DYNAMIC CHARACTERIZATION OF SURFACE TOPOGRAPHY OF PLASTIC FILMS

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Abstract: It is well known that surface roughness plays an important role on the handling and winding of flexible polymer films such as PET which is widely used in various applications. In order to characterize the surface topography of such materials, an air layer is squeezed between a rigid smooth substrate and a film sample. For that purpose a novel experimental set-up has been built. Using an interferometric method and image processing, we have observed the evolution of the air layer thickness and measured its reduction for several configurations and squeezing pressures. It is found that the reduction of the central air layer thickness follows a linear law versus time allowing a parameter, called "dynamic roughness", to be defined. This parameter, which characterizes the kinetics of the air layer being squeezed, represents the dynamic manifestation of the influence on the flow of more conventional "static" parameters representative of the film roughness. We have developed a theoretical model based on the hypothesis of perfectly flexible film samples and on the concept of equivalent smooth surfaces. The predictions are in good agreement with the experimental results and for each film tested the value of the characteristic parameter associated to its "dynamic roughness" is determined.

INTRODUCTION

Flexible media such as thin plastic films or paper webs are wound up to form rolls. Aspect defects may occur during and after processing. These defects are due to mechanical instabilities which may occur when the stress generated within the roll is greater than some critical value.
Several theoretical approaches, published by various authors [1-13], have lead to numerical simulations of the residual stress generated within a roll. These models, based on continuous accretion of layers, do not take into account entrapment of air between the film layers and do not incorporate surface roughness which is actually well known to play an important role in the aerodynamic phenomena induced by web motion. For example, the natural roughness of paper

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and its porosity confer to this material a higher limit of winding speed compared to the one reached for plastic materials. Typically, a film of pure PET is so smooth that it is impossible to handle it because of short range forces leading to detrimental phenomena such as triboelectricity or adhesion. Therefore, fillers are commonly added to generate some surface roughness. It has been proposed in refs.[14 -17] a first step towards the improvement of the "accretion models" by taking into account the air interlayers. The role of surface topography, which is a key question, has been addressed only by a few authors, see for instance refs.[18 - 21]. Within that framework it is very important to know how surface topography influences air entrainment or exhaust during winding. For that purpose, an experimental study is carried out to characterize the consequence of roughness on the capacity of a film to evacuate an air layer squeezed between two layers under controlled conditions. As a first step, we investigated the effects of rigidity and roughness on the total air evacuation time under prescribed squeezing conditions, ref. [22]. In order to complete these preliminary experimental results, we used an interferometric method coupled with image processing to have access to the reduction kinetics of the air layer thickness as a function of the film properties, namely : roughness and thickness. We have observed that the evolution of the air layer thickness versus time, under prescribed pressure and geometry, leads to a new parameter called "dynamic roughness", characteristic of each film tested.

FILM SAMPLES

Bi-oriented PET (Poly(Ethylene)Terephtalate) is a semi-crystalline polymer, with a crystalline structure oriented in two orthogonal directions. Because of its good mechanical properties, it is commonly used in magnetic tape or packaging industries. It has a Young's modulus of about 4.5 to 6.5 GPa, and a Poisson coefficient of 0.26 to 0.3. As quoted before, the incorporation of mineral fillers during polymerization confers to the film a specific surface topography.

The concept of "roughness" is somehow difficult to define, because it basically contains much information. For the sake of simplicity, it is useful to characterize "roughness" by one single parameter. For example the total roughness (R_t), which represents the maximum peak-to-valley distance or the average roughness $R_a = \frac{\sum_i |R_i - \overline{R}|}{N}$ which is the averaged value of the profile over a prescribed length of the sample, are classically used for describing metallic surfaces. However, they are not adequate for PET film surfaces, ref. [23]. Therefore it was found necessary to propose a specific approach involving a more sophisticated description of the surface topography, which can be achieved by 3D roughness measurement. In our case, a WYKO® apparatus was used. Within that framework, a parameter (R_h) which corresponds to the value of the highest five peak-to-valley distances averaged over a given area of the sample is often introduced. These descriptive data were enriched by tests more appropriate to study the static behavior of an air layer squeezed between a film sample and a smooth substrate. The residual thickness of the air layer as a function of the squeezing pressure was measured by means of an electrostatic field. The details of this experiment, carried out by Rhône Poulenc Films Company, cannot be reported here due to confidentiality reasons. Nevertheless, it is possible to give here the following empirical relationship which was proposed: see ref. [16].

$$e_f(P_a) = (e_f)_0 \, e^{-\sqrt{\frac{P_a}{P_0}}} \quad (1)$$

where: e_f represents the final air layer thickness after applying the squeezing pressure P_a. P_0 denotes some parameter characteristic of the film and $(e_f)_0$ the equilibrium air layer thickness when $P_a = 0$. If we assume that when the sample is displayed on a smooth substrate without pressure ($Pa = 0$), it lays on its highest five peaks, coefficient $(e_f)_0$ will be assimilated to parameter R_h as defined above.

In which follows, the dynamic behavior of an air layer squeezed between a film sample and a solid substrate is studied. Two sets of samples have been tested. The first one is composed of 3 PET films having the same nominal thickness (h = 12 μm) and different surface topographies (R_h comprise between 1.5 and 1.9 μm). The second set of samples is the counterpart of the first one, i.e.: two films having the same surface topography (R_h = 1.5 μm) but two thickness values: 7 and 12 μm.

EXPERIMENTAL SET UP

Only the basic features of the experimental set-up sketched in Figure 1 are summarized here. A more detailed description can be found in refs.[22] and [24].

A polished glass disk is put on a flat support having a circular slit connected to a vacuum pump. In order to study the influence of the disk diameter, several disks were used. A sample of plastic film is displayed on the glass plate and sub-ambient pressure is applied by operating the vacuum pump. The air layer which initially separates the film from the glass plate is partially evacuated and a quasi circular front starts from the slit and propagates towards the center: see Figure 2.

Monochromatic light (wave length λ = 0.589 μm) is used to illuminate the film from above, by means of a two-way mirror. Newton rings are formed and show the shape of the air gap between the film and the glass plate in the vicinity of the propagating front as they move towards the center. A CCD camera coupled with image processing is used to count the number N of black (or white) rings at the center. The reduction of the air interlayer thickness Δe is easily computed by using elementary optics laws: $\Delta e = e_i - e(t) = N\dfrac{\lambda}{2n}$, where e_i is the initial air layer thickness, e(t) the instantaneous air layer thickness, and n the air refraction index. Finally, the total evacuation time is measured for each sample.

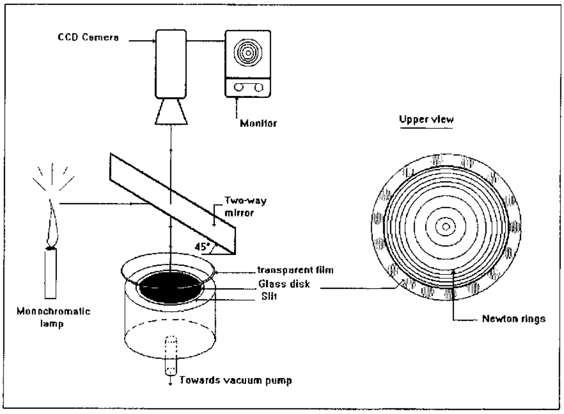

Fig. 1: Experimental set up

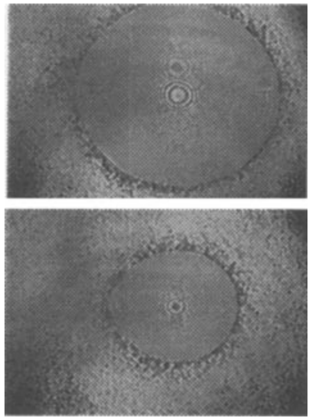

Fig. 2: Evolution of the front at two different times.

EXPERIMENTAL RESULTS

Each sample was squeezed under several values of the sub-ambient pressure, for different values of the slit radius. The time origin (t = 0) corresponds to the time when the vacuum pump starts operating. It has been shown in refs. [22] and [24] that the total evacuation time depends on the film characteristics (roughness, stiffness) and on the operating conditions (pressure, slit diameter). In addition to these global results, the velocity of the rings at the center (and consequently the central air layer reduction $\Delta e(t)$) and the front kinetics R(t) are investigated.

It is observed that the reduction of the air layer thickness is linear, this tendency being valid for any sample and any set of operating conditions. For example, Figure 3 shows the air thickness reduction as a function of time $\Delta e(t)$, for different films, the squeezing pressure and the slit radius being chosen respectively equal to : P_a = 79000 Pa and R_o = 0.0225 m. The continuous lines correspond to the experimental curves, whereas the browken lines represent the linear regressions. Certain curves do not intersect the origin because for some films the Newton rings appear with a little delay. There is no clear explanation for this behavior which probably comes from the response time of the device. Note that it actually does not affect the slopes of the curves.

We can therefore adopt the following law for the instantaneous thickness of the air layer e(t) at the center: $e(t) = e_i - k \cdot t$, where t is the time and k is a "new parameter" which is characteristic of each sample.

The determination of the front radius (R) as a function of time (t) is done in a straightforward way by interpreting the recording of the phenomenon pictures, image per image.

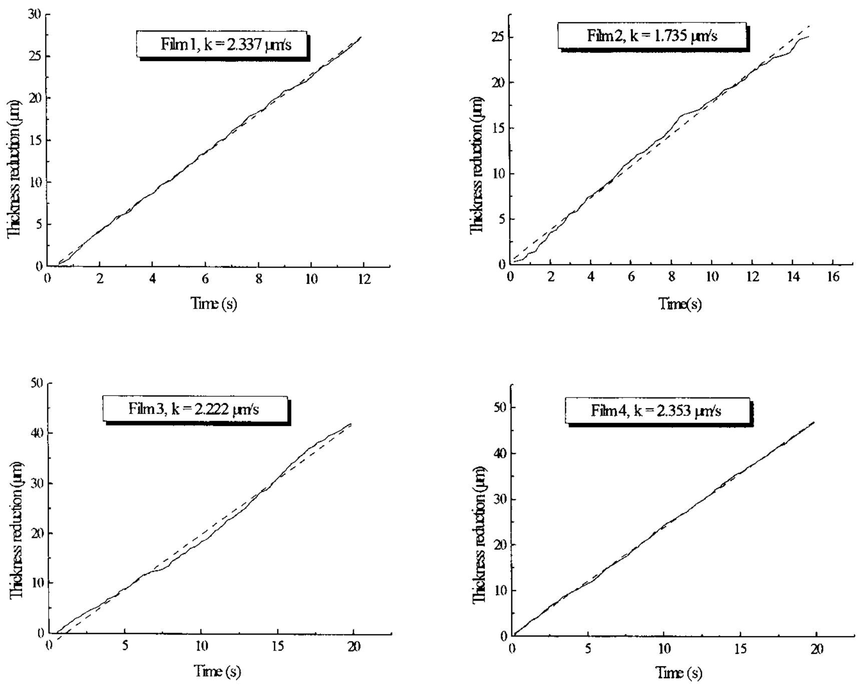

Fig. 3: Air thickness reduction as a function of time, $\Delta e = e_i - e(t)$

MATHEMATICAL MODEL

The objective is to predict the front evolution R(t) by assuming that the air layer thickness at the center linearly decreases according to the experimental law proposed. The principle of the method is the same as that used in [16] or [22], but we introduce here the reduction of the air layer thickness at the upstream zone of the front according to the linear law presented above. In other words, the air layer thickness does not keep constant but depends on time as shown in sketch 4.

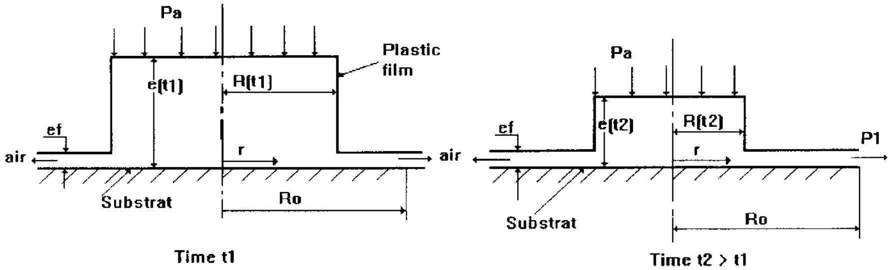

Fig. 4 : Model features

The flow is assumed to be a squeeze flow due to an applied pressure P_a equal to the absolute value of the sub-ambient pressure. It is considered to be quasistatic, inertialess and the fluid (air) to be incompressible.

As shown in Figure 4, the flow domain is divided into two zones by the propagating front R(t).

1)- Upstream the front: $(0 < r < R(t))$, the pressure is equal to P_a and the air layer thickness linearly decreases according to $e(t) = e_i - k \cdot t$. As the front moves towards the center, the volume reduction of this zone is merely equal to :

$$Q_v(t) = -\frac{\partial V}{\partial t} = 2\pi\,(e_f - e(t))\,R(t)\frac{\partial R(t)}{\partial t} - \pi R(t)^2 \frac{de(t)}{dt}$$

which can be written as, knowing that $e(t) = e_i - k \cdot t$:

$$Q_v(t) = -2\pi\,(e_i - kt - e_f)\,R(t)\frac{\partial R(t)}{\partial t} + \pi R(t)^2 k \qquad (2)$$

2)- Downstream the front $(R(t) < r < R_o)$, the flow is a Poiseuille radial flow between two surfaces separated by a gap equal to e_f. Actually e_f is an average value, the rough film being assimilated to an "equivalent smooth surface". As indicated before, the ultimate mean value of the air layer squeezed between a smooth surface and a rough film depends on the applied static pressure, Eq. (1). Assuming that $(e_f)_0$ is equal to R_h equation (1) now reads:

$$e_f(P_a) = R_h\, e^{-\sqrt{\frac{P_a}{P_0}}} \qquad (1')$$

The values of parameter P_0 has been determined through the measurement of the global evacuation time and specified in ref. [22].

Elementary calculation based on Reynolds thin film flow theory leads to the following expression for the volumic flow rate:

$$Q_v = -\frac{\pi}{6\mu}\frac{\partial p}{\partial r}\, r\, e_f^{\,3} \qquad (3)$$

where p is the pressure in the gap (p is a function of the current radius r and of time t), and μ stands for air viscosity.

Q_v is independent of the current radius r, which yields to the following expression :

$$r \frac{\partial p}{\partial r} = A(t) \qquad (4)$$

where A(t) is some function of time to be determined by the boundary conditions:

$$p\,(r = R_o) = P_1 = 0 \qquad \text{ambient pressure} \qquad (5)$$

$$p\,(r = R(t)) = P_a \qquad \text{applied pressure} \qquad (6)$$

after integration, with conditions (5) and (6), equation (4) becomes:

$$p(r,t) = \frac{P_a}{\ln \frac{R(t)}{R_o}} \ln \frac{r}{R_o} + P_1 \qquad (7)$$

which by insertion into equation (3) gives:

$$Q_v = -\frac{\pi}{6\,\mu} \frac{P_a}{\ln \frac{R(t)}{R_o}} e_f^{\,3} \qquad (8)$$

The flow rate (Q_v) is equal to the volume reduction of the upstream zone, given by equation (2). After elementary rearrangements one gets:

$$k\,R(t)^2 \ln(\frac{R(t)}{R_0}) + 2\,R(t)(-e_i + k\,t + e_f)\ln(\frac{R(t)}{R_0})(\frac{dR(t)}{dt}) + \frac{1}{6}\frac{P_a}{\mu} e_f^3 = 0 \qquad (9)$$

Recall that e_f is a function of P_a. Using equation (1'), expression (9) finally becomes :

$$kR(t)^2 \ln(\frac{R(t)}{R_0}) + 2R(t)(-e_i + k\,t + R_h e^{-\sqrt{\frac{P_a}{P_0}}})\ln(\frac{R(t)}{R_0})(\frac{dR(t)}{dt}) + \frac{1}{6}\frac{P_a}{\mu}(R_h\, e^{-\sqrt{\frac{P_a}{P_0}}})^3 = 0 \quad (10)$$

The initial condition allocated to this ordinary differential equation corresponds to the fact that the radius of the front is equal to the radius of the slit just when starting the test :

$$R\,(t = 0) = R_0$$

Equation (10) associated to its initial condition is integrated numerically using the Runge-Kutta method of a fourth order. The solution gives the time evolution of the front radius R(t), for a given set of data R_0, μ and P_a. Parameters e_i, R_h, P_0 and k are obtained from the experiments. The initial thickness e_i is the thickness final value $e_f(P_a)$ plus the total thickness reduction Δe ($t = t_f$).

The results from the calculation compared with the experimental data are presented in figure 5.

The general curve shape based on the experiments (dots) is well represented by the theoretical prediction (solid lines). The differences between calculated and experimental data are always less then 15% which corresponds to a fairly good agreement and confirms our proposal to describe the dynamic roughness characteristic of each film by parameters P_0 and *k*.

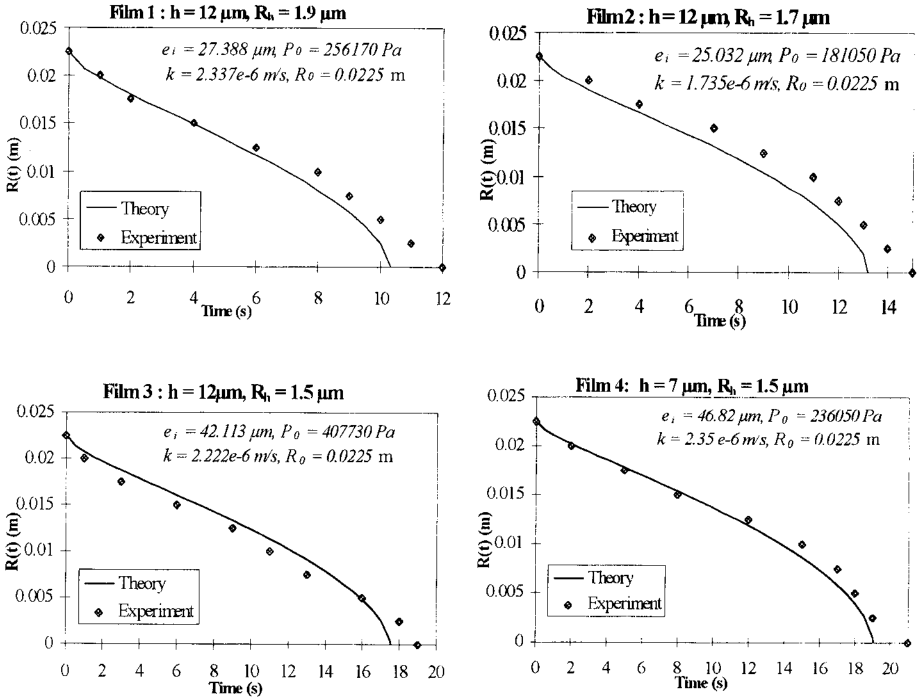

Fig. 5 :Experimental and numerical front evolutions as functions of time

CONCLUSION

The objective of this work was to complete the static descriptions of PET film surfaces by introducing the concept of "dynamic roughness". For that purpose, new parameters are proposed to characterize the kinetics of an air layer being squeezed between a rough film and a smooth substrate, under prescribed conditions. An elementary mathematical model leads to a fairly good agreement between the air layer reduction at the center of the sample and the propagation of the front due to air aspiration. However, no obvious correlation is observed between the two dynamic roughness parameters introduced and the parameter commonly used for static description of PET film surfaces. In addition, the dynamic parameters are not sufficient by themselves to rank various surface topographies. These results clearly suggest the following tracks for future work:

- The static description of a film surface cannot be adequately achieved by one single parameter but needs to be more sophisticated, involving peak density, peak height distribution, etc...
- From a theoretical point of view, a model taking into account the actual gap (involving a pertinent description of the walls surface topography) and the mechanical properties of the film (stiffness) should be developed.

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REFERENCES

(1) H. C. Altmann,*TAPPI J.* **49**, N° 8, 347 (1966)

(2) J. D. Pfeiffer, *TAPPI J.* **49**, n° 8, 342 (1966)

(3) H. Tramposh, *ASME J. Appl. Mech.* **32**, 888 (1967)

(4) W. G. Harland, *Polym. Eng. Sci.* 7, 58 (1967)

(5) J. D. Pfeiffer, *TAPPI J.* **62**, n° 10, 83 (1979)

(6) H. P. Yagoda, *J. Appl. Mech.* **47**, n°2, 847 (1980)

(7) H. P. Yagoda, *Mech. Res. Comm.* **7**, 103 (1980)

(8) H. P. Yagoda, *Mech. Res. Comm.* 7, n°3, Part I,181(1980)

(9) H. P. Yagoda, *Mech. Res. Comm.* 7, n°4, Part II,233(1980)

(10) J. D. Pfeiffer, *TAPPI J.* **64**, n° 4, 342 (1981)

(11) D. Connoly And D. Winarski, *Proc. ASLE - Int. Conf.* SP 16, 172, San Diego (1984)

(12) J. D. Pfeiffer, *TAPPI J.* 342 (Oct 1987)

(13) Z. Hakiel, TAPPI J. **70**, n° 5, 113 (1987)

(14) J. D. Pfeiffer, Proc. 1990 *TAPPI Finishing and Converting Conf. TAPPI Press, Atlanta, GA, 233* (1990)

(15) P. Bourgin and F. Bouquerel, Trans. ASME., Adv. Info. Storage Sys. **5**, 493 (1993)

(16) F. Bouquerel,.*PhD Thesis*, Ecole Centrale de Lyon, France (1993)

(17) J. K. Good and M. W. Holmberg, *Proc. 2nd. Int. Conf. Web Handling*, Stillwater, OK, USA, 246 (1993)

(18) J. K. Good and Y. Xu, *Proc. 2nd. Int. Conf. Web Handling,* Stillwater, OK, USA, 213 (1993)

(19) A. W. Forest Jr. and V. L. Anderson, *Proc. 4th. Int. Conf. Web Handling,* Stillwater, OK, USA, 44 (1997)

(20) M. Handa, *Proc. 4th. Int. Conf. Web Handling,* Stillwater, OK, USA, 512 (1997)

(21) P. Bourgin, *Proc. 4th. Int. Conf. Web Handling,* Stillwater, OK, USA, 161 (1997)

(22) M. Boutaous and P. Bourgin, *Proc. 4th. Int. Conf. Web Handling,* Stillwater, OK, USA, 224 (1997)

(23) B. Bhushan, *Tribology and Mechanics of Magnetic Storage Devices*, Chap. 2, Springer, 2nd. Edition (1996)

(24) M. Boutaous, *PhD Thesis*, Université Louis Pasteur de Strasbourg, France (1998)