A Model for the Formation of Mura During the One-Drop-Filling Process

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ABSTRACT

The One-Drop-Filling (ODF) process for manufacturing liquid crystal cells can lead to alignment defects called ODF mura. We propose a theoretical model for the coalescence of droplets and elastic/inelastic deformation to the director structure during ODF to provide insight into the formation of ODF mura.

1 INTRODUCTION

Liquid crystal devices are ubiquitous in modern day life, and faster and more accurate manufacture of these devices is required to meet increasing global demand. The optimisation of the manufacturing process generally involves attempting to reduce manufacturing time by increasing flow velocities and filling speeds. However, implementing such changes runs the risk of causing elastic/inelastic deformation to the director structure which is crucial to the display.

A common method of filling the liquid crystal layer in liquid crystal devices (LCDs) used by display manufacturers is the One-Drop-Filling (ODF) method (see, for example, [1] and [2]). In the first stage of the ODF process, a bottom substrate is coated with an alignment layer in order to correctly orient the liquid crystal layer within the cell. Droplets of liquid crystal are then dispensed onto the bottom substrate and are allowed to equilibrate. In vacuum, a top substrate is then lowered at a constant speed onto the droplets, squeezing them and eventually creating a continuous thin film of liquid crystal within the cell. Finally, the cell is cured and sealed to make it ready for use in LCDs. Although this method is an efficient way to fill liquid crystal cells used in LCDs, it is known that it can cause elastic/inelastic deformation to the director structure known as "ODF mura" which, in turn, can affect the optical performance of the final display.

Fig. 1 shows an example of ODF mura formed in a three droplet ODF test cell. In particular, Fig. 1 shows non-uniformity within the test cell. Specifically, there are three linear regions of non-uniformity between the origins of each droplet (indicated with the hand-drawn circles in Fig. 1) creating an inverted "Y-shape" in the centre of the cell and a radial non-uniformity away from the centre of the cell. For many LCD modes the ODF mura may recover over time, but for the Polymer Stabilised Vertically Aligned (PS-VA) mode [3], any elastic/inelastic deformation to the director structure is "locked in" after UV curing of the reactive mesogen material. Since the cause of ODF mura is still not understood, we aim to provide insight into the formation and cause of ODF mura by modelling the squeezing and coalescence of the droplets during ODF.

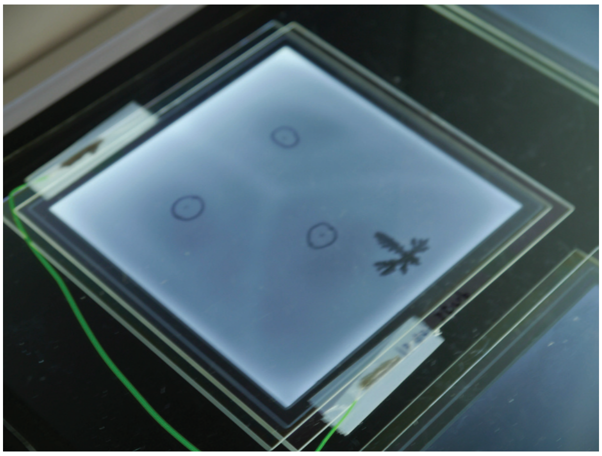

Fig. 1 ODF mura formed in a three droplet ODF test cell observed at low gray level. We use test cells with a continuous transparent electrode on the top substrate and a fine patterned fish-bone shaped electrode on the bottom substrate. Both substrates are coated with homeotropic alignment material. The three droplets are deposited on the bottom substrate in positions indicated with hand-drawn circles.

2 RESULTS

After it has been deposited, each droplet is modelled as a cylinder of fluid (with a constant volume V) being squeezed by the decreasing gap between the substrates $h(t)$, which increases the cross-sectional area $A(t)$ and the radius $r(t)$ of the droplet. The top substrate moves with a constant downward speed, S_p, starting at some initial height, H_0, at $t=0$, so that the position of the top substrate is given by $h(t) = H_0 - S_p t$ for $0 \leq t < t_{max}$, where $t_{max} = H_0/S_p$. We assume that the timescale for changes in the droplet shape due to surface tension is much longer than that of squeezing, and so the effects of surface tension can be neglected. This assumption allows the calculation of the spreading behaviour of multiple droplets to be determined by geometrical methods using conservation of volume.

In principle, any arrangement of droplets can be considered, but for brevity here we just consider an initial arrangement of three identical droplets with initial radii $r(0)$, where $0 < r(0) < L$, positioned at the vertices of an equilateral triangle with side length $2L$, as shown in Fig. 2 (top left).

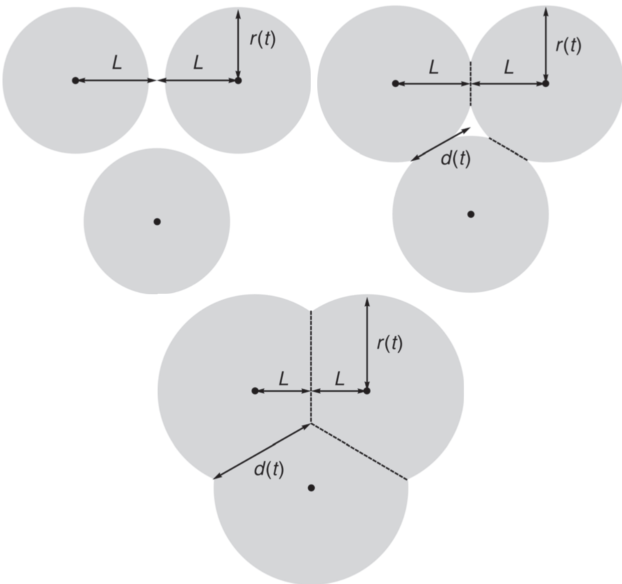

Fig. 2 The three phases of coalescence of three identical droplets; (top left) initial phase ($0 \le t \le t_c$), (top right) partially coalesced phase ($t_c < t \le t_f$), and (bottom) the fully coalesced phase ($t_f < t < t_{max}$).

Initially, the droplets are not touching and so each behaves like a single isolated droplet. A single isolated droplet has constant volume $V=h(t)A(t)$ and cross-sectional area $A(t)=\pi r(t)^2$, and therefore radius $r(t)=(V/\pi h(t))^{1/2}$. The radial speed of the boundary of a single isolated droplet can be found by differentiating $r(t)$ with respect to time to yield $\dot{r}(t) \propto (H_0 - S_p\, t)^{-3/2}$. Note that, in theory, for a single isolated droplet $\dot{r}(t)$ approaches infinity as the gap between the substrates approaches zero, i.e. as $t \to H_0/S_p$. (In practice, of course, the squeezing is stopped at some time before t_{max} to create a cell with a prescribed non-zero gap between the substrates.)

When there are multiple droplets, the droplets will meet and start to interact at some time before $t=t_{max}$. In particular, for the present arrangement of three droplets, the droplets will meet at time $t=t_c$ defined by $r(t_c)=L$, and then enter the partially coalesced phase shown in Fig. 2 (top right). An implicit equation for the droplet radius $r(t)$ during the partially coalesced phase can be determined analytically.

Eventually, at a later time $t=t_f$ where $t_c < t_f < t_{max}$, the central gap between the droplets closes up entirely and the droplets enter the fully coalesced phase shown in Fig. 2 (bottom). An implicit equation for the droplet radius $r(t)$ during the fully coalesced phase can again be determined analytically. As in the initial phase, in the partially and fully coalesced phases the radial speed of the boundary of the droplets can be obtained by differentiation.

The radial speed of the boundary of the droplets $\dot{r}(t)$ is plotted as a function of time t in Fig. 3, for the ODF parameter values shown in Table 1. Fig. 3 shows that in all three coalescence phases $\dot{r}(t)$ increases as the gap between the substrates decreases. We can also determine the radial speed of the corners formed between the droplets in the partially and fully coalesced phases shown in Fig. 2 (top right and bottom). In particular, this speed, denoted by $\dot{d}(t)$, is found to always be larger than $\dot{r}(t)$, as also shown in Fig. 3.

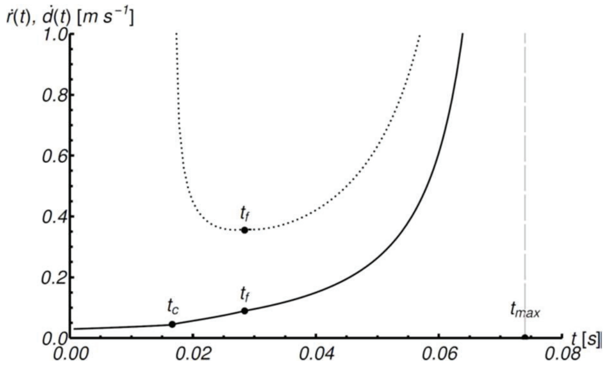

Fig. 3 Radial speed of the boundary of the droplets $\dot{r}(t)$ (solid) and radial speed of the corners between droplets $\dot{d}(t)$ (dotted), as functions of time t for three identical droplets for the ODF parameter values shown in Table 1. The times t_c, t_f, and t_{max} are indicated and recorded in Table 1.

Symbol	Value
V	4.501×10^{-9} [m^3]
H_0	7.400×10^{-5} [m]
S_p	1.000×10^{-3} [ms^{-1}]
L	5.000×10^{-3} [m]
t_c	1.669×10^{-2} [s]
t_f	2.840×10^{-2} [s]
t_{max}	7.400×10^{-2} [s]

Table 1 ODF parameter values.

Given the location of the ODF mura shown in Fig. 1, and the fact that the present model predicts that the corner speed $\dot{d}(t)$ is larger than the radial speed of the droplet boundary $\dot{r}(t)$, we hypothesise that the formation of ODF mura is associated with elastic/inelastic deformation to the director structure caused by the droplet boundary advancing across the alignment layer. We therefore use the value of $\dot{r}(t)$ predicted by our model to estimate the elastic/inelastic deformation to the director structure caused by the spreading droplets. Specifically, the elastic/inelastic deformation to the director structure at any point is assumed to be proportional to the radial speed of the droplet boundary as it passes over that point. In particular, areas with larger values of $\dot{r}(t)$ then correspond to areas where the spreading droplet front causes a high shear or torque on the alignment layer which could lead to the formation of ODF mura. The elastic/inelastic deformation to the director structure for three droplets is shown in Fig. 4 for the ODF parameter values shown in Table 1, where decreasing greyscale shows increasing $\dot{r}(t)$, i.e. increasing elastic/inelastic deformation to the director structure. In particular, Fig. 4 shows increasing elastic/inelastic deformation to the director structure towards the outer edges. The theoretical prediction of elastic/inelastic deformation to the director structure shown in Fig. 4 shows a striking similarity to the ODF mura shown in Fig. 1. In particular, both Fig. 1 and Fig. 4 show three lighter linear regions of non-uniformity between the origins of each droplet creating an inverted "Y-shape" in the centre of the cell and lighter regions towards the edges of the substrate, possibly suggesting a link between areas of high $\dot{r}(t)$ and the positions of the ODF mura. Possible methods to reduce $\dot{r}(t)$, and hence potentially to reduce the ODF mura, would be to dispense droplets into more lower volume droplets or to decrease the speed at which the top substrate is lowered.

Fig. 4 Elastic/inelastic deformation to the director structure for three identical droplets predicted by the present model. Decreasing greyscale shows increasing elastic/inelastic deformation to the director structure.

3 DISCUSSION

The present model suggests a possible mechanism for the formation of ODF mura due to elastic/inelastic deformation to the director structure caused by the droplet boundary advancing over the alignment layer. However, other mechanisms for ODF mura (such as colour filter structures and liquid crystal properties [4]) have also been suggested, and so further theoretical and experimental investigations of this potentially multifaceted problem are still required. It should be noted that this work uses a relatively simple model, and a more detailed model accounting for surface tension (see, for example, [5]) may provide a more accurate prediction of the radial speed of the droplet boundary.

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