Flow Visualization Studies in Scaled-Up Gravure Grooves and Cells

Xiuyan Yin and Satish Kumar*

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Abstract: Gravure coating and printing are processes that are capable of producing thin coatings or fine patterns on substrates at high speeds by using a cylinder engraved with sub-millimeter scale grooves (for coating) or cells (for printing). A scaled-up groove and cell were built to study flow inside actual gravure grooves and cells during the emptying process. For the experiments with a scaled-up groove, a flat glass plate is passed horizontally over the groove under fully flooded conditions, and a large eddy is observed whose strength depends on the angle between the groove and the direction of the moving top. If the moving top is changed to glass with a convex curved surface, a recirculation is also obtained inside the groove when the top approaches the groove. Then, the recirculation becomes separated from the other fluid inside the groove and follows the top as it leaves the groove. For the experiments with a scaled-up cell, a glass top with a convex curved surface is passed horizontally over the cell. The results reveal that the larger the capillary number and the larger the thickness of liquid on the lands, the larger the amount of liquid remaining inside the cell after the moving top passes over the cell.

Introduction

Gravure coating and printing are processes that are capable of producing thin coatings or fine patterns on substrates at high speeds by using a cylinder engraved with sub-millimeter scale grooves (for coating) or cells (for printing). The gravure grooves or cells are usually fed liquid by rotating the roll in a pan of liquid as shown in Fig. 1. A flexible doctor blade scrapes off excess liquid on the lands (unengraved part between the grooves or cells), leaving a very thin lubricating film of liquid on the lands to prevent scratching of the web and wear of the roll surface. The liquid in the grooves or cells is partly transferred to a web that is backed by a deformable roll. Then the cell, which may have been

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*Department of Chemical Engineering and Materials Science, University of Minnesota

only partially emptied, returns to the pool to be refilled. The controlling phenomena of gravure coating and printing on microscopic scales are not well documented because the actual grooves and cells are so small that it is difficult to observe flow inside them directly. So, it is necessary to construct a scaled-up groove or cell to study the emptying process. In this area, previous work has been performed by Noyola *et al.* (2000), who studied bubble behavior in single cells and rheological effects on liquid removal.

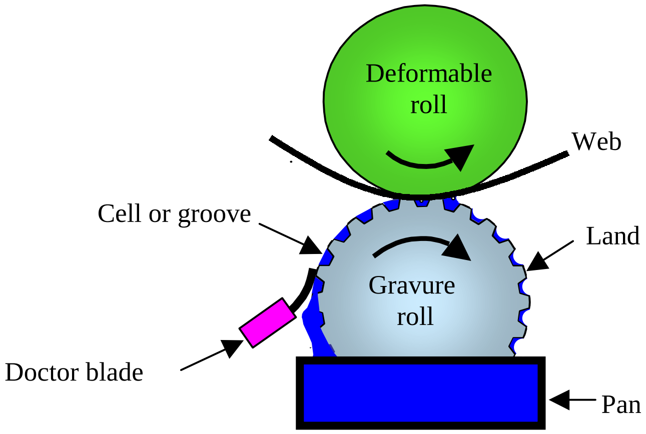

Figure 1: Schematic of gravure process

Experimental Set-up

In order to understand the emptying process, flow visualization experiments with a scaled-up groove and a scaled-up cell were performed. The apparatus shown in Fig. 2 was employed in our experiments. To obtain the groove, a channel was cut on an aluminum cube (25mm × 13mm × 6mm) by an electric discharge machine. The cross section of the groove is a trapezoid with upper width 1.5mm, lower width 0.9mm, and height 1.2mm. The two ends of the groove are open. A tiny hole was drilled on the bottom of the groove for injecting tracers that can be used to visualize the flow. The cell is made by cutting a slice, whose thickness is about 1.5mm, from the cube with a groove and then sealing both ends. The support consists of several layers of glass plates and adjusts the gap between the groove and the top (The gap is set to less than 1 mm in these experiments). The top, which can be made of different materials, is attached to the top plate to mimic the web. In experiments, the top plate is fixed on a positioning device (this is not shown in Fig. 2) that is moved by a microstepping motor. Video images taken from the front side were recorded. All experiments were conducted at room temperature.

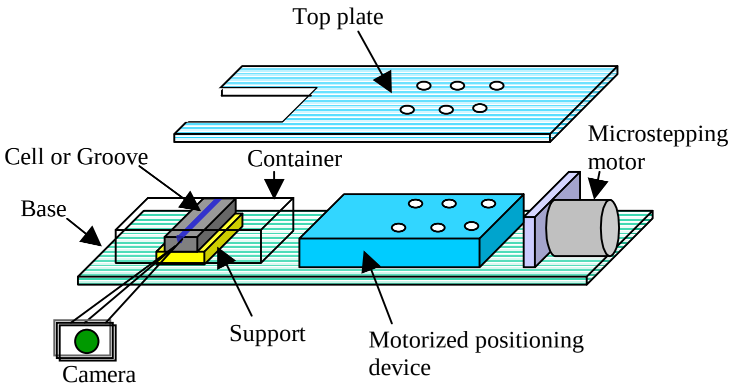

Fig 2. Experimental set-up

For the experiments with a scaled-up groove, water served as the coating liquid and was held in a glass container (7.5cm × 7.5cm × 2.5cm) in which the groove was submerged. The flow tracers are polymer flakes with average size $6 \times 30 \times 0.07\mu m$.

Results for the Groove

When a glass top with a curved surface passes horizontally over a groove that is fully flooded by liquid in the container, a large eddy is observed in the groove (Fig. 3(a)). As the top leaves the groove, the eddy is separated from the other fluid inside the groove and follows the exiting top (Fig. 3(b)). The flow pattern in Fig. 3(b) appears to be consistent with recent computations by Powell et al. (2000) on a related problem. They performed two-dimensional finite-element calculations to determine the velocity distribution when a meniscus passes over a groove. Note that there is no meniscus in our experiment and that the flow is driven by a rigid top. It is difficult to make a meniscus in our groove because both ends of the groove are open and cannot prevent liquid from flowing out. Although a rigid top is used in our experiment and the groove is fully flooded by coating liquid, the flow looks similar to that calculated when a meniscus is present.

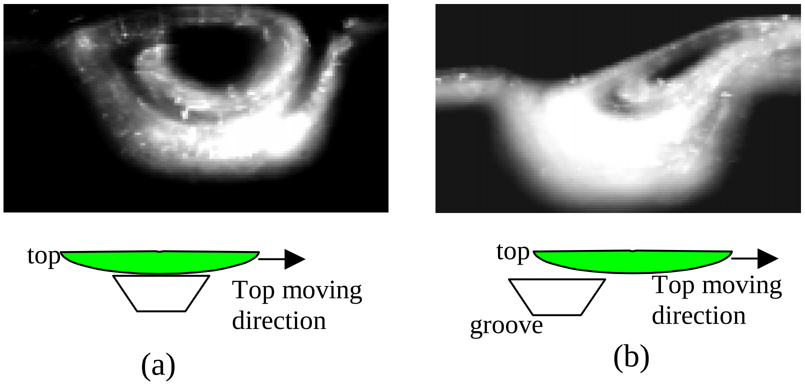

Fig 3. Flow pattern in the groove (a) when the top approaches the groove. An eddy forms (b) when the top is leaving, and the eddy is separated from the other fluid.

In order to study the properties of the recirculation, the glass top with a curved surface is replaced by a flat glass top, so that the recirculation can be developed more completely. It was found that the strength of the recirculation depends on the angle between the groove and the orientation of the moving top (see Fig. 4). As the angle increases, the strength of the recirculation increases. If the angle is 90°, the flow is like a driven cavity flow. When the angle is less than 45°, the recirculation becomes unclear and even disappears. When the angle is 0°, i.e. the direction of motion of the top is parallel to the groove, the flow is like a Couette flow and there is no recirculation at all. In the range of speeds investigated (0.0003-0.15 m/s), the flow patterns are the same for different speeds (results not shown here).

Results for the Cell

For the experiments with a scaled-up cell, mixtures of water and glycerin in different ratios served as coating liquids in order to obtain liquids with different viscosities. Only a small droplet of liquid is put into the cell and a very thin film of liquid is on the land. After a glass top with a convex curved surface is passed horizontally over the cell, we measured the amount of liquid remaining in the cell by using a micro-syringe. If the cell is not fully emptied and the coating solution includes a volatile solvent, the solvent may evaporate between emptying and refilling of the cell and make the solution concentrated or produce a solid residue. The residue could lead to variations in coating thickness in two

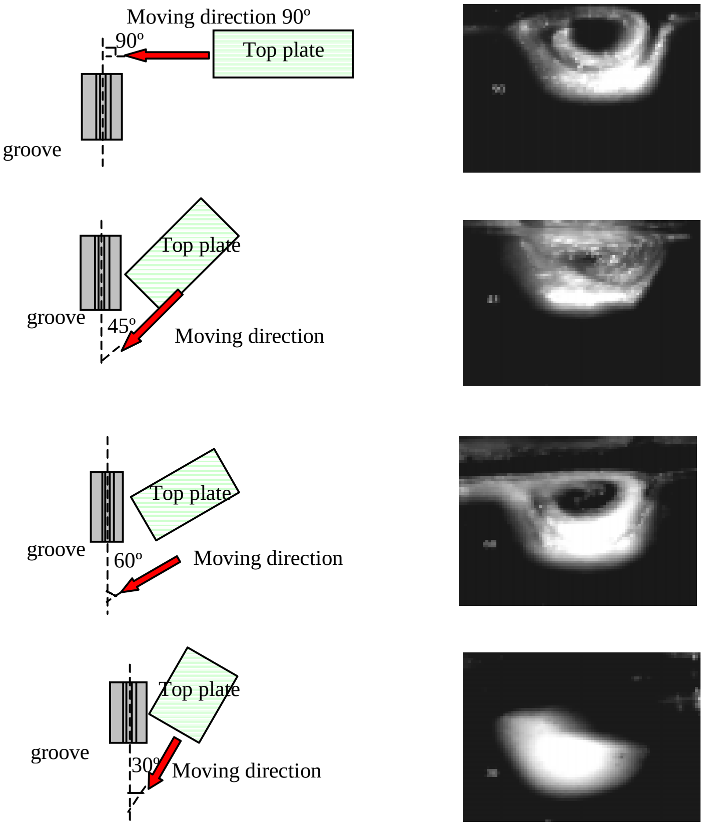

Fig 4. Effect of relative direction on flow pattern

ways: 1) it could attach to the walls of the cell, so that the volume of the cell is changed; 2) it could dissolve into the liquid during refilling, so that the concentration of coating liquid is increased. Thus, controlling the amount of liquid remaining in the cell is an important factor in improving coating quality.

The measurement results reveal that the amount of liquid remaining in the cell after the top has completely passed over it depends on the capillary number and the thickness of liquid on the lands (Fig. 5). The capillary number is defined as $\mu U/\sigma$, where μ is the liquid viscosity, U is the speed of the top plate, and σ is the surface tension of the liquid. It provides a ratio of viscous forces to surface tension forces. The different capillary numbers were obtained by using liquids with different viscosities and changing the speed of the glass top. For the same capillary number, less liquid remains for a flat-filled cell (a very thin lubricating film of liquid on the land, ~0.05 mm) than for an over-filled cell (larger thickness of liquid on the land, ~0.3-0.5 mm). For every filling situation, the amount of liquid remaining increases as the capillary number increases. If the capillary number is small enough and the thickness of liquid on the lands is small enough, the cell may be totally emptied. Every data point shown in Fig. 5 is the average value of a set of experiments for the corresponding capillary number.

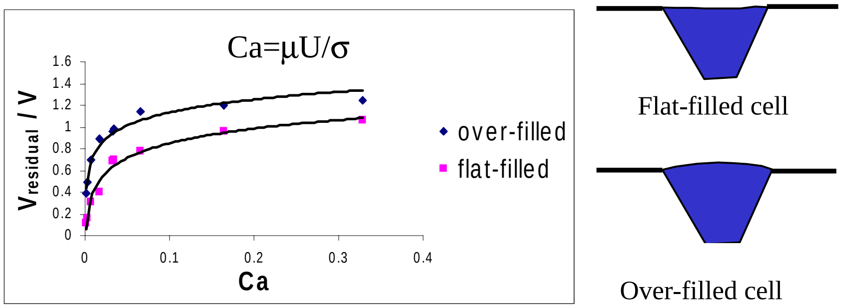

Fig 5. The effect of capillary number and thickness of liquid on the land on the amount of liquid removed from the cell

Conclusions

The results from experiments with a scaled-up groove show that the recirculation generated in the groove may be attached to the top as it is leaving, and the strength of the recirculation decreases as the angle between the groove and the direction of the moving top decreases. The results for a scaled-up cell reveal that the larger the capillary number and the larger the thickness of liquid on the lands, the larger the amount of liquid remaining inside the cell after the moving top passes over the cell.

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