Tensile and Elastic Behavior of Tencel Continuous Filaments

Iram Abdullah,[1] Richard S. Blackburn,[1] Stephen J. Russell,[1] Jim Taylor[2]

[1]*Centre for Technical Textiles, University of Leeds, Leeds, UK*
[2]*Lenzing Fibers Ltd., Derby, UK*

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ABSTRACT: Tencel is a regenerated cellulose fiber produced using an environmentally-responsible dry-jet wet-spinning process, which contributes to its excellent mechanical properties. In this study, the tensile properties of Tencel continuous filaments are characterized and the effect of twist on mechanical properties, including breaking load and extension, are considered. Peak strength was obtained in Tencel filaments of 140 t m^{-1}. The elastic behavior of Tencel monofilament was observed by assessing the recovery from strain-induced energy and the elastic recovery was found to be low. Along with time dependency, Tencel has the ability to stabilize its deformed state by forming new crosslinks, and this influences the elastic behavior. In simple extension cycles, the same low elasticity was observed. Cumulative extension cycles were also performed to characterize the behavior of filaments subjected to repeated strain and to determine the resultant hysteresis effects. Permanent elongation was observed at 2% imposed strain, which suggests that the filament has low extensibility. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 99: 1496–1503, 2006

Key words: Tencel filament; tensile strength; filament elasticity; cumulative extension cycles; creep

INTRODUCTION

Tencel fibers spun from cellulose solution in *N*-methylmorpholine-*N*-oxide (NMMO) hydrate have been proven commercially successful in textile and nonwoven products because of their excellent mechanical properties in the wet state when compared with viscose rayon.[1–5] The manufacturing process is environmentally benign because the nontoxic NMMO solvent used is almost all completely recycled.[6–8] Owing to these advantages, many technical developments of Tencel fiber and its structure–property relationships have been reported.[9–14] However, there is very little reported on the elastic behavior. The elastic behavior influences the load elongation, crease recovery, dimensional stability, and serviceability of clothing and technical textile fabrics constructed from the filaments and is therefore of significant interest.

One way of observing the characteristic tensile behavior of fiber or filament is by load–elongation or stress–strain curves in which the breaking point is reached, but textiles are seldom designed to withstand single applications of stress-strain at such high magnitude. During their life, conventional fabrics experience a series of repeated stress applications and removals, including bending, twisting, tensioning, and abrasion. To resist destruction, the specimen must exhibit good elastic recovery on removal of stress, it must be capable of absorbing energy imparted to it and of releasing this energy upon removal of stress without occurrence of failure.[15,16]

The deformation of a material is governed by two major components; immediate elastic deflection and delayed deflection, commonly known as creep. Creep has two classes: *primary creep*, which is the recoverable portion of delayed deflection; and *secondary creep*, which is nonrecoverable and is characterized as permanent deformation.[17] At strains below the yield point in the load–elongation curve, according to Hooke's law, there will be immediate elastic recovery, but textile materials are not perfectly elastic. They do not immediately return to their original form upon removal of stress. However, they may return completely (if secondary creep is absent), even though the recovery is delayed.

The area under the curve is a manifestation of the energy expended in straining the specimen and this energy is also absorbed by the specimen. Hence, primary creep, secondary creep, and instantaneous elastic deflection all contribute to the energy absorption capacity of the specimen. It has been shown by Hamburger[18] that in repeated load applications the contribution of secondary creep is negligible, since it is removed in the course of the first few cycles; both immediate elastic deflection and creep deflection are

Correspondence to: R. S. Blackburn (r.s.blackburn@leeds.ac.uk).

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recoverable upon removal of the load. They both contribute to the absorption and return of energy necessary for proper performance under repeated stress, and the contribution of creep deflection depends upon the rate of primary creep and time interval between stress cycles.[18] Therefore, the properties that are desirable in a specimen that is to be subjected to repeated stress as shown by Hamburger are a low modulus of elasticity, a large immediate elastic deflection, a high ratio of primary to secondary creep, a high magnitude of primary creep, and a high rate of primary creep.

EXPERIMENTAL

To investigate the load–elongation behavior of Tencel filaments, a Textechno Statimat tester was used. The filament's elastic properties were characterized using a standard method ASTM D 1774–94.[19] In addition to simple extension cycles, cumulative extension cycles were also produced to enable the hysteresis effects to be observed. The Tencel continuous multifilament yarn studied in this work was supplied by Lenzing (Spondon, UK) and were development samples. The specifications of the multifilament yarn as supplied were 172 monofilaments of 0.99 tex.

Determination of load–elongation curves

The Tencel multifilaments were conditioned at 22 °C and 45% RH for 72 h. A gauge length of 200 mm was used on the tensile tester and specimens were tested at a crosshead speed of 300 mm min^{-1}. A load cell of 100 N was used to test a minimum of 5 samples of filament yarn per sample. The mechanical properties were determined 5 times and an average value taken. Samples of the multifilament yarn that contained only a small amount of producer twist were twisted on a ring-twister to observe the effect of twist level on mechanical behavior. The twist levels were applied according to theoretical twist values and then the actual twist values were determined 10 times by a hand operated James H. Heal and Co Ltd. twist tester and an average value taken.

Determination of elastic properties

The experiments performed were of three types: (a) The elastic properties of the filaments were determined according to standard method ASTM D 1774–94. The original multifilament yarn was conditioned at 22 °C and 45% RH and then carefully untwisted. The resultant monofilaments were mounted on card board apertures of 60×150 mm^2. A constant-rate-of-extension machine, Instron 1122, was used and the specimen was extended to three extension levels, 2%, 5%, and 7%, at a rate of 10 mm min^{-1}. When the required extension was reached, the crosshead was stopped for

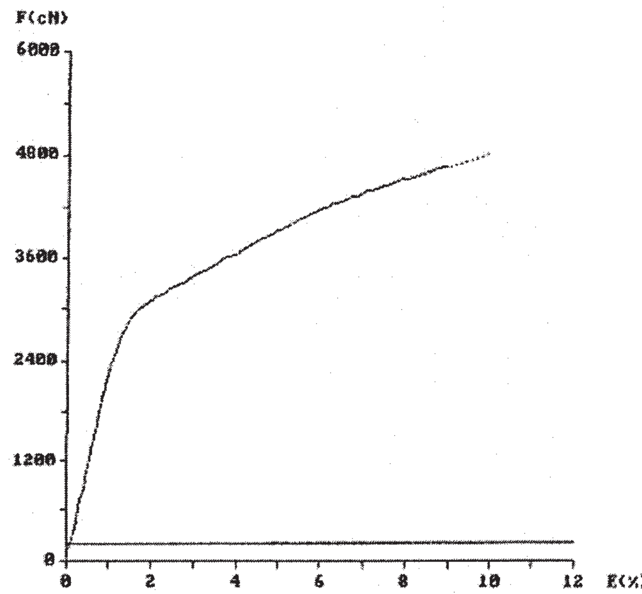

Figure 1 Average load–elongation curve of Tencel filament yarn.

1 min, to allow stress relaxation. After 1 min, the filament was relaxed at the same rate of crosshead travel used in the extension cycle until the initial gauge length (150 mm) was reached. After 3 min waiting time, the specimen was reextended to the level of initial extension and the same relaxation procedure was preformed. (b) In a simple extension cycling procedure, the monofilament was repeatedly extended between the initial gauge length of 150 mm and the fixed elongations of 2%, 5%, and 7%. The monofilament was stretched 19 times at the fixed extension level. (c) In the cumulative extension cycling, the monofilaments were repeatedly stretched at fixed extensions of 2%, 5%, and 7%; however, every time the slack was removed manually.

RESULTS AND DISCUSSION

Load–elongation curve of filament yarn

The load–elongation curve of the Tencel filament yarn (Fig. 1) is nonlinear. The curve represents the characteristic behavior of a filament with an initial linear elastic portion (Hookean), a yield point, an approximately linear portion after yielding, and then further extension before the break point. On removal of force, the recovery is irreversible and new crosslinks will form to stabilize the deformed state. The mechanical properties of the multifilament yarn are shown in Table I.

The load–elongation curves of the twisted filament yarns are shown in Figure 2; the twisted yarns show the same characteristic behavior. The effect of twist on mechanical properties is shown in Table II and it

TABLE I
Mechanical Properties of Tencel Filaments

Status	No of tests	Values
Extension at break	5	9.8%
Breaking load	5	4940.41 cN
Work of rupture	5	7505.66 cN cm
Tenacity	5	28.89 cN tex
Linear density	1	171 tex
Twist	10	88 t m^{-1}
Breaking time	5	4 s

TABLE II
Effect of Twist on Linear Density, Tensile Strength, and Extension and Breaking Time

Twist (t m^{-1})	Linear density(tex)	Tensile strength (cN)	Extension (%)	Breaking time (s)
88	171	4450.66	7.31	2.93
140	74	4497.54	8.58	3.45
244	178	4449.21	9.56	3.84
336	185	4300.77	11.61	4.67
454	196	3956.69	14.37	5.75
604	218	3103.54	14.95	6.03
786	243	2404.28	15.22	6.12

follows a classical trend; at 140 turns per meter (t m^{-1}) there is a small increase in tensile strength of the filament yarn, which is due to the binding effect of twist, but this effect is small. As the twist increases the tensile strength gradually decreases. The increase in breaking elongation is due to the effect of obliquity, induced by the spiralling of filaments around the filament axis. Yarn kinking starts at 336 t $m^{-1}$and the contraction in length markedly increases linear density, elongation at break, and breaking time.

Elastic properties

The elastic properties of the dissected monofilaments are shown in Figure 3, plotted against extension at break. There is gradual decrease in strain recovery and a corresponding increase in the permanent deformation. The work recovery is very low and at small imposed extension it is only 14.9%. This suggests that the specimen does not have the ability to release energy upon removal of load or its recovery is highly time-dependent.

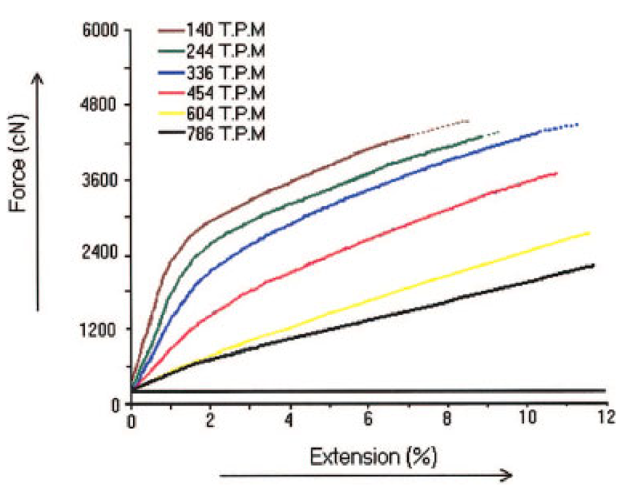

Figure 2 Average load–elongation curves of Tencel filament yam at different level of twist. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Simple extension cycling

A typical example of the behavior of the Tencel monofilament in simple extension cycling is shown in Figure 4. The extension cycling behavior was observed at 2% and 5% extension (Fig. 5). At 7% extension, monofilaments were broken during the third cycle.

The shape of the initial load–elongation curve is different from the shape of the rest of the curves; this suggests that the filament suffers permanent deformation as a result of the first cycle. The specimen was slackened after each cycle. There is a gradual decrease in the peak breaking load, an increase in the permanent deformation, and a decrease in the elastic recovery. After nine cycles, the load–elongation curves are alike in shape and displacement, i.e., superimposing on repeated extension cycles. The behavior observed in simple extension cycling corresponds to the occurrence of secondary creep. As long as slack is present, there will be no absorption of energy and no occurrence of primary creep; thus, after the ninth cycle, the work recovery and permanent deformation remain unchanged.

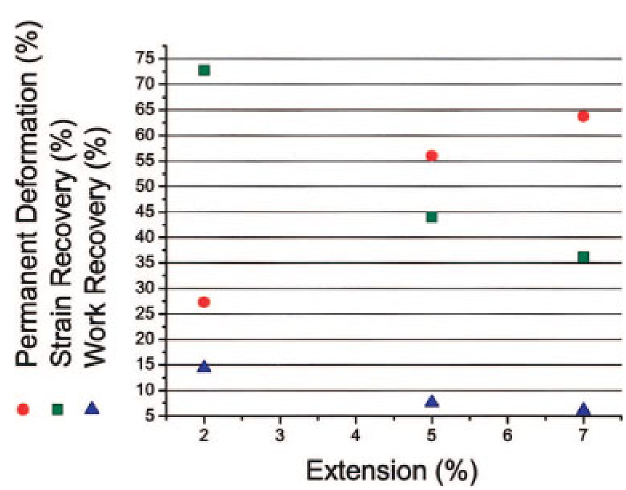

Figure 3 Average elastic properties of monofilaments at 2%, 5%, and 7% extension. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

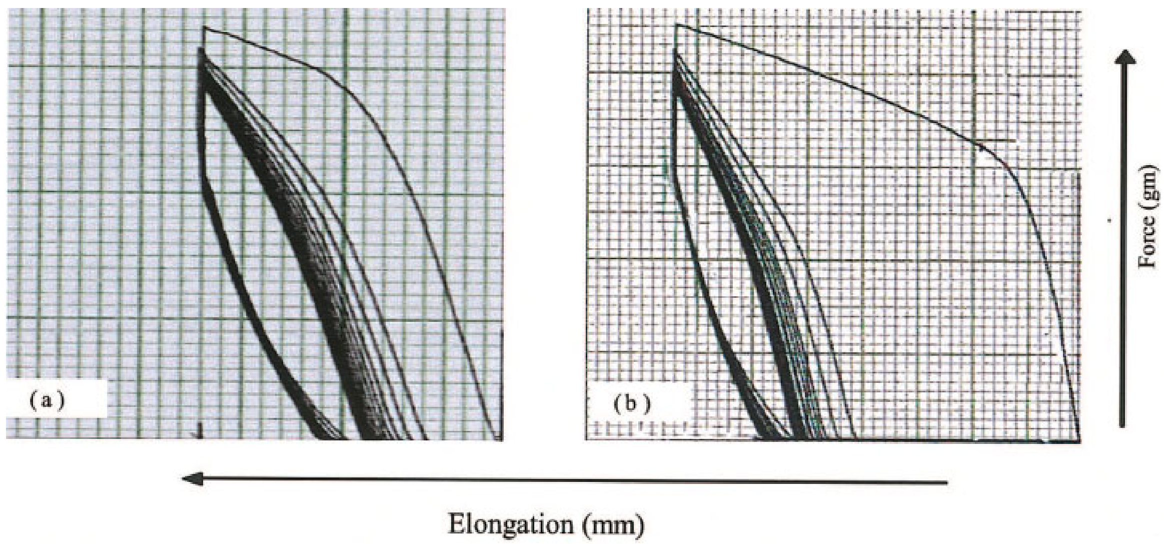

Figure 4 Typical load–elongation plots of Tencel monofilament: (a) 2% extension cycles and (b) 5% extension cycles. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Cumulative extension cycling

Hearle's theory of cumulative extension cycling

The cumulative extension theory[20] is based on the following assumptions: (a) The stress–strain curve in simple extension is ABE (Fig. 6), if a specimen is strained to point B and allowed to recover to C, it is assumed that, on restraining, the original stress–stain curve will rejoin at B and then follow towards E. (b) On first reaching any strain level, such as B, the elastic recovery (*r*, ratio of elastic strain *R* to total strain ε) will be a function of strain ε; in particular, *r* will be independent of previous history at lower strain levels.

Figure 7 illustrates the behavior in cumulative cycling; an imposed strain is applied to the material and then released. The material is permanently strained after this first cycle. The slack P is removed and then the imposed strain is again applied. The strain on the material in the second cycle is now $\varepsilon_2 = P_1 + \varepsilon_1$. After the second cycle the permanent strain is P_2 and is removed before applying ε_1; and so on.

Summarizing this we have:

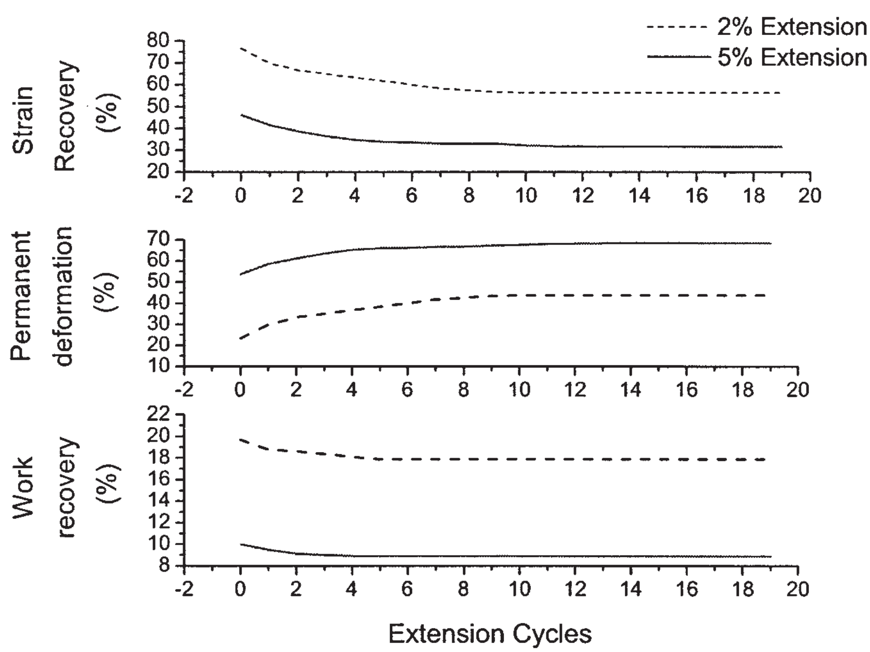

Figure 5 Elastic recovery curves at 2% and 5% extension level: permanent deformation; strain; and work recovery, vs. number of cycles.

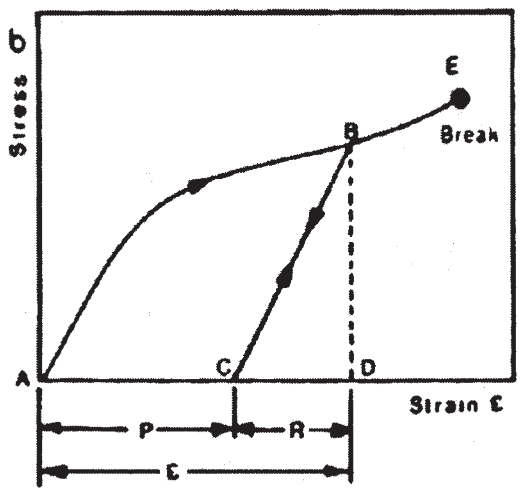

Figure 6 Idealized model of recovery behavior.

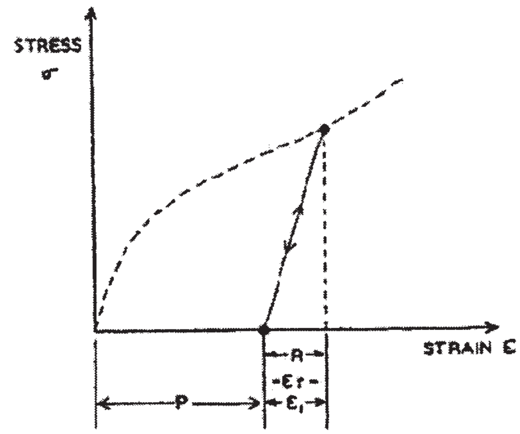

Figure 8 Limiting condition in cumulative extension cycling.

First cycle: Imposed strain = ε_1; strain recovery = r; permanent strain = P_1

$$P_1 = (1 - r_1)\varepsilon_1 \quad (1)$$

Second cycle: total strain = ε_2

$$\varepsilon_2 = P_1 + \varepsilon_1 = (1 - r_1) + \varepsilon_1 \quad (2)$$

Permanent strain = P_2

$$P_2 = (1 - r_2)\varepsilon_2 \quad (3)$$

(n − 1) cycle: permanent strain = P_{n-1}

$$P_{n-1} = (1 - r_{n-1})\varepsilon_{n-1} \quad (4)$$

nth cycle: total strain = ε_n

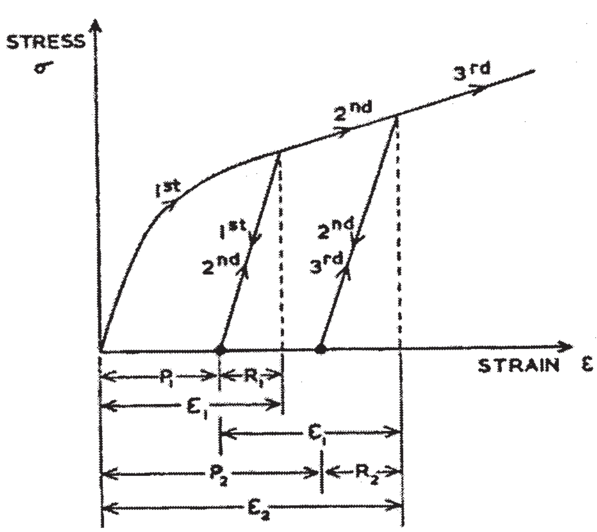

Figure 7 Cumulative extension cycling.

$$\varepsilon_n = P_{n-1} + \varepsilon_1 = (1 - r_{n-1})\varepsilon_{n-1} + \varepsilon_1 \quad (5)$$

(n + 1) cycle: total strain = $\varepsilon\bar{n}1$

$$\varepsilon_{n-1} = P_n + \varepsilon_1 = (1 - r_n)\varepsilon_n + \varepsilon_1 \quad (6)$$

The strain will have reached a limiting value when the total strain in the successive cycle remains unaltered, i.e., when

$$\varepsilon_n = \varepsilon_{n-1} \quad (7)$$

Thus,

$$\varepsilon_n = (1 - r_n)\varepsilon_n + \varepsilon_1 \quad (8)$$

$$\varepsilon_n r_n = \varepsilon_1 \quad (9)$$

In general, the condition for limiting extension is thus

$$\varepsilon r = \varepsilon_1 \quad (10)$$

This condition states that at the limit, the strain recovered after a cycle just equals the imposed strain, so that there is no additional straining in the next cycle, as illustrated in Figure 8.

A computer model was developed by Hearle and Plonsker[20] and limiting extension values at 2–10% extension levels were predicted for nylon, polyester, acetate, and viscose (Fig. 9). These limiting extension values were then compared with the experimental limiting extension values for each filament. For experimental measurements, an Instron tensile tester (constant rate of extension) was used. The chosen crosshead speed was 500 mm min^{-1} and chart speed was 1000 mm min^{-1}. A 250-mm gauge length was used for all tests. The limiting extension was assumed to be reached when strain differs by less than 1×10^{-8}.

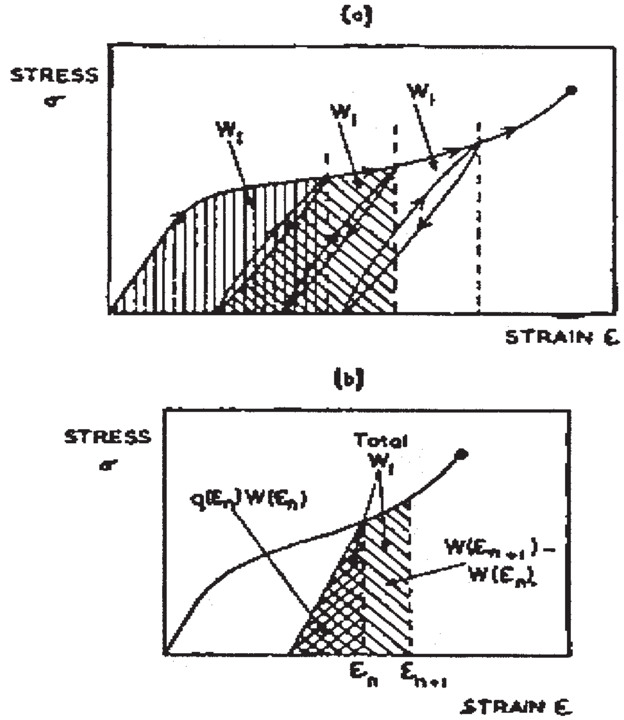

Figure 9 (a) energy cycling and (b) limiting condition in energy cycling.[20]

Energy cycle

This energy cycling behavior, also developed by Hearle, is more closely related to practical use of fibers; the behavior is similar to cumulative extension behavior. This works on the same assumptions made for cumulative extension cycling, and thus can be analyzed in the following way.

Let W_1 be the energy imposed in each cycle; $W(\varepsilon)$, the work absorbed in extending the specimen of the first occasion from zero strain to strain ε; and $q(\varepsilon)$ is the work recovered from strain, then work recovered in nth cycle from strain is $q(\varepsilon_n)W(\varepsilon_n)$. Assuming recovery along strictly the same path, the total energy absorbed in the next cycle must be given by

$$W_1 = q(\varepsilon_n)W(\varepsilon_n) + [W(\varepsilon_{n+1}) - W(\varepsilon_n)] \tag{11}$$

Thus,

$$W(\varepsilon_{n+1}) = [1 - q(\varepsilon_n)]W(\varepsilon_n) + W_1 \tag{12}$$

This is analogous to eq. (6). The condition for limit, namely $W(\varepsilon_{n+1}) = W(\varepsilon_n)$, will yield

$$q(\varepsilon)W(\varepsilon) = W_1 \tag{13}$$

Application of theory

In this study, Hearle's theory is used to observe cumulative cycling behavior of Tencel monofilaments at 2%, 5%, and 7% extension levels (Fig. 10). The strain behavior observed is also compared with the experimental strain behavior observed by Hearle for nylon, polyester, acetate, and viscose filaments.[20]

For a large imposed strain at the 7% extension level, the Tencel monofilament breaks during the second cycle, this is because the 7% extension level is very close to the breaking extension of the filament. At the same extension level, polyester, acetate, and viscose displayed elongation until breaking. The filament goes through at least 10–20 extension cycles before breakage. Nylon showed a change in behavior at 10.7% extension; below 10.7% imposed extension, nylon achieves a stable limit and at 10.7% imposed extension the length increases indefinitely.

At an imposed extension of 5%, the Tencel monofilament breaks in the third extension cycle or there is very small elongation of the specimen. At 5% imposed extension, viscose, and acetate also continued to elongate until they broke between 10 and 20 cycles; however, a change in cycling behavior of polyester was observed at a 5% imposed extension level, the behavior exhibiting a steadily increasing extension.

The strain behavior of Tencel filament at 2% imposed extension is shown in Figure 10. There is a steady increase in extension such that the fiber breaks in the region of cycles beyond those considered in this experiment. At the same extension level viscose exhibited continuing extension behavior whereas acetate and nylon achieved a stable limit after the first few cycles. The achievement of a stable limiting state after a limited number of cycles is a valuable characteristic of a textile specimen. The experimental behavior observed by Hearle was qualitatively similar to the predicted behavior from the computer model, but quantitatively the results showed higher limiting extension

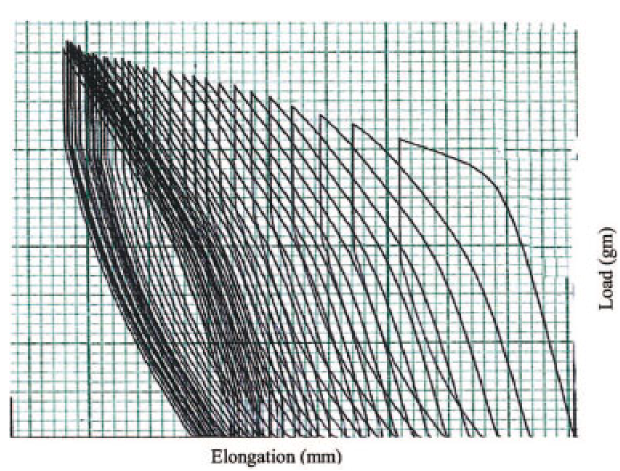

Figure 10 Typical load–elongation curves in cumulative cycling of Tencel monofilament at 2% extension. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

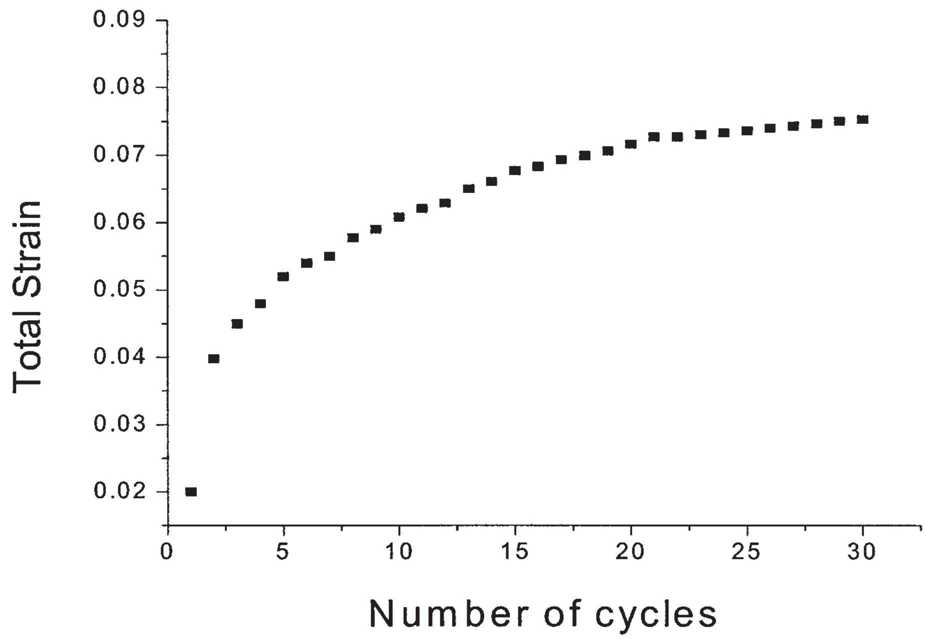

Figure 11 Total strain during cumulative cycling.

values than the predicted values, and a change of limiting extension to continuing extension at lower values of imposed extension such as 2%. This can be explained by the addition of secondary creep which was ignored in the theory.

In this study, in addition to strain behavior, the permanent strain, work recovery, and the total energy values were also determined and are plotted against total strain in Figure 12. There is a steady increase in permanent strain; however, the maximum energy was absorbed in the first two cycles; in the subsequent cycles, the absorption of energy is low. The work recovery decreased in the first two cycles, but there is a steady increase in the work recovery after the second cycle, which, according to Hearle, could be because the secondary creep now has less time to permanently elongate the specimen. In addition to secondary creep, the behavior observed also corresponds to the occurrence of primary creep.

Investigations of the structure-property relationships of Tencel filaments show that Tencel has a high degree of crystallinity and molecular orientation, even in amorphous areas.[1,2,12] The ratio of crystalline to amorphous areas is 9:1, which is quite high compared to viscose and modal fibers.[1,8] The tensile properties of Tencel filaments are due to the high orientation of the crystallites, but this, combined with the lower proportion of amorphous regions, gives filaments low extensibility. During repeated strain or stress applications, the stretching of crystallites and the elastic stretching and bending of chains occurs in the amorphous regions. First the secondary bonds between the chains are involved; on breakage of these secondary bonds in amorphous regions, primary creep (behavior of primary bonds) subsequently takes place. The achievement of limiting extension is a state where the energy absorbed by the specimen becomes equal to the energy recovered or the recovered strain equals the imposed strain. Thus, at this stage there will be no permanent deformation. The increase in permanent deformation of the Tencel filament suggests the continuing breakage of secondary bonds and stretching of the crystallites.

CONCLUSIONS

In this work, some of the important tensile properties of Tencel filaments including load–elongation and elastic recovery have been studied. We have also indicated the extent to which filaments can be twisted, which is important in determining the subsequent processing performance and the influence on subsequent fabric properties. Peak breaking load is obtained at 140 t m^{-1}. The elastic properties were determined using standard method ASTM D 1774–94. The results show that Tencel filaments have poor elastic recovery, which gradually decreases in simple extension cycles. In cumulative extension cycling, results show that at large and medium imposed extension Tencel filaments break eventually in the second extension cycle. However, for small imposed extension, increasing permanent elongation was observed. The magnitude and rate of primary creep is apparently low in Tencel filaments. We have ignored the affect of time dependency and relative humidity, which may be expected to influence tensile properties because of the hydro-

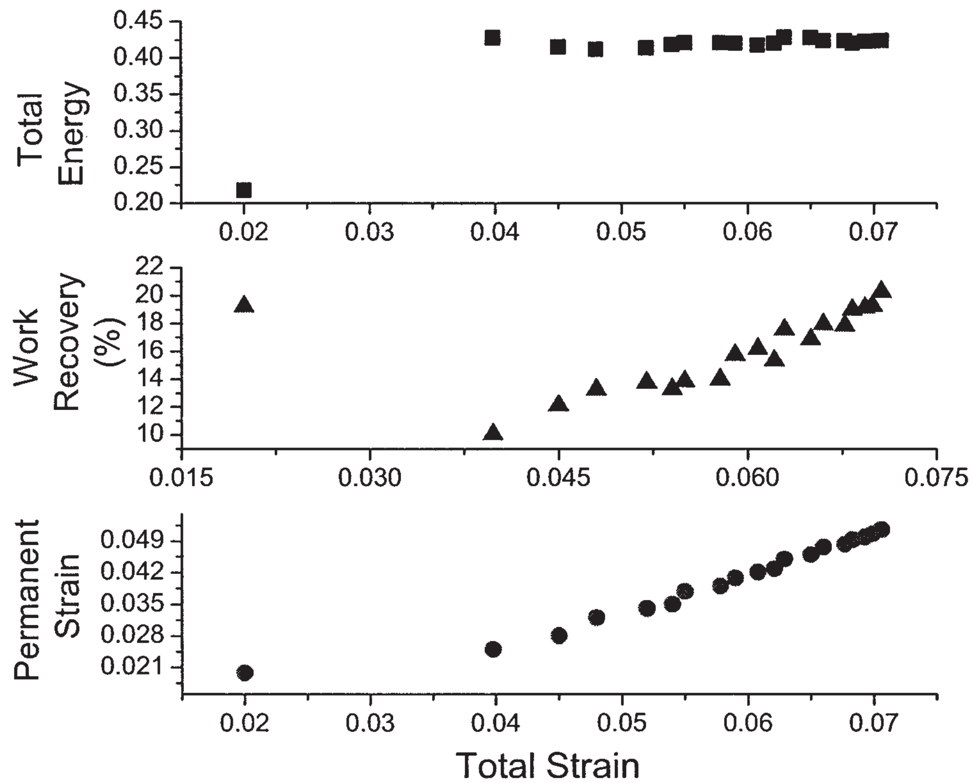

Figure 12 Cumulative cycling behavior of Tencel monofilament: total energy; work recovery; and permanent strain, vs. total strain.

philicity of Tencel. Further work is needed to observe the viscoelastic time dependency effects, and the effects of relative humidity and temperature on filament properties.

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