

Studies on the Stretching of Polypropylene Film. I. Two-Step Biaxial Stretching

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Synopsis

A polypropylene film was stretched at 100–160°C., quenched to room temperature, and then restretched at the same temperature perpendicularly to the first stretching. The reorientation behavior was investigated by using optical and x-ray methods. During the restretching the monoaxial orientation caused by the stretching is converted into a new monoaxial orientation through a balanced state, where $n_{pp} = n_{ps} > n_{ss}$. The more or less parallel orientation to the film surface of the polypropylene molecules, brought about by the first stretching, proceeds further on restretching. n_{ss} is a linear function of the degree of stretching in area v_A . The inclination of this line is independent of the type of deformation, stretching, or restretching, provided the temperature is kept constant. At 160°C. the plot of n_{ss} versus thickness is less steep than it is at 100 or 130°C. The overall reorientation apparently proceeds according to Kratky's first deformation law. The x-ray pattern of a restretched film is a four-point diagram which indicates the existence of a pair of reorientation axes inclined symmetrically against the stretching axis. The inclination grows larger with restretching, and the axes merge into the restretching axis at extreme restretching. This phenomenon is less pronounced when the restretching is carried out at higher temperatures. The density of the restretched film is determined mainly by the stretching temperature, but extreme restretching has a tendency to lower it very slightly.

INTRODUCTION

Biaxially oriented film can be prepared in several ways: two-step biaxial stretching, one-step biaxial stretching, and polyaxial stretching. In two-step biaxial stretching, a film is stretched at first monoaxially at the softening temperature and quenched to room temperature. It is then restretched perpendicularly to the first stretching direction again at the elevated temperature. In one-step biaxial stretching, film is stretched simultaneously along the two directions crossing perpendicularly to each other. In polyaxial stretching, a film is blown or homogeneously stretched radially.

It is believed that there is a bright future for biaxially stretched films because of their superior qualities,¹ especially of high impact strength, but only a few papers have reported the relation between the morphological features of the biaxially stretched film and the stretching conditions.

Precise studies have been carried out on the orientation behavior of polypropylene filaments, which furnish information on the monoaxial

stretching of polypropylene film as the first step in biaxial stretching. According to these studies, stretching at temperatures lower than 100°C. causes the conversion of some fraction of the monoclinic form of polypropylene into the paracrystalline¹⁻¹¹ and a moderate percentage of the *a* axis orientation remains even after considerable stretching.^{5,8,10,12,13}

Sobue and Tabata² reported that the (040) plane becomes parallel to the film surface on biaxial stretching of polypropylene film. The trend is especially marked when the film is rolled. DeVries¹⁴ and Heffelfinger et al.^{15,16} have studied the same problem on other polymers.

The present paper describes the orientation brought about by the two-step biaxial stretching of polypropylene film. The other types of stretching, will be described in detail in subsequent papers.^{17,18}

EXPERIMENTAL

Sample

The polypropylene film used was prepared from a polypropylene homopolymer of molecular weight 22×10^4 and 82% tacticity (extraction method) and supplied by Chisso Corporation (#1077). It was in the paracrystalline state, nearly isotropic, 0.1 mm. in thickness, and of density 0.889 g./cm.³ Electron microscopy (replica method) indicated that small spherulites developed on one surface of the film but not on the opposite surface. The melting point was 168°C. according to dilatometric measurement run at a heating rate of 0.5°C./min.

Two-Step Biaxial Stretching

A film strip (I), $15 \times 6-15$ cm., was mounted on a frame which was put in a poly(ethylene glycol) bath controlled at 100 or 130°C. and stretched along the machine direction (pp) after 5 min. preheating. When stretching of desired degree was achieved, the strip was taken out of the bath, quenched in water at room temperature, and detached from the frame. In the case of the 160°C. stretching, the strip was immersed at first in a bath at 140°C., the temperature was raised to 160°C. during a 5-7 min. preheating, and the actual stretching was carried out at 160°C. This modified operation was necessary, as otherwise the strip would not keep its shape due to premelting (see below). All the strips were washed free of poly(ethylene glycol) with water.

The degree of stretching λ_1 was calculated from the change in distance between two marks on the strip on stretching ($l_0 \rightarrow l$).

$$\lambda_1 = 10^2(l - l_0)/l_0 \quad (1)$$

The rate of stretching was 100%/min. It was confirmed that the effect of stretching rate upon the orientation degree was negligibly small in the range 10-1000%/min.

The above temperature range of stretching was selected as a result of the observation that the polyaxial stretching of the same film could be achieved only above 100°C.¹⁷

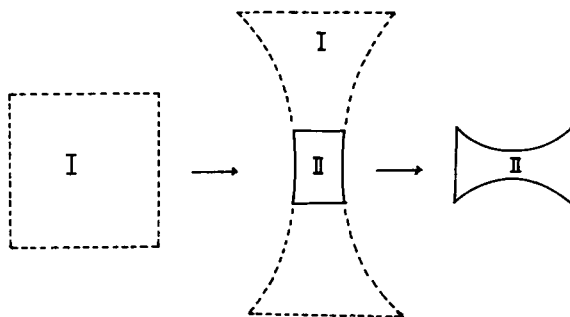


Fig. 1. Schematic representation of the two-step biaxial stretching.

A strip (II), 5 cm. in width was cut from the stretched strip I as shown in Figure 1 and restretched perpendicularly to the direction of first stretching pp at the same temperature and the same rate as in the first stretching; the 160°C. restretching could be carried out by putting strip II directly in the 160°C. bath. The restretching degree relative to the length of strip II was designated by λ_2 .

Determination of the Refractive Indices

Three refractive indices, n_{pp} , n_{ps} , and n_{ss} , parallel to the stretching direction (pp), the transverse or restretching direction (ps), and normal to the film surface (ss), respectively, were measured with an Abbé refractometer at 20–21°C. by a previously described method.¹⁹ For this purpose the specimen was placed between the prisms of the refractometer with a small quantity of a mounting material. (Benzyl alcohol was used since it was confirmed that benzyl alcohol did not penetrate into the specimen and had no effect upon the refractive index reading.)

As is well known, the refractive index depends upon density as expressed by the Lorenz-Lorentz law or Gladstone-Dale's formula, so the refractive index readings were corrected to the values at the standard density, 0.900 g./cm.³.

Determination of Density d and Correction of the Refractive Index

The density was determined by a flotation method at 20–21°C., methanol-water being used as a medium. By plotting the density obtained against the corresponding refractive index of the isotropic state $n_{iso} = 1/3(n_{pp} + n_{ps} + n_{ss})$ a linear relation was found, (Fig. 2), irrespective of the crystalline state of the sample. In Figure 2 the sample I is paracrystalline, II is partially crystalline, and III and IV are almost completely crystalline. This is analogous to the investigation by Tanzawa²⁰ of other polymers. The relation in Figure 2 can be expressed empirically by eq. (2), which is very akin to Gladstone and Dale's formula.

$$(n_{iso} - 0.9353)/d = 0.6294 \quad (2)$$

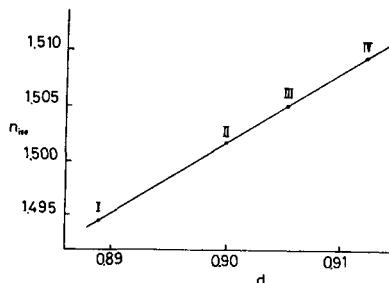


Fig. 2. Relation between refractive index and density of polypropylene.

The density d in this study was obtained by putting the measured n_{iso} into eq. (2); then the refractive index n_i ($i = pp, ps, \text{ or } ss$) could be corrected according to eq. (3) by using this density.

$$(\text{observed } n_i - 0.9353)/d = (\text{corrected } n_i - 0.9353)/0.900 \quad (3)$$

All the observed points other than I–IV are on the line in Figure 2, but they are omitted from the figure for brevity.

Determination of the Density Crystallinity X_d

Crystallinity was calculated from the density by eq. (4), where values of 0.936 g./cm.^3 and 0.870 g./cm.^3 were used for the crystalline density $d_c^{4,21}$ and the amorphous density d_a^{22-24} respectively.

$$1/d = X_d/d_c + (1 - X_d)/d_a \quad (4)$$

X-Ray Photograph

A recording x-ray diffractometer equipped with a copper target (Geiger-flex, Rigaku Denki Ltd.) was used at 35 kv. and 15 ma. The films were exposed perpendicularly to the incident x-ray beam.

RESULTS AND DISCUSSION

Optical Investigation

In Figures 3–5 the broken lines are the n_i versus λ_1 during the first stretching at 100, 130, and 160°C., respectively, while the solid lines show the change in n_i during the restretching. The state of each starting film for restretching is expressed by λ_1 on the stretching curve, which is now designated λ_{12} . As shown in Figure 3, n_{pp} increases to 1.519 and n_{ps} and n_{ss} decrease to 1.493 at $\lambda_{12} = 200\%$; on the contrary, n_{pp} decreases and n_{ps} increases during the restretching as λ_2 grows larger, hence the n_{pp} coincides with the n_{ps} at $\lambda_2 = 120\%$ (biaxially balanced state). n_{ss} , which was equal to n_{ps} , during the first stretching, decreases further on restretching. Consequently n_{pp} becomes equal to n_{ss} at $\lambda_2 > 600\%$. In the range $\lambda_2 = 120\text{--}600\%$ the deformation was heterogeneous, involving necking; therefore, no points could be obtained.

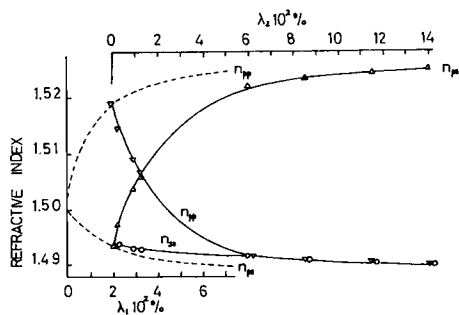


Fig. 3. Change in refractive indices during two-step biaxial stretching at 100°C.

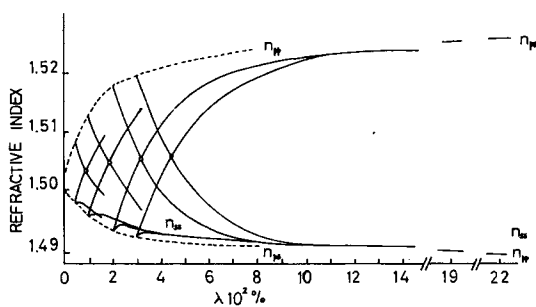


Fig. 4. Change in refractive indices during two-step biaxial stretching at 130°C.

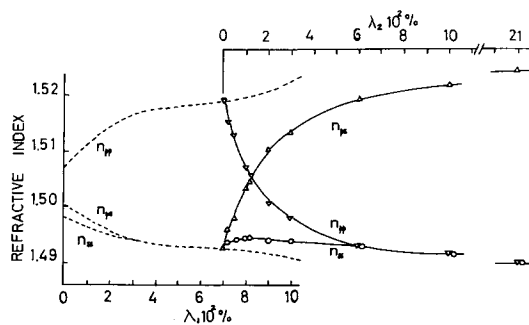


Fig. 5. Change in refractive indices during two-step biaxial stretching at 160°C.

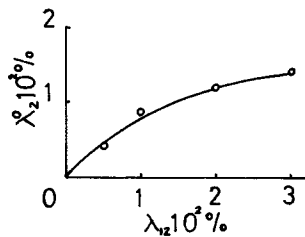


Fig. 6. Relation between λ_{12} and λ_2 .

In Figure 4 results for four restretchings starting from the four different λ_{12} values are shown. The observed points are omitted to avoid overcrowding. The n_t versus λ_2 curves are nearly parallel to each other and they also resemble those in Figure 3. The value of λ_2 bringing about the balanced state is designated by λ_2^0 and is found to increase with increasing λ_{12} of the starting film, as shown in Figure 6, with the corresponding n_{ss} decreases.

The orientation behavior during the 160°C. restretching (Fig. 5) resembles qualitatively the above two cases (Figs. 3 and 4) and the curves are less steep; this is similar to the trend in the monoaxial stretching.

In Figure 3-5 the birefringence $\Delta n = n_{pp}$ or $n_{ps} - n_{ss}$ exhibited a maximum of 0.036. Δn of a completely oriented fiber is estimated to be 0.040 at $d = 0.900$ g./cm.³ as described in detail in the following paper;¹⁷ hence the experimentally obtained orientation at the ultimate stretching or restretching is considered to be extremely high.

For the purpose of comparing the temperature effect, the data in the three restretchings are listed in Table I.

TABLE I
Comparison of the Orientation Behavior During
Restretching at Various Temperatures

Temp., °C.	λ_{12} , %	$\Delta n \times 10^3$ (initial)	λ_2^0 , %	$\Delta n \times 10^3$ (final)
100	200	26.1	<120	35.1
130	300	26.1	>140	34.6
160	700	26.2	>120	34.8

To reach the equal orientation degree, $\Delta n = 26 \times 10^{-3}$, λ_{12} must be varied from 200 to 700% according to the temperature, while λ_2^0 is 120-140% and nearly independent of the temperature. Therefore, for example, in the case of 160°C., $\Delta n = 26 \times 10^{-3}$ is brought about by $\lambda_{12} = 700\%$. However, the film is disoriented to zero birefringence by λ_2 of only 120%.

As described already λ_2^0 is the restretching degree relative to strip II, which has been oriented in some degree along the pp direction. Thus λ_2 larger than λ_2^0 can be expressed as λ_2' , the restretching degree relative to the biaxially balanced state, according to eq. (5). On replotting the n_{ps} against the λ_2' as the

$$1 + \lambda_2'/100 = (1 + \lambda_2/100)(1 + \lambda_2^0/100)^{-1} \quad (5)$$

representative of n_t , the orientation behavior at 100-160°C. can be best compared, as shown in Figure 7.

Here again a trend similar to that in the case of the monoaxial stretching can be seen, i.e., the difference between the 100°C. and 130°C. curves is smaller than the difference between the 130°C. and the 160°C. curves. On comparison with Figures 3-5 it is clearly seen that the restretching is less

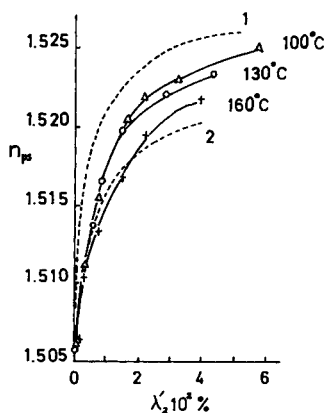


Fig. 7. Comparison of n_{ps} vs. λ_2' at various temperatures and curves calculated according to the Kratky's first deformation mechanism: (1) assuming $n_{ss} = n_\alpha$ and (2) assuming $n_{ss} = 1.4944$.

dependent on temperature than the stretching, and the curves are more steep in the former case than in the latter.

Since for polymers containing polypropylene it has been found that the monoaxial stretching proceeds approximately according to Kratky's first deformation law,²⁵ the same comparison was tried here. However in the present case the starting film is balanced biaxially and isotropic in two dimensions but not in three dimensions. Thus the intensity distribution formula of structural units after the stretching v must be two-dimensional in the present case. This relation was calculated by Kratky as expressed by eq. (6), where J_0 and J are the intensities of the structural unit making an angle φ with the stretching direction before and after stretching, respectively.

$$J/J_0 = v^{3/2} \{ 1 + (v^3 - 1) \sin^2 \varphi \}^{-1} \quad (6)$$

Then eqs. (7)–(9) can be derived from eq. (6):

$$\langle \cos^2 \varphi \rangle = (v^3 - v^{3/2}) / (v^3 - 1) \quad (7)$$

$$f = \frac{1}{2} \{ 3 \langle \cos^2 \varphi \rangle - 1 \} \quad (8)$$

$$\begin{aligned} n_{pp} &= n_{iso} + \frac{2}{3} \Delta n^0 f \\ &= 1.5017 + (\frac{2}{3}) 40 \times 10^{-3} f \end{aligned} \quad (9)$$

Here v is equal to $1 + \lambda_2'/100$ in the present authors' notation and φ is the angle between the c axis and the ps -direction. By using these relations n_{pp} versus λ_2' can be calculated as indicated by the dotted curves 1 and 2 in Figure 7, assuming $n_{ss} = n_\alpha = 1.4886$ and $n_{ss} = 1.4944$, respectively, where n_α is the refractive index along the a or b axis. Curve 1 is the extreme case where all the c axes lie completely parallel to the film surface. The observed relation at 100°C. or 130°C. starts from $n_{iso} = 1.5055$ and coincides comparatively well with the curve 2 up to $\lambda_2' = 50\%$, then de-

parts from it, and approaches curve 1. This is because n_{ss} decreases and approaches n_α during the restretching. The smaller departure from curve 2 at 160°C. is due to the smaller change in n_{ss} . It may thus be concluded that restretching, too, proceeds approximately according to Kratky's first deformation law. The precise deformation mechanism, however, is open to question because unfolding of lamellar crystals must be considered along with the orientation process proposed by Kratky.

Thickness versus n_{ss}

n_{ss} decreases by stretching or restretching as shown above. It was also found that the thickness D of a strip decreases with λ_2 with a small maximum in the early stage of the restretching in a similar manner to n_{ss} . By plotting n_{ss} against the corresponding D , a linear relation was found (Fig. 8). All the points, except for a few points in the case of 130°C., seem to fall on the same line regardless of the degree of stretching and the type of deformation, stretching, or restretching, provided the temperature is not changed. Therefore n_{ss} seems to be a simple function of the relative thickness of the film, i.e., the stretching degree in area v_A . Thus, the more highly expanded the film is in area, the flatter lie the helical isotactic polypropylene molecules. Of course the n_{ss} versus v_A relation is likely to depend on the stretching conditions—mainly by the temperature—because the n_{ss} versus v_A line at 100°C. coincides exactly with the 130°C. line while it differs considerably from the 160°C. line. This temperature effect has already been pointed out.

As to the empirical relation between the orientation degree f and v of a stretched fiber, DeVries²⁶ proposed a general expression [eqs. (10) or (10')] from the result of Kordes et al.,²⁷

$$df/d(\ln v) = C_1 + C_2 f \quad (10)$$

$$f = -C_1/C_2 + 1/C_2 v^{C_2} \quad (10')$$

where C_1 and C_2 are constants, C_2 being $-1/2$ or -1 .

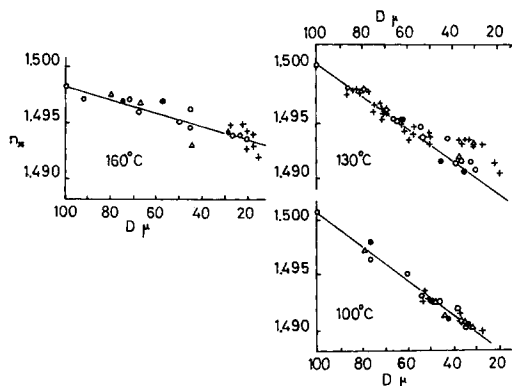


Fig. 8. Plots of n_{ss} vs. thickness: (Δ) monoaxially stretched at 10%/min.; (\circ) monoaxially stretched at 100%/min.; (\bullet) monoaxially stretched at 2000%/min.; (+) biaxially stretched.

The expression of Sheehan and Wellman,²⁸ eq. (11), is a special case of eq. (10'), where η is another constant.

$$f = \eta(1 - v^{-1}) \quad (11)$$

In the case of biaxially balanced films similar relations are expected.

$$f = -1/2(1 - v_A^{-1}) \quad (12)$$

$$= -1/2[1 - (D/D_0)] \quad (12')$$

and

$$n_{ss} = n_{iso} - 1/3\Delta n^0 [1 - (D/D_0)] \quad (13)$$

According to Figure 8, eq. (13) is valid not only for balanced films but also for unbalanced ones. It is surprising when it is considered that the orientation of a film which contains spherulites can be expressed by such a simple relation because spherulites deform in a very complex manner according to electron microscopic investigations.²⁹⁻³¹

Density

The density of the film is determined mainly by the temperature of the first stretching and it changes very slightly by restretching—only of the order of 0.002–0.003 (Fig. 9). Greater stretching or restretching has a tendency to decrease d slightly. This is considered to be brought about by the cavities caused by high stretching or restretching.

The crystallinity calculated from the density ranged from 47 to 68%.

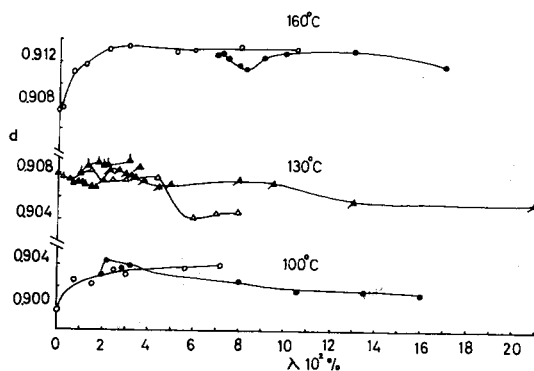


Fig. 9. Density vs. λ_1 or λ_2 . Open and solid marks represent the stretched and the restretched films, respectively, at 130°C., with (\blacktriangle) $\lambda_{12} = 50\%$, (\triangle) $\lambda_{12} = 100\%$; (\blacktriangle) $\lambda_{12} = 200\%$.

X-Ray Investigation

The x-ray diffraction photographs of the films restretched at 130°C. are reproduced in Figure 10. The starting film (Fig. 10a), with $\lambda_{12} = 200\%$ and $\lambda_2 = 0$, is in some degree oriented crystalline. With increase in the degree of restretching, the diffraction arcs (110), (040), and (130) become

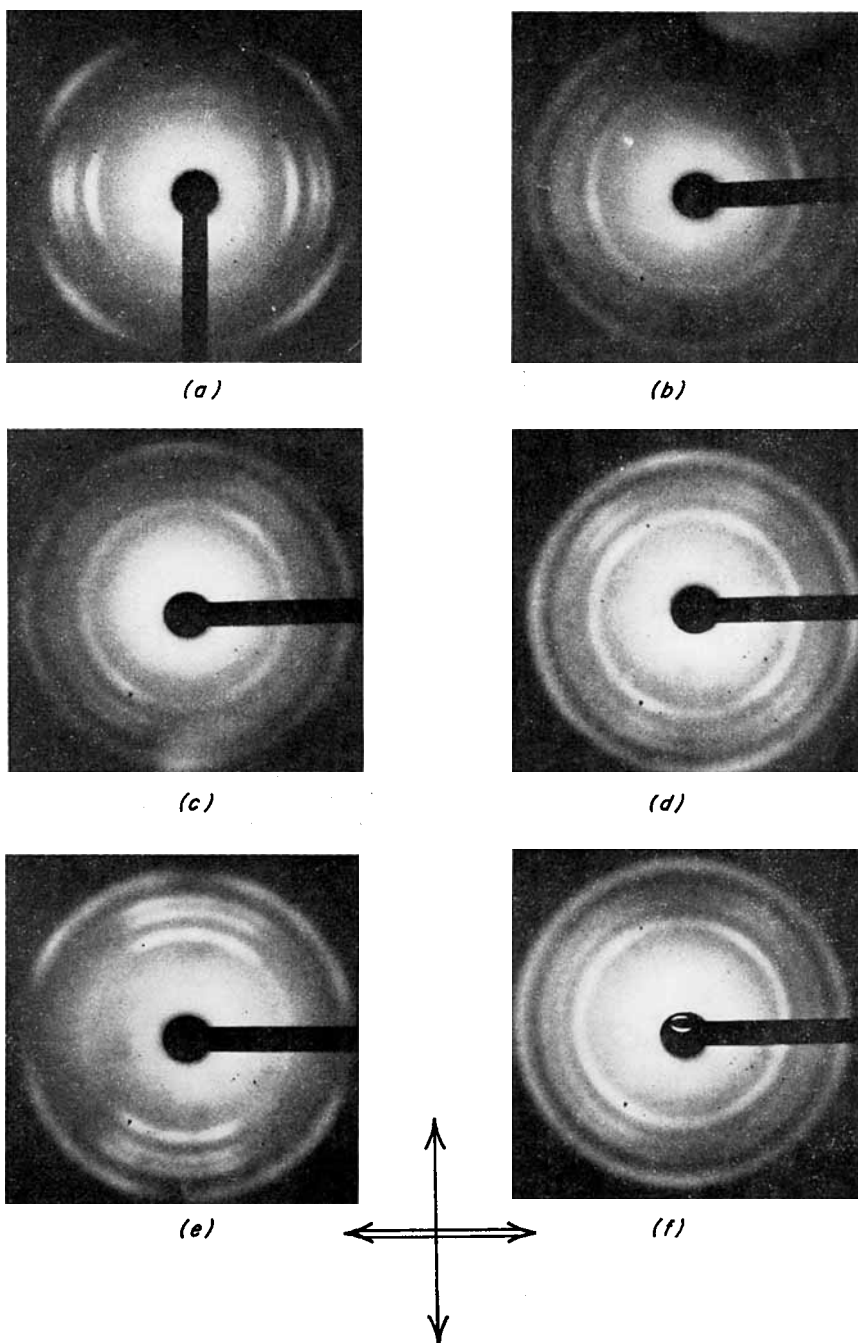


Fig. 10. X-ray diffraction photographs of the films restretched at 130°C.: (a) starting film, $\lambda_{12} = 200\%$, $\lambda_2 = 0$; (b) restretched film, $\lambda_{12} = 200\%$, $\lambda_2 = 70\%$; (c) restretched film, $\lambda_{12} = 200\%$, $\lambda_2 = 100\%$; (d) restretched film, $\lambda_{12} = 200\%$, $\lambda_2 = 180\%$; (e) restretched film, $\lambda_{12} = 200\%$, $\lambda_2 = 300\%$; (f) restretched film, $\lambda_{12} = 100\%$, $\lambda_2 = 70\%$. Incident x-ray beam is perpendicular to the film surface. \leftrightarrow and \rightleftarrows indicate the stretching and restretching directions, respectively.

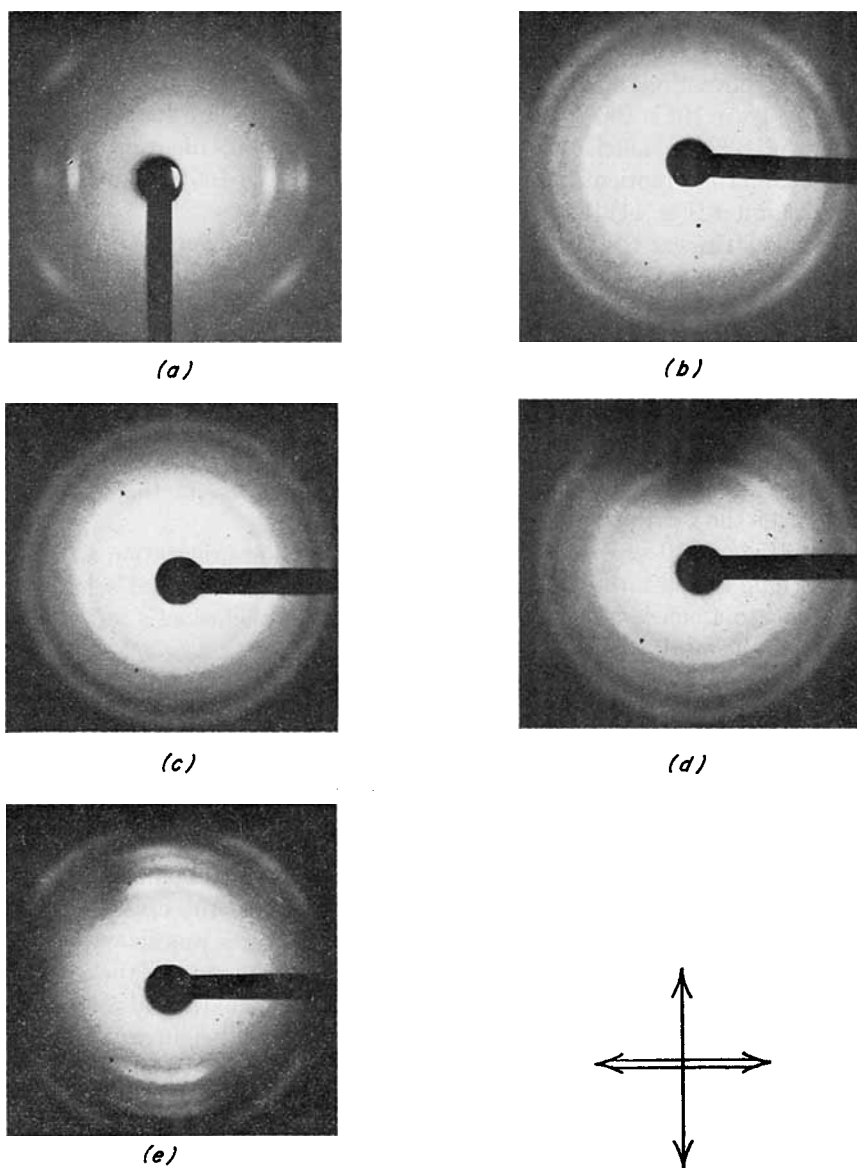


Fig. 11. X-ray diffraction photographs of films restretched at 160°C. Conditions as for Fig. 10. (a) starting film, $\lambda_{12} = 700\%$, $\lambda_2 = 0\%$; (b) restretched film, $\lambda_{12} = 700\%$, $\lambda_2 = 50\%$; (c) restretched film, $\lambda_{12} = 700\%$, $\lambda_2 = 120\%$; (d) restretched film, $\lambda_{12} = 700\%$, $\lambda_2 = 200\%$; (e) restretched film, $\lambda_{12} = 700\%$, $\lambda_2 = 600\%$.

broadener (Fig. 10b) but not monotonously. Figures 10c, 10d, or 10e indicate four-point diagrams. This indicates the existence of a pair of orientation axes parallel to the film surface but inclined symmetrically, $\pm \varphi$, against the pp axis.

This angle φ increases as λ_2 becomes larger. In Figure 10e an ordinary orientation axis, $\varphi = 90^\circ$, can be observed besides the above two axes. The (111) diffractions appear reasonably at the corresponding positions.

λ_{12} of Figure 10f is 100% and smaller than that in Figure 10a; hence the smaller λ_2 (70%) is sufficient to bring about the four-point diagram.

This abnormal reorientation occurs also during the 160°C. restretching but it is fainter (Fig. 11) than in Figure 10.

When a strip was restretched at temperatures lower than 100°C. cracks appeared running oblique and symmetrically against the pp direction. This phenomenon became less marked as the temperature of restretching increased and at 100°C. it was already too faint to be visible. This is the reason why the restretching was carried out at 100°C. or higher temperatures in these experiments. Although with restretching at 100°C. or above the cracks, to which the helical molecules run parallel, are invisible to the naked eye, the phenomenon seems to occur on a submicroscopic scale even at such high temperatures. This gives rise to the four-point diagram on the x-ray photographs.

From Figures 10 and 11 it can be seen that the new orientation at higher restretching seems to be monoaxial about the ps axis and not selectively uniplanar to a considerable extent if any. This conclusion is not contradictory to the results of the optical investigations.

Change in Crystallinity of the Film During Preheating

It has been pointed out repeatedly in this study that the orientation becomes less as the temperature is raised in any type of stretching. This trend is especially marked at 160°C. On the one hand, the density of the stretched film increases almost linearly with the stretching temperature. This apparently contradictory phenomenon may be due to a nonequilibrium change at different stages. So a rough comparison of the crystallization behavior during the preheating at different temperatures was attempted.

For this purpose a dilatometer containing definite amounts of the original film and mercury was plunged into a thermostatted oil bath, and changes in the capillary height were followed until an equilibrium height was reached ($t = 30$ min.). Then the dilatometer was cooled to room temperature and the second run was made successively in the same manner. Curves 1 and 2 in Figure 12 are the readings of the first and the second runs. The experiments were carried out at 100, 120, 130, 150, and 160°C.

The difference of the capillary heights between the two successive runs at the start, ΔH_0 , is the result of the crystallization during the first dilatometric cycle, of which the crystallization in the cooling process, ΔH_c , is smaller than ΔH_0 . ΔH_0 is 13, 18, 20, 23, and 28 cm. in experiments from 100°C. to 160°C. and it is clear that the crystallinity becomes progressively higher as the temperature rises from 100 to 160°C. ($t = 30$ min.).

$\Delta H_0 - \Delta H_t$ at any time t after plunging the dilatometer into a heating bath at temperature T is directly proportional to the volume change due to the crystallization and premelting while the temperature of the polymer

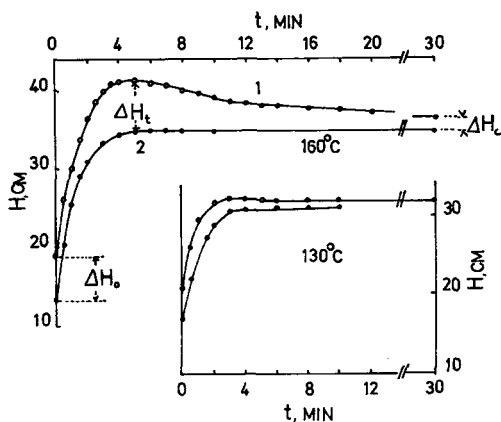


Fig. 12. Capillary heights of the successive two dilatometries: (1) first run; (2) second run.

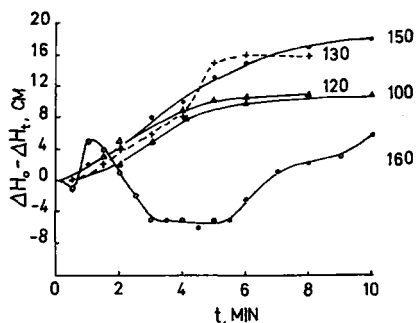


Fig. 13. Estimation of crystallinity during preheating at various temperatures.

approaches T . Therefore, the crystalline state of the polymer during the preheating can be compared roughly with this quantity.

Figure 13 shows plots of $\Delta H_0 - \Delta H_1$ versus t in the 100–160°C. range. At 100–150°C. $\Delta H_0 - \Delta H_1$ increases monotonously, while at 160°C. it decreases at first and takes negative values at $t = 2$ –7 min. This means that the volume increases due to premelting at this stage. It is clear from this that the film crystallizes gradually as its temperature rises in the preheating bath during the 100–150°C. stretching, while it premelts at first before the crystallization starts in the 160°C. bath. This explains that in the 160°C. stretching the preheating temperature must be raised gradually from 140 to 160°C. because the film does not keep its shape on premelting when it is heated quickly to 160°C. The fact that the orientation decreases progressively as the stretching temperature increases from 100 to 150°C. in spite of the higher crystallinity of the stretched film may be attributable to a progressively increased thermal motion within the crystalline region rather than a slight decrease in crystallinity during the

stretching. Abnormal behavior at 160°C. is considered to be caused by the combined effects of the lowest crystallinity due to the premelting and the most violent thermal motion at the temperature close to the melting point. The higher crystallinity of the more highly stretched film at higher temperatures is the result of the longer time of crystallization in the cooling process.

The above phenomena are of course affected by the fine structure of the original film; study of this is in progress.

The authors wish to thank the Ministry of Education for a grant-in-aid for fundamental scientific research. We are also grateful to the Chisso Corporation for kindly supplying the film used in this study.

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Résumé

Un film de polypropylène a été étiré à 100–160°C et refroidi à température de chambre, et à ensuite été réétiré à la même température perpendiculairement au premier étirement. Le comportement à la réorientation a été étudié en utilisant des méthodes

optiques et aux rayons-X. Au cours du réétirement, l'orientation monoaxiale causée par l'étirement le transforme en une orientation monoaxiale nouvelle au moyen d'un état en équilibre, où $n_{pp} = n_{ps} > n_{ss}$. L'orientation, plus ou moins parallèle à la surface du film, des molécules de polypropylène, causée par le premier étirement continue par le réétirement. n_{ss} est la fonction linéaire du degré d'étirement dans la surface v_A . L'inclinaison de cette ligne est indépendante du type de déformation, d'étirement ou de réétirement, pourvu que la température soit gardée constante. A 160°C, le n_{ss} , en fonction de l'épaisseur, est moins raide qu'elle ne l'est à 100 ou 130°C. La réorientation globale obéit apparemment à la première loi de déformation de Kratky. Le réseau de rayons-X du film réétiré est un diagramme à quatre points qui indique l'existence d'une paire d'axes de réorientation inclinés symétriquement par rapport à l'axe d'étirement. L'inclinaison croît fortement avec le réétirement et les axes se fondent dans les axes de réétirement à réétirement extrême. Ce phénomène est moins prononcé lorsque le réétirement est effectué à des températures plus élevées. La densité du film réétiré est principalement déterminée par la température d'étirement mais la réétirement extrême a une tendance à la diminuer légèrement.

Zusammenfassung

Ein Polypropylenfilm wurde bei 100–160°C gereckt und auf Raumtemperatur abgeschreckt; dann wurde er bei der gleichen Temperatur senkrecht zur ersten Reckungsrichtung gereckt. Das Reorientierungsverhalten wurde optisch und röntgenographisch untersucht. Bei der zweiten Reckung verwandelt sich die durch die erste Reckung verursachte monoaxiale Orientierung über einen Zwischenzustand mit $n_{pp} = n_{ps} > n_{ss}$ in eine neue monoaxiale Orientierung. Die durch die erste Reckung bewirkte, mehr oder weniger zur Filmoberfläche parallele Orientierung der Polypropylenmoleküle wird durch die zweite Reckung verstärkt. n_{ss} ist eine lineare Funktion des Reckungsgrades im Gebiet v_A . Die Neigung dieser Linie ist bei konstant gehaltener Temperatur vom Deformationstyp, Reckung oder Querreckung unabhängig. Bei 160°C ist die Abhängigkeit von n_{ss} von der Dicke weniger steil als bei 100 oder 130°C. Die Brutto-Reorientierung verläuft offenbar nach dem ersten Deformationsgesetz von Kratky. Das Röntgendiagramm, eines doppelt gereckten Filmes ist ein Vier-Punkte-Diagramm, was für das Vorhandensein eines Paares von Reorientierungsachsen mit symmetrischer Neigung gegen die Reckungsachse spricht. Die Neigung wird bei der zweiten Reckung grösser und bei extremer Querreckung fließen die Achsen zur Querreckungsachse zusammen. Diese Erscheinung tritt bei Querreckung bei höheren Temperaturen weniger stark hervor. Die Dichte des doppelt gereckten Films ist prinzipiell durch die Reckungstemperatur bestimmt, die extreme Querreckung zeigt aber eine Tendenz zu einer schwachen Herabsetzung der Dichte.

Received May 25, 1966

Revised February 6, 1967

Prod. No. 1580