

The Dimensional Changes of Partially Oriented Polyester Yarns Subjected to Dry and Wet Heat

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Synopsis

The dimensional changes of partially oriented (PO) polyester yarns subjected to dry and wet heat under different tensions and at different temperatures are described. The mechanical properties of the PO yarns, together with those of the heated yarns, have been measured. A tentative theory of the changes in structure taking place in the yarns is suggested.

INTRODUCTION

Partially oriented polyester yarns are produced with different degrees of molecular orientation by varying the speed of winding after spinning the polyester. These partially oriented yarns (POY) are then used in the simultaneous draw texturing (SDT) process to produce textured yarns. In this process the PO yarns are drawn over a hot heater ($\sim 210^{\circ}\text{C}$) at the same time a false twist process is applied. The shrinkage forces and shrinkage characteristics of the PO yarns therefore have an important part to play in the structure and stability of the subsequent textured yarns, thus it is necessary to understand these factors if satisfactory textured yarns are to be produced.

In this first part, the dimensional behavior, together with the mechanical properties of the PO and derived yarns, is described. In a subsequent publication, the structural changes occurring during this process will be presented.

EXPERIMENTAL

Method of Shrinkage

The partially oriented (PO) yarns investigated were experimental samples supplied by Viscosuisse Ltd.; these yarns had been wound at 3000, 3500, 4000, and 4500 m/min, giving decitex values of 311, 268, 235, and 208, respectively. To facilitate description, these yarns will be referred to as WS 3000, and so on.

In the shrinkage experiments a single loop of yarn 25 cm long was hung on a steel rule and a small predetermined weight was attached to the bottom of the loop. This assembly was either heated in a glass-fronted oven or in a large conical flask filled with water, according to the conditions required. The changes in length of the loop were noted after periods of heating.

Reference to Figure 1 will make clear the nature of the dimensional changes observed under low loads. Position A represents the initial length (l_1) of the yarn before heating. On heating there is an initial rapid contraction to point B as the sample attains the temperature of its environment. Usually this initial con-

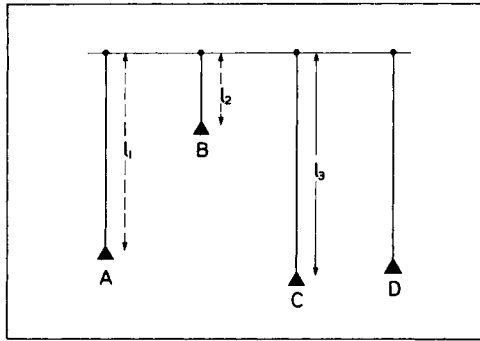


Fig. 1. Diagrammatic representation of dimensional changes under low loads.

traction to length l_2 takes a few seconds. After this initial contraction the yarn then starts to extend (under the same load) and eventually reaches an equilibrium length l_3 measured after 15 min of heating (position C). Very little change takes place on cooling the yarn (position D). The dimensional changes observed are obviously dependent on the applied tension; if the tension is large enough, extension beyond the initial length takes place immediately on heating and the initial shrinkage behavior described is not observed (Fig. 2).

Shrinkage was observed in dry heat at 100, 180, and 210°C and in water with and without 3.0 g/l. Palanil A (dye carrier: BASF) at 95°C. Results are shown in Tables I–VIII, and typical results are shown in Figure 2. The tension per strand of the loop is given in the results.

Mechanical Properties

The mechanical properties of the yarns were determined with an Instron tensile testing machine. The rate of extension of the cross head was 10 cm/min, the time to break was 20 ± 3 sec, and the range used was 0–2000 g. Ten specimens, 10 cm long, were measured for each sample, and the mean of the ten individual results for each property was recorded.

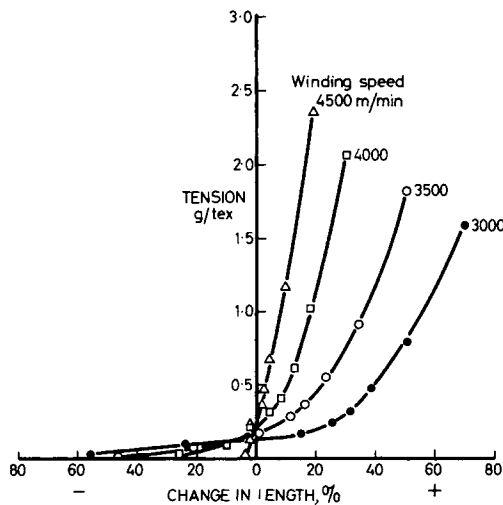


Fig. 2. Dimensional changes after 15 min heating in the oven at 210°C.

TABLE I
Dimensional Changes of Partially Oriented Polyester Yarn, Dry Heat at 100°C

Load, ^a g	WS = 3000 m/min			3500 m/min			4000 m/min			4500 m/min		
	Tension, ^b g/tex	Change %		Tension, ^b g/tex	Change %		Tension, ^b g/tex	Change %		Tension, ^b g/tex	Change %	
		Initial	Equilib.		Initial	Equilib.		Initial	Equilib.		Initial	Equilib.
1.0	0.02	-61.2	-57.6	0.02	-56.1	-48.2	0.02	-40.5	-26.8	0.02	-4.8	-3.5
5.0	0.08	-50.3	-34.3	0.09	-46.9	-29.5	0.10	-30.1	-14.8	0.12	-3.4	-2.5
10.0	0.16	-37.3	-2.0	0.18	-33.5	-9.0	0.21	-17.0	-5.3	0.24	-2.3	-1.6
15.0	0.24	-20.5	+15.0	0.28	-16.3	+3.1	0.31	-6.4	+0.2	0.36	-1.5	-0.8
20.0	0.32	-4.1	+20.8	0.37	-3.0	+9.6	0.41	-1.8	+2.8	0.47	-0.8	-0.2
30.0	0.48		+28.4	0.55		+13.5	0.62		+5.8	0.71		+0.5
50.0	0.80		+44.3	0.92		+25.3	1.03		+11.2	1.19		+3.0
100.0	1.60		+62.7	1.83		+41.3	2.07		+24.0	2.37		+10.2
0		-63.7			-58.4			-42.4				-4.9

^a Load on the loop.

^b Tension per strand.

TABLE II
Dimensional Changes of Partially Oriented Polyester Yarns, Dry Heat at 180°C

Load, ^a g	WS = 300 m/min		3500 m/min		4000 m/min		4500 m/min	
	Tension, ^b g/tex	Change % Initial Equilib.	Tension, g/tex	Change % Initial Equilib.	Tension, g/tex	Change % Initial Equilib.	Tension, g/tex	Change % Initial Equilib.
1.0	0.02	-56.5	0.02	-56.6	0.02	-48.9	0.02	-27.0
5.0	0.08	-48.9	0.09	-48.1	0.10	-26.4	0.10	-14.0
10.0	0.16	-36.8	0.18	-37.1	0.21	-3.6	0.21	-1.0
15.0	0.24	-22.0	0.28	-20.3	0.31	+8.6	0.36	+2.9
20.0	0.32	-7.7	0.37	-4.8	0.41	+14.7	0.47	+5.6
30.0	0.48	+35.3	0.55	+20.0	0.62	+20.0	0.71	+9.9
50.0	0.80	+48.4	0.92	+31.1	1.03	+31.1	1.19	+16.2
100.0	1.60	+66.1	1.83	+44.5	2.07	+26.8	2.37	+13.4
0		-70.0		-57.8		-39.9		-4.3

^a Load on the loop.

^b Tension per strand.

TABLE III
Dimensional Changes of Partially Oriented Polyester Yarn, Dry Heat at 210°C

Load, ^a g	WS = 3000 m/min		3500 m/min		4000 m/min		4500 m/min	
	Tension, ^b g/tex	Change % Initial Equilib.	Tension, g/tex	Change % Initial Equilib.	Tension, g/tex	Change % Initial Equilib.	Tension, g/tex	Change % Initial Equilib.
1.0	0.02	-55.7	0.02	-46.7	0.02	-44.4	0.02	-5.0
5.0	0.08	-23.3	0.09	-20.6	0.10	-36.0	0.12	-3.9
10.0	0.16	+15.1	0.18	+0.3	0.21	-21.8	0.24	-2.8
15.0	0.24	+25.6	0.28	+11.3	0.31	-10.5	0.36	-1.8
20.0	0.32	+31.0	0.37	+16.9	0.41	-2.3	0.47	-1.0
30.0	0.48	+38.2	0.55	+23.4	0.62	+12.0	0.71	+4.9
50.0	0.80	+50.7	0.92	+34.4	1.03	+18.2	1.19	+9.8
100.0	1.60	+70.1	1.83	+50.4	2.07	+30.9	2.37	+19.2
0		-65.2		-56.9		-36.2		-5.1

^a Load on the loop.

^b Tension per strand.

TABLE IV
Dimensional Changes of Partially Oriented Polyester Yarns in Water at 95°C

Load, ^a g	Tension, ^b g/tex	W = 3000 m/min		3500 m/min		4000 m/min		4500 m/min				
		Change %		Change %		Change %		Change %				
		Initial	Equilib.	Initial	Equilib.	Initial	Equilib.	Initial	Equilib.			
1.0	0.02	-52.5	-49.6	0.02	-44.9	0.02	-35.3	0.02	-27.5	0.02	-5.3	-4.0
5.0	0.08	-44.5	-31.5	0.09	-33.7	0.10	-23.1	0.10	-17.4	0.12	-4.1	-2.6
10.0	0.16	-29.0	-6.3	0.18	-23.0	0.21	-7.9	0.24	-7.6	0.24	-2.3	-1.6
15.0	0.24	-14.2	+8.3	0.28	-7.8	0.31	+2.7	0.36	-0.6	0.36	-1.4	-0.7
20.0	0.32	-3.0	+17.5	0.37	-1.5	0.41	+7.5	0.47	+1.8	0.47	-0.6	-0.1
30.0	0.48		+28.4	0.55		0.62	+15.0	0.71	+4.6	0.71		+1.6
50.0	0.80		+43.0	0.92		1.03	+24.8	1.19	+11.5	1.19		+3.6
100.0	1.60		+64.5	1.83		2.07	+42.4	2.37	+23.3	2.37		+10.1

^a Load on the loop.

^b Tension per strand.

TABLE V
Dimensional Changes of Partially Oriented Polyester Yarns in Water + 3.0 g/l. Palamil A (Carrier) at 95°C

Load, ^a g	WS = 3000 m/min		3500 m/min		4000 m/min		4500 m/min	
	Tension, ^b g/tex	Change % Initial Equilib.	Tension, g/tex	Change % Initial Equilib.	Tension, g/tex	Change % Initial Equilib.	Tension, g/tex	Change % Initial Equilib.
1.0	0.02	-39.4	0.02	-45.0	0.02	-34.1	0.02	-21.9
5.0	0.08	-23.2	0.09	-35.4	0.10	-21.0	0.10	-13.7
10.0	0.16	-27.8	0.18	-20.9	0.21	-4.7	0.21	-4.6
15.0	0.24	-12.7	0.28	-6.9	0.31	+3.9	0.31	+0.2
20.0	0.32	-2.1	0.37	-0.5	0.41	+9.2	0.41	+2.9
30.0	0.48	+28.1	0.55	+15.2	0.62	+25.0	0.62	+5.8
50.0	0.80	+41.7	0.92	+41.7	1.03	+25.0	1.03	+10.6
100.0	1.60	+61.5	1.83	+39.4	2.07	+23.7	2.07	+23.7

^a Load on the loop.

^b Tension per strand.

TABLE VI
Tension to Prevent Shrinkage

WS, m/min	Tension, g/tex											
	100°C		180°C		210°C		95°C (water)		95°C (water + carrier)			
	Initial	Equilib.	Initial	Equilib.	Initial	Equilib.	Initial	Equilib.	Initial	Equilib.	Initial	Equilib.
3000	0.35	0.18	0.35	0.15	0.35	0.12	0.33	0.21	0.33	0.33	0.19	0.19
3500	0.40	0.25	0.40	0.20	0.40	0.20	0.43	0.25	0.43	0.39	0.24	0.24
4000	0.46	0.30	0.45	0.24	0.45	0.24	0.45	0.34	0.45	0.43	0.28	0.28
4500	0.60	0.40	0.52	0.32	0.50	0.30	0.53	0.47	0.53	0.48	0.47	0.47

TABLE VII
Contraction under 0.1 g/tex Load

WS, m/min	Contraction %									
	100°C		180°C		210°C		95°C (water)		95°C (water + carrier)	
	Initial	Equilib.	Initial	Equilib.	Initial	Equilib.	Initial	Equilib.	Initial	Equilib.
3000	47	30	47	24	49	16	42	28	37	19
3500	44	26	48	20	47	14	32	19	34	19
4000	32	15	36	13	36	10	25	17	21	12
4500	4	3	4	2	4	2	5	3	3	3

TABLE VIII
Extension under 1.5 g/tex Load

WS, m/min	Extension %				
	100°C	180°C	210°C	95°C (water)	95°C (water + carrier)
3000	61	64	68	62	60
3500	36	41	46	37	35
4000	17	21	24	17	17
4500	5	9	12	6	5

A typical stress-strain curve for a PO yarn is illustrated in Figure 5, and the mechanical properties derived from similar curves are shown in Table IX. The initial modulus refers to the region before the yield point in the curve and the postdraw modulus to the initial part of the elastic region after the draw region. The other properties are defined and derived in the normal way.

Table X refers to similar mechanical properties derived from stress-strain curves determined from yarn after initial contraction, and Table XI refers to the mechanical properties of the yarn at equilibrium under the given conditions. All mechanical properties were determined at 20°C and 65% and 65% RH.

RESULTS AND DISCUSSION

Changes in Length

The results for changes in length under the conditions of dry heat are given in Tables I-III, and for wet heat, in Tables IV and V. Typical results are illustrated in Figure 2. The tension to prevent shrinkage can be derived from the value at which the appropriate curves cut the ordinate axis, and these values of tension are listed in Table VI.

The tension to prevent the initial shrinkage does not vary with the temperature for three of the partially oriented yarns; the fourth yarn (WS 4500) shows a small decrease in the tension required as the temperature is raised. The tension to keep the final equilibrium length to that of the original can be similarly derived from the appropriate data (Fig. 2). This tension decreases as the temperature of heating is raised. If the yarns behaved like true rubbers above the glass transition temperature, an increase in tension as the temperature was raised

TABLE IX
Mechanical Properties of Partially Oriented Polyester Yarns

Mechanical property	Winding speed, m/min			
	3000	3500	4000	4500
Tex	31.77	27.31	24.22	21.06
Tenacity, g/tex	19.56	21.89	23.93	27.50
Breaking load, g	621.6	597.9	579.6	579.1
Extension, %	144.9	112.5	87.1	71.8
Initial modulus, g/tex	222.2	262.3	321.7	422.8
Yield load, g	168.6	164.4	167.2	172.6
Draw load, g	148.6	140.0	140.7	161.4
Draw extension, %	52.3	32.2	19.7	8.5
Postdraw modulus, g/tex	24.7	28.1	31.8	25.5
Work of rupture, g/tex	13.05	11.79	10.62	11.57

TABLE X
Mechanical Properties of PO Yarn after Initial Contraction at 180°C

Breaking load, g	Initial tension (strand), g/tex	Contraction (-), %	Tex	Tenacity at break, g/tex	Extension at break, %	Predraw modulus, g/tex	Yield load, g	Draw load, g	Draw extra., %	Postdraw modulus, g/tex	Work of rupture, g/tex
637.3	0.02	-62.4	89.0	7.2	389	124.2	339	310	163	1.8	17.4
589.3	0.16	-36.2	49.1	12.0	290	162.2	221	187	143	8.3	16.7
611.0	0.32	-6.5	33.9	18.0	169	180.7	176	151	67	23.4	14.1
WS = 3000 m/min											
590.8	0.02	-56.1	65.3	9.1	355	94.4	225	221	105	(2.0)	17.9
576.4	0.18	-34.9	44.1	13.1	232	168.5	196	173	103	9.9	14.7
626.6	0.37	-4.5	28.6	21.9	127	246.2	169	147	36	23.8	13.7
WS = 3500 m/min											
533.2	0.02	-43.2	39.5	13.5	197	152.7	173	166	67	6.2	13.5
588.8	0.21	-21.4	30.2	19.5	141	244.6	165	143	37	17.1	13.5
590.5	0.41	-2.8	24.4	24.2	92	306.8	161	154	18	24.4	12.2
WS = 4000 m/min											
626.2	0.02	-4.9	22.1	28.3	85	399.3	161	159	7	17.6	13.9
618.6	0.24	-2.7	21.5	28.8	82	363.3	166	163	10	22.6	13.8
610.8	0.47	-1.0	20.8	29.4	76	463.2	174	174	8	24.4	13.4
WS = 4500 m/min											

TABLE XI
Mechanical Properties of Polyester Yarns at Equilibrium at 180°C

Mechanical property	Winding speed m/min									
	3000		3500		4000		4500		5000	
Tension (g/tex)	0.16	1.60	0.09	0.18	1.83	2.07	0.12	0.24	0.12	2.37
Contraction (-)/extension (+)	-8.6	+65.8	-27.3	-4.3	+44.5	+26.8	-2.2	-1.2	-2.2	+13.4
Tenacity, g/tex	29.1	19.7	37.6	28.1	21.8	18.3	32.4	21.1	32.4	17.8
Breaking load, g	15.5	33.6	14.5	20.9	30.2	37.2	28.2	31.3	28.2	33.1
Extension at break, %	450.9	661.6	543.4	586.9	658.6	689.6	630.1	659.0	630.1	587.0
Initial modulus, g/tex	128.1	32.4	155.2	110.9	33.5	38.3	75.7	73.4	75.7	42.5
Work of rupture, g/tex	301.7	566.1	262.4	343.1	522.4	507.0	431.5	453.3	431.5	482.9
Work of rupture, g/tex	13.7	8.0	15.3	15.4	7.5	10.8	14.6	15.2	14.6	10.0
Corrected tenacity, g/tex (see text)	35.4	44.5	37.0	44.1	40.3	51.4	49.5	54.3	49.5	47.2
Corrected work of rupture, g/tex (see text)	31.2	10.6	39.0	32.3	10.0	14.9	25.6	26.3	25.6	14.3

would be expected, so it is implied from these results that the yarns do not behave as true rubberlike networks of random chains. The x-ray diagrams of the partially oriented yarns WS 3000–4000 are typical of noncrystalline solids, although evidence of some orientation is given. The x-ray diagram of the yarn WS 4500, on the other hand, is that of a well-oriented crystalline polyester together with a noncrystalline background scatter. If the PO yarns are heated while held to length, they all give x-ray diagrams of crystalline polyester with different orientations. It is likely, therefore, that the factors preventing true rubber elasticity are associated with internal cohesions and the crystallization of the polymer. Further structural details will be discussed in a subsequent publication.

By reference to Table VI it will be seen, as would be expected, that the tension to prevent the initial contraction is greater than that necessary to ensure that the equilibrium length after heating for 15 min equals the original length. The practical consequence of this in relation to texturing and other similar heat processes applied to polyester yarns and fabrics is that the application of heat above the glass transition temperature causes a high initial tension to be produced, followed by a decay of tension accompanied by crystallization processes in the polyester fiber. This is in accordance with the work of Pinnock and Ward,¹ who followed similar processes in more detail.

The results for the contraction of partially oriented polyester yarns under a small tension of 0.1 g/tex show (Table VII, Fig. 3) that the lower the winding speed, the greater the contraction at equilibrium. The contraction of the yarn WS 4500, however, varies very little with temperature, and this could partly be due to the fact that it is initially crystalline, whereas the other PO yarns are noncrystalline initially.

Values for the contraction in water at 95°C can be compared with those for the contraction expected by heating in the dry state at 95°C by a small extrapolation of the curves (Fig. 3). These results seem to divide the PO yarns into two groups—PO yarns with lower contractions in water (WS 3000 and WS 3500) and those with higher contractions in water (WS 4000 and WS 4500) than in the dry state at 95°C. Thus, there seems to be between these two groups a change in morphology that could be associated with the degree of orientation in the noncrystalline phase.

The results in Table VII also show that in the dry state over the temperature range of 100–200°C there is little variation in the initial contraction under a small

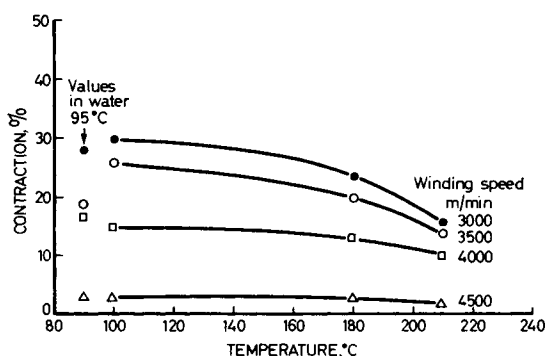


Fig. 3. Dimensional changes for yarn heated under 0.1 g/tex load for 15 min.

load with any given partially oriented yarn, but the contraction at equilibrium does vary with the winding speed of the PO yarn and is greatest for the lower temperatures (Fig. 3). It can also be seen that the carrier Palanil A in the water causes small changes in the shrinkage behavior. Carrier, therefore, reacts to some extent with the morphology of the polyester yarns, and such changes must play a part during the use of carriers to promote dyeing.

The results (Table VIII) for the extension of the yarn under a high tension (1.5 g/tex) are of particular interest. The extension under this tension increases as the temperature is raised [Fig. 4(a)], as would be expected. The extension decreases almost linearly with the winding speed of the partially oriented yarn [Fig. 4(b)] up to WS 4000, again as would be expected, and then tends to start to level off at 4500. This behavior is probably connected with the presence of a crystalline fraction in the yarn WS 4500 which modifies the rubberlike elasticity of the yarn at high temperatures. Similar results are found for the yarns extended in water at 95°C, and the addition of carrier does not have any significant effect on the results.

The results of the changes of dimensions of partially oriented yarns under the influence of dry and wet heat show that true rubberlike elasticity is not displayed. It is probable that the reason for the departure from true rubberlike behavior is connected with the formation of internal cohesion points possibly by the attraction of the benzene rings of adjacent chains by π bonding, and in particular with crystallization of a portion of the yarn. The fact that a yarn that has a

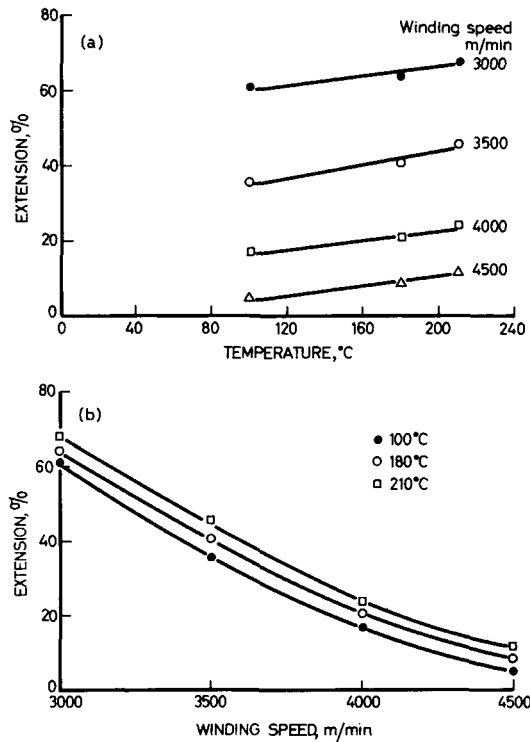


Fig. 4. (a) Variation of extension % with temperature for yarns held under a tension of 1.5 g/tex. (b) Variation of extension % with the production winding speed for yarns held under a tension of 1.5 g/tex and heated to different temperatures.

crystalline fraction initially can behave in a similar way to yarns that are initially noncrystalline seems to indicate a noncrystalline network phase in all the yarns that is the cause of the shrinkage behavior. Such evidence is thus in favor of a two-phase structure in polyester yarns, but the presence of two phases must not be confused with the old fringe-micellar theory.

Mechanical Properties

The mechanical properties of the partially oriented yarns are shown in Table IX, and a typical stress-strain curve is given in Figure 5. As might be expected, the extension at break and the draw extension are related to the production winding speed so that as the winding speed (WS) is increased, these extensions are reduced. These results arise because as the winding speed is increased, there is a greater extension taking place during production. If a network is set up in the spinning process, there should be a limit to the extension of such a network and therefore less extension permitted in later processing as the production extension increases. The initial modulus, as well as the tenacity at break, also increases with the winding speed, as might be expected. The postdraw modulus, however, only increases with winding speed for the PO yarns that are noncrystalline. There is a fall in value for the crystalline PO yarn (WS 4500), implying a maximum value at the point of crystallization. The work of rupture reduces as the winding speed increases, reaching a minimum and rising again for the crystalline PO yarn. Yield loads and draw loads do not vary greatly for the noncrystalline PO yarns, but the crystalline PO yarns (WS 4500) give higher values for these parameters.

After initial contraction at 180°C under various tensions, the yarn was removed from the oven before it started to re-extend, cooled rapidly, and the mechanical

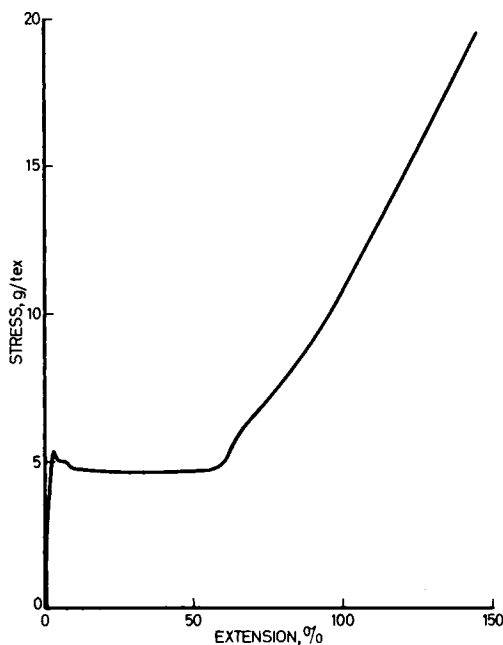


Fig. 5. Stress-strain curve for PO yarn produced at a winding speed of 3000 m/min.

properties determined for this contracted state of the yarn. Results are shown in Table X: the stress-strain curves were similar to that illustrated on Figure 5. The tex value is higher than that for the original yarn in consequence of the yarn having contracted in length, and this fact introduces difficulties in the interpretation of the results in terms of structure. Thus, yarn WS 3000 had a breaking tenacity of 19.6 g/tex, but when shrunk under tension of 0.02 g/tex and retested, the apparent breaking tenacity was 7.2 g/tex. The yarn thus appears to have become considerably weaker on shrinkage, but this is due to the value of tex used in the calculations. To make comparisons in terms of structure, it is necessary to allow for dimensional changes taking place on shrinkage or extension during the heat treatment. This affects mainly the tenacity and extensions at break.

To interpret the tensile strength data in terms of structurally significant quantities, it is useful to compare the tenacity calculated on the basis of the tex values at the breaking extension, rather than on the basis of the original tex or of the tex after heat treatment. It is therefore necessary to correct for changes in tex caused by the dimensional changes during the heat treatment and during the break in the tensile test. The tex at break can be derived simply from the measured tex of the specimen and the known changes taking place during test. Thus it can be shown that

$$\text{tenacity at break} = \text{measured tenacity} \frac{E + 100}{100}$$

where E is the extension percent at break. The data for the PO control yarns before heat treatment were corrected in the same way, so that direct comparison of results could be made.

Structurally, it is necessary to see whether the extension at break simply includes the dimensional changes that took place during the heat treatment or if structural changes took place that modified such a simple algebraic relationship. To do this, the extension at break has to be calculated in terms of specimen length that had been returned to the original structural condition before heat treatment, i.e., to take into account the original dimensional shrinkage or extension that took place during heat treatment. Thus, the specimen length for a shrunk yarn is theoretically greater than that taken, and smaller for yarn that had extended during heat treatment. A standard test length of 10 cm is taken for Instron measurements, and it is this length that had to be corrected before calculating the apparent extension at break owing to the structure. A simple calculation shows that if the yarn had shrunk during the heat treatment then the apparent extension at break ($A\%$) is given by

$$A\% = \frac{E - S}{S + 100} \times 100$$

where $E\%$ is the measured extension at break and $S\%$ is the known original shrinkage. Similarly, for a yarn that had extended during treatment,

$$A\% = \frac{e(E + 100) + 100E}{100}$$

where e is the known original extension percent during treatment. Calculations based on the data for yarn treated at 180°C are given in Tables XII and XIII and illustrated in Figure 6.

TABLE XII
Mechanical Properties of Partially Oriented Polyester Yarns after Initial Contraction at 180°C

Yarn WS, m/min	Initial tension g/tex	E , %	Tenacity, g/tex	Corrected tenacity, g/tex	Work of rupture, g/tex
3000	PO control ^a	145	19.6	48.0	13.05
	0.02	389	7.2	35.2	17.4
	0.16	290	12.0	46.8	16.7
	0.32	169	18.0	48.4	14.1
3500	PO control ^a	113	21.9	46.6	11.8
	0.02	355	9.1	41.4	17.9
	0.18	232	13.1	43.5	14.7
	0.37	127	21.9	49.7	13.7
4000	PO control ^a	87	23.9	44.7	10.6
	0.02	197	13.5	40.1	13.5
	0.21	141	19.5	47.0	13.5
	0.41	92	24.2	46.5	12.2
4500	PO Control ^a	72	27.5	47.3	11.6
	0.02	85	28.3	52.4	13.9
	0.24	82	28.8	52.4	13.8
	0.47	76	29.4	51.7	13.4

^a Control PO yarns before heat treatment.

It will be seen from Figure 6 and Table XII that for the partially oriented yarns that are noncrystalline (WS 3000–4000), shrinkage under a low tension, i.e., virtually free shrinkage, causes a loss in tenacity at break. A possible explanation is that the number of internal cohesion points present in the partially oriented yarn have decreased during the shrinkage process. As the tension is increased during shrinkage, less relaxation of the structure takes place and the tenacity at break approaches that of the untreated PO yarns; and under the highest tensions used, an increase in cohesion takes place, leading to a slightly stronger

TABLE XIII
Apparent Extension at Break of PO Polyester Yarns at Equilibrium at 180°C

Initial tension, g/tex	Change in length, %	Extension at break, %		
		Measured	Apparent	PO Control
WS = 3000 m/min				
0.16	-8.6	128	101	145
1.60	+65.8	32	119	145
WS = 3500 m/min				
0.09	-27.3	155	100	113
0.18	-4.3	111	102	113
1.83	+44.5	34	94	113
WS = 4000 m/min				
2.07	+26.8	38	75	87
WS = 4500 m/min				
0.12	-2.2	76	72	72
0.24	-1.2	73	71	72
2.37	+13.4	43	62	72

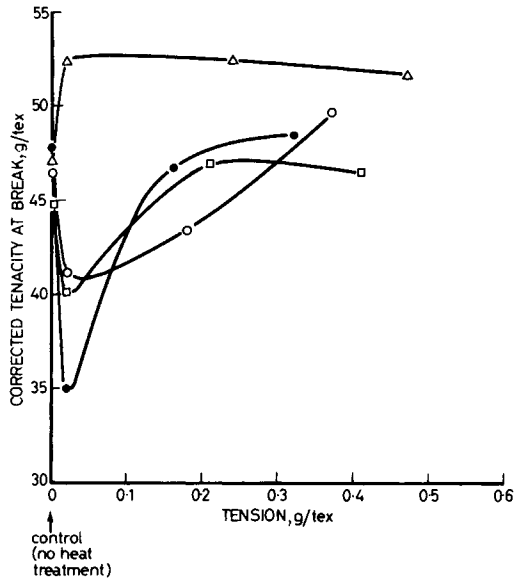


Fig. 6. Relation of corrected tenacity at break with tension for PO yarns produced at different winding speeds, m/min: (●) 3000, (○) 3500, (□) 4000, (△) 4500.

structure at break than for the corresponding control yarns. The crystalline PO yarn (WS 4500) shows that despite shrinkage under tension taking place, there is a strengthening of the yarn at break. In considering the values for the extension at break, it is useful to consider the extension values calculated on the basis of the original length of the yarn prior to heat treatment i.e., the percentage by which the length after the extension in the tensile test is greater than the original length. Table XIII lists these values; with only one exception, the apparent extension at break for yarns treated at 180°C under equilibrium conditions gives reduced extensions compared with the untreated control yarn. A possible explanation is that under equilibrium conditions, some internal cohesion of the structure has taken place and this can prevent the full extension expected. The anomaly occurs with the crystalline PO yarns (WS 4500) that suffer only small shrinkages under small tensions, and here the structure has virtually reversible characteristics.

The results for the work of rupture (Table XII) show that all heated yarns after initial contraction have higher values for the work of rupture than the control yarn, but these values decrease as the tension on the yarn increases. This suggests that as the tension is increased, the yarn becomes stiffer and more brittle during the heat treatment and could be connected with the degree of crystallinity increasing, but other structural measurements are needed to investigate such an interpretation.

The nature of the internal cohesion forces cannot be determined from these experiments, but it seems likely that the shrinkage is determined to some extent by the partial unlocking of these internal cohesions, as well as by the shrinkage owing to entropy changes. Recovery from shrinkage leading to extension appears to involve the reformation of some of these cohesive points as well as crystallization. The data therefore appear to suggest that the polyester has a two-phase structure, one crystalline and the other capable of reversible elastic effects. The

cohesive forces seem to be connected mainly with the second phase, a noncrystalline phase which is probably partly oriented. Such cohesive forces are not necessarily connected with three-dimensional order and therefore cannot be termed crystalline as suggested by Bosley,² since to do so leads to confusion with genuine crystalline regions. The relative amounts of the two phases in the different yarns will depend on their prehistory, and it is likely that in some of the control PO yarns, one phase, the crystalline phase, is absent.

CONCLUSIONS

An examination of the dimensional changes that take place during the application of dry or wet heat to partially oriented polyester yarns and an investigation of the mechanical properties of the heated products suggest that the structure of polyester yarn can be interpreted in terms of two phases. The relative quantity of the two phases, one a noncrystalline phase with some rubberlike properties, which acts as a matrix, and the other a three-dimensionally ordered crystalline phase, will vary according to the prehistory of the polyester yarns, and one phase, the crystalline phase, may be absent in some yarns. This type of interpretation of the polyester structure is in general accord with that given by Pinnock and Ward¹ and Bhat and Bell.² A more detailed investigation of the conditions of formation and properties of the crystalline phase will be published in a separate communication.

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