Theoretical Investigation of Jetting and Wetting Phenomena for the Fabrication of TFT LCD Color Filters

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Abstract

Although years of trials for the fabrication of TFT LCD color filters with the piezo Drop-On-Demand (DOD) inkjet printing technology have been made, the underlying physics of jetting and wetting has not been fully understood. In this study, the key engineering issues, jetting and wetting, are investigated with mathematical models.

1. Introduction

The fabrication of TFT LCD color filters with the piezo DOD inkjet printing technology differs from the spin casting and slit coating technologies in terms of the degree of complexity [1].

The piezo DOD inkjet printing technology involves multi-physics such as piezoelectricity, fluid-structure interaction, acoustics and fluid dynamics for processes such as drop formation, impact, spreading and drying or solidification. When it goes deeper, materials science for inkjet head components and ink, and surface chemistry should be considered all together.

This underlying complexity of the piezo DOD inkjet printing technology hampers the experimental identification of numerous phenomena. Among them, two engineering difficulties such as the appearance of voids in a subpixel, which is caused by incomplete filling of ink, and visible swathe marks after ink drying become critical.

The appearance of visible swathe marks on a TFT LCD color filter patterned by a piezo DOD inkjet print head is primarily caused by the droplet volume variation across nozzles. As shown in Fig. 1(a), if all droplets have the same volume, then the colorant film after drying in subpixels, the dimensions of which are assumed to be exactly the same, would be the same thickness and visible swathe marks would not appear.

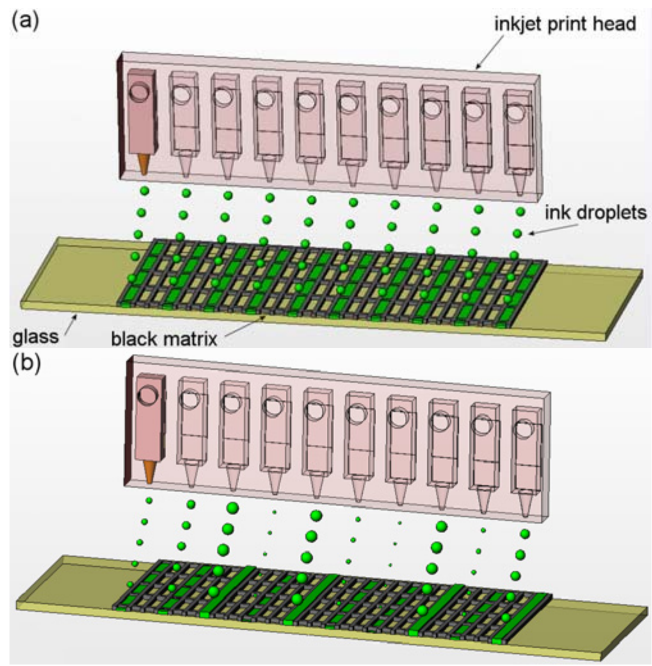

Fig. 1. Illustration of a TFT LCD color filter patterned by a piezo DOD inkjet print head. (a) even droplets and uniform colorant film formation. (b) non-even droplets and non-uniform colorant film formation.

In reality, there are numerous causes of visible swathe marks, not only the droplet volume variation, but it is suspected that the droplet volume variation might be the primary cause of visible swathe marks and it is required to identify the primary factor which causes the droplet volume variation.

After ink droplets are fired from nozzles, they impact and start spreading in a subpixel. To prevent ink from incomplete filling and spillover into neighboring subpixels, the surface energies of glass and black matrix (BM) are required to be carefully controlled.

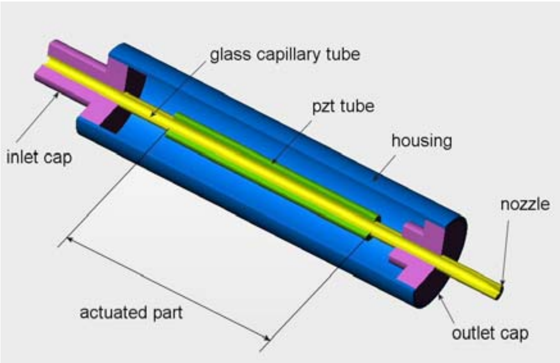

Fig. 2. Sectional view of a MicroFab print head.

In this study, mathematical models are employed to identify one possible cause of visible swathe marks and the influence of the surface conditions in filling a subpixel.

2. Numerical experiments

As stated in Section 1, there are various factors which might cause visible swathe marks. Part of factors come out of a piezo DOD inkjet print head itself and hence it has been thought that the primary cause of visible swathe marks is a hydraulic crosstalk [2].

In this study, the influence of the nozzle tolerance is investigated with a numerical method, as the primary source of the droplet volume variation. It is obvious that the employment of a numerical method makes it possible to investigate the influence of only one factor. Otherwise, it is extremely difficult or impossible to avoid the interference of other factors.

The question, how the nozzle tolerance affects the droplet volume variation, came across into the first author's mind when the author looked back at the development trend of the piezo DOD inkjet printing technology. The nozzle diameter has incessantly decreased with no doubt for the past few decades.

At the early version of a piezo DOD inkjet printer, the droplet size was approximately 81.17 μm in diameter. However, it becomes 12.41 μm and below nowadays [3]. It is noteworthy that if the volume tolerance is set to ±2%, then the tolerance of a droplet is around 1.08 μm for the droplet of 81.17 μm in diameter. However, the tolerance becomes 0.17 μm for the droplet of 12.41 μm in diameter.

If the droplet size has a sort of relationship with the nozzle diameter, then it can be questioned what nozzle tolerance it would be like to meet the volume tolerance of ±2%.

To investigate this question, mathematical models were developed with a single nozzle piezo DOD inkjet print head (MicroFab Technologies, Inc., TX, USA), as shown in Fig. 2.

Two cases with the nozzle diameters of 30 μm and 50 μm are modeled and the range of tolerance is set ±2 μm. The driving voltage rises from 0 V to 30 V for 3 μs. After a dwelling time for 15 μs, the applied voltage comes to 0 V for 3 μs. The repetition rate is set 2 kHz. Ethylene glycol is used as a model fluid in numerical experiments.

The introduction of analytical solutions for a MicroFab inkjet print head and a 1D numerical model for the drop formation is omitted in this study due to the page limit. However, readers could find them from the reference [4].

Once ink droplets are fired and impact on a substrate, they start spreading out and filling the subpixel.

Droplet impact and spreading has been numerically solved in a literature and elsewhere [5]. However, a numerical approach, which solves the governing equations of fluid dynamics, is computationally expensive and hence an alternative was sought for.

The question of the authors was whether ink could completely fill the subpixel under given contact angles of ink against glass, θ_g, and BM, θ_b. This must be of the crucial concern to developers of ink and black matrix as well as process engineers who perform surface treatments to BM patterned glass substrates.

Several assumptions were made: (1) ink viscosity is low enough to ignore the viscous friction force, (2) ink has a very low vapor pressure so that ink can reach the final equilibrium energy status before it significantly dries out.

Ink for a piezo DOD inkjet print head has a low vapor pressure to prevent nozzle clogging and a low viscosity, below 20 cPs at the jetting temperature but typically less than 15 cPs. Therefore, the above requirements are loosely met.

With the above assumptions, the surface evolution technique is employed to check whether ink can be confined in a subpixel without dewetting, which leaves voids, or overspill into adjacent subpixels [6].

The subpixel sizes tested are 109 μm × 355 μm × 1 μm for a 32" display panel and 221 μm × 721 μm × 1 μm for a 65" display panel. The solid contents of ink are assumed 5 and 10 volume % and the required ink volumes are calculated to form 1 μm thick films for both cases. The contact angle of ink against BM, θ_b, is set 60º. Figure 3 shows a typical simulation result of Surface Evolver.

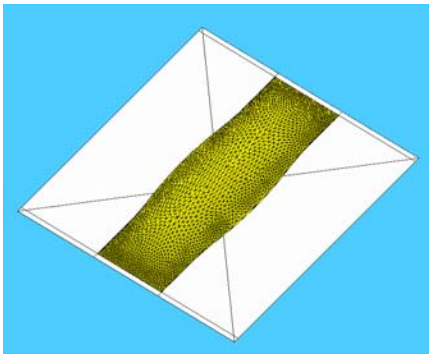

Fig. 3. Simulation result with Surface Evolver.

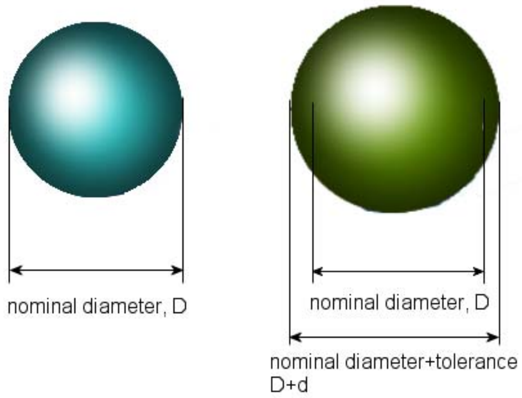

Fig. 5. Illustration of droplet size and volume with a certain tolerance.

3. Results and discussion

The simulation results of the nozzle diameters, 30 μm and 50 μm with given driving conditions, are shown in Fig 4. It can be seen that the droplet volume variation against the given tolerance range of ±2 μm, when the nozzle diameter is 50 μm, is much flatter than that with the nozzle diameter 30 μm. This can be explained with the ratio of the tolerance of the nozzle diameter to the nominal nozzle diameter.

Because the typical droplet size is proportional to the nozzle diameter, the bigger nozzle tends to produce the bigger droplet. As shown in Fig. 5, if a droplet has the variation in diameter caused by the nozzle tolerance, then its volume differs from that with the nominal diameter and at a certain nozzle tolerance, the bigger droplet diameter has a less sensitivity in volume to the nozzle tolerance.

It is noteworthy, however, that the droplet volume tolerance is not directly related with the nozzle tolerance at the same scale.

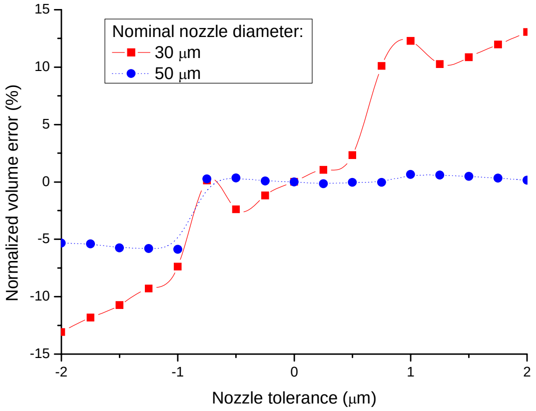

Fig. 4. Normalized droplet volume variation against nozzle tolerance.

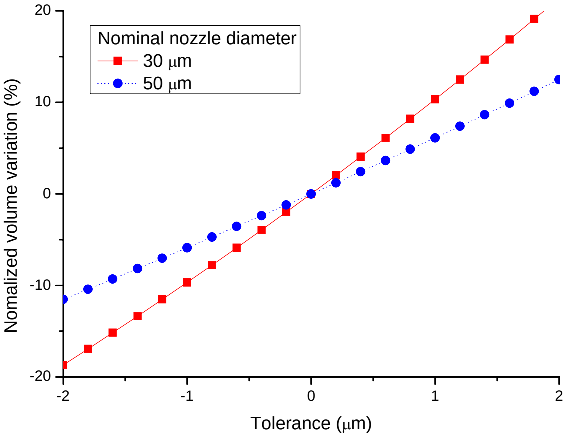

Fig. 6. Normalized droplet volume error against the tolerance of a droplet in diameter.

Ink spreading and filling is mainly governed by the minimization of the free energy. To prevent ink from overspilling, BM should have a high contact angle, θ_b, against ink. At the same time, ink must completely fill the subpixel without leaving any voids.

First, to avoid spillover of ink into neighboring subpixels, ink is placed over the subpixel and its recession is observed, as shown in Fig. 3. The contact angle of ink against BM, θ_b, is decided by the pre-determined specification that ink recedes enough to leave any overspill region less than 7 μm.

The contact angle of ink against glass, θ_g, is decided with the conjecture that when the bottom surface area covered by ink is equal to the subpixel area, then ink will cover the entire subpixel.

As shown in Fig. 7, the contact angle of ink against glass, θ_g, should get lower as the size of a subpixel gets larger when the solid content of ink keeps constant.

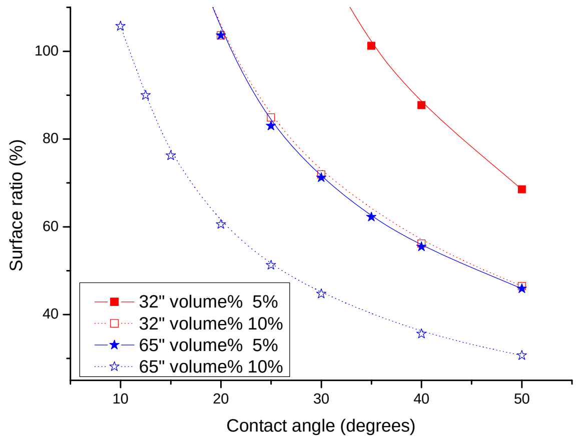

Fig. 7. Ink spreading against various contact angles of ink against glass.

When the ink concentration gets higher, then the contact angle, θ_g, should get lower, too. It is noteworthy that the contact angles required for 32" and 65" display panels differ each other.

As the size of a display panel gets larger, the size of a subpixel gets larger too. This makes landing accuracy of a jet easier and decreases the chance for ink to spill over into adjacent subpixels. The success of the fabrication of a small display panel, however, does not guarantee the success of the fabrication of a large display because of the requirement of a much low contact angle.

4. Summary

According to the numerical experiments, it is found that the mechanical nozzle tolerance becomes more significant as the nominal nozzle diameter decreases. On the other hand, it is found that a piezo DOD inkjet print head with a bigger nominal nozzle diameter might tend to inherently produce more uniform ink droplets in volume even at the same mechanical nozzle tolerance.

It suggests reconsideration of the current research and development direction in the piezo DOD inkjet printing technology for large area display applications. Instead of the reduction of the nominal nozzle diameter, the numerical experiments suggest the enlargement of the nominal nozzle diameter, unless the mechanical nozzle tolerance is greatly improved.

There are, however, other factors which might contribute to the appearance of visible swathe marks, even some factors not directly related with the piezo DOD inkjet print head itself. Further investigations are required to find out all possible factors.

The ink filling process in a subpixel is mathematically investigated with the surface evolution technique, instead of computationally expensive numerical methods such as a finite element method (FEM). It is found that the optimum surface conditions of the black matrix and glass substrate against colorant ink show the dependence of subpixel size and ink concentration, not constant values [7].

For more realistic contact angle data, the input datafile of Surface Evolver is being further developed by the authors.

5. Acknowledgements

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6. References

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