μm (Oh = 0.38, Re = 1.7, and We = 0.4).*

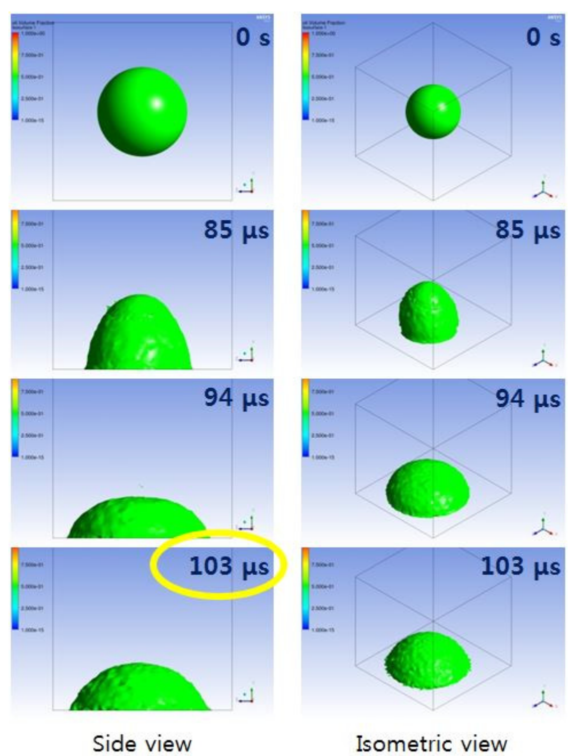

***Figure 7**. Impact, spreading, and recoiling of a single droplet of the acrylate resin ink in piezoelectric inkjet three dimensional printers. The diameter of the droplet is 20 μm (Oh = 0.54, Re = 0.83, and We = 0.2).*

the smooth deposition of the droplet as in Fig. 6, and the time for the ink droplet to be stabilized in the deposition process was about 103 μs. This time is smaller than that in the case in Fig. 6, where the droplet diameter is two times that of the current case.

Conclusion

We have successfully developed the numerical models for the drop dynamics of the ink resin in piezoelectric inkjet three dimensional printers. We have numerically analyzed the impact, spreading, and recoiling of the resin ink droplet under various printing conditions. Our numerical results and models can be used to elucidate the physics behind the ink flow and to present solutions for resolving the deformation problems of the products fabricated from the inkjet three-dimensional printers.

Acknowledgement

We would like to thank ANFLUX for the technical support for use of ANSYS-CFX.

References

[1] Y. Yasuo, H. Takao, M. Mitsunobu, and N. Soh, "A New UV Curable Inkjet Ink: Follow-up Report," NIP 29 & Digital Fabrication Conference, 395 (2013).
[2] M. Pasandideh-Fard, S. Qiao, S. Chandra, and J. Mostaghimi, ''Capillary effects during droplet impact on a solid surface,'' Phys. Fluids 8, 650 (1996).
[3] H.-Y. Kim and J.-H. Chun, ''The recoiling of liquid droplets upon collision with solid surfaces,'' Phys. Fluids 13, 643 (2001).
[4] T. J. Snyder, Y. Chen, and M. Weislogel, "Line-on-Line Image Formation Analysis for Inkjet and Digital Fabrication Purposes," NIP 29 & Digital Fabrication Conference, 18 (2013).
[5] CHR. Mundo, M. Sommerfield, and C. Tropea, ''Droplet-wall collisions: experimental studies of the deformation and breakup process,'' Int. J. Multiphase Flow, 21, 151 (1995).

Author Biography

Kun Joong Park is a senior engineer, Ohyun Baek, Yongtaek Hong, and Changbae Park are principal engineers, and Keon Kuk is a 'Master' of Digital Media and Communications R&D Center of Samsung Electronics in Suwon, Korea.

