

Experimental study of the transverse mechanical properties of polyamide 6.6 monofilaments

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Abstract In this paper, we analyse experimental results concerning the transverse mechanical properties of PA6.6 monofilaments. Three diameters of such monofilaments (120, 230 and 400 μm) were compressed at seven different speeds, varying from 1 to 5,000 $\mu\text{m}/\text{min}$, until a maximum force of 2,000 N. The results show a high degree of anisotropy: the transverse Young's modulus is less than one-tenth the value of the longitudinal one. In general, as the speed increases, more energy is needed to compress the monofilament and the curves representing the evolution of the contact width as a function of the force per unit length are in descending order. This happens in the plastic region, as long as the phenomenon is well stabilised, and indicates a viscoelastoplastic behaviour of PA6.6 monofilaments in the transverse direction. Transverse relaxation tests confirmed this behaviour. However, the curves representing the evolution of the diameter as a function of the force per unit length are not always in descending order as the speed increases. These curves also show a change in the optical properties of the compressed monofilament. Scanning Electron

Microscope photos of transversely compressed PA6.6 monofilaments revealed that the monofilament seems to fibrillate inside its core.

Introduction

Polyamide monofilaments first appeared in 1938. Toothbrushes, clothes etc. can be distinguished within their first applications. Later on, their important mechanical properties (such as their excellent wear and fatigue resistance, their high strength and toughness) extended their domain of applications. Nowadays, they are also used in composite matrices (as reinforcement, like in car and aeroplane tyres), in many industrial applications (like in paper making machines), in seat belts, parachutes, ropes, fishing lines and nets. Thus, because of the steady expansion of the use of this kind of monofilaments, combinations of longitudinal and transverse loads are generally encountered. When polyamide monofilaments are found under such conditions, any study of their stress–strain behaviour or failure mechanisms must also include their transverse mechanical properties and the possibility of transverse damage. Since nowadays, the research concerning the mechanical properties of polyamide monofilaments has mostly been concentrated in the longitudinal direction. Very little effort has been made to study their transverse mechanical properties. In most cases, these monofilaments were treated as isotropic elastic cylindrical structures. It is correctly argued that this assumption is clearly inadequate for the analysis of monofilament behaviour in complex structures.

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Consequently, the monofilament anisotropy should be determined by detailed measurements of the transverse compression properties.

In spite of the fact that transverse mechanical properties are difficult to approximate, some effort has been done by some authors to develop theoretical models which are valid in the elastic region. The first one is reported by Hadley et al. [1] who considered monofilaments as transverse isotropic elastic cylinders. Thus, a theoretical solution was obtained for the width of the contact area between this cylinder and two parallel rigid plates compressing it across its diameter. By real measurements of the contact width, the Poisson's ratio and the extensional modulus, Hadley et al. [1] also give some first values of the transverse modulus of monofilaments. Later on, Pinnock et al. [2] extended this result by presenting a theoretical solution for the change of the diameter as a function of the linear force, during a transverse compression experiment. With this model, transverse modulus was obtained by measures of the diameter change rather than the contact zone. Using the theoretical results and the transverse load–displacement results, Phoenix and Skelton [3] developed a technique for calculating the transverse modulus and the maximum shear stress at yield or fracture. All this theoretical foundation is based on M'Ewen's [4] result for two elastic cylinders in contact along their generatrix.

To our knowledge, very little effort has been done to study the plasticity of transversely compressed monofilaments. In 1994, Kotani et al. [5] tried to model the plasticity of transversely compressed polyethylene fibres by means of finite elements, in order to analyse the yield region. Later on, Jones et al. [6] showed the first experimental stress–strain curves concerning transversely compressed PPXTA fibres. In 2000, Singletary et al. [7, 8] calculated some transverse mechanical properties of PPTA fibres. They also used a finite element simulation to describe the inelastic transverse deformation of these fibres.

The aim of this paper is to examine some first results we obtained for the transverse mechanical properties of polyamide 6.6 monofilaments using the experimental technique we specially developed in our laboratory [9]. The experiments were done at various speeds in order to study possible viscoelasticity of this type of monofilaments in the transverse direction. We studied the evolution of the linear compression force (the force per unit length) as a function of the displacement, and of the contact width and the diameter as a function of the linear compression force. The viscoelasticity has also been examined by means of transverse relaxation tests. We also observed the evolution of the transverse

Young's modulus (E_T) as a function of the compression speed. Finally, we show some Scanning Electron Microscope (SEM) photos of transversely compressed polyamide 6.6 monofilaments.

Longitudinal behaviour

In order to have a better image of the mechanical behaviour of polyamide 6.6 monofilaments, we briefly state in this paragraph the results we obtained while examining their longitudinal mechanical behaviour. These results have also been published in one of our previous papers [10].

Tensile experiments were performed for PA6.6 monofilaments of 400 μm of diameter at six different speeds varying from 5 to 250 mm/min. We have realised 12 experiments per speed. The length of the specimens was 250 mm and all tests were done at ambient temperature of 20 °C and 65% of relative humidity. Figure 1 shows a comparison between the mean curves of these tensile tests. We can see that the curves are superimposed and that there is no important evolution of quantities like force to rupture as the strain speed increases. The only quantity that changes is the elongation to rupture. The mean Young's modulus value is about 2.5 GPa.

On the contrary, the faces of rupture of PA6.6 monofilaments differ when increasing the strain speed. We show in Fig. 2 photos of such faces of rupture of PA6.6 monofilaments tested at four different speeds: 10, 25, 50 and 125 mm/min (taken at a HITACHI S-2360N Scanning Electron Microscope). As it is seen by the crack length formed during break (Fig. 2a, b), polyamide monofilaments “fibrillate” more when decreasing the tensile speed. This kind of rupture is

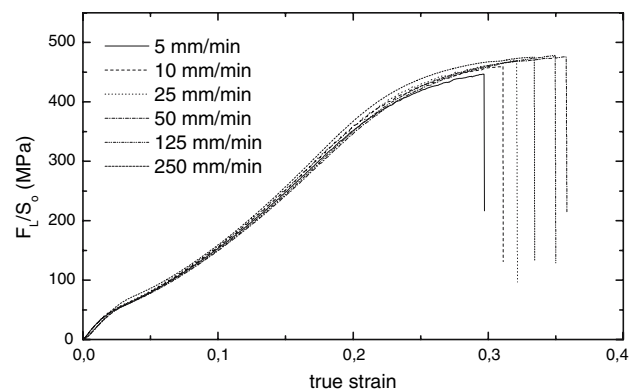
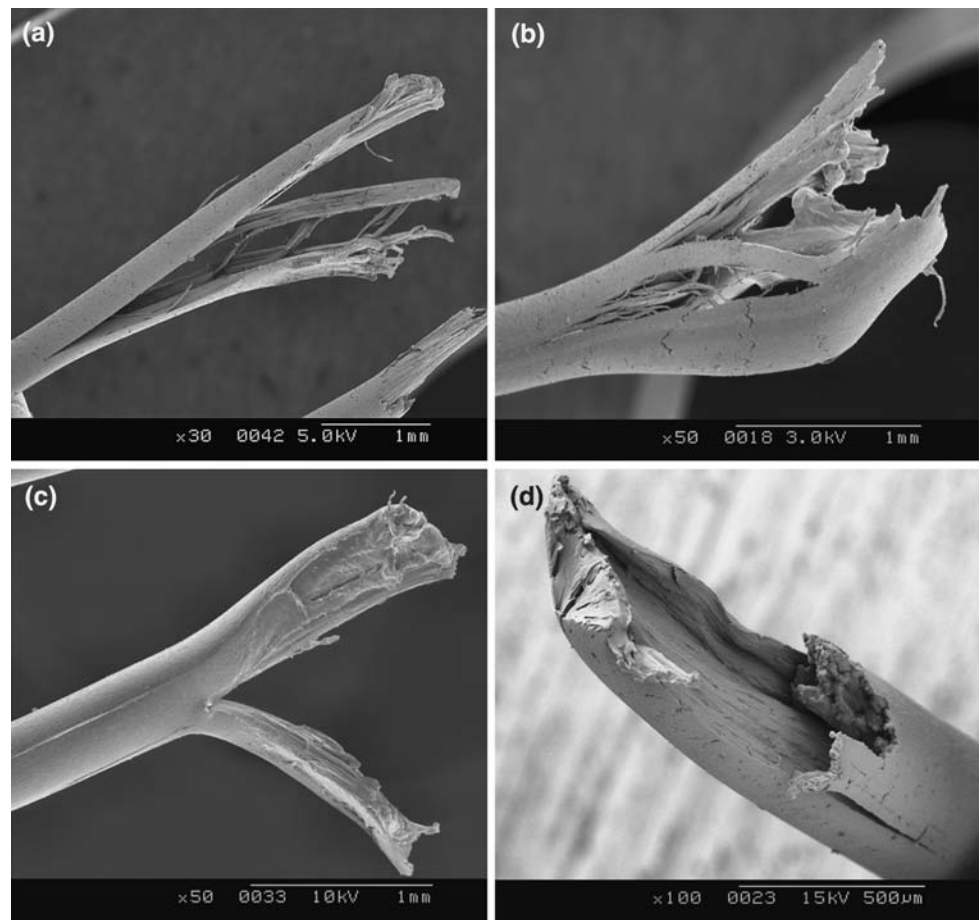


Fig. 1 Comparison between mean tensile curves obtained at different speeds (F_L : tensile force, S_0 : initial section of PA6.6 monofilament)

Fig. 2 SEM photos of the faces of rupture of PA6.6 monofilaments of 400 μm of diameter after tensile break at four different speeds: (a) 10 mm/min, (b) 25 mm/min, (c) 50 mm/min and (d) 125 mm/min



characteristic of highly oriented monofilaments like those of aramide or of high-density polyethylene [11]. For tensile speeds above 50 mm/min, the rupture of polyamide monofilaments becomes fragile (Fig. 2c, d). These observations can be explained as follows: for small speeds, molecular chains can be reoriented, displaced and finally detached, which results to the observed “fibrillation” during rupture. As increasing the tensile speed, molecular chains simply do not have the time to reorient.

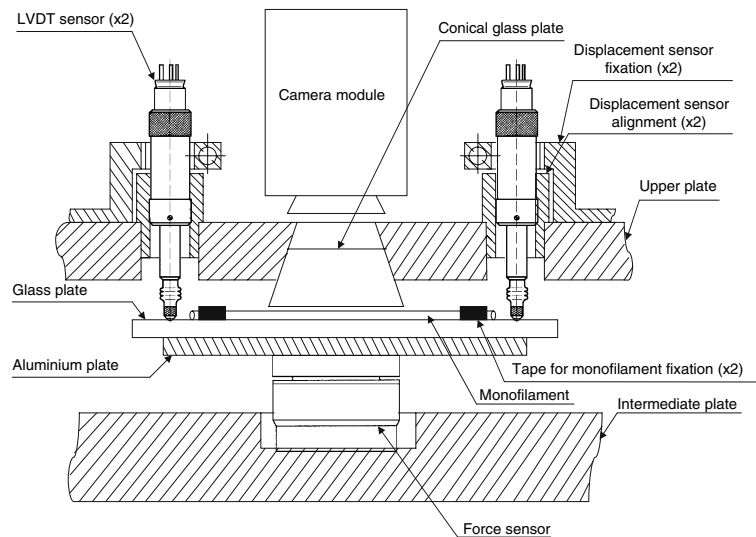
Transverse behaviour

Experimental details

Transverse compression tests were realised using three diameters of polyamide 6.6 monofilaments (120, 230 and 400 μm), at seven different speeds: 1, 10, 100, 500, 1,000, 3,000 and 5,000 $\mu\text{m}/\text{min}$. In order to name these types of monofilaments we use the initial values of the diameter given by the company they were bought and not the ones we measured, which were

found to be slightly higher (see Sect. “Evolution of the diameter as a function of the linear compression force”). Five experiments per speed were fulfilled. In order to realise these tests we used the experimental setup we specially developed in our laboratory (see [9] and Fig. 3), which can transversely compress any kind of polymer monofilament. Thus, we directly measured the compression force and displacement applied on the tested monofilament. Then, by means of a special image analysis method, developed also in our laboratory (see [9]), we calculated the evolution of the diameter of the monofilament and of the contact width between the monofilament and the two glass plates compressing it across its section (see [9] and Fig. 3). All monofilaments were compressed until a maximum force of 2,000 N (~ 40 N/mm, as the length of the compressed monofilament is equal to 51 mm, see [9]). In addition, transverse relaxation tests were also realised; the speed until maximum loading was 5,000 $\mu\text{m}/\text{min}$. All tests (transverse compression and relaxation ones) were done at ambient temperature of 20 $^{\circ}\text{C}$ and 65% of relative humidity.

Fig. 3 Schematisation of the transverse experimental set up (see also [9])



Results and discussion

Evolution of the linear compression force as a function of the mean displacement

The direct measure of the force and the displacement during the transverse compression of a polyamide monofilament permits to plot the evolution of the linear force as a function of the mean displacement (we use the term mean displacement since it represents the mean value of the signals of the two displacement sensors placed on the right and left of the tested monofilament, see [9] and Fig. 3). Such plots are shown in Fig. 4a–c (for the three diameters of PA6.6 monofilaments we tested 120, 230 and 400 μm , respectively), where the mean curves out of five experiments per speed are represented. We remark a strong influence of the compression speed (V), since for all three types of PA6.6 monofilaments the curves are in fully ascending order as V increases. This phenomenon indicates that more energy is needed to transversely compress polyamide monofilaments when raising V .

Evolution of the transverse Young's modulus

Using the force–displacement data, by means of the Phoenix and Skelton technique [3], we calculated the E_T values of the three diameters of PA6.6 monofilaments (120, 230 and 400 μm) at all speeds. These values, along with the mean values of E_T for all three diameters of PA6.6 monofilaments that we tested, are shown in Table 1. We find that for the monofilaments of 230 and 400 μm of diameter, the E_T is located between 100 and 200 MPa. On the contrary, for the smallest monofilament (of 120 μm of diameter), the E_T

is located between 180 and 260 MPa. By examining Table 1, we notice that at all compression speeds the E_T values of the smallest monofilament are superior to the ones of the other two. On the contrary, there is no apparent difference between the calculated E_T values of the other two diameters of PA6.6 monofilaments (230 and 400 μm). This indicates that, in the transverse direction, polyamide monofilaments become stiffer with a significant decrease to their diameter (about four times in our case).

Let us now focus on the PA6.6 monofilament of 400 μm of diameter. The mean value of the E_T corresponding to this type of monofilament was found to be at about 163 MPa. The longitudinal Young's modulus (E_L) of this type of PA6.6 monofilament was found to be about 2.5 GPa (see Sect. "Longitudinal behaviour" and [10]). This means that E_L is more than 10 times superior to E_T . We believe that a similar tendency should appear for the other two diameters of PA6.6 monofilaments, and consequently, for any type of polyamide monofilaments of important diameter. Thus, we confirm the high anisotropy of polyamide monofilaments.

Evolution of the contact width as a function of the linear compression force

Figure 5a–c show the mean curves (out of five experiments) of the contact width evolution as a function of the linear compression force (which means the value compression force divided to the length of the compressed monofilament equal to 51 mm, see [9]). These curves were calculated until the speed of 1,000 $\mu\text{m}/\text{min}$, since for the other two higher speeds (3,000 and 5,000 $\mu\text{m}/\text{min}$) the image acquisition frequency was too

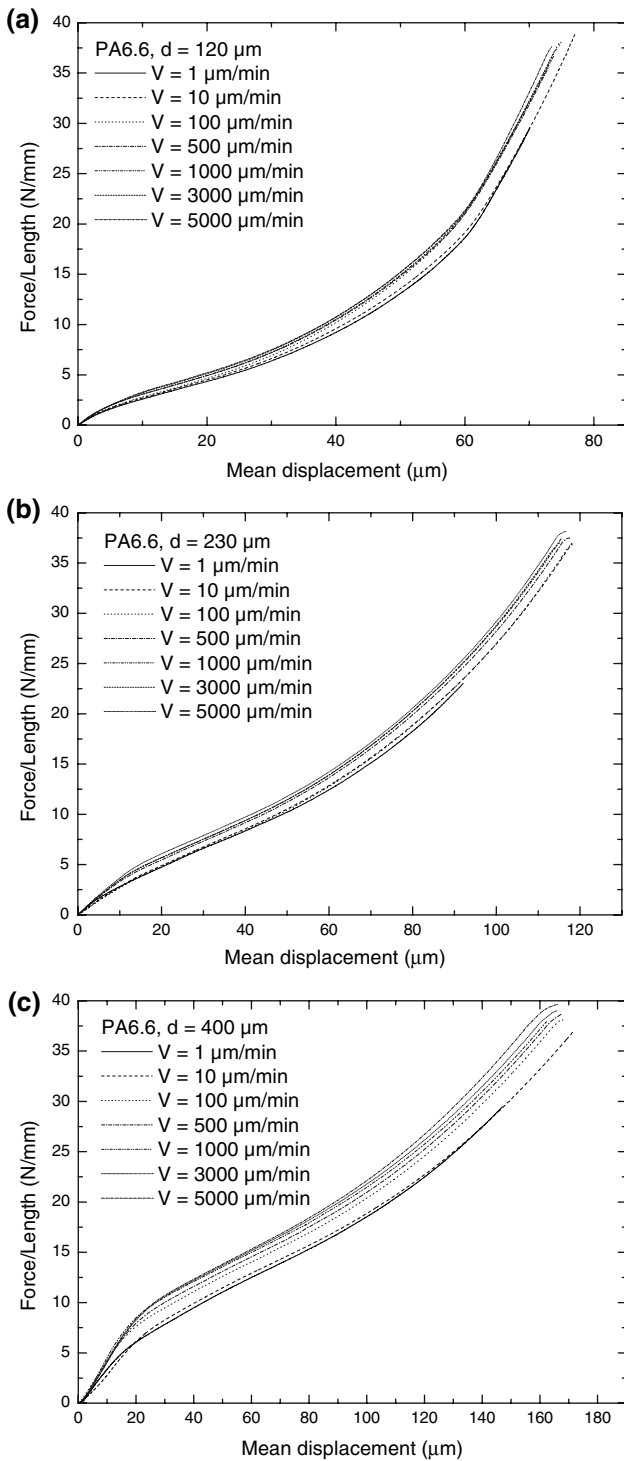


Fig. 4 Linear force as a function of the mean displacement for the three diameters of PA6.6 monofilaments: (a) 120 μm , (b) 230 μm and (c) 400 μm

slow to follow the phenomenon. As previously, we observe that there is a strong influence of the compression speed (V): for the monofilaments of 120 and 400 μm of diameter (Fig. 5a, c), the curves are in fully

Table 1 Transverse Young’s modulus values of the three diameters (120, 230 and 400 μm) of PA6.6 monofilaments (d : initial value of the diameter of the tested monofilament)

V ($\mu\text{m}/\text{min}$)	E_T (MPa)		
	PA6.6, $d = 120 \mu\text{m}$	PA6.6, $d = 230 \mu\text{m}$	PA6.6, $d = 400 \mu\text{m}$
1	180 \pm 22	166	140 \pm 10
10	224 \pm 21	124 \pm 9	123 \pm 17
100	184 \pm 16	106 \pm 10	164 \pm 8
500	208 \pm 20	152 \pm 26	169 \pm 14
1,000	260 \pm 18	158 \pm 34	189 \pm 17
3,000	241 \pm 15	201 \pm 30	172 \pm 13
5,000	242 \pm 21	166 \pm 16	187 \pm 22
Average values	220 \pm 31	153 \pm 31	163 \pm 25

descending order as V increases. This happens as long as the influence of the production method to the physical structure of the monofilament has been eliminated (after a charge of ~ 10 N/mm for the PA6.6 monofilament of 120 μm of diameter and ~ 20 N/mm for the 400 μm one). At the beginning of the experiment, this influence is very important and does not allow any safe conclusions to be taken out. However, the previous tendency observed in the plastic region can be explained by the fact that at small speeds the molecular chains have the time to accommodate themselves to the compression force, to be reoriented etc. Consequently, for the same force level, the contact width becomes smaller as the speed increases. This is in totally accordance with a previous conclusion that more energy is needed to transversely compress the monofilament when increasing the compression speed.

Contrary to the tendency observed for the PA6.6 monofilaments of 120 and 400 μm of diameter, the curves representing the evolution of the contact width as a function of the linear force for the PA6.6 monofilament of 230 μm of diameter (Fig. 5b) seem to be superimposed. There is, however, a small discrepancy between these curves too: the one corresponding to the speed of 1 $\mu\text{m}/\text{min}$ is slightly superior to the one corresponding to the speed of 1,000 $\mu\text{m}/\text{min}$. This means that the compression speed has an effect to this type of monofilament too. This effect, yet, is not as apparent as to the other two diameters of PA6.6 monofilaments that we tested (120 and 400 μm), since it is seen between compression speeds that have very important differences (1 and 1,000 $\mu\text{m}/\text{min}$). This phenomenon is probably due to the more significant effect of the production method to the physical structure of the PA6.6 monofilament of 230 μm of diameter comparing to the other two (differences can be found to interactions between molecular chains, molecular orientation

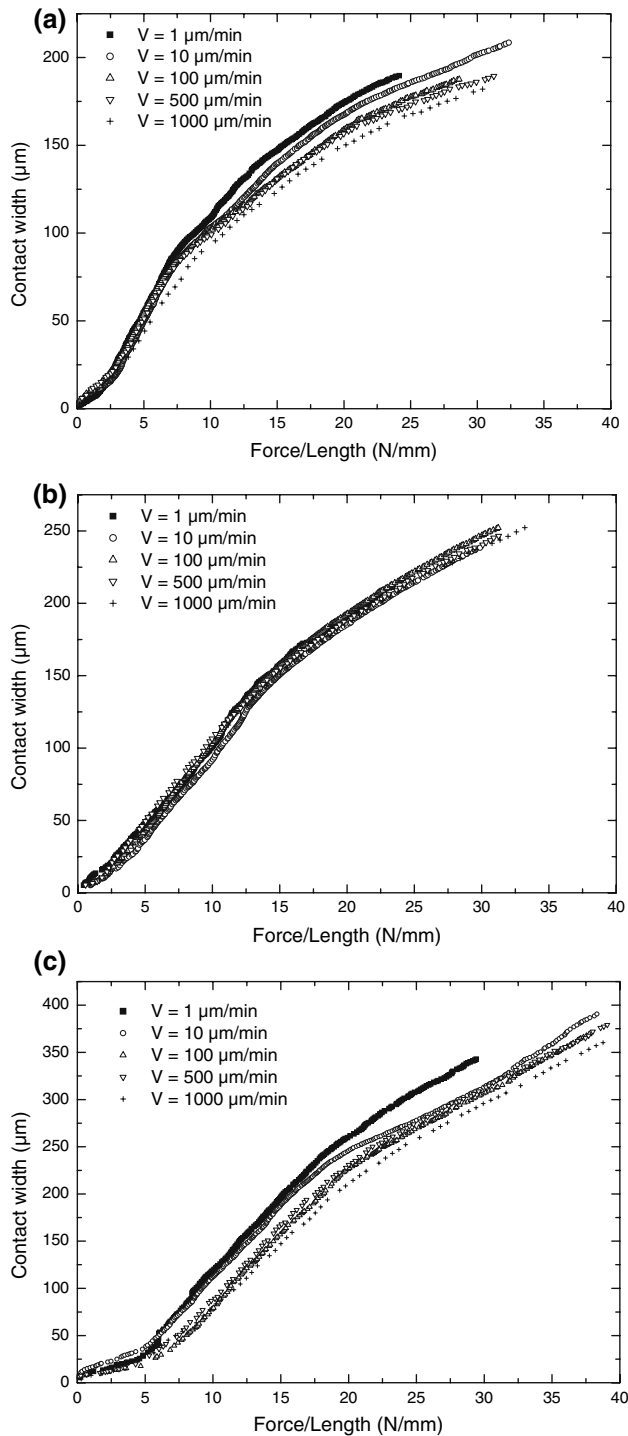


Fig. 5 Contact width as a function of the linear force for the three diameters of PA6.6 monofilaments: (a) 120 μm , (b) 230 μm and (c) 400 μm

etc, see for example [12, 13]). Nevertheless, this case should be considered as an exception to the previous conclusions.

To finish with, let's take a closer look at Fig. 5a–c. We find that, at all compression speeds, the contact

width for the PA6.6 monofilament of 120 μm of diameter reaches the value of 200 μm at the end of the experiment (at the linear compression force of 40 N/mm). For the same force level and at all compression speeds, the value the contact width of the PA6.6 monofilament of 230 μm of diameter reaches the value of 250 μm . Finally, always for the same force level and at all compression speeds, the value of the contact width of the PA6.6 monofilament of 400 μm of diameter is of the order of 350 μm . This means that, for the same force level, the contact width increases when increasing the initial value of the diameter of the compressed PA6.6 monofilament. As before, this happens at all speeds as long as the influence of the production method to the physical structure has been eliminated, since at the beginning of the experiment the phenomenon is not stabilised and no safe conclusions can be deducted. It indicates that the same value of the compression force does not have the same effect when changing the initial value of the diameter of the polyamide monofilament: the more the diameter increases, the more the contact width augments.

Evolution of the diameter as a function of the linear compression force

The mean curves (out of five experiments) of the diameter evolution as a function of the linear compression force for all types of PA6.6 monofilaments we tested, are shown in Fig. 6a–c (until the compression speed of 1,000 $\mu\text{m}/\text{min}$ as previously). We notice also here the influence of the compression speed. However, these curves are not always in fully descending order as V increases, even though the ones corresponding to the speed of 1 $\mu\text{m}/\text{min}$ are superior to the others for all three diameters of PA6.6 monofilaments. Only the evolution of the diameter of the smallest monofilament (of a 120 μm of initial diameter) shows the same tendency as the evolution of the contact width, but after a higher force level than 10 N/mm (~ 20 N/mm). We believe that this happens because of the fact that the forces generated inside the core of the monofilament are more important along the direction of compression (axis 2, Fig. 7) than along the vertical one [14] (axis 1, Fig. 7). Thus, until the compression level of 40 N/mm, the forces along the vertical direction in the PA6.6 monofilaments of 230 and 400 μm of diameter are not important enough to eliminate the influence of the production method to the physical structure, and consequently, to reveal the real tendency of the phenomenon. However, the opposite appears to be the case for the PA6.6 monofilament of 120 μm of initial diameter (see Fig. 6a) after the force level of 20 N/mm.

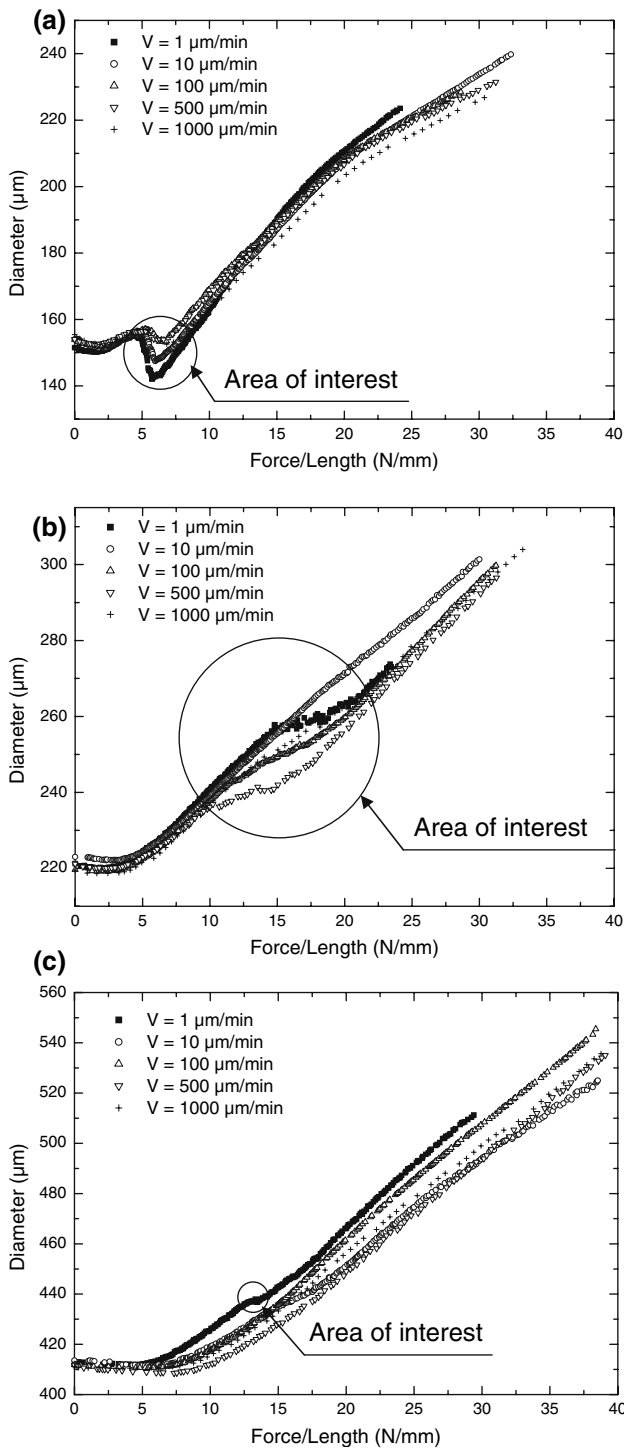


Fig. 6 Diameter as a function of the linear force for the three diameters of PA6.6 monofilaments: (a) 120 µm, (b) 230 µm and (c) 400 µm

This last conclusion is in totally accordance with the tendency observed when examining the percentage of the increase of the initial value of the diameter of the compressed PA6.6 monofilament at the end of the experiment: the PA6.6 monofilament of 120 µm of

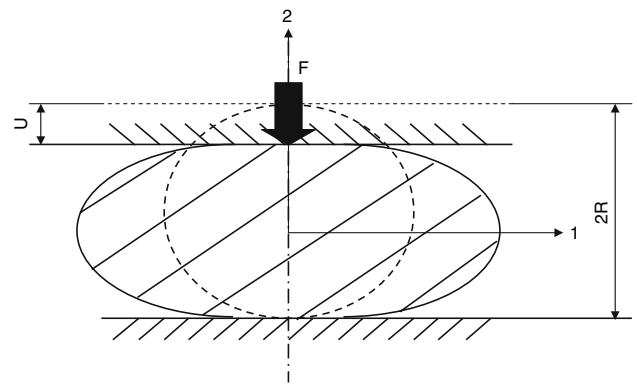


Fig. 7 Schematisation of the section of a transversely compressed polyamide monofilament (F : linear force, U : displacement, $2R$: monofilament initial diameter)

diameter reaches, at all compression speeds, the value of about 230 µm (corresponding to a percentage of increase of about 55%, since the initial value of the diameter of this monofilament was measured at about 150 µm); the PA6.6 monofilament of 230 µm reaches, at all compression speeds, the value of about 300 µm (corresponding to a percentage of increase of about 35%, since the initial value of the diameter of this monofilament was measured at about 220 µm); the PA6.6 monofilament of 400 µm of diameter reaches, at all compression speeds, the value of about 530 µm (corresponding to a percentage of increase of about 30%, since the initial value of the diameter of this monofilament was measured at about 410 µm). This phenomenon also reveals that the same value of the compression force has a more important effect to the evolution of the diameter when decreasing the initial value of the diameter of the tested polyamide monofilament: the more the initial value of the diameter decreases, the more the monofilament is elongated. It happens once the forces generated by the compression along the vertical direction (axis 1, Fig. 7) become important enough to eliminate the influence of the production method to the physical structure of PA6.6 monofilaments, since at the beginning of the experiment no safe conclusions can be taken out.

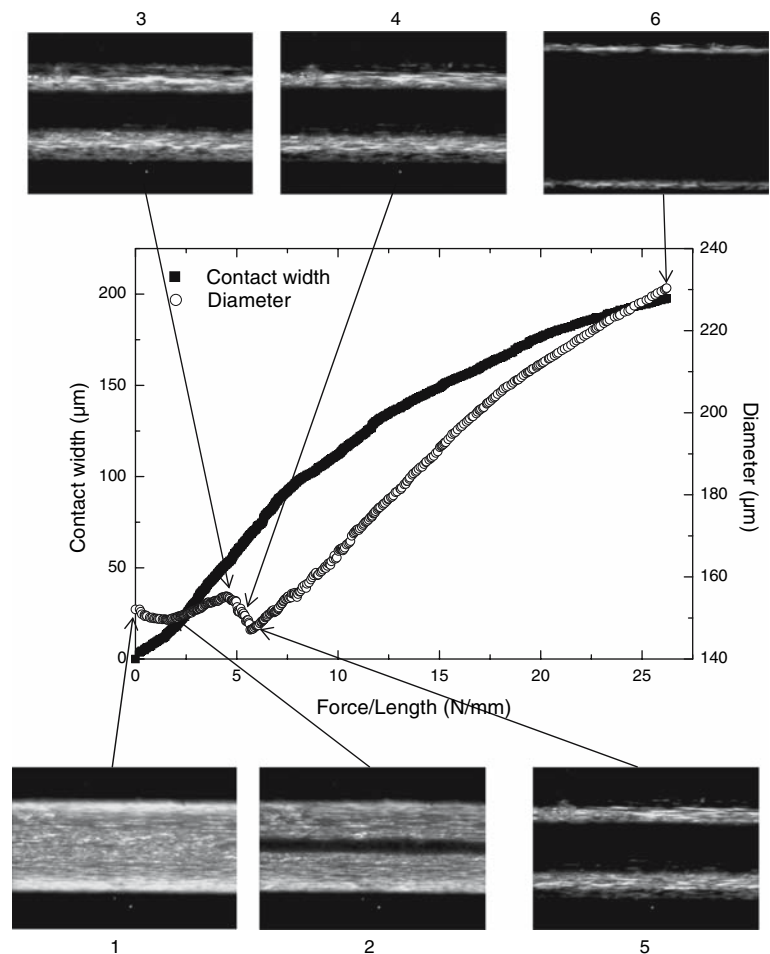
Observing the curves shown in Fig. 6a–c, one could remark a particular change to the slope of almost all of them. For the monofilament of 400 µm of initial diameter, this phenomenon appears only for the speed of 1 µm/min (area of interest, see Fig. 6c). For the 230 µm one, it appears at almost all the curves except the one corresponding to the speed of 10 µm/min (area of interest, see Fig. 6b), where it has also appeared but not at all five experiments done at this speed. For the 120 µm one, this change appears at all compression

speeds without any exception (area of interest, Fig. 6a). For all three types of polyamide monofilaments and for all the curves of Fig. 6, we also notice a small decrease to the initial value of the diameter at the very beginning of the experiment.

In order to explain all these particularities, let's take an experiment done on a PA6.6 monofilament of 120 μm of initial diameter at a compression speed of 1 $\mu\text{m}/\text{min}$ (Fig. 8). This figure shows photos of the monofilament, as it is seen by the camera (which is placed upon the monofilament, see Fig. 1 and [9]), at particular moments during the experiment. Photo 1 shows the monofilament at the beginning of the experiment. Photo 2 shows the monofilament at the end of the zone where the value of the diameter seems to decrease slightly. The difference between the first and the second photo is that the borders of the monofilament are seen clearer on the second photo than on the first one. Thus, it concerns an optical problem and we should consider that the value of the diameter remains constant until the point where it starts to increase. Photo 3 shows the state of the

monofilament just before the zone named “area of interest” (see Fig. 6a). We remark some black pixels formed inside the up part of the monofilament. These points increase as the experiment continues (photo 4, Fig. 9). At the end of this zone, almost half of the up part of the monofilament is not seen by the camera (photo 5, Fig. 9). This phenomenon results to the abrupt change of the slope of the calculated curve representing the evolution of the diameter. We believe that in this zone the monofilament changes its optical properties and does not reflect the light the same way as before. This change does not seem to be similar for all the types of PA6.6 monofilaments we tested (see Fig. 6b, c). This is probably due to the fact that when the initial value of the diameter of the monofilament changes, the effect of the production method to its physical structure differs. However, this optical problem can probably be corrected by using for example optical fibres to enlighten the borders of the monofilament during the experiment. Finally, photo 6 shows the state of the monofilament at the end of the experiment.

Fig. 8 Photos of the PA6.6 monofilament, of 120 μm of diameter, transversely compressed at a speed of 1 $\mu\text{m}/\text{min}$, at interesting moments during the experiment



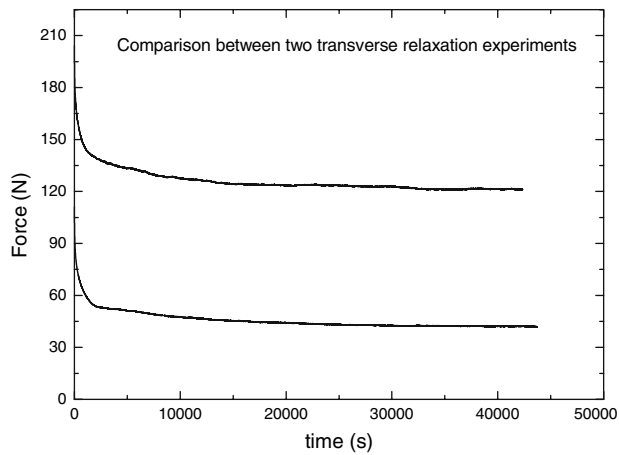


Fig. 9 Comparison between two transverse relaxation tests of the PA6.6 monofilament of 400 μm of diameter

Transverse relaxation experiments

We have noticed until now a strong influence of the compression speed to the transverse mechanical properties of polyamide monofilaments of important diameter. This conclusion makes us believe that their transverse mechanical behaviour should be characterized by some kind of viscoelasticity. In order to verify this, we also realised transverse relaxation tests to the PA6.6 monofilament of 400 μm of initial diameter at two different force levels: 90 and 180 N (see Fig. 9). The results show that the force decreases very rapidly at the beginning of the experiment and attains a residual value at the end (after about 45,000 s of relaxation time). We believe that the other two diameters of PA6.6 monofilaments (120 and 230 μm) should have a similar response to transverse relaxation testing. Therefore, we confirm the viscoelasticity of polyamide monofilaments of important diameter in the transverse direction. Combining now to the fact that during transverse compression tests the influence of the compression speed has been detected once the effect of the production method to the physical structure has been eliminated (see Sects. “Evolution of the contact width as a function of the linear compression force”, “Evolution of the diameter as a function of the linear compression force”), we believe that the transverse mechanical behaviour should be viscoelastoplastic.

Scanning electron microscope photos

In order to finish with this study, it is interesting to examine some Scanning Electron Microscope (SEM) photos of transversely compressed PA6.6 monofilaments. We show such photos, of the three types of

PA6.6 monofilaments tested at a speed of 1 $\mu\text{m}/\text{min}$, in Fig. 10a–c (of 120, 230 and 400 μm of diameter, respectively). These photos show no visible cracks, damage or fibrillation on the skin of the tested monofilament, which could be attributed to the experiment. We only distinguish the contact width. Therefore, we can conclude that the monofilament fibrillates inside its core. The same phenomenon has also been suggested by Singletary et al. [8], when modelling the transverse compression of PPTA fibres. This indicates an interesting difference with the longitudinal rupture that begins from the skin by means of surface cracks, which then propagate inside the core [15].

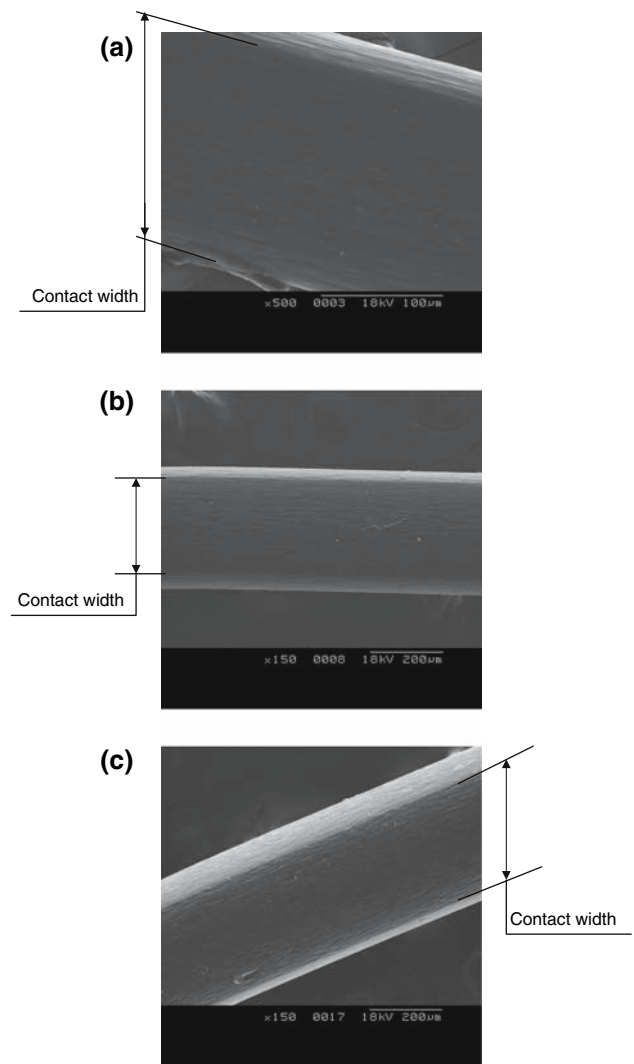


Fig. 10 SEM photos of the three diameters of transversely compressed PA6.6 monofilaments at a speed of 1 $\mu\text{m}/\text{min}$: (a) 120 μm , (b) 230 μm and (c) 400 μm

Conclusions

In this paper, we analysed results concerning the transverse mechanical properties of PA6.6 monofilaments. In order to realize transverse compression experiments and to treat experimental data, we used the technique we specially developed in our laboratory [9]. By varying the speed from 1 to 5,000 $\mu\text{m}/\text{min}$, we were able to observe the influence of the compression speed to the transverse mechanical behaviour of polyamide 6.6 monofilaments. Thus, some very important conclusions were taken out while increasing the speed:

- More energy is needed to transversely compress the monofilament;
- The curves representing the evolution of the contact width as a function of the linear force are in fully descending order; this happens in the plastic region as long as the effect of the production method to the physical structure has been eliminated;
- The curves representing the evolution of the diameter as a function of the linear force seem to have the same tendency as the ones representing the evolution of the contact width, but after a higher force level; this happens because of the fact that forces along the compression direction are much more important than those along the vertical one.

In addition, we find for the same level of the linear compression force once it becomes important enough to stabilize the phenomenon:

- The more the initial value of the diameter of the PA6.6 monofilament increases, the more the contact width augments;
- The more the initial value of the diameter of the PA6.6 monofilament decreases, the more the monofilament is elongated.

All these conclusions indicate that the transverse mechanical behaviour of polyamide monofilaments of important diameter is characterised by a strong viscoelasticity. This viscoelasticity has also clearly appeared when realising transverse relaxations tests. These tests revealed a viscoelastoplastic behaviour of this type of monofilaments in the transverse direction.

Another interesting result, deduced by the evolution of the diameter, is the fact that the optical properties of the monofilament change during the experiment, since it does not seem to reflect the light the same way at the beginning and at the end of the test. The calculation of the transverse Young's modulus,

using the Phoenix and Skelton technique [3], revealed the strong anisotropy of polyamide monofilaments: E_T was found to be more than 10 times inferior to E_L . In addition, the values of E_T show that polyamide monofilaments become stiffer when the initial value of the diameter decreases significantly. SEM photos of transversely compressed PA6.6 monofilaments showed no visible cracks or damage on their skin, meaning that, in the transverse direction, the monofilament fibrillates inside its core.

All these results and conclusions are the very first ones we got using our experimental technique [9]. They open a large field of investigation, since until nowadays, very little data concerning the mechanical behaviour of polymer monofilaments in the transverse direction is known. Further study of this problem will mostly be concentrated on modelling this type of behaviour of polymer monofilaments in order to quantify the parameters characterising the viscoelasticity, and on fatigue tests in order to identify clearly the different regions of the monofilament response to transverse compression (elastic region, yield region, plastic region etc).

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