Rheology and Flow of Paints in Roll Coating Processes

O Cohu and A Magnin

Laboratoire de Rhéologie, B.P. 53, 38041 GRENOBLE Cedex 9 (France)

UMR CNRS 1510 - Université Joseph Fourier Grenoble I - Institut National Polytechnique de Grenoble

Introduction

When a liquid coating is deposited on a solid substrate, it is necessary to control both the thickness and appearance of the film, irrespective of the coating process used. Very often, the quality of the final coating (in terms of both thickness and evenness) is determined by the mechanics of flow during the coating operation.

The products used in coating operations (paints, varnish, adhesives, etc.) are not usually Newtonian fluids. For example, they may be thixotropic yield-stress fluids, in which the consistency drops when an intense shear force is applied, or in contrast increases at rest or under low shear. Such fluids obviously cannot be characterized simply by a "viscosity" value, a single parameter to be introduced into possible models of the coating process. On the contrary, it is necessary to characterize their rheological behaviour with respect to the forces that these fluids undergo throughout the coating process. This type of rheometric characterization and its applications are described here, using the example of continuous coating of foils (roll-coating).

Analysis of the coil-coating process

The coil-coating process is a roll coating operation which is illustrated schematically in Figure 1. A relatively thick film of paint carried by the pick-up roll is forced through the narrow gap between it and the counter-rotating applicator roll. When it leaves this gap, it divides. Part of the paint stays on the applicator roll and is then completely transferred onto the moving substrate. All the paint is transferred due to the fact that the deformable surface of the applicator roll, which is held tightly against the web, moves in the opposite direction to it at the point of contact. Finally, the film is fixed in a baking oven further downstream.

The thickness of the coating deposited on the web is thus determined essentially by the flow of paint between the counter-rotating pick-up and applicator rolls, with the surface of the latter being deformable. It has been shown earlier that the paint passing between these rolls, which are held tightly against one another, is subjected to a high shear rate $\gamma$ of the order of $10^4 \, \text{s}^{-1}$, for a very short time, of about 10 milliseconds.

The flow of a fluid between two counter-rotating rolls (i.e., the adjacent surfaces of which are moving in the same direction) is unstable with regard to a transverse disturbance. This results in the creation of a liquid film of non-uniform thickness, with a rippling cross section. This can be seen through the appearance of parallel lines at regular intervals of a few millimetres, running in the direction of movement of the web. The so-called ribbing defect is inevitable at commercially profitable production speeds.

In order to obtain a perfectly homogeneous appearance in the finished product, it is therefore necessary for any irregularities in the liquid paint film to be levelled as much as possible. This levelling, resulting from the surface tension of the coating, must be achieved before the film is permanently fixed in the oven.

It is clear, therefore, that the evenness of the film is determined largely by the levelling flow that occurs just after the paint is transferred onto the substrate. This flow is characterized by low shear rates, of the order of $10^2 \, \text{s}^{-1}$ (see references 5, 6).

In order to improve the quality of coatings deposited by roller machines, two very different kinds of flow must therefore be considered:

- a very brief flow at high shear rate to control the thickness of the film,
- a flow at low-shear rate, following the previous one, for good-quality appearance.

The rheology of the paints must be determined in relation to this. Firstly, however, we will discuss the rheological behaviour of paints in steady flow regimes.

Steady-state rheology of paints

In order to determine the rheological behaviour of paints flowing under steady shear, a Carriried Weissenberg controlled-speed rotating rheometer was used. This rheometer was equipped with a cone-plate cell (angle $1^\circ$, diameter...
ter 50 or 75 mm) for shear rates of less than $3 \times 10^2$ s$^{-1}$ and a Couette cell (diameter 15 mm, gap 0.3 mm, height 50 mm) for higher shear rates.

With this equipment, it was possible to cover shear rates between $10^2$ and $7.5 \times 10^3$ s$^{-1}$. To reach higher shear rates, corresponding to flow between two counter-rotating rolls, a Gottfert 2601 controlled-speed capillary rheometer was used. This was equipped with two 0.41 mm dies, respectively 48 and 78 mm long. The paints could thus be subjected to shear rates of more than $5 \times 10^4$ s$^{-1}$.

The steady flow curves for a few representative coil-coating paints are given in Figure 2. At high shear rates, corresponding to flow between two counter-rotating rolls, it can be seen that there is a Newtonian plateau for all the paints, where the viscosity does not depend (or hardly depends) on the shear rate. Certain paints, such as paint 1, indeed have a practically Newtonian behaviour over the entire measurable domain. Others, in contrast, have a yield-stress fluid behaviour with a high rise in viscosity at low shear rates – which correspond to levelling flow. Rheological measurements made during unsteady flow conditions, which are discussed below, show that such paints are in fact thixotropic yield-stress fluids. A behaviour of this sort has the advantages of avoiding sedimentation in the paints when they are stored, as the yield stress is opposed to pigment settlement.

**Figure 2**: Rheometric measurement of viscosity during steady shear regime for a few representative paints.

![Figure 2](image)

**Behaviour of paints flowing between two counter-rotating rolls**

The short-duration flow at high-shear rates that is observed between the counter-rotating rolls of the coating head was simulated by using the Rheometric RFX rheometer in the shear configuration. The principle of this instrument is shown in Figure 3. The fluid is introduced at a controlled flow rate $Q$ into the annular channel formed by two coaxial cylinders. The inner (male) cylinder is connected to a torque rebalanced transducer in order to determine the force $F$ exerted by the flow on the instrument; hence the expression for wall shear stress. In addition, with a known prescribed flow rate in the gap, it is possible to work back to an expression for shear rate at the wall. An apparent viscosity is then measured. This is defined as the ratio between the shear stress and shear rate at the wall.

It is possible to adjust the depth of penetration of the cylinder into the tube, and hence modify the length of time the fluid remains in the area of shear. With the arrangement used here (cylinder of 726 µm internal diameter, gap $h = 167$ µm; nominal distance of penetration $L = 3$ mm), it was possible to subject the paints to a shear rate of as much as $10^4$ s$^{-1}$ over a timescale of about 10 milliseconds. This means that the apparent viscosity of the paints could be measured in conditions corresponding precisely to the flow between the two counter-rotating rolls in the coating process.

**Figure 3**: Layout of the RFX rheometer used to study shear

![Figure 3](image)

**Figure 4**: Rheometric measurement of viscosity of thixotropic paint 3 under high shear. Comparison between values measured during steady regime and under short timescale flow

![Figure 4](image)