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Analysis of the Bowing Phenomenon in the Tenter Process of Biaxially Oriented Polypropylene Film

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Abstract−In order to understand the bowing phenomenon in the tentering process of biaxially oriented polypropylene film, a simple mathematical model has been developed by considering the overall continuity equation and relevant momentum equations. The model has been solved analytically by employing a lubrication approximation for an isothermal, Newtonian fluid with variant densities depending upon the external deformation. Both velocity and stress profiles in the tenter process and also birefringence and extinction angle profiles can be calculated accordingly. Geometrical bowing is strongly dependent upon the degree of volume change during extensional deformation. Theoretical prediction is compared with experimental birefringence data with two types of PP resins and two different operation conditions to give us excellent agreement. It can be said that this model is applicable to other biaxially oriented film processes such as PET.

Key words: Polypropylene Film, Tenter Process, Bowing Phenomenon, Birefringence

INTRODUCTION

Biaxially oriented polypropylene film is widely used not only for food packaging but also for general packaging or lamination of other materials in various applications. There are two distinct ways of producing such oriented film: double blown process or tenter process. The latter is preferred because of its high productivity. In the tenter process, polymer film is first stretched 4-6 times along machine direction at lower temperature than its melting, and then preheating, transverse stretching, and thermosetting processes follow in the transverse stretching zone. In this process, one of the major problems is that it may induce mechanical or geometrical anisotropy along the transverse direction, which may cause some problems in printing or curls in the bagging process for packaging. It is usually called a “geometrical bowing” phenomenon.

Even though it has been quite a long time since this kind of OPP film was first introduced on the market not only with PP but also PET and others, there is still no theoretical model to predict geometrical bowing properly. Much research has been focussed on the PET film, which is mainly used for the base film of audio and video tapes. Kase et al. [Kase and Kawano, 1984; Kase and Inoue, 1986] have reported that it is possible to obtain an analytical or numerical solution for the biaxially extended process, but it is not enough to predict any bowing phenomenon properly.

There are several reports on the experimental observation of optical anisotropy of BOPET film [Yamada and Nonomura, 1994], but it is rare to consider birefringence measurement on the BOPP film. There are also some domestic patents for reducing the bowing phenomenon by introducing chill roll between the stretching zone and thermosetting zone, or using a lower stretching temperature as reported in several Korean patents.

In this study, we have tried to set up a proper mathematical model by considering the volume change during the stretching process in order to predict the geometrical bowing and thereafter to predict any optical anisotropy of the film from stress profiles obtained theoretically. Industrial scale experiments have been performed along with these theoretical analysis in order to compare not only the geometrical bowing but also birefringence data with theoretical results.

THEORETICAL MODEL

Theoretical analysis is confined to the transverse stretching zone, and an isothermal Newtonian fluid is adopted for simplicity. As shown in Fig. 1, the velocity in x direction and y direction are assumed independent of thickness direction, and inertia force is neglected. The governing equations in the region of interest are given simply by Eq. (1)-(3).

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

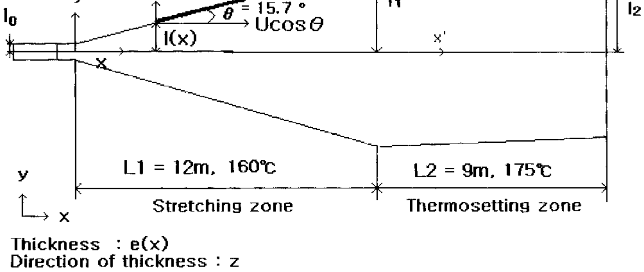

Fig. 1. Schematic illustration for modelling the tenter process of BOPP film.

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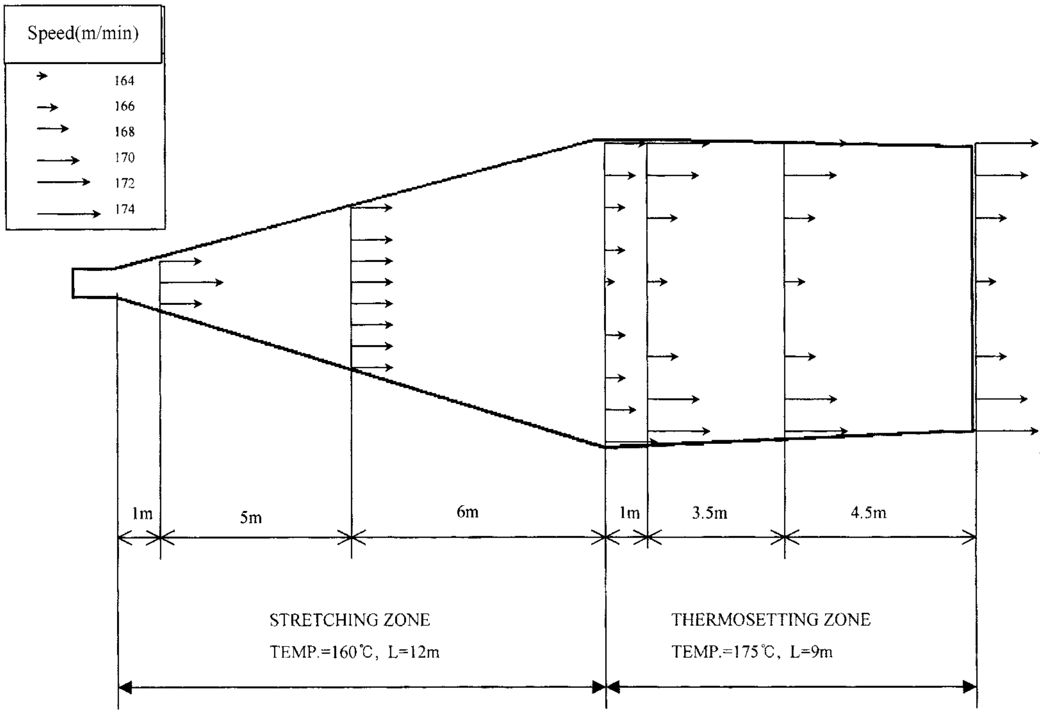

Fig. 2. Computed velocity profile within BOPP film during tenter process.

$$-\frac{\partial p}{\partial x}+\mu\left[\frac{\partial^2 u}{\partial y^2}\right]=0 \tag{2}$$

$$-\frac{\partial p}{\partial y}=-\frac{\partial p}{\partial z}=0 \tag{3}$$

Boundary conditions at the center and the edge are simply given by Eqs. (4)-(5).

$$\text{at } y=0,\ \frac{du}{dy}=0 \tag{4}$$

$$\text{at } y=l(x),\ u=U\cos\theta \tag{5}$$

where $l(x)$ varies with x direction and preset angle θ.

It is well known that in the limited angle, lubrication approximation is possible as suggested in the literature [Kwon and Park, 1989]. Because of thin thickness of the film, it may be possible to use such a lubrication approximation in the entire region of thickness. Then the velocity component can be obtained by

$$u(x,y)=U\cos\theta+\frac{1}{2\mu}(y^2-l^2)\frac{dp}{dx} \tag{6}$$

At steady state, the mass flow rate is kept constant along any position so that pressure-dependent terms can be eliminated.

$$u(x,y)=U\cos\theta+\frac{3}{2}U\left(\frac{y^2}{l^2}-1\right)\left(\cos\theta-\frac{e_0 l_0}{e\,l}\right) \tag{7}$$

What we need to know here is the thickness reduction along the stretching direction. It is quite natural to assume that thickness reduction is governed by the nature of extensional flow and physical properties of polymer melts such as crystallinity and volume change during deformation. Here we would like to assume that the following rule is valid:

$$\frac{e}{e_0}=\left(\frac{l_0}{l}\right)^n;\ n=2\nu+\beta \tag{8}$$

ν is poisson ratio of PP and β is the volume shrinkage index with elongation.

Then it is possible to obtain the velocity profile at any position in (9)-(10) and results can be shown in Fig. 2.

$$u(x,y)=U\cos\theta+\frac{3}{2}U\left[\frac{y^2}{l^2}-1\right]\left[\cos\theta-\left(\frac{l_0}{l}\right)^{1-n}\right] \tag{9}$$

$$u(x,y)=U\cos\theta'+\frac{3}{2}U\left[\frac{y'^2}{l'^2}-1\right]\left[\cos\theta'-\left(\frac{l_0}{l'}\right)^{1-n}\right] \tag{10}$$

Eq. (9) is for the stretching zone and Eq. (10) for thermosetting zone can be obtained similarly.

1. Geometrical Bowing

Once the velocity profiles are obtained, the geometrical bowing can be calculated as a sum of two regions. The final result is given in Eq. (11).

$$\frac{\delta}{D'l_0}=\left[\frac{3L}{2l_0D'}\left(1-\frac{1}{n\cos\theta}\frac{D^n-1}{D-1}\right)\right]+\left[\frac{3L'}{2l_0D'}\left(1-\frac{1}{n\cos\theta'}\frac{D^n-D'^n}{D-D'}\right)\right][1-Y^2] \tag{11}$$

Here we can say that the geometrical bowing is depending not only on the geometrical structure and also n value of the PP.

2. Characteristic Bowing

Even though the geometrical bowing can be calculated and compared with the experimental results, the real interests are in the anisotropy in the properties of the final film. If we apply the stress optical rule, it is possible to predict the birefringence and orientation angle of the final film, where the orientation angle starts from zero when the orientation is parallel to x-axis. The details can be found in the literature [Kim, 1999].

$$\tan 2\chi = \frac{HY}{A' - GY^2} \tag{12}$$

$$\Delta n = C\frac{3\mu U}{l}\sqrt{A'^2 + (H^2 - 2A'G)Y^2 + G^2Y^4} \tag{13}$$

$$A' = A - (2-n)t\frac{E}{2} - (2-n')t'\frac{E'}{2} \tag{14}$$

$$G = \frac{(2-n)t[2c - (3-n)E]}{2(1-n)} \tag{15}$$

$$H = 2(c-E) + 2(c'-E') \tag{16}$$

where $c = \cos\theta$, $t = \tan\theta$, $E = \left(\frac{l_0}{l}\right)^n$, $E' = \left(\frac{l_0}{l'}\right)^{n'}$.

A is a dimensionless parameter concerning the residual stress from the machine directional stretching before the film enters the tenter. Therefore, if machine directional stretching is dominant, the orientation angle would start from 0° to 45°.

Now we have successfully developed a mathematical model to determine not only the geometrical bowing but also birefringence and extinction angle. Before comparing the experimental results with our model, it would be worthwhile to see the parameter sensitivity on these predictions.

3. Parameter Sensitivity

Stretching angle in the tenter process is one of the most important factors governing the anisotropic properties of the film. Fig. 3 shows the birefringence and extinction angle predicted when the angle theta is varied. As expected, it is possible to have a reversed pattern of birefringence according to the angle. The reason is that in this case the MD stretching is fixed but the transverse directional stress can be varied with the change of this angle.

Fig. 4 demonstrates that if we adjust the dimensionless parameter A, we can obtain two different birefringences and the corresponding extinction angle pattern can be obtained. In short, the balance between the stress in MD and TD will be responsible for the final anisotropic properties after all. For A=0.284, it would be near transition from the transverse directional orientation to the machine directional orientation, so that it generates a little artifact far downstream.

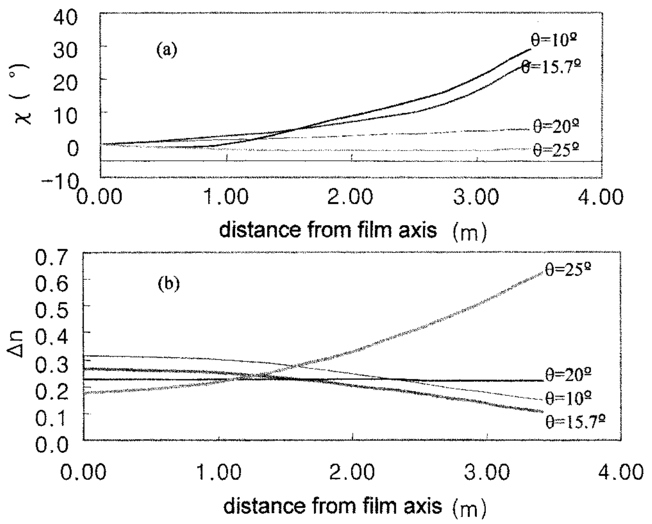

Fig. 3. Extinction angle and birefringence patterns with varying stretching angle (a) extinction angle, (b) birefringence.

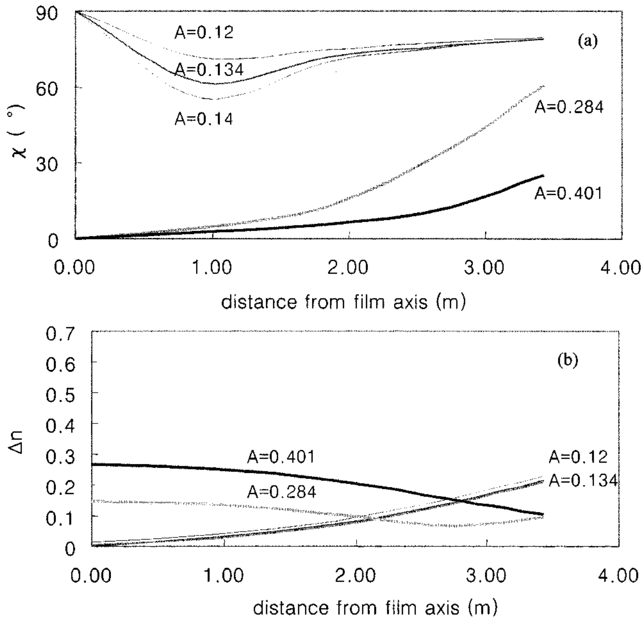

Fig. 4. Extinction angle and birefringence patterns with varying A (a) extinction angle, (b) birefringence.

EXPERIMENTS

In order to demonstrate the validity of our model, we tried to make PP film on a pilot scale. The detailed experimental procedure can be found elsewhere [Kim, 1999].

Once the film was obtained, several parts of the film were cut from the whole film along the transverse direction and then the birefringence and extinction angle were measured in solid state by using the optical apparatus built in the laboratory. Details of optical arrangement and measurement procedure can be found in Kim's thesis

RESULTS AND DISCUSSION

Table 1 shows the operating conditions for making the film. Stan-

Table 1. Two processing conditions for producing BOPP film

Items	Unit	Standard	Test
MD Stretching	times	5.5	5.0
l_0	m	0.375	0.373
l(L)	m	3.75	3.715
l'	m	3.425	3.420
D	times	10	9.96
D'	times	9.13	9.17
θ	deg	15.7	15.56
θ'	deg	2.03	1.41
δ	m	0.325	-

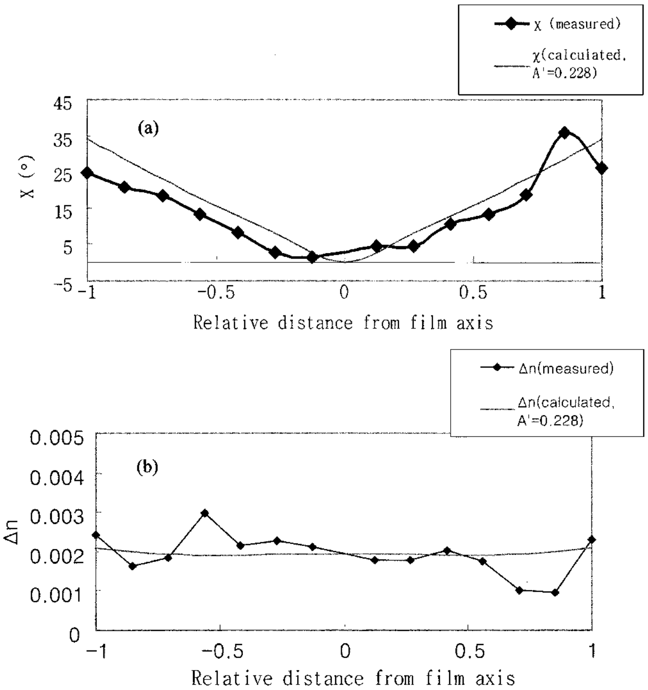

Fig. 5. Measured and calculated extinction angle and birefringence patterns at standard condition (A'=0.228 and n=0.965) (a) extinction angle, (b) birefringence.

dard conditions and the test one are listed here. Measured angle and birefringence data were fitted by adjusting two parameters, n and A', at standard condition as shown in Fig. 5. The volume shrinkage index n was chosen as 0.965 by comparing the total geometrical bowing at the center of the film. In order to obtain the extinction

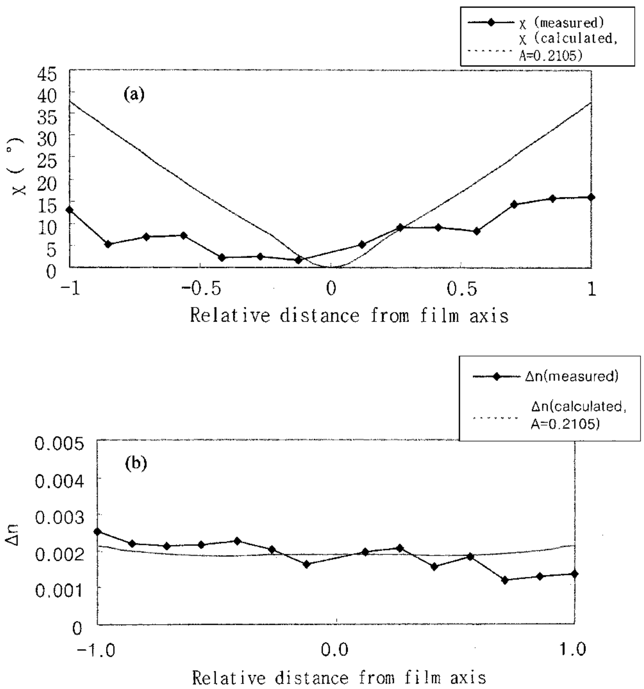

Fig. 6. Measured and calculated extinction angle and birefringence patterns at test condition (A'=0.2105 and n=0.965) (a) extinction angle, (b) birefringence.

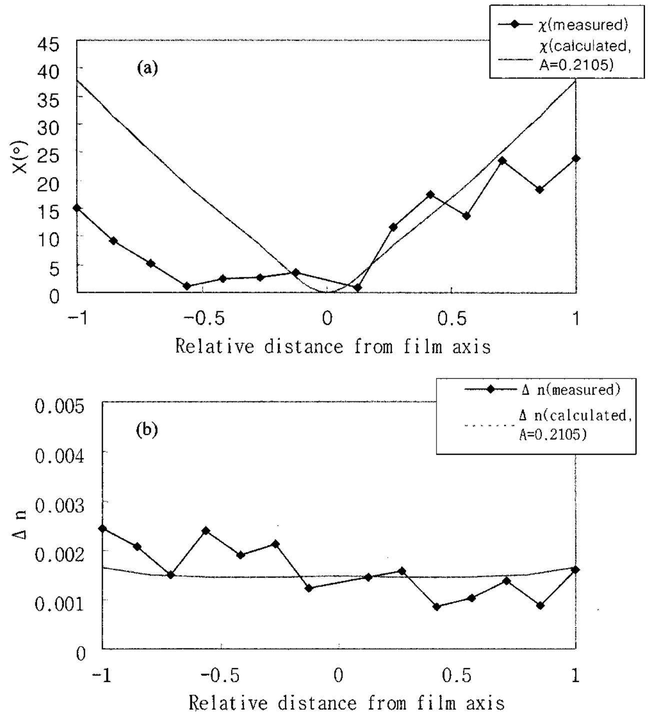

Fig. 7. Measured and calculated extinction angle and birefringence patterns at test condition with different resin (A'=0.2105 and n=0.97) (a) extinction angle, (b) birefringence.

angle and birefringence as a function of relative position from the center, the parameter A' was chosen 0.228. As one can see in the Fig. 5(a) and (b), not only the extinction angle but also birefringence were predicted quite well. In case of birefringence, a stress-optical constant is needed for the absolute scale [Park et al., 1989; Kwon et al., 1999]. Fig. 6 shows the case of different stretching condition in the machine directional stretching zone. Because of somewhat less stretching compared with the standard case, extinction angle and birefringence were observed smaller than before. These trends can be predicted with same parameters except a little smaller value of A'=0.211, which is natural if we consider the physical meaning of A', but extinction angles were a little overestimated. Fig. 7 is for the different resin with test condition so that we fixed A'=0.211 but n' was chosen as 0.97, which would be a parameter depending on the material. Both birefringence and extinction angle pattern can be predicted pretty well.

CONCLUSIONS

It is possible to develop a new mathematical model to predict not only the geometrical bowing but also birefringence pattern in BOPP process by considering the volume change during stretching deformation. As expected, the final birefringence pattern is govened by both MD stretching and TD stretching. The theoretical prediction agrees quite well with real industrial process results, so that it may be concluded that it is possible to apply this kind of model to similar processes with different polymers or different geometries. BOPET film process will be considered next with the same line.

NOMENCLATURE

A, A' : dimensionless parameter related with the residual stress in machine directional stretching zone
c, c' : cosθ, cosθ'
D : l_1/l_0, ratio of widths in the stretching zone
D' : l_2/l_1, ratio of widths in the thermosetting zone
E, E' : dimensionless quantities defined in the text
G : dimensionless quantity defined in the text
H : dimesionless quantity defined in the text
e(x) : thickness of the film
e_0 : initial thickness of the film
$l(x)$: width of the film in stretching zone
$l'(x)$: width of the film in thermosetting zone
l_0 : initial width of the film
L : total length of the stretching zone
L' : total length of the thermosetting zone
n, n' : the volume change index during stretching and thermosetting
p : pressure
t : tanθ
u : x-directional velocity
U : constant velocity of tenter
v : y-directional velocity
x : x coordinate
y : y coordinate
Y : dimensionless y cordinate
z : z coordinate

Greek Letters

β : volume shringage index during elongation
δ : geometrical bowing at the center of the film
θ, θ' : angles of the stretching zone and thermosetting zone
μ : viscosity
ν : Poisson ratio
χ : extinction angle or orientation angle

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