Attempt to Reduce Bowing Distortion in Tentering of Film

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SYNOPSIS

In order to solve the problem of the bowing phenomenon in the tentering process of film, the stretching and thermosetting conditions were examined with a poly(ethylene terephthalate) film. The simulated and experimental results confirmed that decreasing or preventing the transmission to the next thermosetting zone of the longitudinal force generated by the transverse stretching, and then restretching the film in the thermosetting zone, effectively reduces the bowing distortion. The following effects were observed: (1) Once the film is cooled after stretching it in a tenter, the different patterns of its deformation behavior can be obtained. The bowing distortion changes remarkably with the temperature of film and the length of the cooling zone. (2) When the temperature of the cooling zone is not higher than the glass transition point, the effect of the cooling zone in reducing the bowing distortion is at its maximum. The longer the cooling zone is, the less the bowing distortion becomes. However, it becomes almost constant when the length of the cooling zone is at least twice the width of the film. (3) When the cooling zone is set up between the stretching and thermosetting zones, the bowing distortion is almost independent of the thermosetting temperature. (4) Relaxation and restretching in the transverse direction in the thermosetting zone influence the bowing distortion: greater relaxation results in greater bowing distortion and greater restretching results in the less bowing distortion.

INTRODUCTION

Very few studies are available on the film deformation behavior in a tenter, and the tenter has usually been dealt with as a "black box" defying analysis because of its high cost for an experiment and because of the complexity of film behavior in it.

In conventional methods for the manufacture of biaxially oriented film, the physical properties in the transverse direction of the obtained films are generally nonuniform. This nonuniformity of films arises with particular frequency in transverse drawing processes. In transverse drawing processes, the film is drawn by holding both side margins of the film in a tenter with a clasping device such as clips and by imparting tension in the transverse direction by successively shifting the clasping device. Ordinarily, this drawing process is followed by thermosetting, thereby obtaining the desired transversely drawn film. In this process, the side margins of the film are securely constrained by the clasping device, but in the central portion of the film, the effect of the clasping device is relatively small and the constraining force is correspondingly weak. Consequently, when a long film is subjected to transverse drawing by being passed through a tenter, the central portion of the film is affected by the stress in the longitudinal direction (machine direction) generated by the transverse drawing and longitudinal movement of the film, and by the contraction stress generated by the thermosetting process. For example, when drawing and thermosetting are performed consecutively in the same tenter, if straight lines are drawn on the surface of the film in the transverse direction prior to entering the tenter, then these straight lines are deformed as follows. First, in the area where the drawing process commences, the lines are deformed into a convex shape in the direction of advance of the film; then, in the area immediately preceding the completion of the drawing process,

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the deformed lines are restored to their original shape, and immediately after the completion of drawing, the lines are then deformed into a concave shape. Furthermore, this concave deformation reaches its maximum at the beginning of the thermosetting process, and thereafter these curves pass through the tenter without undergoing any further deformation. Hence, the concave deformation remains after the film has emerged from the tenter. This phenomenon is known as *bowing*.

The bowing phenomenon in the tenter is the major cause of the nonuniformity of film characteristics in the transverse direction. The bowing phenomenon causes the difference between the direction of orientation axis at the center of film width and that at the margins, so that it brings the anisotropy of film characteristics such as heat shrinkage, the refractive index, and mechanical properties. For example, the bowing phenomenon causes a lowering of magnetic recording characteristics of the base film for floppy disk use, which requires the isotropy in a plane of film properties, an aberration of printing in the printing and laminating processes and a curl in the bagging process for package use.

Studies on the bowing phenomenon have been published by Kase et al.[1-4] and Sakamoto.[5,6] Kase et al. have theoretically analyzed the deformation behavior of thin uneven rubber film in the tenter process with a finite difference method (FDM). Sakamoto has reported on the theoretical analysis of an ellipsoidal refractive index as an optical anisotropy of poly(ethylene terephthalate) (PET) film due to the bowing phenomenon. Their attempts have not been confirmed experimentally but have only been predicted theoretically.

Previous studies by the authors[7,8] were concerned with observations of the bowing phenomenon throughout the tenter process with a pilot plant and their theoretical analysis by a finite element method (FEM) with simple models as follows: The bowing phenomenon throughout a tenter was experimentally observed with a pilot plant of successive biaxial stretching. The observed results were compared with simulated ones in which the deformation behaviors of film in a tenter were predicted under the assumptions that the film is homogeneous isotropic, homogeneous anisotropic, heterogeneous isotropic, or heterogeneous anisotropic for a two-dimensional elastic body with an FEM. Comparatively good agreement between the simulated and observed results was obtained for a heterogeneous anisotropic elastic body with an initial mesh constructed with a plastic deformation part.

The prevention or suppression of the bowing phenomenon is a priority, but a study on this problem has not been published as far as the authors know. Attempts to reduce the bowing distortion in the tenter by experiments and by theoretical analyses are introduced in this study.

EXPERIMENTAL

Manufacturing Method of Biaxially Oriented Film

Biaxially oriented films with a tenter are generally manufactured by either the successive stretching method or the simultaneous method, where a film cast from a die is simultaneously stretched in both the longitudinal (machine direction: MD) and transverse directions (TD) with only a tenter. Representative successive methods are the MD–TD stretching method and the TD–MD stretching method. In the MD–TD stretching method, a cast film is first drawn in MD between rolls having different revolutions and then stretched in TD with a tenter. In contrast, the TD–MD method a cast film is stretched first in TD and then drawn in MD. In this study the successive MD–TD method shown in Figure 1 was used. The productivity of the MD–TD method is superior to that of other methods, and this method is a typical tenter process for the successive biaxial stretching of PET films. In Figure 1 the extruder (EXT) melts and extrudes the polymer. The extruded film is cast (CA) on a chill roll to form an amorphous sheet. The PET sheet is subsequently stretched in the machine direction (MD) to become a mono-oriented film. The film is then stretched in the transverse direction (TD) and thermoset (TS) to become a bi-oriented film. And finally trimmed (TM) and taken up on the film winder (FW).

In the TD and TS sections of the tenter process, films often develop the so-called bowing phenomenon. Bowing is a kind of uneven stretching in which a straight line drawn transversely on the film entering the tenter bends in a bow shape as the film goes through the TD and TS sections.

Experimental Conditions

The experiments[7] were made by use of a pilot plant shown in Figure 1, which applies a successive stretching (MD–TD) process as follows.

The PET polymer was melted and extruded on a chill roll, thus forming an amorphous film shape. Then while applying different rotational speeds of the rollers, the as-cast amorphous film was drawn longitudinally (in the machine direction) with in-

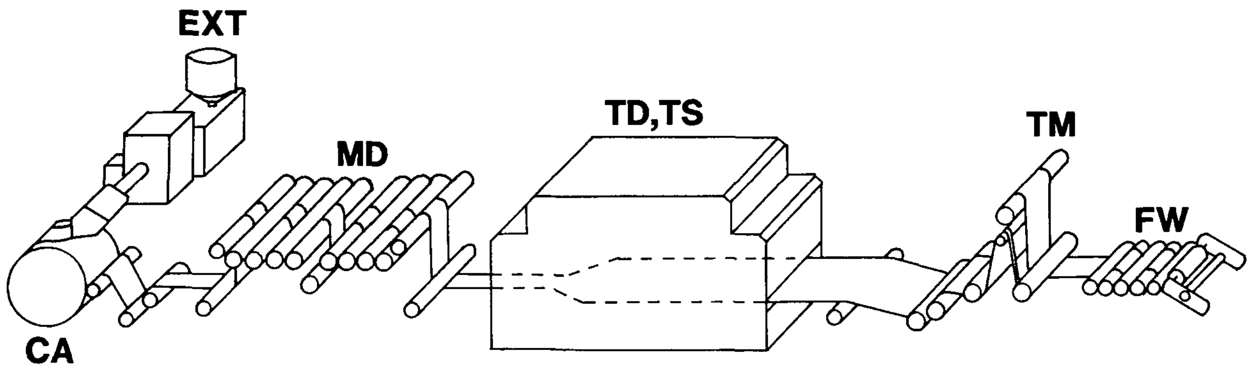

Figure 1 Schematic of representative film production plant.

frared heaters set at the drawing ratio of 3.6 magnification, the preheating roller temperature of 60°C, the drawing roller temperature of 90°C, and the cooling roller temperature of 40°C.

The uniaxially oriented PET film drawn in the machine direction was transversely stretched by the tenter while being held by the tenter clips at the extention ratio of 3.7 magnification, thus being formed into biaxially oriented film. Two kinds of tenters (TD-I, TD-II) were used to study the reduction of bowing distortion.

One (TD-I) is divided into six zones as shown in Figure 2. By use of the tenter, TD-I, experiments were made to examine the influence of the temperatures in the zones (zones 3–5) after the transverse stretching zone (zone 2). The TD-I consists of the preheating (zone 1), transverse stretching (zone 2), first cooling or thermosetting (zones 3–5), and second cooling zone (zone 6). The temperatures in zone 1 (preheating), zone 2 (transverse stretching), and zone 6 (second cooling) were fixed at 90°C, 100°C, and room temperature (ca. 30°C), respectively, as tabulated in Table I.

As shown in Figure 3 another tenter, TD-II is divided into four zones consisting of the preheating (zone 1), transverse stretching (zone 2), thermosetting (zone 3), and cooling zones (zone 4). The temperature of each zone was set at 100°C in the preheating zone, 100°C in the transverse stretching zone, 200°C in the thermosetting zone, and 100°C in the cooling zone, respectively, as tabulated in Table II. The bioriented film in zone 2 was relaxed transversely in zone 3. The ratio of transverse relaxation was −10 to 20% as shown in Figure 3, where

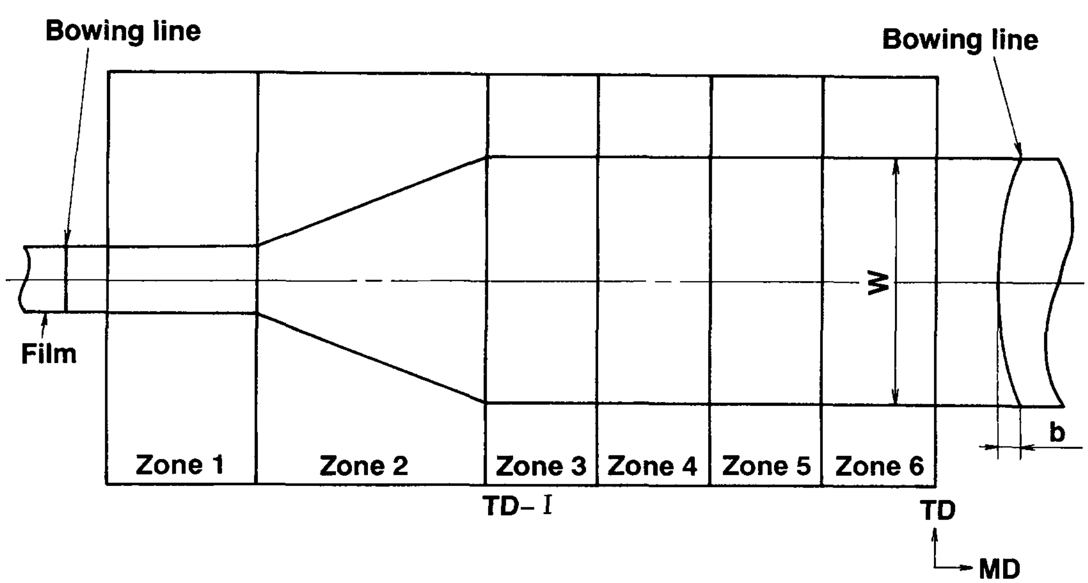

Figure 2 Six zones of tenter TD-I.

Table I Experimental Conditions and Results by TD-I

Case No.	Stretching Ratio in TD (—)	Temperature Zone 1 (°C)	Zone 2 (°C)	Zone 3 (°C)	Zone 4 (°C)	Zone 5 (°C)	Zone 6 (°C)	Relaxation Ratio in TD (%)	Cooling Zone Length, L_c (—)	Bowing Distortion, B (%)
Case 1	3.7	90	100	200	200	100	Cooling	0	0.0	7.8
Case 2	3.7	90	100	100	200	100	Cooling	0	1.19	7.8
Case 3	3.7	90	100	100	100	200	Cooling	0	2.37	6.5
Case 4	3.7	90	100	50	60	200	Cooling	0	2.42	2.8
Case 5	3.7	90	100	60	200	200	Cooling	0	1.20	3.8
Case 6	3.7	90	100	50	60	225	Cooling	0	2.40	2.8
Case 7	3.7	90	100	50	60	250	Cooling	0	2.40	2.8
Function of zone		Preheating	Stretching	Thermosetting or cooling			Cooling			

a negative value denotes transverse restretching and a positive one denotes transverse relaxation.

Definition of Bowing Distortion

The bowing phenomenon is a characteristic problem occurring in the stretching and thermosetting of film in a tenter process. Various methods of film manufacture using a tenter exist now, and the bowing phenomenon varies with the method used, so, the stretching method used in this study is made clear below.

In the manufacture of a biaxially oriented film with a tenter, the bowing phenomenon is inevitable. There are two kinds of bowing phenomenon. One is the geometrical bowing phenomenon in which a straight line drawn across the width of film at the entrance of a tenter changes into a bow shape at the exit of the tenter. The other is the characteristic bowing phenomenon in which the state of molecular orientation is different at each point across the width of film, and as a result the characteristics of film are not uniform over the film width. In this study the geometrical bowing phenomenon is dealt with under the assumption that it corresponds to the characteristic bowing phenomenon.

As shown in Figure 2 the distortion of bowing (B) is expressed as the ratio of the bow height b to the width W of film running out of the tenter, expressed by percentage; that is, $B = 100 \times b/w$ (%). When the film center lags behind the margins, the bow height b is considered positive. The bowing distortion b/W is measured at different positions in a tenter. And then the dimensionless length (L) in the tenter is defined as $L = l/l_T$, where l is the distance from the entrance of the tenter to a certain position in the machine direction and where l_T is the whole length of the tenter.

RESULTS AND DISCUSSION

Simulated Results

Assumptions for Mathematical Modeling of Bowing Phenomenon

The following assumptions for the modeling of bowing are obtained from the results observed.[7,8]

1. The longitudinal (machine direction) force, generated by transverse stretching and heat shrinkage in the tenter, causes the bowing phenomenon.

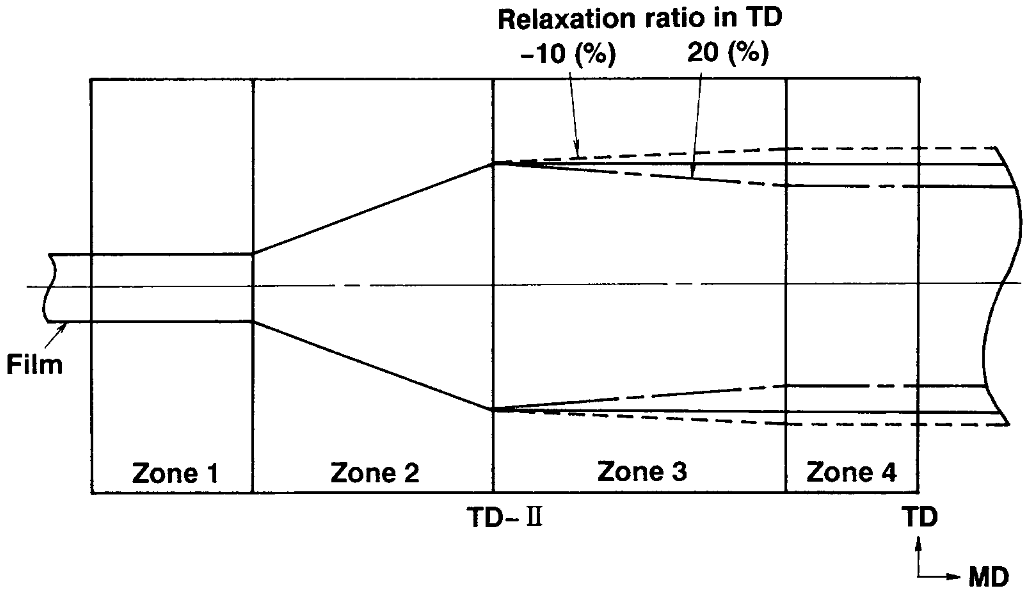

Figure 3 Four zones of tenter TD-II.

2. The bowing distortion reaches its maximum at the highest temperature in the tenter. This is due to the film being at its lowest degree of stiffness and at its highest degree of heat shrinkage. Thereafter the degree of bowing distortion does not change.

Preventing the transmission of the longitudinal force generated by transverse stretching from the transverse stretching zone to the thermosetting zone where the film has the lowest degree of stiffness because of the highest temperature is effective for reducing the bowing distortion. By installing a cooling zone between the transverse stretching zone and the thermosetting zone, the longitudinal force due to the transverse stretching is effectively reduced.

3. The bi-oriented film in the cooling zone between the transverse stretching and thermosetting zones is a homogeneous isotropic elastic body.

Predicted Cooling Zone Length Required for Minimum Transmission of Force

Figure 4 shows the relation between the dimensionless force ($F_c = f/f_0$) applied on the film and the dimensionless distance ($L_c = l_c/W$) from the start of the cooling zone, which is predicted by use of an FEM for an isotropic material with the elastic constants of $E_x = E_y = E_{45} = 6.0$ GPa, $\nu_{xy} = \nu_{yz} = 0.36$, $G_{xy} = 0.5E_x/(1 + \nu_{xy}) = 2.2$ GPa, where E_x and E_y are the Young's moduli, G_{xy} is the shear modulus (rigidity), ν_{xy} is the Poisson's ratio, and E_{45} is the Young's modulus in the direction at an angle of 45° to the machine (longitudinal) direction, and the

Table II Experimental Conditions and Results by TD-II[a]

Case No.	Stretching Ratio in TD (—)	Temperature Zone 1 (°C)	Zone 2 (°C)	Zone 3 (°C)	Zone 4 (°C)	Relaxation Ratio in TD (%)	Bowing Distortion, B (%)
Case 8	3.7	100	100	200	100	0	5.38
Case 9	3.7	100	100	200	100	−10	3.56
Case 10	3.7	100	100	200	100	20	8.18
Function of zone		Preheating	Stretching	Thermosetting	Cooling		

[a] Without first cooling zone ($L_c = 0$).

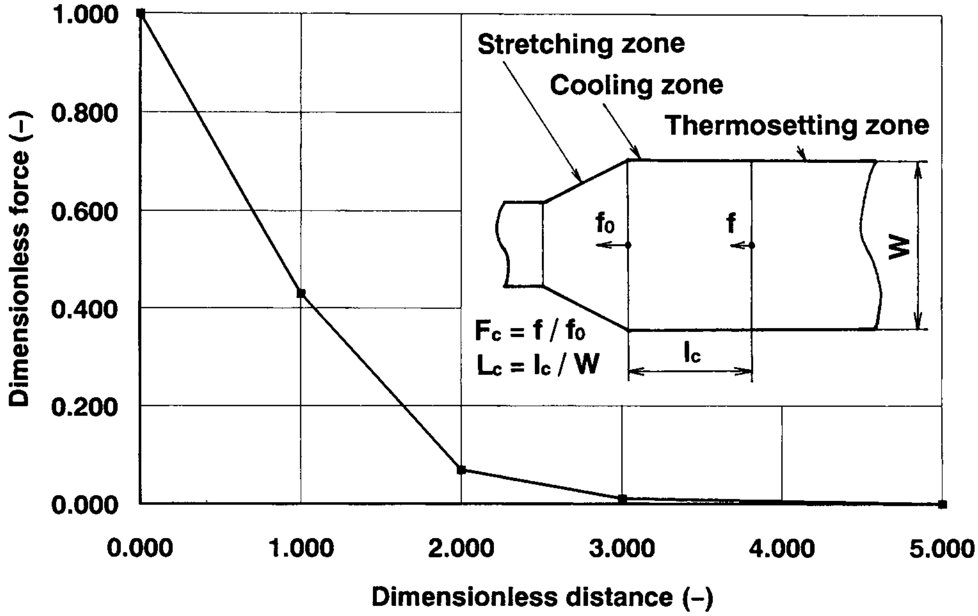

Figure 4 Prediction for influence of dimensionless distance on dimensionless force.

subscripts x and y stand for longitudinal (machine) direction and transverse direction, respectively.

It can be seen from Figure 4 that the force (F_c) applied on the film at the start of cooling zone is attenuated with distance (L_c). That is, F_c at $L_c = 1$ is 0.5 or less of the initial force and F_c at $L_c = 2$ is 0.1 or less. Furthermore F_c at $L_c = 3$ is negligibly small. These results suggest that the installation of a cooling zone with a length in excess of twice the width of film is effective for the reduction of the bowing distortion generated by transverse stretching. This is because the film has higher degree of stiffness in the cooling zone and is mostly deformed elastically but little plastically. As a result little bowing distortion occurs in the cooling zone.

Experimental Results

Experimental Errors

Errors made in drawing lines and measuring the bowing distortion, and due to the fluctuations of conditions such as temperatures, velocities, and characteristics of mono-oriented film before the transverse stretching, all affect the experimental data. But, since the standard deviations (σ_n) are 0.11 and 0.13% and the ranges (maximum–minimum) are 0.32 and 0.33% for the bowing distortion data at each of the five points after the tenter outlet for two experiments on different days under the same conditions, the measurement errors are assumed to be within 0.5%. Because the range can be generally expressed by about $3\sigma_n$, the above results are assumed to be consistent.

Observation of Bowing Distortions Throughout the Tenter Process

Many straight lines were drawn across the film at the entrance of the tenter. The movement of the tenter chains was forced to stop, and the film in the tenter was cooled as soon as possible by electric fans. Then the whole film in the tenter was sampled. The film in the tenter was now shaped into the tenter form, a rectangular-ramp-rectangular shape, according to the type of tenter, TD-I or TD-II, used. By comparing the distortions of the marked lines near the exit of the tenter before cooling with those after cooling, it was confirmed that the bowing distortions hardly changed during the cooling of the film. By use of film obtained by the above procedures, the changes in the bowing distortions throughout the whole tenter were measured.

Influence of First Cooling Zone Conditions (Length, Temperature) on Bowing Distortion

Table I shows the averages of five measurements of the bowing distortion after the outlet of the tenter TD-I under different temperatures in thermosetting. As typical examples, the changes of the bowing distortions B ($B = 100 \times b/W$) in the tenter are shown in Figure 5 for cases 1 to 4. In Figure 5 the position

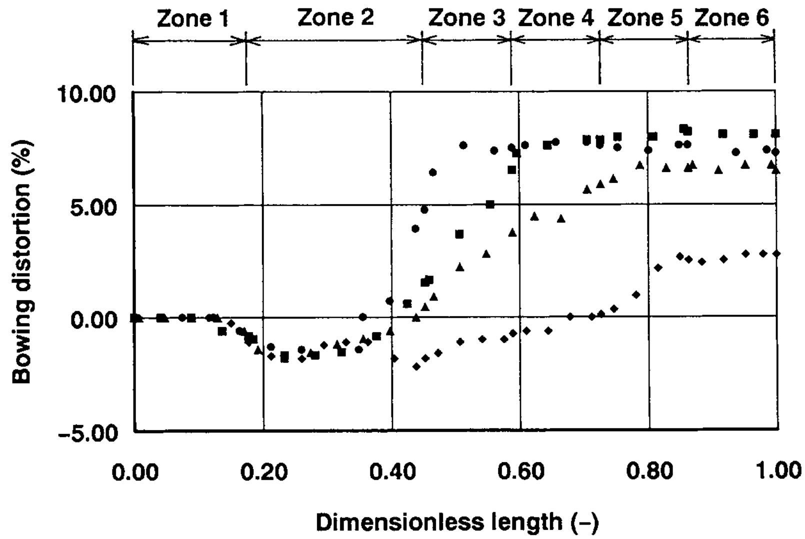

Figure 5 Experimentally observed changes of bowing distortions in the tenter TD-I: (●) Case 1; (■) Case 2; (▲) Case 3; (♦) Case 4.

in the tenter is expressed as the dimensionless length L ($L = l/l_T$), which is the distance from the entrance of the tenter l divided by the whole length of the tenter l_T.

Case 1 shows the experimental results of an ordinary tentering process, which consists of preheating (zone 1: 90°C), transverse stretching (zone 2: 100°C), thermosetting (zones 3, 4: 200°C), and cooling (zone 5: 100°C; zone 6: 50 ~ 60°C without control) zones. This case shows the same deformation patterns (the changes of bowing distortions) of film in the tenter as the previous observation results[8] obtained by the tenter TD-II: The bowing distortions remain insignificant in the preheating zone; in the transverse stretching zone, the film develops a negative (reverse) bowing with a convex shape followed by a quick change into positive (regular) bowing with a concave shape; then, the bowing distortion takes its maximum positive value in the first half of the thermosetting zone; thereafter the bowing distortion maintains a high positive level.

It can be considered that the bowing phenomenon occurs as follows: Both margins of film held by the chain clips of the tenter are bound. However, the binding force due to the chain clips decreases as it approaches the center of film width. As a result the longitudinal (machine direction) force generated by transverse stretching and heat shrinkage in the tenter causes the bowing phenomenon. As the stiffness of film in the thermosetting zone is at its lowest owing to the highest temperature in the tenter, the longitudinal force greatly affects and enlarges the bowing distortion in the thermosetting zone.

The bowing distortion in the thermosetting zone has a maximum value near the beginning of thermosetting zone and subsequently keeps constant at the maximum value. The temperature of film reaches its highest value near the beginning of the thermosetting zone. As a result the film has its lowest stiffness and highest heat shrinkage near the beginning of the thermosetting zone. Therefore, the film is deformed by the longitudinal force due to heat shrinkage and transverse stretching at the highest temperature position, producing a maximum bowing distortion. Thereafter the film keeps its maximum bowing distortion under the highest temperature or less because the longitudinal force does not reoccur.

Case 2 shows the experimental results of a tentering process with a cooling zone (zone 3) between the transverse stretching and thermosetting zones. The process consists of preheating (zone 1: 90°C), transverse stretching (zone 2: 100°C), first cooling (zone 3: 100°C), thermosetting (zone 4: 200°C), and second cooling (zone 5: 100°C; zone 6: 50–60°C without control) zones. This case shows deformation patterns of film in the first cooling zone (zone 3), which differ from those of case 1. The bowing distortions in case 2 are less than those in case 1. However, the maximum bowing distortion in case 2 is almost the same as that in case 1, except that the film develops a negative bowing followed by a quick change into positive bowing in zone 4 of case 2 rather than in zone 3 as for case 1.

Case 3 shows the experimental results of a tentering process with a cooling zone (zones 3 and 4) longer than that in case 2 between the transverse stretching and thermosetting zones. This process consists of preheating (zone 1: 90°C), transverse stretching (zone 2: 100°C), first cooling (zones 3 and 4: 100°C), thermosetting (zone 5: 200°C), and second cooling (zone 6: 50–60°C without control) zones. This case shows deformation patterns of film after the first cooling zone that differ from those of case 1 or 2, where the bowing distortions in case 3 are less than those in cases 1 and 2. Accordingly, the maximum bowing distortion in case 3 also becomes slightly less than that in cases 1 and 2.

Case 4 shows the experimental results of a tentering process with a cooling zone (zones 3 and 4) of lower temperature than that in case 3 between transverse stretching and thermosetting zones. This process consists of preheating (zone 1: 90°C), transverse stretching (zone 2: 100°C), first cooling (zone 3: 50°C; zone 4: 60°C), thermosetting (zone 5: 200°C), and second cooling (zone 6: 50–60°C without control) zones. This case shows much lower bowing distortions, throughout the tenter, than those in other cases. The maximum bowing distortion in case 4 is less than half of that in cases 1 and 2.

It can be seen from comparisons of bowing distortions (B) among cases 1, 4, and 5 that a longer first cooling zone between transverse stretching and thermosetting zones generates less bowing distortion (B). Comparison of cases 2 and 5, and cases 3 and 4 shows a greater decrease in bowing distortion at the lower temperature of the first cooling zone. As shown in Figure 6, a temperature below the glass transition point of film is effective for the reduction of bowing distortion in the first cooling zone, but the effect of a temperature above the glass transition point is minimal in cases 1, 2, and 3. In particular, the installation of a shorter first cooling zone in case 2 has hardly any effect in reducing the bowing distortion at the temperature above the glass transition point. These experimental results support the predicted results. Such results can be explained as follows: When the mono-oriented film whose margins are both held by tenter clips is stretched in the transverse direction, the transverse stretching produces a new longitudinal (machine direction) force that causes the bowing distortions. Usually, the bowing distortion reaches its maximum in the thermosetting zone, where the temperature is at its highest and where the stiffness of film is therefore so low that the film can be deformed easily by the force. On the other hand, when the tenter is newly equipped with a cooling zone between the transverse stretching and thermosetting zones, the film is deformed very little. Because of its high stiffness at the lower temperature, there is little longitudinal force produced by the transverse stretching and transmitted to the high-temperature thermosetting zone. As a consequence, the bowing distortions remain reverse at the end of the transverse stretching zone and first become zero in the vicinity of the end of the cooling zone, as shown in case 4 of Figure 5. After the film passes through the cooling zone, the bowing distortion reaches its maximum in the thermosetting zone. Thereafter the bowing distortion hardly changes. As the final bowing distortion with the cooling zone after transverse stretching is less than half of that without the cooling zone, as shown in case 4 of Figure 5, the bowing distortion due to

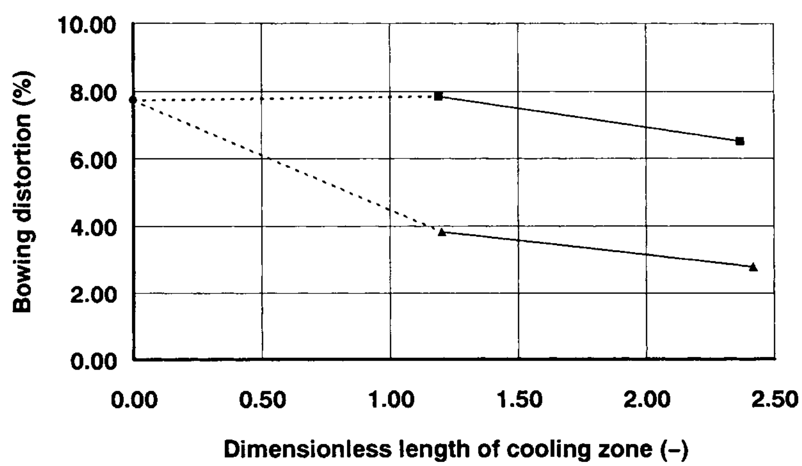

Figure 6 Influence of dimensionless cooling zone length on final bowing distortion: (●) Case 1; (■) Case 2, 3; (▲) Case 4, 5.

the transverse stretching is considered to be more than half of the ordinal bowing distortion without the cooling zone.

Though the bowing phenomenon due to the longitudinal force generated by transverse stretching and shrinkage is fundamentally inevitable in the tenter, the distortion can be reduced by decreasing or preventing the transmission of that longitudinal force to the thermosetting zone.

Influence of Thermosetting Temperatures on Bowing Distortion with First Cooling Zone

There are many problems in applying this method of reducing bowing distortion to the production process of film. The tenter must be equipped with a first cooling zone to follow immediately after transverse stretching. We now consider a modification of a tenter in the production process. As the tenter is limited in length, the first cooling zone must also be limited in length, keeping in mind the length of the thermosetting zone required to control tendencies of film such as heat shrinkage. It is postulated that a higher thermosetting temperature will make up for the deficit in the length of the thermosetting zone.

Figure 7 shows the relationship between the temperatures of thermosetting and the bowing distortions of film in tenters equipped both with and without[8] the first cooling zone between the transverse stretching and thermosetting zones. The first cooling zone consists of Zones 3 and 4 ($L_c \doteqdot 2.4$) with temperatures lower than the glass transition point as tabulated in cases 4, 6, and 7 of Table I. It can be seen from Figure 7 that the bowing distortion does not change with the thermosetting temperature of higher than 200°C for the tenter with the first cooling zone (cases 4, 6, and 7), but it increases with temperature for the tenter without the first cooling zone.

For the tenter without the first cooling, the increase of the bowing distortion with the thermosetting temperature is due to the fact that a higher thermosetting temperature causes lower stiffness and higher heat shrinkage of film, as reported previously.[8] It can be expected from these results that the reduced length of the thermosetting zone due to the installment of the first cooling zone will be compensated by a higher thermosetting temperature, keeping both the bowing distortion and heat shrinkage low. This supports the theory that the cooling method is an effective measure for reducing the bowing distortion, though there are a lot of difficulties to be solved in applying the cooling method.

Effect of Transverse Relaxation on Bowing Distortion

The authors have already reported[8] the influence of transverse relaxation on the bowing distortion without the first cooling zone under the conditions of the preheating temperature of 90°C (zone 1), the stretching temperature of 100°C (zone 2), the thermosetting temperature of 200°C (zone 3), and the cooling temperature of 100°C (zone 4) in the tenter TD-II. The study reported that allowing the film to relax transversely in the thermosetting zone tended to increase bowing distortion. Transverse restretching in the thermosetting zone tended to suppress bowing. Because the binding force between both margins of film becomes weaker at a higher trans-

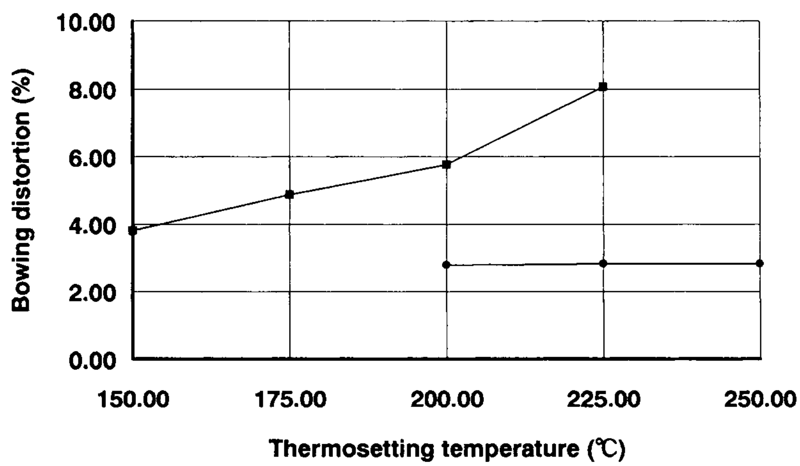

Figure 7 Influence of thermosetting temperature on final bowing distortion: (●) with cooling zone, (■) without cooling zone.

verse relaxation ratio, the film is easily distorted by the longitudinal forces due to transverse stretching and shrinkage of film. The study, however, was never reported on the changes of bowing distortions in the whole tenter without the first cooling zone.

Figure 8 shows the changes of bowing distortions in the tenter TD-II for various ratios of transverse relaxation as tabulated in cases 8 to 10 in Table II. It can be seen from this figure that the bowing distortions have almost the same changes before thermosetting (in zones 1 and 2) but that they have different changes after transverse stretching (in zones 3 a ıd 4). When the ratio of relaxation is higher, as for case 10, the bowing distortions become bigger. On the other hand, when restretching the film in the transverse direction during thermosetting, the bowing distortions become less. These can he considered to result from the following. That the deformation behaviors of film are almost the same under various relaxation ratios before thermosetting is due to the fact that the same longitudinal forces are generated by transverse stretching under the same stretching conditions (cases 8–10). The difference among the final bowing distortions is due to the difference among the binding forces acting on the film in thermosetting under various relaxation ratios. In the thermosetting zone, the binding force generated by the shrinkage of film becomes weaker under a higher relaxation ratio, so that the film becomes easily deformed by the longitudinal force produced by transverse stretching and consequently the bowing distortions become bigger.

Transverse restretching during thermosetting is one of the most effective measures for an ordinary tenter without the cooling zone after transverse stretching, if the change in film characteristics due to restretching permits.

The above can deduce the following measures of bowing distortion reduction: (1) to prevent the transmission of the longitudinal force generated by transverse stretching such as the installment of cooling zone or nip roll between transverse stretching and thermosetting; (2) to reduce the longitudinal force generated by transverse stretching such as a higher transverse stretching temperature, a lower transverse stretching speed, lower molecular orientation of uni-axially oriented film by a lower stretching ratio, or relaxation in the machine direction before transverse stretching and addition of a plasticizer; (3) to bind heat shrinkage of film in thermosetting by restretching; and (4) to decrease the film width distribution of heat shrinkage in thermosetting by rolls or a tenter with changeable clip intervals.

CONCLUDING REMARKS

The simulation by an FEM was carried out in order to predict the most effective length of the cooling zone between transverse stretching and thermosetting zones. The successive distortion patterns of drawn lines were observed over the whole tenter un-

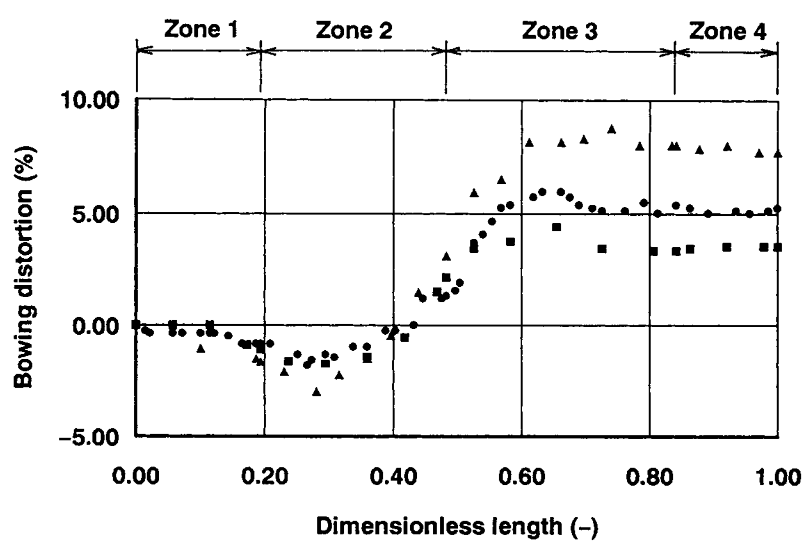

Figure 8 Experimentally observed changes of bowing distortions in the tenter TD-II: (●) Case 8; (■) Case 9; (▲) Case 10.

der various conditions (length, temperature) of the cooling zone in order to verify the simulated results experimentally with a poly(ethylene terephthalate) film. From the simulated and experimental results, the authors confirmed that decreasing or preventing the longitudinal force generated by transverse stretching from being transmitted to the next thermosetting zone is effective for the reduction of bowing distortion. For preventing the transmission of the force, it is necessary for the zone cooled below the glass transition point of film to have a length longer than at least twice the film width. Restretching during thermosetting is also an effective measure for reducing bowing distortion. We will continue to study the mechanism of the deformation behavior of film in a tenter.

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