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A Review of Gravure Coating Systems

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1. Introduction

Gravure roll coating is a technique used to coat fluids of a wide range of viscosities (up to 1500mPa s) onto substrates at speeds of up to 900 m/min (Booth, 1970,1990). Coat thicknesses in the range of less than 1 micron up to 50 microns can be achieved, making this a versatile process which is finding application across a growing number of market sectors.

Gravure roll coating differs from many of the conventional roll coating techniques in that one of the rolls is patterned with a surface engraving (the 'gravure' or 'anilox' pattern). Both the shape and the size of the gravure pattern can be varied which affects the final properties of the coating.

The term 'gravure roll coating' covers a number of distinct gravure coating arrangements. Two common variants of these are direct gravure coating and offset gravure coating, see Figure 1. Direct gravure coating is where the fluid transfer takes place directly from the gravure roll to the web, whilst in offset gravure coating, fluid is transferred first from the gravure roll to a smooth deformable roll (often termed the applicator roll), and then from the deformable roll to the web. Whilst both are described as gravure coating processes, the fluid mechanics of these two processes are very different and will be described separately.

Gravure 'coating' is distinct from gravure 'printing' (or roto-gravure), in that gravure coating is designed to give uniform coverage on the substrate whilst gravure printing is designed to print specific patterns. The quality of gravure coating can be defined in terms of the thickness and variation of the coating, whilst the quality of gravure printing will include quantification of print characteristics such as resolution and edge definition. This article will focus on gravure coating, but many of the emerging markets, for example in the manufacture of electronic products such as solar cells, require both large areas of uniform coating but with good edge definition.

This article will first describe the range of gravure cells available and typical manufacturing techniques, together with the important parameters that specify the gravure roller, before describing in more detail the two distinct gravure roll coating processes.

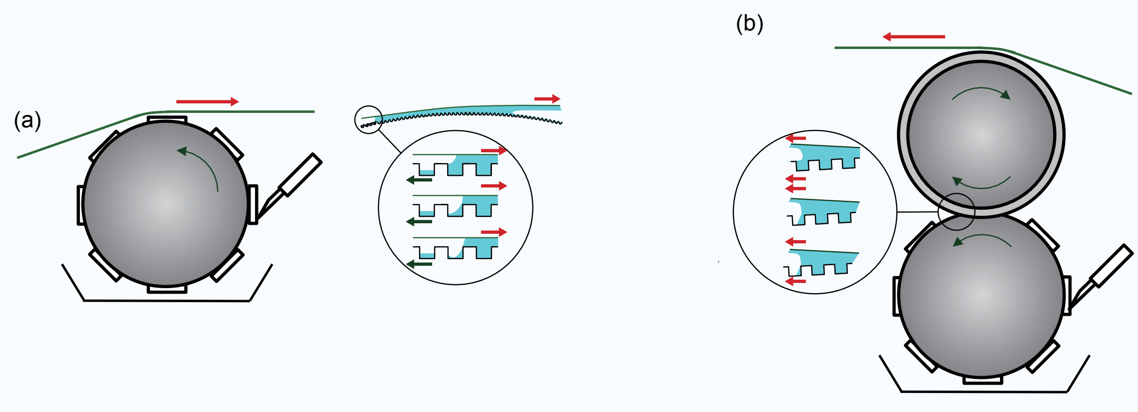

Figure 1 (a) the direct gravure process where the gravure roll and web are in intimate contact, (b) offset gravure coating where transfer is from (i) the gravure roll to the (deformable) applicator roll and (ii) subsequently from the applicator roll to the web

2. Gravure Cell Specification

Correctly specifying the gravure cell is crucial to the success of the gravure coating process, since the shape and size of the cell define the operability windows of the coating process. The cells themselves fall into two distinct categories—trihelical patterns which are continuous grooves that run at some angle around the roll surface and discrete patterns that consist of individual gravure cells cut into the roll surface. Figure 2 shows a series of images of typical gravure cells.

The process for manufacturing cells can be divided into two categories—direct engraving of the cylinder or etching of a cylinder through either chemical or laser means. Direct engraving is where a master shape is forced into the roll surface to cause an indentation. This can be done using a diamond tipped stylus onto a copper plated roll, with each indentation forming one gravure cell, or taking a hard master knurling tool and rolling this against the copper plated surface. In both cases a hard chromium layer is subsequently plated onto the roll surface to provide longevity of operation. Etching of a cylinder can either take place *via* a chemical or laser ablation process. Of these, the use of lasers for direct ablation of the surface is by far the most common process. The roll is prepared by thermal spray coating of a ceramic material onto the surface of the roll. This is finished to give a smooth surface. A high-powered laser is then used to ablate the surface to give the desired pattern. The ceramic is hard and gives excellent wear resistance. The choice of the manufacturing process directly dictates the shape of the gravure cell. Direct engraving is often associated with quadrangular, pyramidal and trihelical cells, whilst those cells produced by laser engraving tend to be hexagonal in shape.

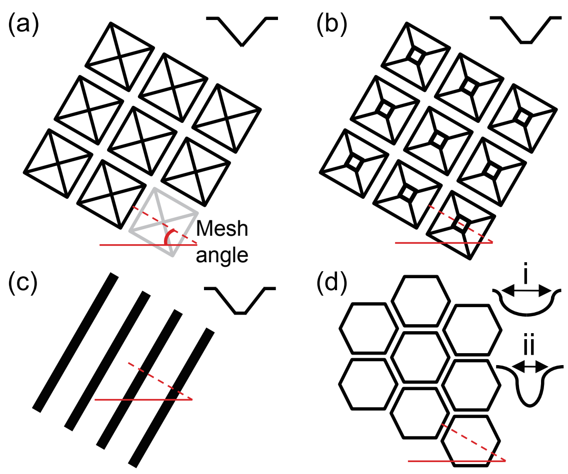

Figure 2 Schematic showing typical gravure cells. (a) pyramidal, (b) quadrangular, (c) continuous trihelical, (d) laser engraved ceramic cells. A cross-section through each of the cells along the line of engraving is also shown

Quantitatively, the cells are described by the average cell volume and the line count. In addition, the pattern of cells will lie at some angle to the axis of the gravure roll, this is known as the mesh or engraving angle and typically lies between 30 and 60 degrees (Fig. 2).

The average cell volume is used to express the volume of the gravure cells contained on a unit area of roll surface. One typical industry unit includes BCM (Billion Cubic Microns per square inch), or to convert to the SI unit, 1 BCM is equal to 1.55cm^3/m^2 or 1.55 microns. The average cell volume expressed in SI units is the same as average incoming film thickness if the fluid within the cells were evenly distributed over the roll surface, giving an intuitive link between average cell volume and equivalent inlet thickness. The line count of the cell is a linear count of the cells along the angle of engraving with typical units being lpi (lines per inch) or lpcm (lines per cm). Typical screen counts can lie anywhere between 20 and 1500lpi, with average cell volumes of 1.5 to 75 microns (1 to 50 BCM), depending on the manufacturing method and cell shape.

Whilst these parameters are commonly used for the specification of gravure rolls, there are other parameters which are of importance in understanding the behavior of gravure coating processes. Figure 2(d, i-ii) shows a schematic of the cross-section through two gravure cells of the same cell volume and the same line count. Clearly the shape of the two cells is different, and as discussed later the characteristics of fluid transfer out of these cells will differ. This highlights a third parameter that is of importance—that of the area of cell opening per unit area of roll surface. This parameter is not explicitly controlled during manufacture, and is one point of inconsistency between two rolls specified only by the cell volume and line count.

3. Direct Gravure Coating

Direct gravure coating, Figure 1(a), is one of the most simple of the coating processes from a mechanical perspective, but (for single layer coatings at any rate) the fluid mechanic processes are perhaps one of the most complex. It consists of a gravure roller rotating in a bath of fluid (or alternatively through an enclosed feed chamber), the action of which fills the gravure cells with fluid. Excess fluid is removed from the surface of the roll, so that the cells alone meter fluid into the coating transfer region, using a doctor blade. Kapur (1999) demonstrated that as the loading of the reverse angle doctor blade against the roll is increased, the coated film thickness falls to some minimum, associated with the point where excess fluid above the roll surface has been removed. Wear models have been postulated to account for the wear of the doctor blade as a function of time (Hanumanthu, 1999). The gravure cells enter the coating transfer region, where fluid is transferred out of the cells onto the web, held against the roller with some tension, *T*, and a wrap angle, *β*. The web generally moves in the opposite direction to that of the roll to give a wider coating window (Benkreira and Cohu, 1998). This coating transfer region is illustrated in Figure 3. At the upstream meniscus, the pressure gradient generated across the bead causes a fraction of the fluid to be evacuated from the cell.

For a Newtonian fluid, the key parameters that determine the behavior of the system are the fluid properties (viscosity and surface tension), the web speed and the roll speed, and to a lesser extent the web tension and wrap angle. Both the shape and the size of the gravure cell also play a key role in determining the final coating properties. For a given gravure pattern, there is only a small window over which the coating thickness can be varied through changing process parameters. Therefore the correct specification of the gravure pattern at the outset is important.

Experimental work of Kapur (2003) demonstrates the interplay between cell shape and size. A smooth shallow cell was found to give better pickout (defined as the fraction of the fluid evacuated from the cell) than a more angular and deeper cell. The effect of increasing the web speed whilst keeping the roll speed constant has also been explored. Here the pickout asymptotically increases to some maximum value below the theoretical maximum value of 1. This suggests that a proportion of fluid within the cell remains trapped. If this fluid remains in the base of the cell it may have a significantly increased residence time within the process. Once this upper limit has been reached, then further increases in the web speed result in a decrease in the coated film thickness since the flux of coating solution onto the web remains constant, but the average film thickness reduces as the web speed increases. At high web-to-roll speed ratios, the upper limit of the operating window is dictated by the point the coating bead between the web and roller breaks, causing streaking along the web. Typical behavior is illustrated in Figure 3.

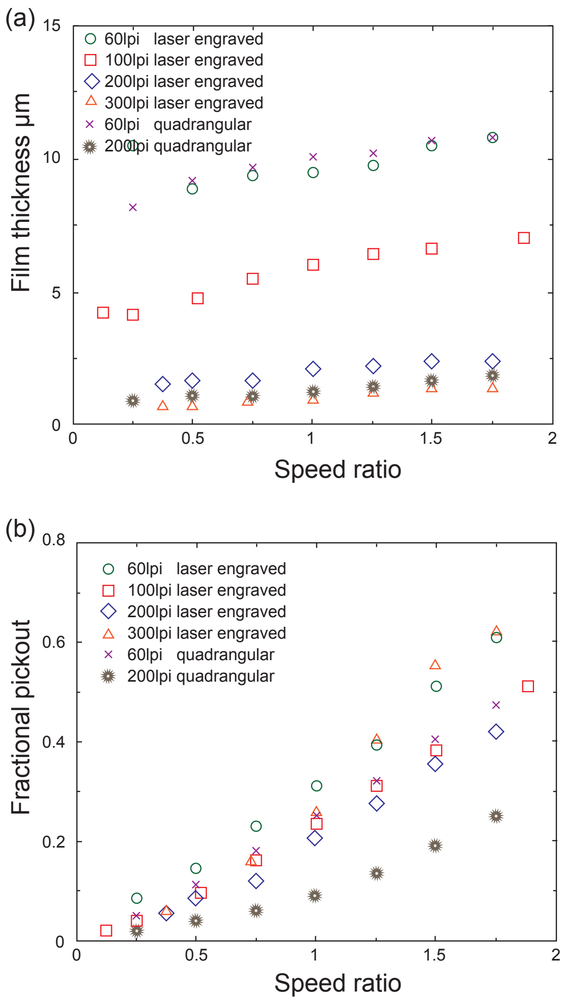

Figure 3 Typical variation in (a) coated film thickness and (b) fractional pickout for a range of gravure rolls as the web-to-roll speed ratio is varied.
Conditions: roll speed 0.66m/s, fluid viscosity 1mPa s, surface tension 33mN/m. (taken from Kapur (1999))

Efforts are ongoing to develop appropriate models to capture the behavior of the direct gravure coating process. Early work considered the complex evacuation process at the upstream meniscus, where a pressure gradient causes fluid to be swept out of the cell. Rees (1995) studied the behavior of a single (2-dimensional) cell as it moved beneath a meniscus, Schwartz *et al*. (1998) studied a more realistic cell pattern but used lubrication theory to examine the effect of the cell geometry on pickout. However, without knowledge of the conditions within the entire coating bead, it is not possible to relate the emptying behavior of the cell to the process parameters. A more recent method (Hewson *et al*. 2011) has used a multi-scale approach to link the large scale fluid mechanics within the coating bead to that of the small scale fluid mechanics within a single gravure cell. Computational fluid dynamic simulations model the flow between a single cell and moving web (an example of which is shown in Fig. 4), and a modified lubrication approach based on these findings is used

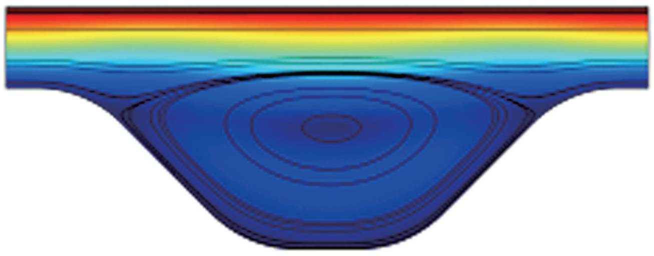

Figure 4 Flow between the moving web and the gravure cell within the web-to-roll transfer region. The black lines show the streamlines and highlight a closed eddy within the cell, the colors indicate the magnitude of the velocity (blue = low, red = high)

to approximate the dynamics of the whole bead. Early results from this approach look promising and offer the potential for a fully predictive framework in which the influence of the parameters that define the direct gravure coating process can be fully explored.

4. Offset Gravure Coating

In offset gravure roll coating, illustrated in Figure 1(b), there is an intermediate transfer from the gravure roll to a deformable roll. The smooth liquid film on the deformable roll is then metered onto the web, most commonly via a forward or reverse kiss coating nip. The addition of this extra transfer region gives additional flexibility in adjusting the final film thickness on the web. The kiss coating processes are illustrated in Figure 5.

Whilst the direct gravure process described in section 3 is generally run in reverse mode, the transfer between the gravure roll and the deformable roll is generally run in forward mode, with both roll surfaces passing through the coating transfer region in the same direction. This is to minimize wear on the deformable roll. The pickout process from the gravure cell is significantly different than that of direct gravure coating as illustrated in Figure 1(b).

There is little published work describing the transfer between the gravure roll and deformable roll. Kapur (1999) showed that as the nip force between the gravure roller and the deformable roll increases, then the film thickness decreases to some lower limit. Similarly, as the speed of the two rolls are increased (noting that the ratio of speeds between the gravure roll and the deformable roll is fixed at 1 to prevent excessive wear) then the film thickness leaving the gravure-deformable transfer region asymptotes to some limiting value. For the range of gravure cells presented by Kapur *et al*. (2001) covering a range of quadrangular and laser engraved rolls with volumes between 10 and 60 microns and line counts of 60 and 200lpi), this occurred at relatively low speeds (<60m/min), which suggests that in most practical situations the film thickness that is transferred into the kiss coating nip is not strongly affected by speed. The pickout from these cells at this asymptotic limit lies between 10 and 25%, and in common with direct gravure coating, shallow smooth cells give a greater fractional pickout.

What is much better understood is the kiss coating region that exists between the deformable roll and the moving web. Here there are two possible arrangements, reverse kiss coating (Figure 5(a)), where the web and roll motion through the fluid transfer region are in opposite directions and forward kiss coating (Figure 5(b)) where the web and roll motions through the transfer region are in the same direction.

Since the roll is smooth, the use of lubrication theory to establish an analytic model is valid. For the reverse kiss coat, Gaskell *et al*. (1998a) developed a model that to predict the film thickness (H_{web}) incorporated the effects of applicator speed (U_{app}) web-to-roll speed ratio (S), roll radius (R), the web tension (T) and wrap angle (β) and the fluid properties of viscosity (μ) and surface tension (σ). This resulting expression,

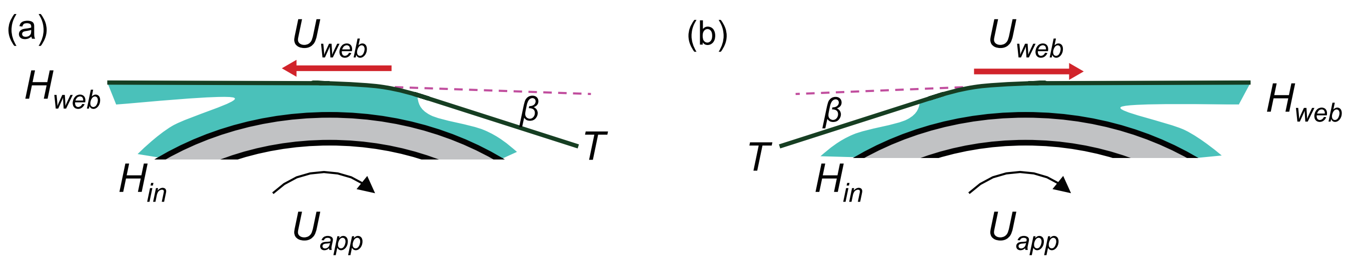

Figure 5 (a) reverse mode kiss coating nip (b) forward mode kiss coating nip

$$H_{web} = \frac{R}{S}\left[\frac{H_{in}}{R} - \frac{6}{5}\left(\frac{\mu U_{app}}{\sigma}\right)(1-S)^2\left(\frac{\sigma}{T\beta}\right)\right] \qquad (1)$$

is valid for S<1 and non-zero wrap angles.

At speeds ratios greater than 1 in the reverse mode of operation, all fluid is observed to transfer from the applicator roll to the web and the resulting thickness is given by

$$H_{web} = \frac{H_{in}}{S} \qquad (2)$$

For the forward mode of operation, the fluid pressure within the kiss bead has to overcome the tension holding the web onto the substrate. If the inlet has an excess of fluid, the action of the web will cause some metering of the fluid so only a limiting amount passes the gap between the web and roll. Eshel and Elrod (1965) derived an expression for a foil bearing which can be used to estimate this limiting thickness

$$H_{min} = 0.65R\left[\frac{6\mu\left(U_{web} + U_{app}\right)}{T}\right]^{2/3} \qquad (3)$$

As is often the case, the inlet film thickness produced from the gravure-deformable nip will be less than this limiting thickness, and in this case all the inlet film will transfer between the web and roll. The effective film thickness is given by

$$H_{eff} = \min\left(H_{min}, H_{in}\right) \qquad (4)$$

At the outlet, the fluid carried through the coating bead must split between the upper moving web and the deformable roll surface. Assuming the film-split follows that of a forward roll coating arrangement (Gaskell *et al*. 1998b), where the fluid is split depending on the web-to-roll speed ratio, then the final coated film thickness is given by

$$H_{web} = \frac{H_{eff}S(S+3)}{3S+1} \qquad (5)$$

where S is the ratio of the web speed to applicator speed.

5. Conclusions

Gravure coating is a versatile process which is finding application across a growing number of sectors. To fully understand the process, it is important to recognize the differences between different arrangements of coat heads and to understand the interaction of each fluid transfer region. Models are extremely useful in understanding this behavior and can be used as a guide in both specifying equipment at the design stage and in troubleshooting during operation. For gravure coating these models are under continuous development and offer the exciting prospect of being able to establish a formal link between the process parameters and the final film thickness.

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