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# Mechanical Properties of Polypropylene Multifilament Yarns in Dependence of their Drawing Ratio

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In the present work we investigated mechanical properties of multifilament PP yarns spun at three spinning regimes and at different drawing ratios to settle the rational spinning parameters of yarns to be used for certain textile purposes. The yarns coded as PP1, PP2 and PP3 were spun in the Laboratory of Fibre Materials Science, Tampere University of Technology on a Fourné laboratory melt spinning unit at corresponding drawing ratios of 3.73, 5.53 and 7.30. The PP granules were supplied by Inka Oy. The spinnerets numbered 10 holes each of 0.5 mm in diameter. Indices of stress-strain behaviour including the ultimate resistance, tensile moduli and yield points, as well as stress relaxation data at three different levels of elongation below the second yield point (2 %, 5 % and 10%) are analysed on the basis of data obtained on a Zwick/Z005 universal testing machine and using *testXpert*® software. Elongation at break of the yarns greatly decreases while elongation at first yield point shows tendency to decrease with the increase of drawing ratio. Breaking tenacity, initial and secondary moduli of the yarns are in strong linear dependence on drawing ratio. Stress relaxation amount at high drawing ratios and at elongation of 10 % shows the definite tendency to decrease. The attempt is made to interpret stress relaxation data by the parameters of Kohlrausch's equation.

*Keywords*: polypropylene, spinning, drawing ratio, stress-strain properties, relaxation.

## 1. INTRODUCTION

Nowadays polypropylene (PP) fibre is one of the most popular synthetic fibres due to its low cost and a set of valuable properties. During last decades the growth rate of its production is higher than of such distinguished fibres as PES, PA and PAN. Production of PP multifilament yarns in 2003 comprised 1.7 mln. t and it was by 13 % higher than in 2002 [1]. The range of PP fibre and yarn application fields depends on the product mechanical properties, which in turn are mostly determined by the fibre spinning and drawing parameters because during spinning, drawing and heat setting the proper supramolecular structure of the fibre is formed [2 – 6].

Among such usual properties as strength and extensibility, one of distinct features of PP fibre is a well-marked viscoelasticity, manifesting in a high time-dependency of their mechanical behaviour [7 – 9]. A study of materials viscoelastic behaviour is a subject of great importance from viewpoint of the material processing or its usage according to the specific purpose as well as of the theory of viscoelasticity originated from the material structure [10 – 12]. To provide information about the viscoelastic behaviour of a polymeric material various experimental techniques have been used, among which stress relaxation is in common use. A number of studies on stress relaxation in textile fibres and other polymeric materials, published during last decade, should be mentioned [13 – 19].

In this study we investigated mechanical properties of multifilament PP yarns spun at three spinning regimes and at different drawing ratios to settle spinning parameters of the yarns to be used for certain textile purposes.

## 2. YARN SPINNING

The yarns conventionally coded as PP1, PP2 and PP3 were spun in the Laboratory of Fibre Materials Science, Tampere University of Technology on a Fourné laboratory melt spinning unit. The granules of isotactic PP were supplied by Finnish Company Inka Oy. The main spinning parameters of the yarns are presented in Table 1.

**Table 1.** Yarn spinning parameters

| Parameter | Unit of measurement | Yarn codes | | |
|---|---|---|---|---|
| | | PP1 | PP2 | PP3 |
| *Spinneret* | | | | |
| Number of holes | – | 10 | 10 | 10 |
| Hole diameter | mm | 0.5 | 0.5 | 0.5 |
| Hole length | mm | 1.5 | 1.5 | 4.5 |
| *Spinning pump* | | | | |
| Speed | $min^{-1}$ | 20 | 20 | 12 |
| Production | $cm^3/min$ | 24 | 24 | 14,4 |
| Melt feeding speed | m/min | 12.23 | 12.23 | 7.34 |
| *Drawing* | | | | |
| Godet 1 | m/min | 150 | 150 | 150 |
| temperature | °C | 40 | 40 | 50 |
| Godet 2 | m/min | 300 | 450 | 500 |
| temperature | °C | 60 | 60 | 70 |
| Double godet | m/min | 600 | 900 | 1200 |
| temperature | °C | 90 | 90 | 90 |
| *Winding speed* | m/min | 560 | 830 | 1095 |
| *Drawing ratio* | – | 3.73 | 5.53 | 7.30 |
| *Yarn linear density* | | | | |
| theoretical | tex | 17.9 | 12.1 | 5.5 |
| Real | tex | 17.8 | 12.4 | 5.6 |

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Theoretical linear density of the yarn (in tex) is calculated by formula [2]:

$$T_{th} = \frac{P_p \cdot k \cdot \rho_f}{v_w} 10^3, \qquad (1)$$

where $P_p$ is the production of spinning pump, cm$^3$/min; $k$ is the correction factor for the equipment ($k = 0.464$); $\rho$ is the fibre density ($\rho = 0.90$ g/cm$^3$); $v_w$ is the yarn winding speed, m/min.

As it can be seen from Table 1, the maximum difference between the real and theoretical values of yarn linear density did not exceed 2.5 %.

## 3. STRESS-STRAIN PROPERTIES

All tensile tests were performed on Zwick/Z005 universal testing machine in standard atmospheres for testing (ISO 139). Stress-strain data of the yarns were obtained at the gauge lengths of 500 mm for PP3 yarns and of 250 mm for PP1 and PP2 yarns, at the speed of relative extension of 1.25 %/s, and at pretension of 0.25 cN/tex. 25 specimens of each yarn were tested and stress-strain curves were obtained. Typical of them are shown in Fig. 1.

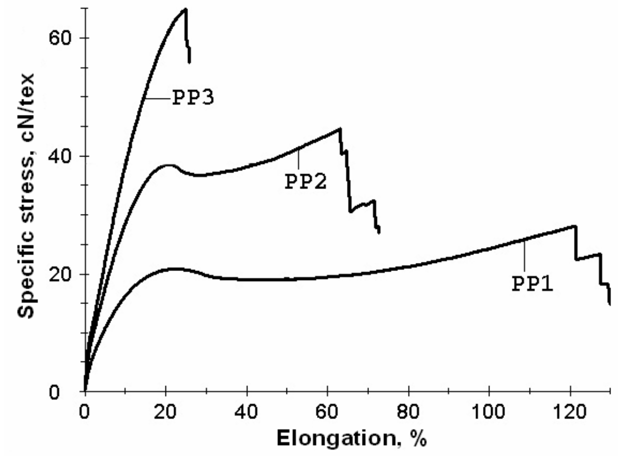

**Fig. 1.** Stress-strain curves of PP yarns

In stress-strain curve (the curve of the yarn PP1 is shown in Fig. 2 as an example) we can recognize the initial high-slope part in which the approximate proportionality between stress and strain is held on. Above the limit of proportionality, at certain point A conventionally named as a first yield point a distinct instant change in a curve slope occurs. This point is correlative with some release of freedom and the relative movement of neighbouring molecular chain elements preferably in the amorphous regions [11]. At point B of the stress-strain curve named as a second yield point the marked spontaneous elongation of the yarn begins without any increase in tensile stress. This is determined by orientational displacements and rearrangements of molecular chains, crystallites and fibrils. At the end of the second yield zone (point C in Fig. 2) stress begins to increase as well, and this ends with the yarn break. The yarn PP3 has no second yield point B because the main orientational rearrangements have formed during its high-scale drawing. As all the yarns are zero-twist, their single filaments break gradually (Fig. 1, 2). The point D at maximum tensile force is considered as break point of a yarn.

Metrological characteristics of the testing machine as well as *testXpert®* software enabled to change the scale of the stress-strain curves in a wide range and to get much more valuable information from them than just the familiar indices of a yarn break – tensile strength and ultimate extensibility.

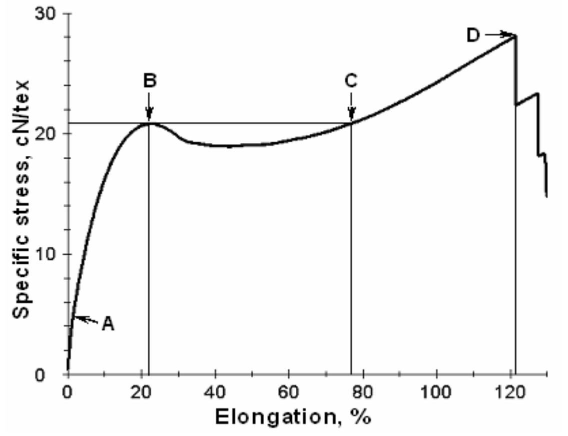

**Fig. 2.** Characteristic points of stress-strain curve

**Table 2.** Stress-strain properties of PP yarns

| Parameter | Yarns | | |
|---|---|---|---|
| | PP1<br>17.8 tex | PP2<br>12.4 tex | PP3<br>5.6 tex |
| Breaking force, N | 4.70<br>(±0.15) | 5.50<br>(±0.15) | 3.63<br>(±0.05) |
| Breaking tenacity, cN/tex | 26.4 | 44.3 | 64.8 |
| Elongation at breaking force, % | 122.4<br>(±5.7) | 61.1<br>(±4.1) | 24.3<br>(±0.6) |
| *Work of break*: | | | |
| absolute, J | 1.10<br>(±0,06) | 0,67<br>(±0.05) | 0,28<br>(±0.01) |
| specific, J/g | 248 | 215 | 99 |
| *Modulus*: | | | |
| initial, cN/tex | 439<br>(±12) | 756<br>(±33) | 934<br>(±30) |
| secondary, cN/tex | 157 | 257 | 325 |
| pre-break, cN/tex | 18 | 82 | – |
| *Limit of proportionality*: | | | |
| specific stress, cN/tex | 2.4 | 2.9 | 3.2 |
| elongation, % | 0.5 | 0.4 | 0.3 |
| *First yield point*: | | | |
| specific stress, cN/tex | 4.8 | 6.6 | 7.2 |
| elongation, % | 1.5 | 1.1 | 0.9 |
| *Second yield point*: | | | |
| specific stress, cN/tex | 20.8 | 38.5 | – |
| elongation, % | 23 | 21 | – |
| *End of the second yield:* | | | |
| elongation, % | 76 | 42 | – |

Three kinds of tensile modulus were measured reflecting the yarn resistance to extension at the different stages. Modulus as a generic term represents a slope of stress-strain curve to the elongation axis and is expressed as a ratio of specific stress to the relative elongation.

The initial modulus of the yarn was estimated as the slope of initial linear part of the stress-strain curve continuing up to the limit of proportionality. The secondary modulus was estimated as the slope of the part of the curve just above the first yield point while the pre-break modulus (only for PP1 and PP2 yarns) was estimated as the slope of the ultimate curve's part preceding the break point.

Stress-strain properties of the yarns are presented in Table 2. It is seen that drawing ratio has great influence upon the ultimate resistance power of PP yarns as well as upon the response to low strains. The increase in drawing ratio results in great decrease of the yarn extensibility, much more than the increase of the tensile strength. This feature in turn reflects by the marked decrease of the yarn work of break. From Fig. 3 it is seen that breaking tenacity and initial modulus of the yarns are in strong direct linear dependence on drawing ratio. The same dependence is obtained for the secondary modulus (coefficient of determination $R^2 = 0.9891$). Elongation at first yield point shows tendency to decrease with the increase of drawing ratio. However, the second yield starts at approximately the same elongation. Though the yarn PP3 breaks before it reaches the second yield point, we can see the "embryo" of the latter at break point of the yarn. Elongations at second yield point of the yarns PP1 and PP2 are notably comparable with elongation at break of the yarn PP3.

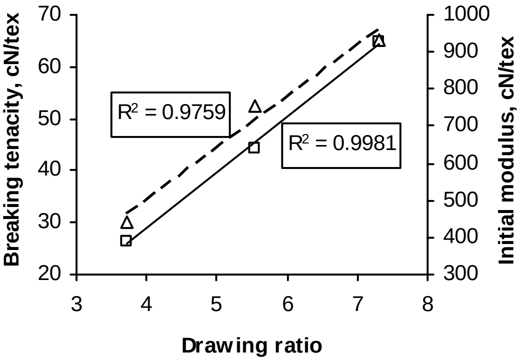

**Fig. 3.** Dependence of breaking tenacity (□, ——) and initial modulus (△, – – –) of the PP yarns on their drawing ratio

As it is seen, the yarn PP3 produced by high drawing ratio possesses beneficial stress-strain properties such as high initial modulus and strength, moderate extensibility to be used for many purposes in the textile industry. On the other hand, why the less oriented yarns PP2 and even PP1 could not also be used in the cases (e. g. for hosiery) when the tension would not exceed 5 cN/tex?

## 4. STRESS RELAXATION

In stress relaxation experiments the gauge length was 500 mm for all tested yarns. The yarns at a rate of 1.25 %/s were extended up to the three different elongation values below the second yield point ($\varepsilon_t = 2$ %, 5 %, and 10 % of the gauge length), then stress decrease was monitored at constant elongation $\varepsilon_t$ over a period of time $t^* = 3160$ s (over a period 10000 s for the yarn PP3 at the elongation of 5 %). The moment at which elongation $\varepsilon_t$ reached the target value was determined to be the time $t^* = 0$. Five to twelve specimens were tested to calculate the mean values of stress. Before testing every specimen was freely laid for 48 h in the standard atmospheres out of package.

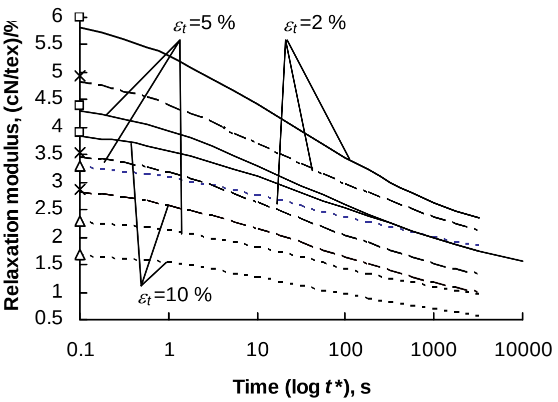

**Fig. 4.** Stress relaxation curves of the PP yarns: · · · · · – PP1; – – – – PP2; ——— – PP3; □, ×, △ – the corresponding relaxation moduli at $t^* = 0$

Stress relaxation behaviour of the yarns is shown in Fig. 4 as the change of relaxation modulus (specific stress divided by elongation $\varepsilon_t$) in time. For each yarn the initial (at $t^* = 0$) stress at the same value of the imposed strain is very different: at $\varepsilon_t = 2$ % the initial stress of the yarn PP3 is almost two times as high as that of the yarn PP1 and 2.3 times as high as at $\varepsilon_t = 10$ %. During fast extension some of tie molecules and fibrilles in the specimen are mostly stretched and impose large local stresses. Afterwards the local stresses are distributed on a larger number of stretched structural units and the resultant stress on a yarn slowly decreases. The decrease of stress in time occurs in different way in different yarns. For the yarn PP1 at $\varepsilon_t = 2$ % the decrement of stress over the period $t^* = 3160$ s is 44 % of the initial stress and at $\varepsilon_t = 10$ % it increases up to 67 %. Conversely, for the yarn PP3 at $\varepsilon_t = 2$ % the stress decrement is 61 % and at $\varepsilon_t = 10$ % it lowers to 55 %. This means that the display of viscoelastic properties of the yarns show a tendency to decrease with the increase in the structure orientation. Similar results were obtained by Djoković, Kostoski and Dramićanin for the linear low density polyethylene (LDPE) [17].

During the time of monitoring the curves of stress decrease do not reach plateaus and show no evidence of relaxation approach to any "equilibrium" state. It has been previously shown [20] that the value of assumed residual (at $t^* = \infty$), say, "equilibrium" stress can be calculated by using the Kohlrausch's equation:

$$f(t^*) = f_\infty + (f_0 - f_\infty)\exp\left(-t^*/\tau_k\right)^n, \qquad (2)$$

where $f(t^*)$ is (specific) stress at given time; $f_0$ is the initial (at $t^* = 0$) value of stress; $\tau_k$ is relaxation time (after Kohlrausch); $n$ is a power coefficient.

The parameters of the equation (2) were calculated on the base of four experimental specific stress values taken at time moments $t^* = 0$ s, 316 s, 1000 s, and 3160 s by the established procedure [21, 22]. The results are given in Table 3. From the residual ("equilibrium") stress the residual relaxation modulus $E_\infty = f_\infty / \varepsilon_t$ is also obtained.

It is seen from Table 3 that the residual relaxation modulus of the yarns decreases with the elongation value $\varepsilon_t$ but increases with increase of drawing ratio. The same

**Table 3.** The parameters of Kohlrausch's equation for the PP yarns

| Elongation ($\varepsilon_t$), % | PP1 (17.8 tex) | | | | PP2 (12.4 tex) | | | | PP3 (5.6 tex) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $f_\infty$, cN/tex | $E_\infty$, (cN/tex)/% | $\tau_k$, s | $n$ | $f_\infty$, cN/tex | $E_\infty$, (cN/tex)/% | $\tau_k$, s | $n$ | $f_\infty$, cN/tex | $E_\infty$, (cN/tex)/% | $\tau_k$, s | $n$ |
| 2 | 3.07 | 1.53 | 288.4 | 0.234 | 3.39 | 1.70 | 122.4 | 0.221 | 3.98 | 1.99 | 86.4 | 0.244 |
| 5 | 3.72 | 0.74 | 188.9 | 0.250 | 5.28 | 1.06 | 119.6 | 0.253 | 7.35 | 1.47 | 114.8 | 0.255 |
| 10 | 4.34 | 0.43 | 145.0 | 0.278 | 6.67 | 0.67 | 205 | 0.251 | 13.8 | 1.38 | 246.1 | 0.250 |

tendency has been obtained for PP films [20] and LDPE [17] showing the increase in polymer crystallinity on drawing ratio and the residual relaxation modulus $E_\infty$ to be a particular measure of structural order of oriented polymer. Relaxation time (after Kohlrausch), however, decreasing with the increase of drawing ratio at low levels of elongation, markedly increases at elongation of $\varepsilon_t = 10$ %. The power coefficient $n$ essentially depends on the range of time within which the experimental stress data are taken to calculate the parameters of Kohlrausch's equation, consequently its values are nearly invariant.

## 5. CONCLUSIONS

The PP yarns spun on a Fourné laboratory melt spinning unit with different drawing ratios possess beneficial mechanical properties to be used for various purposes in the textile industry. Increase in drawing ratio causes the increase in breaking tenacity and in the initial and secondary moduli of the yarns.

With the increase of structure orientation of the yarns provided by drawing the display of their viscoelastic properties show a tendency to decrease.

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