WINDING PLASTIC FILMS: EXPERIMENTAL STUDY OF SQUEEZE FILM FLOW BETWEEN ONE SMOOTH SURFACE AND ONE "ROUGH" SURFACE

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ABSTRACT :

The present paper is concerned with experiments which consist in squeezing an air layer between a rigid, smooth surface and a flexible, rough one.

The experimental rig is composed of a smooth glass plate, with a circular slit allowing air aspiration to be done around it. A thin (few microns thick) plastic film is laid on the glass plate and air separating the glass and the film surfaces is removed by means of a vacuum pump. A circular front appears on the film surface, and moves towards the centre, as the film is pressed onto the glass plate.

A monochromatic lamp is used to insulate the surfaces from above and Newton rings can be observed as the front moves. The duration of this operation is measured by a chronometer.

Typically, the measured time depends on the plate diameter, the sub-ambient pressure exerted, the film flexural rigidity (or its thickness) and its surface roughness.

A set of experiments have been carried out for several values of the sub-ambient pressure and of the slit diameter.

The results are well reproducible: for a given sample, the characteristic time is proportional to the squared value of the diameter. The dependence on the sub-ambient pressure is more complicated. A simple model using a semi-empirical formulation is suggested on the basis of the experimental data.

NOMENCLATURE :

e_i : initial air layer thickness
e_f : final air layer thickness
h : plastic film nominal thickness
P, P_a, P_1 : current pressure, applied pressure, ambient pressure
Qv : volumic flow rate
r, R_0, R(t) : current radius, slit radius, front radius
R_a, R_t : average roughness, total roughness

R_h : value of the highest five peak-to-valley distances averaged over a given area
t : time
t_f : final time
μ : air dynamic viscosity
V : volume of air entrapped in the upstream zone

INTRODUCTION :

One of the objectives of mastering web handling is to avoid the defects (for instance wrinkles) generated during and after winding a flexible medium (typically a plastic film). These defects are due to mechanical instabilities which may accur when the stresses within the roll are greater than some critical values. It is well established that residual air layers strongly influence the stress state within a roll of plastic film : see [1] to [5]. The surface properties of flexible media (i.e. their topography) are of prime importance for their behaviour in web handling, in terms of air entrapment and exhaust.

The responses of several samples of plastic (PET) film are investigated by means of a specific experimental rig.

EXPERIMENTAL SET UP :

A polished glass disk is put on a flat support having a circular slit connected to a vacuum pump : see Figure 1.

A sample of polyester 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 : a quasi circular front starts from the slit and propagates towards the centre of the film.

A monochromatic lamp (λ = 0.589 microns) is used to insulate the film from above. Newton rings moving towards the centre are formed and show the shape of the air gap between the film and the glass plate in the vicinity of the propagating front. A CCD camera coupled with image processing is used to count the number of rings at the centre. The reduction of the air interlayer is easily computed by using elementary optics laws. The corresponding time is measured for each sample. It reveals to be very reproducible for a given type of film (i.e. characterised by its thickness and its roughness).

EXPERIMENTAL RESULTS :

The key idea is to discriminate the effects of flexural rigidity and of roughness on air evacuation conducted in controlled squeezing conditions.

On the one hand, it is well-known that flexural rigidity is proportional to h^3, where h is the plastic film nominal thickness. On the other hand, the concept of "roughness" is somehow difficult to define, because it basically contains much information. For the sake of simplicity, it is useful to characterise "roughness" by one single parameter. It was found that classical parameters, such as : the "total roughness (R_t)", which represents the maximum peak-to-valley distance or the " average roughness (R_a)" which is some averaged value of the profile over a prescribed length of the sample are not adequate. A more sophisticated description was necessary. A parameter (R_h) corresponding to the value of the highest five peak-to-valley distances averaged over a given area of the sample was used.

Two sets of samples have been tested. The first one is composed of 3 PET films having the same nominal thickness (h = 12 microns) and different surface topographies (R_h = 1.5; 1.7; 1.9 microns). 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 microns) but two thickness values : 7 and 12 microns.

Each sample was submitted to several values of the sub-ambient pressure, for different values of the slit radius. In each case, the air layer thickness reduction (e_i - e_f) is much larger than the final thickness (e_f). Therefore, in which follows, the initial air layer (e_i) will be assimilated to the layer air reduction (e_i - e_f).

It has been plotted in figures 3 (i.e. 3.1, 3.2, 3.3) the air evacuation time values versus the squared values of the slit radii, for subambient pressure ranging from -92105 to -13158 Pa, referenced to ambient pressure. Each case (for instance 3.1) corresponds to a given value of R_h.

The corresponding results for the second set of samples have been plotted in figures 4 (i.e. 4.1 and 4.2).

Figures 5 (5.1 to 5.3) and 6 (6.1 and 6.2) represent the evacuation time values versus the subambient pressure values for different slit diameters and for the same two sets of film samples as in figures 3 and 4 respectively.

It can be observed in figures 3 and 4 that air evacuation time is proportional to the squared value of the slit radius (i.e. to the area of the facing surfaces), independently of the film nominal thickness (h) and surface roughness (R_h). This result is consistent with a simple model based on the squeeze flow between two smooth surfaces, the lower one being rigid and the upper other one being assumed perfectly flexible [2]. However the latter model predicts that air evacuation time is inversely proportional to the applied subambient pressure, which is clearly not the case in our experimental results : see figures 5 and 6. Therefore, an improved version of the model is described in which follows.

A SIMPLE THEORETICAL MODEL :

A simple model of the air flow corresponding to the experimental test is proposed.

The flow is assimilated to a squeeze flow due to an applied pressure P_a equal to the absolute value of the sub-ambient pressure.

The flow is considered to be quasistatic, inertialess and the fluid (air) incompressible [7].

As shown in figure 2, the flow domain is divided into two zones by the propagating front (as defined by $r = R(t)$) :

1)- Upstream the front (i.e. in the zone defined by : $0 < r < R(t)$), the pressure is equal to P_a and the air layer thickness remains constant (e_i). As the front moves towards the centre, the volume reduction of this zone is equal to :

$$\frac{dV}{dt} = 2\pi\,(e_i - e_f)\,R(t)\,\frac{dR(t)}{dt} \tag{1}$$

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. Additional experiments [2], have shown that the ultimate mean value of the air layer squeezed between a smooth surface and a rough film depends on the applied static pressure : $e_f(P_a)$.

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

$$Qv = -\frac{\pi}{6\mu}\frac{\partial p}{\partial r}\,r\,e_f^{\,3} \tag{2}$$

this value being independent of the current radius r, one gets :

$$r\,\frac{\partial p}{\partial r} = A(t) \tag{3}$$

Where A(t) is some function to be determined by the boundary conditions:

$$p\,(r = R_0) = P_1 \qquad \text{ambient pressure} \tag{4}$$
$$p\,(r = R(t)) = P_a \tag{5}$$

Hence :

$$p(r,t) = \frac{P_a - P_1}{\mathrm{Ln}\,\dfrac{R(t)}{R_0}}\,\mathrm{Ln}\,\frac{r}{R_o} + P_1 \tag{6}$$

since the ambient pressure is taken as a reference, P_1 is set equal to zero. The following expression is deduced for the flow rate :

$$Qv = -\frac{\pi}{6\mu}\,\frac{P_a}{\mathrm{Ln}\,\dfrac{R(t)}{R_o}}\,e_f^{\,3} \tag{7}$$

Now, this flow rate is equal to the volume reduction of the upstream zone , equation (1), which leads to :

$$-(e_i - e_f)\,R(t)\,\mathrm{Ln}\,\frac{R(t)}{R_0}\,\frac{d}{dt}R(t) \;=\; P_a\,\frac{e_f^{\,3}(P_a)}{12\,\mu} \tag{8}$$

This ordinary differential equation is integrated analytically, the initial conditions being :

$$R\,(t = 0) = R_0 \tag{9}$$

Hence:

$$(e_i - e_f)\left[\frac{R_o^{\,2}}{4} - \frac{R^2(t)}{4}\left(2\,\mathrm{Ln}\,\frac{R(t)}{R_o} - 1\right)\right] \;=\; P_a\,\frac{e_f^3}{12\,\mu}\,t \tag{10}$$

The duration of air evacuation t_f corresponds to the time for which $R(t) = 0$, which leads to :

$$\boxed{t_f \;=\; 3\,\frac{e_i - e_f(P_a)}{e_f^{\,3}(P_a)}\,R_0^{\,2}\,\frac{\mu}{P_a}} \tag{11}$$

It is immediately seen that t_f is proportional to the squared value of the slit diameter as predicted by the experiments. The dependence on the applied pressure is more complicated, and depends on the form of function $e_f\,(P_a)$.

Experiments reported in [3] showed that the following empirical relationship holds :

$$e_f(P_a) \;=\; (e_f)_0\,e^{-\sqrt{\frac{Pa}{P0}}} \tag{12}$$

Where P_o and $(e_f)_0$ are parameters depending on both film roughness and thickness. Parameter $(e_f)_0$ can be interpreted as the asymptotic limit, when $t\to\infty$, of the air layer thickness separating the substrate and the film if no additional pressure is applied ($P_a = 0$ referenced to atmospheric pressure). In which follows, it is assumed that $(e_f)_0$ can be assimilated to R_h (as defined before). Hence :

$$e_f(P_a) \;=\; R_h\,e^{-\sqrt{\frac{Pa}{P0}}} \tag{13}$$

Where P_0 depends on film thickness and roughness.

Expression (11) finally becomes :

$$\boxed{t_f \;=\; 3\,\frac{e_i - R_h\,e^{-\sqrt{\frac{P_a}{P_o}}}}{R_h^{\,3}\,e^{-3\sqrt{\frac{Pa}{Po}}}}\,R_0^{\,2}\,\frac{\mu}{P_a}} \tag{14}$$

COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL RESULTS:

Formula (14) is used to fit the experimental data shown in figures 5 and 6. Parameter R_h is determined for each film (roughness measurement); parameters μ, R_0 and P_a are prescribed in each test whereas e_i and t_f are measured. The only "free" parameter is P_0, which surely depends on both film roughness and flexural rigidity.

For each experiment point, P_0 is computed, then averaged over all the experimental points. Hence, for a given film, a unique value of parameter P_0 is introduced into formula (14) to draw curves t_f versus P_a for various values of R_0. In figures 5 and 6, the continuous lines correspond to these "theoretical" curves.

Fairly good agreement can be observed. Due to the lack of experimental data, only a tendency can be proposed for the dependence of parameter P_0 on R_h (roughness) and h (thickness) respectively :

- when h increases P_0 increases ;
- P_0 is not a monotonous function of R_h which tends to prove that additional parameters are necessary to describe the surface topography (density of peaks ? ...)

CONCLUSION :

The test which has been developed can be considered as a way to magnify the effect of surface roughness, and hence a way to quantify a sort of " dynamic roughness" associated with the "evacuation time".

Future developments would consist in :

1 - Investigating more in depth the relationship between parameter P_0 on the one hand and parameters characteristic of the film flexural rigidity and roughness respectively on the other.

2 - Introducing this concept of a "dynamic roughness" into the models of film winding.

3 - Optimizing the surface topography profiles in terms of parameters t_f, through parameters more closely connected to the topography description (for instance R_h,P_0...).

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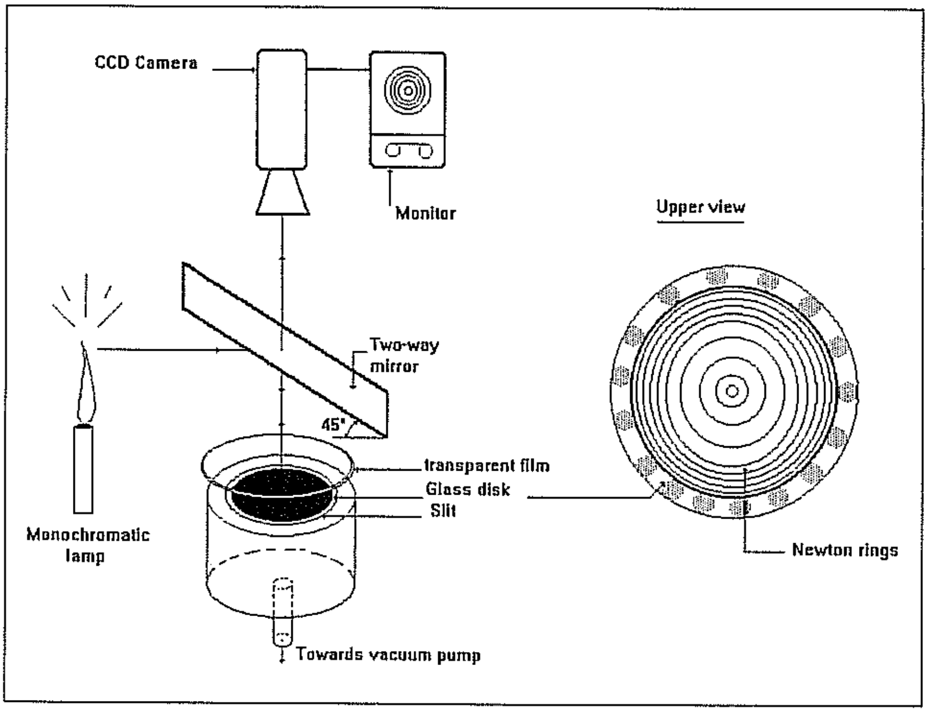

Fig 1 Sketch of the experimental set-up.

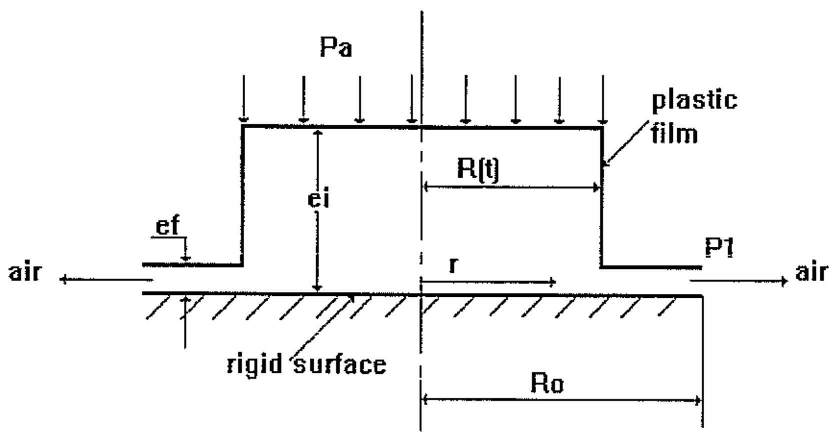

Fig. 2 Model features

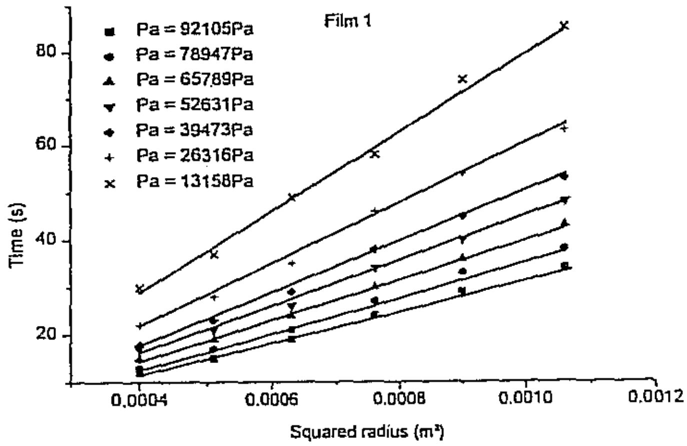

Fig. 3.1 : Film 1 (Rh = 1.9 µm, ei # = 70 µm)

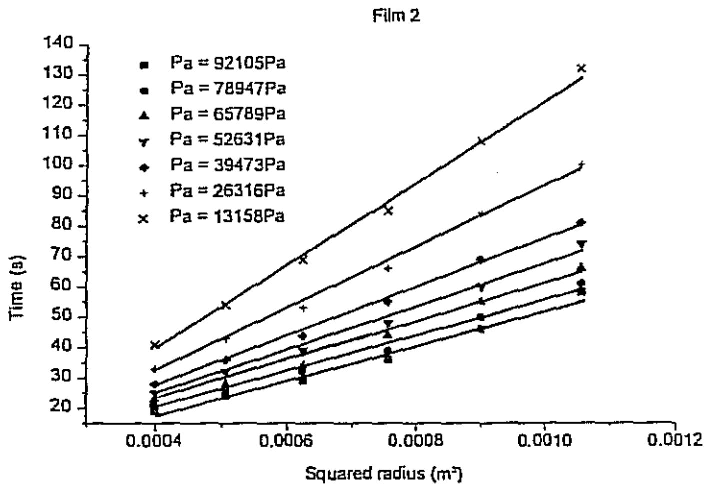

Fig. 3.2 : Film 2 (Rh = 1.7 µm, ei # 60 µm)

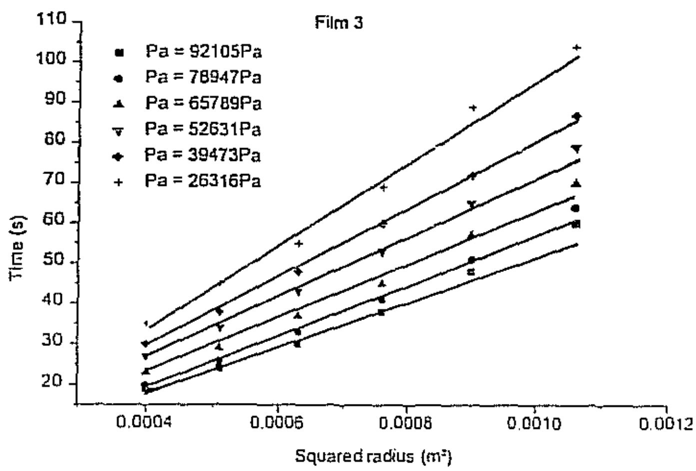

Fig. 3.3 : Film 3 (Rh = 1.5 µm, ei # 74 µm)

Fig.3 : air evacuation time versus the squared values of the slit radius
(first set of film samples : h = 12 µm)

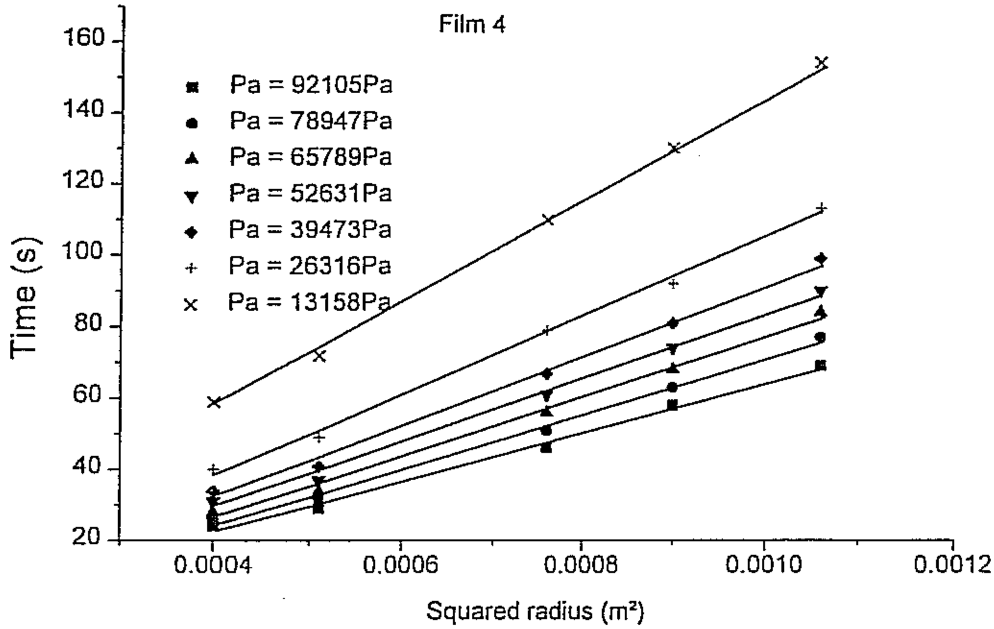

Fig.4.1 : Film 4 (h = 7 μm, ei # 70 μm)

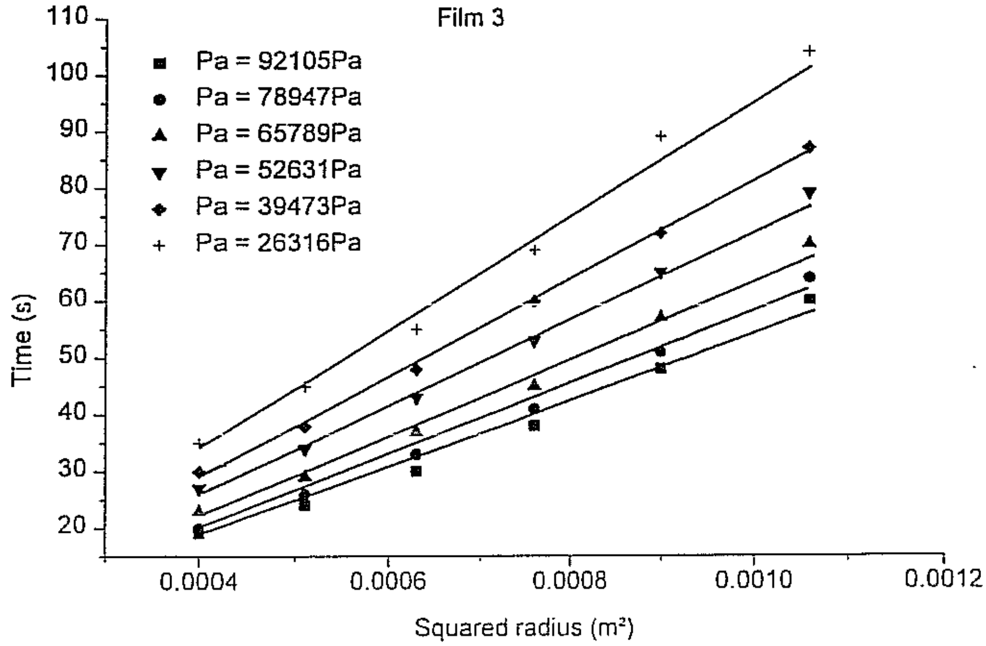

Fig. 4.2 : Film 3 (h = 12 μm, ei # 74 μm)

Fig.4 : air evacuation time versus the squared values of the slit radius (second set of film samples : R_h = 1.5 μm)

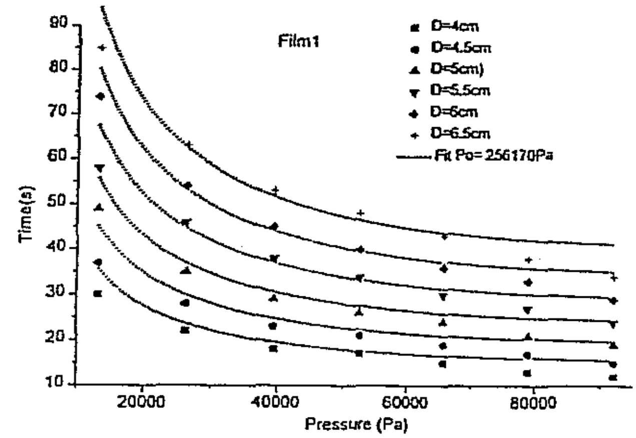

Fig. 5.1 : Film 1 (Rh = 1.9 μm, ei # 70 μm)

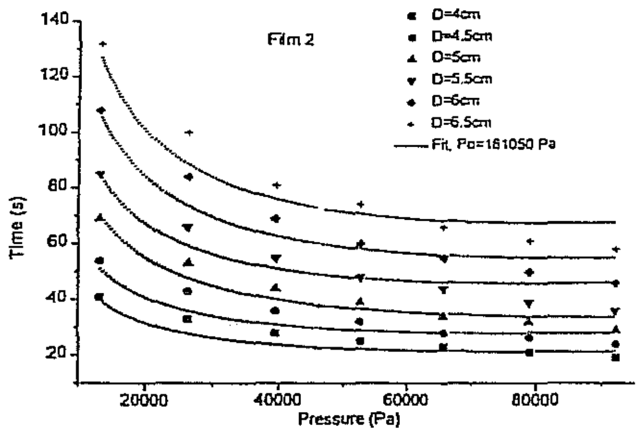

Fig. 5.2 : Film 2 (Rh = 1.7 μm, ei # 60 μm)

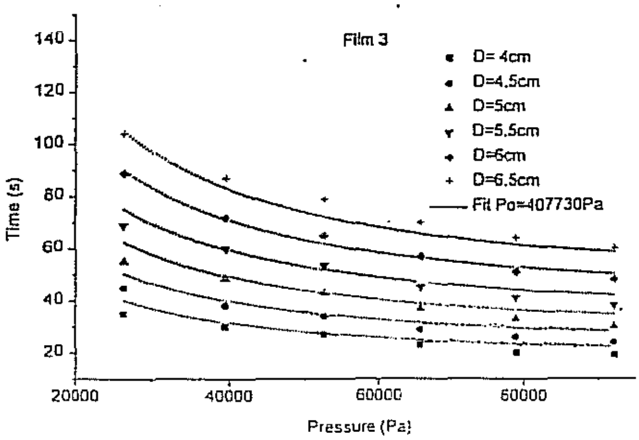

Fig : 5.3 : Film 3 (Rh=1.5 μm, ei # 74 μm)

Fig.5 : air evacuation time versus the subambient pressure absolute value for several slit diameterrs (first set of film samples : h = 12 μm)

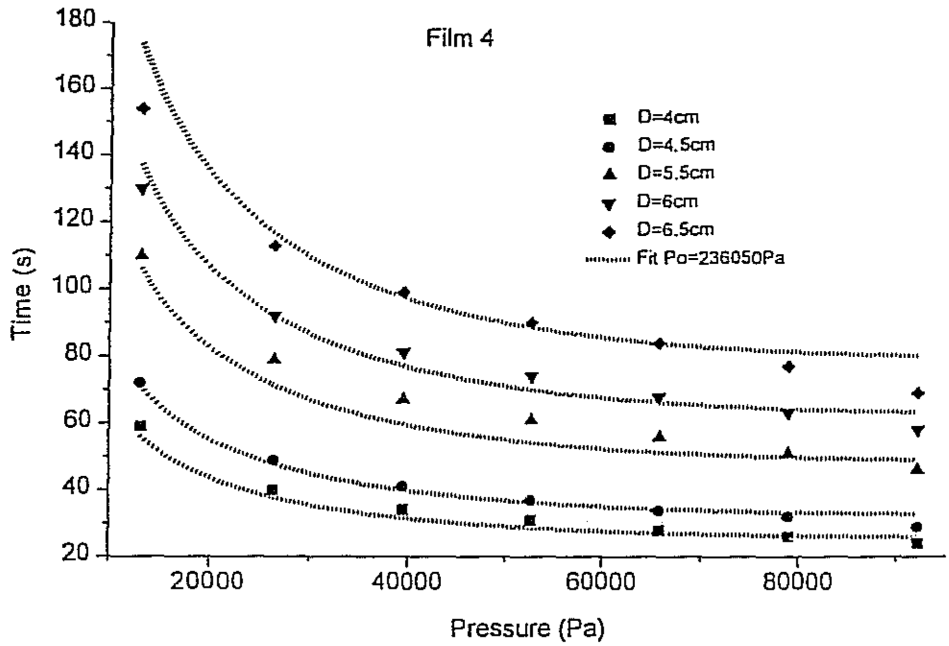

Fig. 6.1 : Film 4 (h = 7 μm, ei # 70 μm)

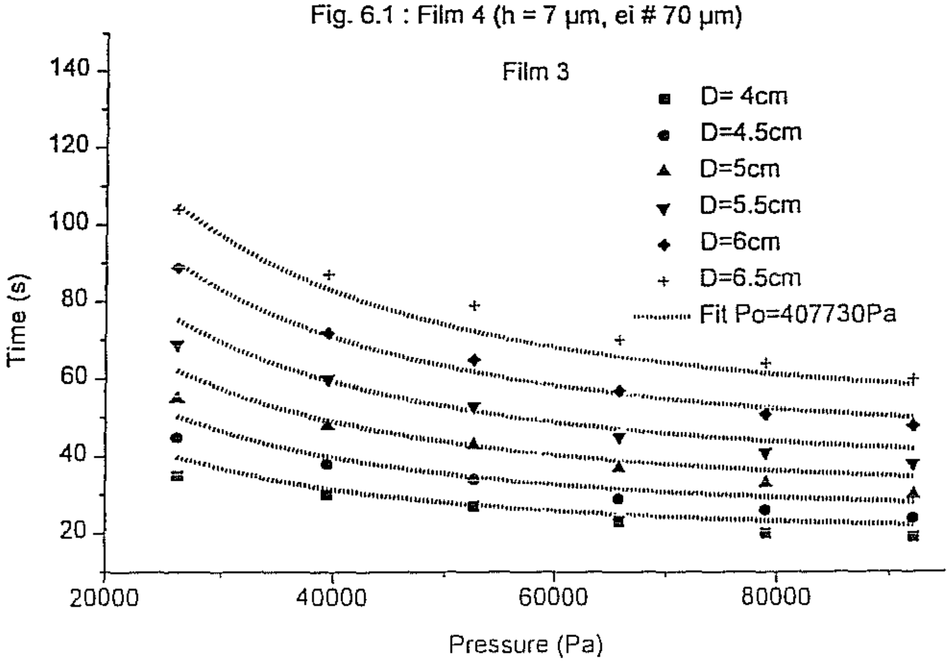

Fig : 6.2 : Film 3 (h=12 μm, ei # 74 μm)

Fig.6 : air evacuation time versus the subambient pressure absolute value for several slit diameterrs (second set of film samples : $R_h = 1.5\ \mu m$)

Question - What technique did you use to measure the surface roughness of the films and how important is it to know the pressure at the edge of the slip and how did you measure that because it may not be the same as possibly your vacuum pump pressure?

Answer – The surface topography is given by optical interferometry. For question 2, we impose a given amount of pressure to the vacuum pump which is connected to the slip around the disc. It involves between 0 and –12%

Question - Can you speculate on optimum topography would be for winding if you could choose an optimum topography for winding.

Answer - We can say for the equilibrium of the plastic film on that the time can be optimized. My feeling would be that the optimum time requested for the air initial layer being entrapped to be evacuated after a few revolutions of the new roll. So the adequate surface topography would be that which would lead to innate final equilibrium thickness under the given pressure if the film has time to evacuate the layer then it is fine. Otherwise you don't have an equilibrium after you have air exhaust after winding.

Thank you.