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Theoretical analysis of jetting and ink filling processes for TFT LCD colour filters

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Abstract

The fabrication of TFT LCD colour filters with the piezo Drop-On-Demand (DOD) inkjet printing technology has gained attention from industries. However, this technology differs from previous processes such as spin and slit coating technologies in terms of the degree of complexity. Different from spin and slit coating processes, the piezo DOD inkjet printing technology has the capability to selectively deposit ink droplets on the positions, which greatly saves the waste of materials in producing TFT LCD colour filters. This feature, however, draws two engineering difficulties. First, the ink droplet volume should be carefully controlled to avoid the total ink volume variation among subpixels, which, otherwise, could cause visible swathe marks. Second, ink droplets must be confined without the introduction of unfilled regions in a subpixel and spilling over into the adjacent subpixels. In this study, two fundamental theoretical analyses are performed to investigate one possible cause of visible swathe marks and suggest a concise way to derive the optimum surface conditions which eventually confine ink in a subpixel.

Introduction

The piezo DOD inkjet printing technology has been an issue in industries. Its inherent feature to deposit ink selectively into target positions, which is called an additive process, has a great impact on the saving of precious materials. The most optimistic view predicts almost 100% usage of materials can be used in manufacturing processes. It is an on-demand technology, which needs virtually no lead time. It is also referred to as digital printing technology or cad-to-drawing technology, which eliminates the need of masks. It is a scalable technology, which means the size of a substrate is not of the main concern.

Due to the above advantages over conventional processes, especially photolithographic processes, numerous efforts have been made from academic and industrial sides. This printing technology has been explored as a possible manufacturing process for a multicolour light emitting polymer display [1,2]. It is endeavoured for the patterning of thin film transistors [3,4]. Among numerous efforts, the most vivid R&D activities have been the employment of the piezo DOD inkjet printing technology to TFT LCD colour filters, as shown in Fig. 1 [5,6].

The piezo DOD inkjet printing technology, however, differs from previous processes such as spin and slit coating technologies in terms of the degree of complexity. In jetting, the droplet volume variation across nozzles tends to leave visible swathe marks on an inkjet printed TFT LCD colour filter and this is one of main hurdles for the employment of the piezo DOD inkjet printing technology on production lines.

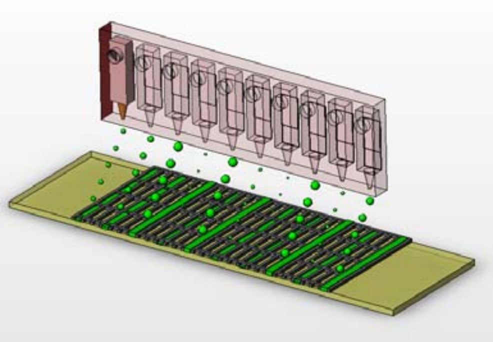


Figure 1: Illustration of the fabrication of a TFT LCD colour filter with the piezo DOD inkjet printing technology.

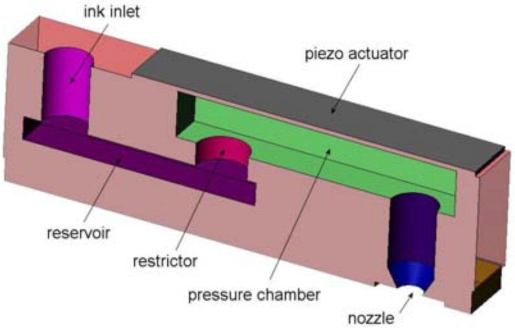


Figure 2: Cross sectional view of a typical piezo DOD inkjet print head.

After ink droplets are jetted through nozzles and impact on a subpixel, they start spreading and eventually fill the subpixel. During this filling process, however, ink tends to spill over into adjacent subpixels or introduce defects, generally at the corners of the subpixel. These problems are primarily caused by the improper surface conditions of black matrix (BM), hereinafter referred as bank, and glass against ink. Therefore, developers of ink and BM must be aware of the basic guideline of the required surface condition when they formulate materials, unless they are willing to perform numerous trials at the expense of time and money.

In this study, the numerical experiments were performed to investigate one possible cause of the droplet volume variation across nozzles and the optimum surface conditions for each size of a TFT LCD panel with ink having different solid contents. According to the numerical results, the current R&D direction of a piezo DOD inkjet print head is found to need re-consideration to minimize the appearance of visible swathe marks and a new R&D direction is suggested. In ink filling, prerequisite guidelines for chemists of ink and black matrix, and process engineer are suggested, too.

Numerical Experiments

As introduced in the above, the most important part to reduce the droplet volume variation across nozzles of a piezo DOD inkjet print head starts from the inkjet print head itself. To individually control each droplet volume from each nozzle, a function, commonly referred as Drive-Per-Nozzle (DPN), was devised. This function individually controls the voltage applied to piezo actuators, one of which is shown in Fig. 2.

By changing the magnitude of the voltage whilst the voltage rise, dwell and fall times are fixed to pre-determined values, as shown in Fig. 3, the deflection change rate of the piezo actuator changes. It alters the magnitude of pressure waves inside the pressure chamber of a piezo DOD inkjet print head and eventually the velocity and volume of a droplet ejected through a nozzle change.

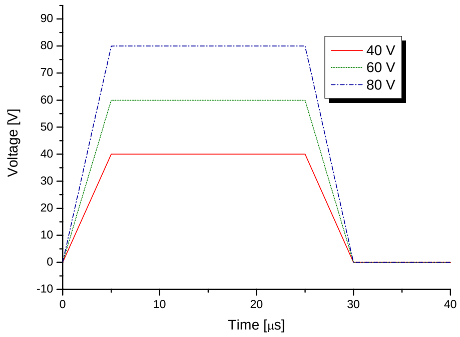


Figure 3: Exemplary driving waveforms of a piezo DOD inkjet print head.

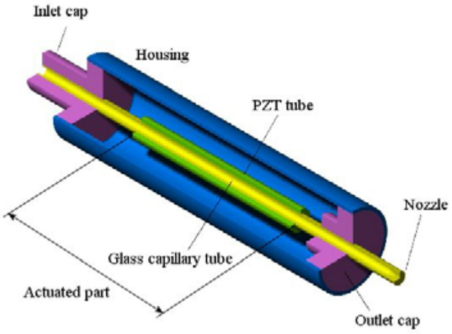


Figure 4: Sectional view of a MicroFab print head.

In this study, the piezo DOD inkjet print head modelled is a squeeze type piezo DOD inkjet print head (MicroFab Technologies, TX, USA), as shown in Fig. 4, because no information on a commercially available industrial piezo DOD inkjet print head was disclosed to the authors. Details of the mathematical modelling is omitted due to the page limit of this paper but they can be found in references, including the dimensions of the modelled piezo DOD inkjet print head [7,8].

There are numerous possible causes of the droplet volume variation across nozzles. One of them is the nozzle diameter variation caused by imperfect micromachining. If the nozzle diameter is slightly bigger or smaller than the nominal nozzle diameter, then the velocity and volume of ink droplets might deviate from one another.

To explore the influence of the variation of nozzle diameter, two nominal nozzle diameters, 30 µm and 50 µm, are simulated with a predetermined driving condition, 3 µs (0 V)-15 µs (30 V)-3 µs (0 V) at 2 kHz, and ethylene glycol as ink. At each nozzle diameter, the tolerance of ±2 µm is given. It should be noted that the driving conditions and ink properties are not of the main concern because the purpose of these experiments is to find out how the variation of nozzle diameters affects the velocity and volume of ink droplets.

Once ink droplets are fired into target positions from nozzles, they impact and spread out on a substrate. To confine ink in a subpixel, the most common way is to use relatively hydrophobic banks which prevent ink from spilling over into neighbouring subpixels.

The first question to ink chemists and process engineers tends to be what contact angles for the substrate, which ink should wet, and the bank, which ink should not run over, must be like. If the contact angle of ink against the substrate, θ_g, is too high, then ink will not completely fill the subpixel and tend to leave unfilled regions. If the contact angle of ink against the bank material, θ_b, is too low, then ink has an opportunity to run into the adjacent subpixels. At the first development stage of materials such as ink and bank, therefore, the maximum contact angle of ink against substrate, θ_g, and the minimum contact angle of ink against the bank material, θ_b, should be known as the basic rule of thumb.

The most common way to model ink spreading in a confined well has been numerical methods which solve the governing equations of fluid dynamics [9]. Although this approach might provide sufficient information on ink impact and spreading, it needs too many computational resources.

For this purpose, it is found that the surface evolution technique, which seeks for the surface configuration where the surface energy becomes minimal, is concise and useful [10]. In simulations, the contact angle of ink against the bank material, θ_b, is set to 60°, while the contact angle of ink against glass, θ_g, varies from 30° to 45°. It is assumed that ink, 5 vol%, is deposited in the subpixel, the size of which is 108.7 μm × 354.7 μm × 1 μm and the volume of ink is 771441 μm^3, which finally leaves a 1 μm thick film.

Results and Discussions

The simulation results with the nozzle diameters of 30 μm and 50 μm, when the tolerance of ±2 μm is given, are shown in Fig. 5. It should be noted that the droplet volume variation with the nozzle diameter of 50 μm is much smaller than that with the nozzle diameter of 30 μm through the given tolerance range. This plot shows that the droplet volume variation with a bigger nozzle diameter tends to be smaller, compared to a small nozzle diameter.

This can be explained with the ratio of a certain nozzle tolerance to the nozzle diameter. For example, when the nozzle tolerance is given 0.5 μm, its ratio to the nozzle diameter of 30 μm is 1.67%. However, the ratio to the nozzle diameter of 50 μm with the same nozzle tolerance is 1%. Therefore, as the nozzle diameter of a piezo DOD inkjet print head increases, the droplet volume variation tends to decrease and this might lead to the less appearance of visible swathe marks on TFT LCD colour filter and light emitting polymer display.

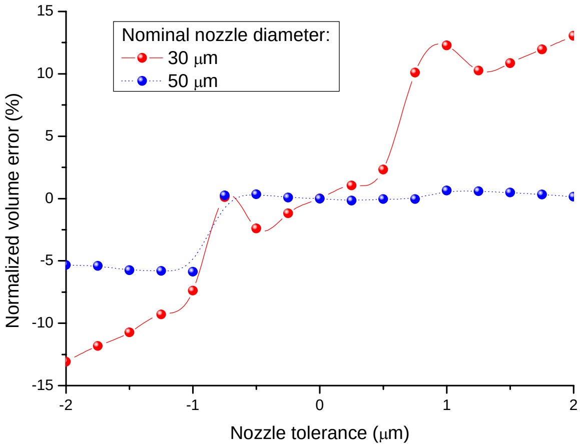
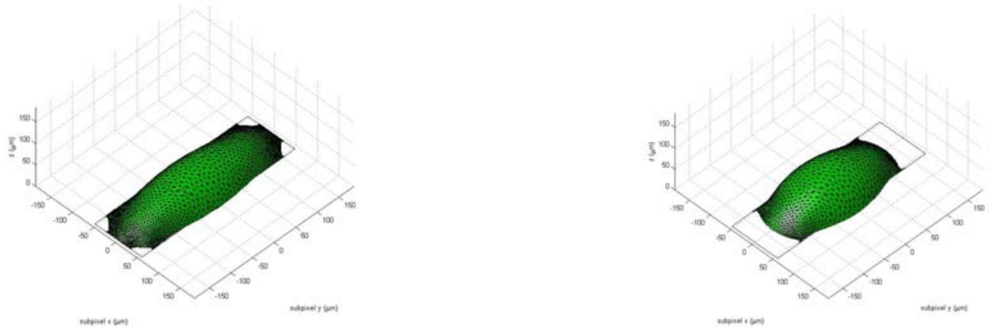


Figure 5: Influence of the nozzle diameter tolerance on the droplet volume.

The ink filling processes are simulated on the computer equipped with Intel Pentium IV 3.6 GHz for CPU and 2 Gbytes for memory. The CPU time taken with Surface Evolver is 76.35±24.7 sec, which greatly saves the computational resources. The results are shown in Fig. 6.

Below a certain contact angle, θ_g=30° in this case, ink fills the subpixel completely and hence no unfilled regions are introduced. However, as the contact angle, θ_g, increases, unfilled regions starts found at the corners, as shown in Fig. 6 (b). Above a certain contact angle, θ_g=45° in this case, ink does not touch the bank and fully recedes to form a bulged surface.

(a) θ_b=60° and θ_g=30° (b) θ_b=60° and θ_g=35°



(c) θ_b=60° and θ_g=40° (d) θ_b=60° and θ_g=45°

Figure 6. Simulation results with Surface Evolver.

Conclusions

Through this study, two fundamental aspects of the piezo DOD inkjet printing technology for display applications are numerically investigated. Numerical experiments for the influence of the nozzle tolerance on the droplet volume show that as the nozzle diameter increases, the droplet volume variation tends to be smaller at a given tolerance. This is explained by the ratio of the nozzle tolerance to the nozzle diameter. For the ink filling process, the surface evolution technique shows a concise approach to find out contact angles required to confine ink in a subpixel. The calculated contact angles can be used as a guideline to developers of ink and bank materials.

Acknowledgements

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