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Effect of anisotropic thermal expansion on the torsional actuation of twist oriented polymer fibres

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Abstract

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Effect of anisotropic thermal expansion on the torsional actuation of twist oriented polymer fibres

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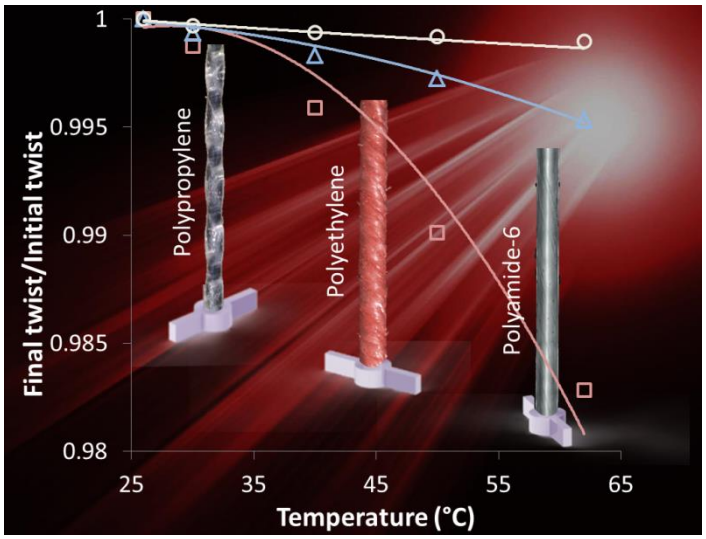
Abstract

Torsional actuation of twisted polymer fibres is the basis for high performance tensile actuation when these fibres are formed into coils. The thermally-induced torsional actuation of twisted polyamide-6 fibres can be predicted by a single helix approximation when the measured diameter and length direction thermal expansion coefficients are known. The single helix model illustrates the sensitivity of the magnitude of torsional actuation to the volume expansion anisotropy for a given volume change. The applicability of the model has been further assessed by investigating three polymer fibres that display different thermal expansion anisotropies. Commercially available polyethylene, polypropylene and polyamide-6 fibres were twisted to the maximum extent without coiling and then heat treated to fix the twisted structure. Heating the twisted fibres between 26 – 62°C resulted in a partial untwist which was reversed during cooling. The single-helix model of the twisted fibres was used to accurately predict the torsional stroke based on the measured fibre length and diameter change during heating. Comparative torsional stroke of twisted polyamide-6, polyethylene and polypropylene was explained in terms of materials thermo-physical properties. Generated blocked torques was also correctly predicted by the single-helix model when combined with the measured fibre torsional stiffness. Variances between torsional stiffnesses were found to be dependent of different anisotropic thermal properties of tested fibres.

Keywords

Twisted fibre; torsion; actuation.

Graphical Abstract



1. Introduction

Torsional actuation by the reversible partial untwisting of highly twisted fibres or yarns has been recently described in a range of materials, including carbon nanotubes [1-5], graphene [6], and oriented polymers [7, 8]. These systems have shown impressive performances in terms of torsional stroke (rotation), speed and torque generation. Torsional strokes produced by a volume expansion have exceeded one full turn per millimetre length of the actuating fibre [5, 6]. Rotation speeds in excess of 10,000 revolutions per minute were recorded for electrically heated carbon nanotube yarns infiltrated with paraffin wax [3] and similar systems have generated torque densities of up to 8 Nm/kg based on the actuating yarn mass [3]. Potential applications of the torsional actuators include micro-robotics [9], microfluidic mixing [1], microsensors [10], and energy-harvesting devices [8]. Furthermore, the torsional actuation is directly coupled to large scale tensile actuation when the twisted fibres and yarns are formed into coils (Fig. 1c) [3, 7]. Coiled polymer fibres generate very high tensile strokes, stress and power densities [11] and can be easily made from readily-available commodity polymer fibres, such as polyesters, polyamides and polyethylenes.

Torsional actuation occurs during volume change of systems that incorporate a helically oriented and mechanically stiff element (Fig. 1a). Macroscopic examples include elastomeric bladders wrapped with reinforcing fibres where inflation of the bladder causes rotation of the unclamped end [12]. The geometric relationship between the fibre wrap angle (α_f), the number of turns (N) the reinforcing fibre makes for a length of bladder (L) and bladder

diameter (D) is illustrated in Fig. 1b. Applying this single helix model to approximate the structure of twisted polyamide-6 fibres where α_f is the initial wrap angle at the fibre surface has provided remarkably accurate predictions of the thermally-induced torsional actuation [13]. When a volume change occurs, the ratios of final to initial turns (λ_n), fibre length (λ_l), fibre diameter (λ_d) and string length (λ_s) for a single helix are geometrically related by [1, 7, 13]:

$$\lambda_n = \left[\frac{1}{\tan^2\alpha_f}\left(\frac{\lambda_s^2-\lambda_l^2}{\lambda_d^2}\right)+\frac{\lambda_s^2}{\lambda_d^2}\right]^{1/2} \quad (1)$$

Fibre untwist of a few percent of the initially inserted twist is expected for small volume expansions (Fig. 1d), which is in agreement with experimental observations for twisted polyamide-6 fibres when heated from 26 – 62°C [13]. Over this temperature the polyamide-6 fibres expanded anisotropically in the diameter direction with negligible change in length. As shown in Fig. 1d, larger torsional strokes for a given volume change are expected for isotropically expanding fibres and fibres that show a predominant length direction expansion when heated.

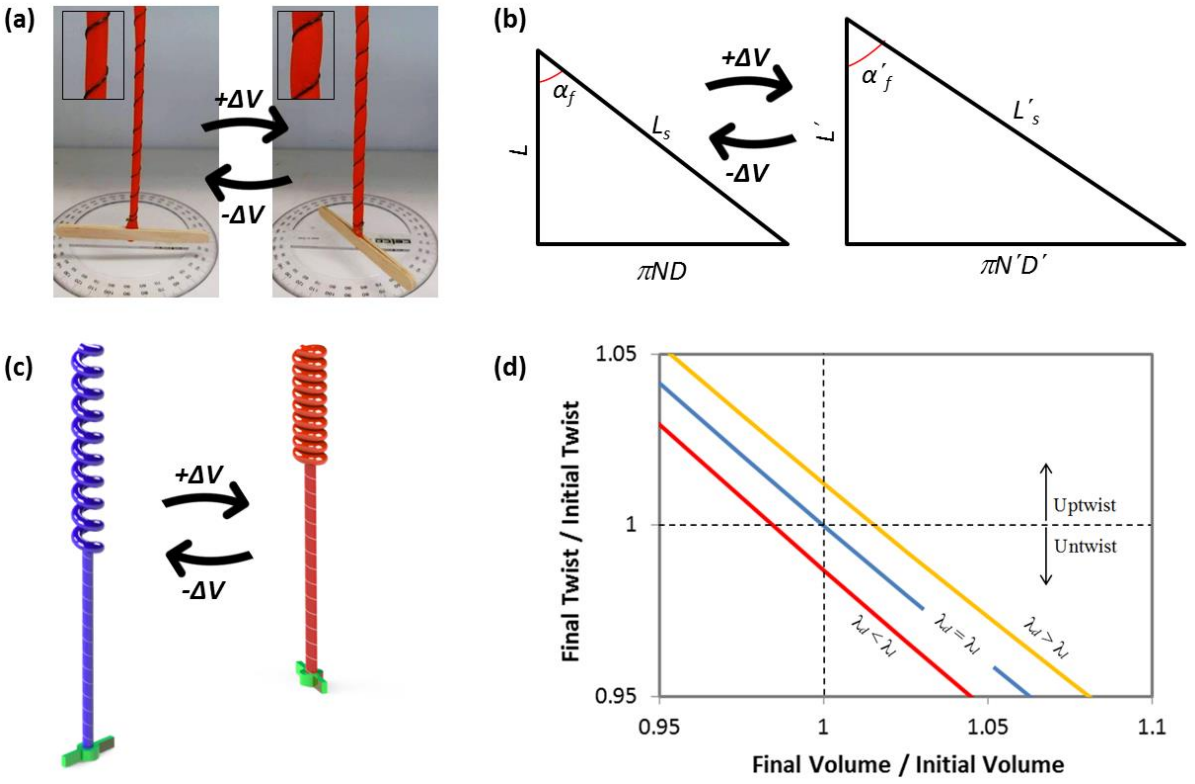


Fig. 1. (a) Torsional actuation occurs during volume change (ΔV) in systems that incorporate a mechanically stiff helical element, such as elastomer tube wrapped with reinforcing fibres.

(b) The geometrical relations between cylinder length (L), diameter (D), number of wraps made by the reinforcing fibre (N) and the wrap angle (α_f) are illustrated by the right-angle triangle with the hypotenuse formed by the continuous length of the reinforcing fibre (L_s). (c) Schematic illustration of the combined torsional and tensile actuation occurring in a twisted and partially coiled polymer fibre during volume change. Volume expansion causes partial fibre untwist that generates a length contraction in the coiled region. (d) Single helix model predictions for change in twist as a function of volume change for three different volume change anisotropies, where λ_d and λ_l are the ratios of the final to initial diameters and lengths, respectively.

The aim of the present study was to extend the single helix analysis to explore twisted fibre systems where both length and diameter changes occurred on heating. Oriented fibres of polyethylene and polypropylene were chosen to compare with polyamide-6. Choy *et al.* [14] have shown that these three polymers show different thermal expansion anisotropies over the temperature range of interest. Comparison of torsional strokes from these different fibres is reported and the differences are explained in terms of thermo-physical properties of fibre materials. Torque generated during heating of similarly fabricated actuators is also measured and theoretically validated by using torsion mechanics.

2. Experimental

2.1. Twist insertion and sample characterization

Commercially received ultra-high molecular weight oriented polyethylene braided fibre (DYNEEMA braided fishing line) and polypropylene monofilament (textile thread - Tengzhou Tuoliduo Industrial & Trade Co. Ltd.) were twisted by attaching their top end to a rotating motor and the bottom end to a suspended mass that retains the fibre tensioned at constant stress (10 MPa). The bottom end of the fibre is restricted from rotation around the vertical axis thus every turn of the motor produces one turn of twist to the fibre. In a certain range of tensions, after several turns, the fibre starts to buckle and forms a coiled loop. The motor rotation was stopped at the onset of coiling and the twisted section of fibre was utilized in further experiments. This fabrication method produces a temporary twisted configuration on the fibre surface and requires an additional annealing process to set the newly formed helical structure. Previous studies on twisted polyamide fibres have shown that annealing at temperatures approaching the melting point are most effective. Differential scanning

calorimetry (DSC) was used to determine melting points and suitable heat-setting temperature of twisted fibres for both polyethylene and polypropylene samples. The twisted samples were held at the determined temperature with firm end clamping for 30 minutes. The samples were cooled to ambient temperature over 2 hours while still keeping them tethered at both ends to prevent twist loss.

Surface morphology of fabricated samples was characterized by using an optical microscope (Leica Z-16). The number of twists per initial fibre length was microscopically evaluated and also calculated by using the measured twist bias angle and twisted fibre diameter as demonstrated previously [1, 15].

2.2. Thermally-induced physical characterization

The test set-up shown in Fig. 2 was used to observe the length and diameter thermal expansion of twisted polyethylene and polypropylene fibres. One end of the twisted sample was attached to a lever arm force / distance transducer with micrometre length resolution (Aurora Scientific 305B). A metal hook was used to attach the fibre to the lever arm which allowed axial movement of the fibre at the tethering point but fully restricted the torsional rotation. The other end of the fibre was connected to a rigid support through an ultra-low stiff commercial thread (30 µm diameter polyamide-6 monofilament). This thread applied negligible opposing torque to the twisted fibre and allowed free rotation during heating. A thermal imaging camera was used to measure the temperature on the fibre surface, and in-parallel, an optical microscope was placed radially to the fibre to observe the change in diameter. Length changes in the sample were recorded from the lever arm signal in terms of temperature increase when exposed to an infrared heating source (IXL 275W infrared heat lamp).

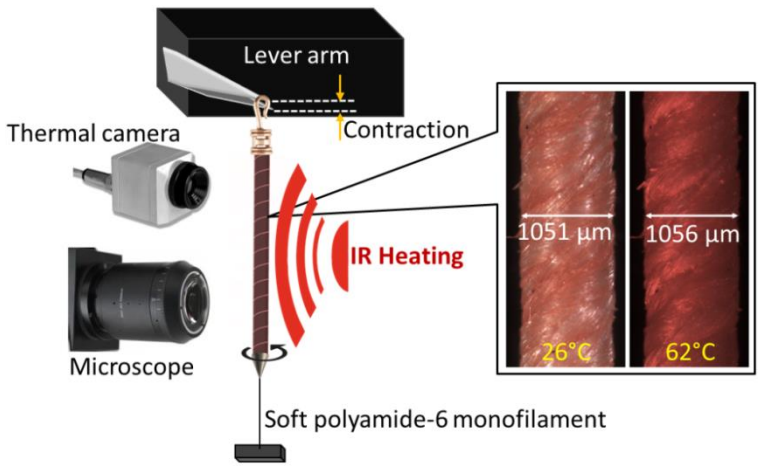


Fig. 2. Schematic illustration of thermally induced test for measuring dimensional changes in twisted fibre (inset shows the example of radial thermal expansion of twisted polyethylene fibre heated in between 26 – 62°C).

The radial expansion measurement of polypropylene was found difficult because of the small dimensional changes occurring. Therefore, our previously developed oil bath method for measuring thermal expansion of an immersed object was utilized [13]. Initially, thermal volume expansion of silicon oil in a glass tube was measured over the 26 – 62°C temperature range. Afterwards, seven units of identical twisted polypropylene fibre were immersed in the oil filled glass tube and the thermal volume expansion of the whole unit was then determined. The following describes both radial and axial length changes in the fibres on heating [13]:

$$r' = \sqrt{\frac{R^2[(L'-L)-(L_1'-L_1)]}{l'-l} + r^2} \qquad (2)$$

Here, silicon oil height poured in glass tube is L_1 at 26°C, combined oil with immersed fibre liquid level is L at 26°C, fibre length is l at 26°C and fibre radius is r at 26°C. The notation ($'$) denotes the parameters at 62°C.

2.3. Torsional actuation tests and torsional property evaluation

Thermally induced torsional actuation tests were performed in a torsion testing apparatus developed in-house [15]. The apparatus includes an electrically heated chamber, a DC power supply, programmable temperature controller (Electro Chemical Engineering Pty Ltd) and the lever arm force/distance transducer system (Aurora Scientific 305B). One fibre end was firmly clamped and the other end attached to a shaft supported by two near frictionless air bearings. A high modulus fibre wrapped around the bearing was connected to the lever arm transducer. Fig. 3 demonstrates the test apparatus and related assembly used to measure torsional actuation. Isotonic torsional stroke ($\phi_{isotonic}$) was determined from the lever arm displacement under an opposing and constant normal force (F_N) applied to the surface of the shaft to give a constant torque (τ_{ext}) acting on the twisted fibre. The same torsion tester was also used to measure the torque generated during heating/cooling of the twisted fibre. In this case, the lever arm was operated in the isometric mode (constant length) to prevent fibre rotation and provide a measure of the blocked torque ($\tau_{blocked}$).

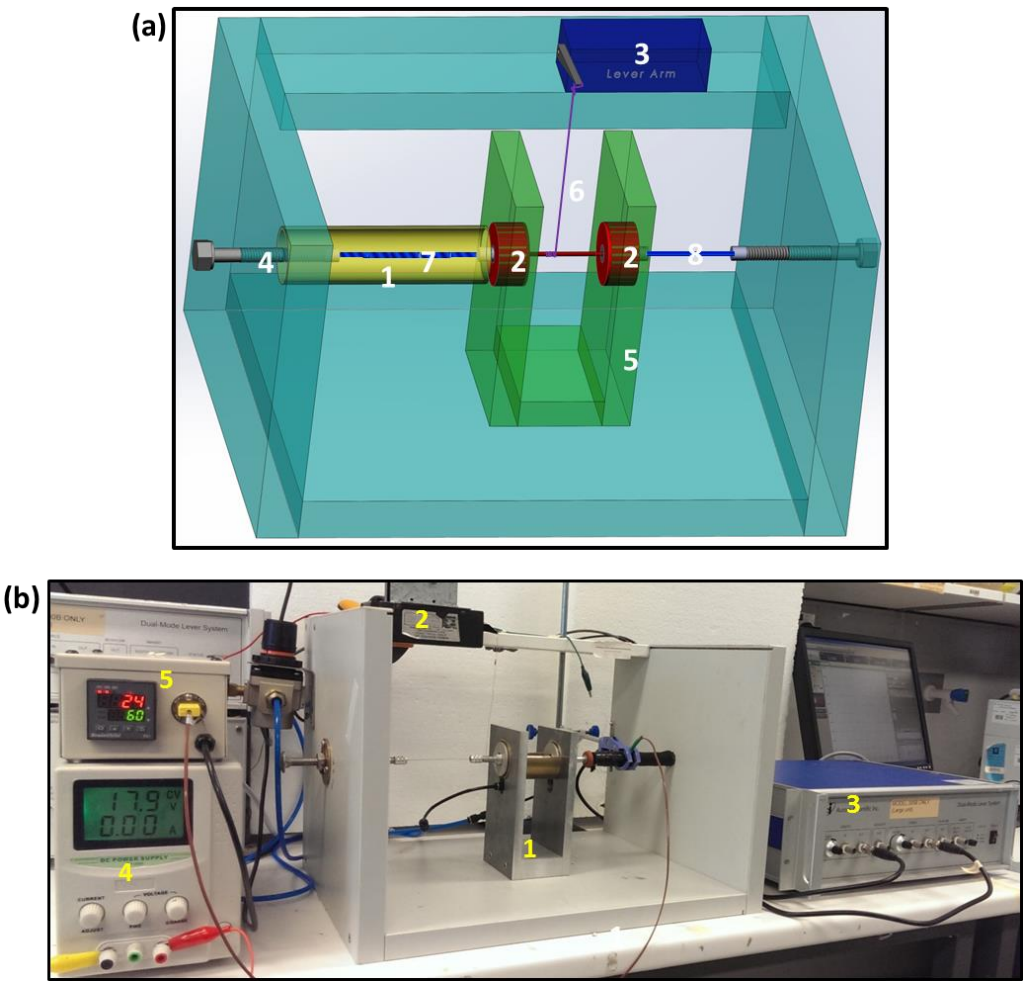


Fig. 3. (a) CAD model of torsional actuation test apparatus; (1) heating zone, (2) ultra-low friction air bearings, (3) lever arm force/distance transducer, (4) movable fibre gripping clamp, (5) support for air bearings, (6) connecting fibre between lever arm force/distance transducer and bearing shaft, (7) actuating muscle fibre, and (8) fibre acting as return spring keeping the actuating muscle straight and well positioned. (b) Test assembly for torsional actuation testing; (1) test apparatus, (2) lever arm force/distance transducer, (3) lever arm controller, (4) DC power supply, and (5) programmable temperature controller [15]. "Reprinted from Characterisation of Torsional Actuation in Highly Twisted Yarns and Fibres, Volume 46, Shazed Aziz, Sina Naficy, Javad Foroughi, Hugh R. Brown and Geoffrey M. Spinks, Polymer Testing, 88-97, Copyright (2015), with permission from Elsevier".

The torsional stiffness [16] of the twisted fibres was evaluated at the two temperature extremes representing the actuated (high temperature) and non-actuated (low-temperature) states. The lever arm system was used to rotate the shaft and measure the required torque. As in previous studies [13], the fibres were found to be linearly elastic in torsion and the

torsional stiffnesses given by the slope of the torque / rotation data. The free rotation (ϕ_{free}) expected during the heating of the twisted fibre could be then be calculated from the measured isotonic torsional stroke using:

$$\phi_{isotonic} = \phi_{free} + \tau_{ext}\left(\frac{1}{S'_A} - \frac{1}{S_A}\right) \quad (3)$$

by including the measured torsional stiffnesses in the non-actuated (S_A) and actuated (S'_A) states.

3. Results

3.1. Surface morphology and thermo-physical properties

Twisting a single ply polyethylene braid (606 µm diameter) produced a complex and non-uniform helical structure [Fig. 4a]. In contrast, when two identical lengths of the polyethylene braid were twisted together the result was a compact plied fibre of uniform diameter as a result of the co-wrapping of the two fibres [Fig. 4b]. The reduced diameter of 1050 µm after twisting highlights the considerable compaction in the twisted fibres of the individual micro-filaments that form the braided fibres. The number of twists was calculated as ~680 turns per meter which closely compares with manually counted 648 turns per meter during twist insertion.

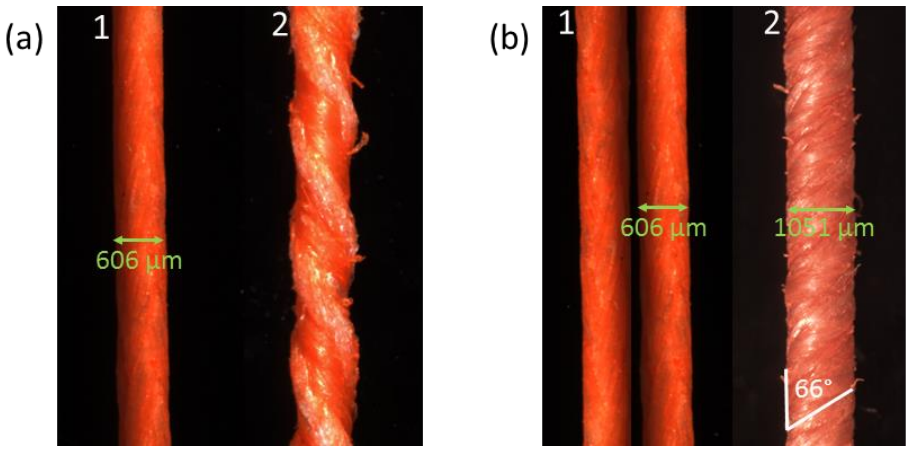


Fig. 4. Polyethylene braided structures; (a) single ply fibre in 1. as-received and 2. twisted form; and (b) two plies of same fibre in 1. as-received and 2. twisted form.

A polypropylene fibre of ~350 µm diameter was also twisted to the point of coil formation. Fig. 3 shows optical micrographs at different stages of the twisting process. Fig. 5a represents

the precursor fibre and Fig. 5b shows the fibre after maximum twist insertion. However, significant 'necking' or plastic deformation was observed after twist insertion. The average fibre diameter was found to have increased during twisting by ~10% from ~350 µm to ~384 µm. The bias angle of the inserted twist was measured microscopically and found to be ~32°. The amount of twist inserted was calculated and found to be ~514 turns per meter of initial fibre length. Twist count during twisting was 492 turns per meter of precursor fibre length which closely approximates the calculated value.

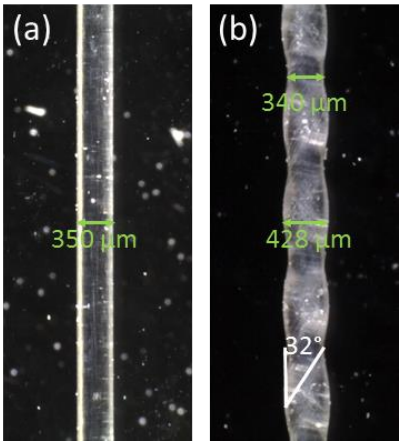


Fig. 5. Polypropylene monofilament structures; (a) as-received, and (b) highly twisted form.

DSC tests were conducted to evaluate the melting point of twisted samples and then an acceptable heat-setting temperature was determined. Fig. 6a shows the DSC result of twisted polyethylene where a first melting peak was observed at ~145°C and a second melting peak at ~154°C. Double melting peaks in a DSC experiment have been ascribed previously to melting of less stable crystalline structures followed by recrystallization and remelting of more stable crystals [17, 18]. An acceptable heat-setting temperature of 120°C was chosen for the twisted polyethylene braids so that any melting of the crystal structures was avoided. Fig. 6b shows the DSC results of twisted polypropylene monofilaments where the melting temperature was evaluated to be ~167°C. Again, a heat-setting temperature of 120°C was proposed and used which was sufficiently below the melting peak temperature.

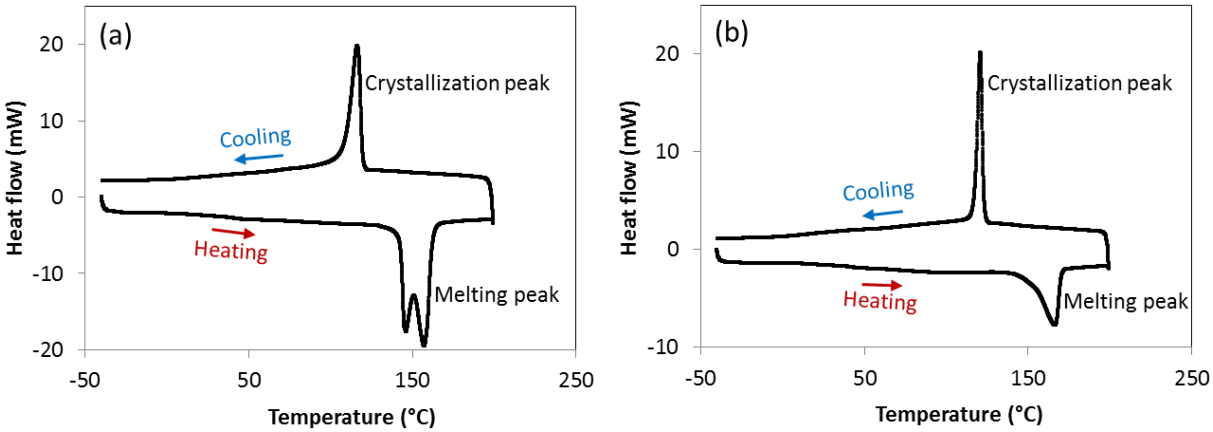


Fig. 6. DSC results of twisted polyethylene and polypropylene fibre.

Torsional stiffnesses of both polyethylene and polypropylene fibres were measured from torque-stroke curves at 26°C (non-actuated state) and 62°C (actuated state). Fig. 7 shows the relationship of applied torque to torsional stroke where the inverse slope of the lines denotes torsional stiffness. Torsional stiffness of a twisted polyethylene fibre of 70 mm in length was found to be ~667 and ~400 µN.m at 25 and 62°C, respectively. The twisted polypropylene of 350 µm diameter and 70 mm in length had a considerably smaller torsion stiffness of ~54 and ~52 µN.m at 25 and 62°C, respectively. To aid detailed theoretical calculation of free stroke over the 25 – 62°C temperature range, torsional stiffness of both fibres were also measured at 30, 40, and 50°C. Table 1 shows the torsional stiffness results at different temperatures. Torsional stiffness is determined by the product of shear modulus and polar moment of area and the latter is proportional to fibre diameter to the fourth power. Considering the 2.5 fold larger diameter of the polyethylene twisted fibre in comparison to the polypropylene fibre, the measured torsional stiffness suggest a ratio of shear moduli of the polyethylene fibre to polypropylene fibre of ~20%. However, the shear moduli of these polymers should be comparable, but the multifilament structure of the polyethylene braid reduces the apparent shear modulus in comparison to an equivalent diameter monofilament.

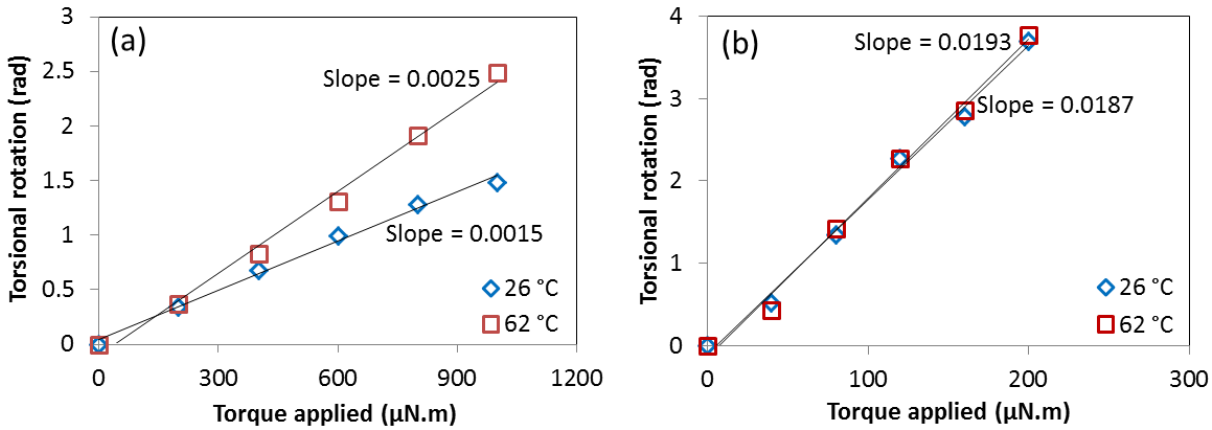


Fig. 7. Torsional rotation of twisted fibre under mechanically applied torque; (a) polyethylene braided fibre, and (b) polypropylene fibre. (Inverse slope of each curve denotes torsional stiffness).

Table 1. Torsional stiffness of twisted fibres in several temperatures.

Temperature (°C)	Torsional stiffness (µN.m)	
	Twisted polyethylene fibre	Twisted polypropylene fibre
26	667	54
30	556	53
40	500	53
50	435	52
62	400	52

3.2. Anisotropic thermal volume expansion of twisted fibres

The twisted fibres were heated slowly using an infrared heating source which allowed the fibres to be imaged with a microscope and changes in diameter could be obtained. The lever arm transducer system provided a measurement of the fibre length change. Within the 26°C to 62°C temperature range, the twisted polyethylene fibre showed radial thermal expansion of ~0.48% with an axial thermal contraction of ~0.06% (Fig. 8). These observations are similar to previously published results for the anisotropic thermal expansion of oriented high density polyethylene fibre over this temperature range [14]. However, there is no such report for thermal expansion in ultra-high molecular weight oriented polyethylene fibre, such as used in the present study. Thermally-induced dimension changes of polypropylene fibre were also examined within the same temperature range of 26°C to 62°C. A radial thermal expansion of

~0.12% was obtained along with *in situ* axial thermal contraction of ~0.04% (Fig. 8). Compared to the thermal expansion across the fibre, both polyethylene and polypropylene show little axial thermal contraction which also supports the previous examples regarding thermal properties of oriented polymers [14, 19].

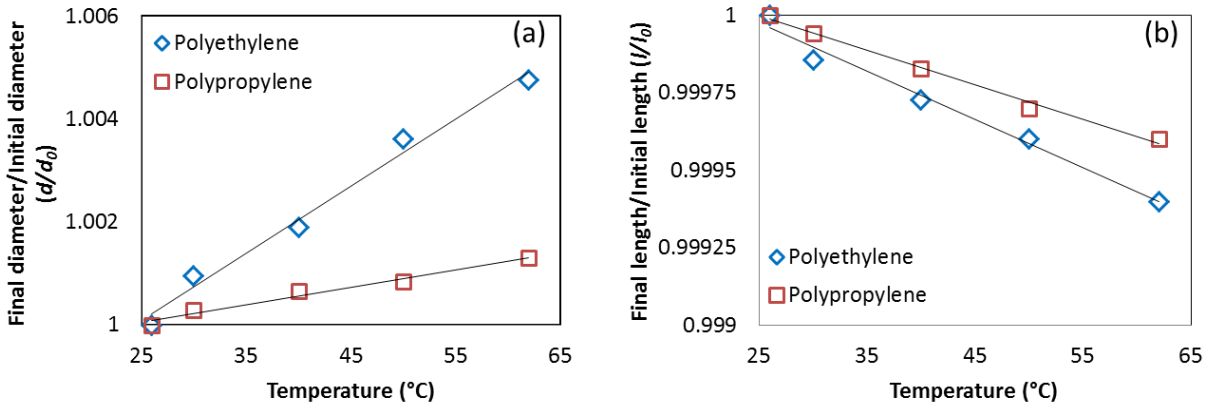


Fig. 8. Thermal expansion behaviour of twisted polyethylene and polypropylene fibres; (a) diameter expansion plot against increasing temperature, and (b) axial contraction plot against increasing temperature.

3.3. Torsional stroke and torque generation

Isotonic torsional stroke was measured at a small fixed applied torque and then converted to an equivalent free rotation at zero external torque by using torsional stiffness values (Table 1) in equation (3). Fig. 9 shows the torsional stroke of twisted polyethylene fibres (opposed by 72 µN.m torque) and polypropylene fibres (opposed by 40 µN.m torque). The calculated free rotations are also plotted to demonstrate the comparison in actuation magnitudes. The differences in the isotonic and free strokes are small because of the small external torques used and the small change in torsional stiffness of the fibres over the temperature range used. Free rotation of twisted polyethylene and polypropylene fibre was found to be -1.21 and -0.22 °/mm, respectively, over the 26 – 62°C temperature range. Both the fibres have shown good reversibility and the results were reproducible for several actuation heating and cooling cycles. In comparison, the torsional stroke of polyamide-6 twisted fibres over the same temperature range was -3.14 °/mm [15].

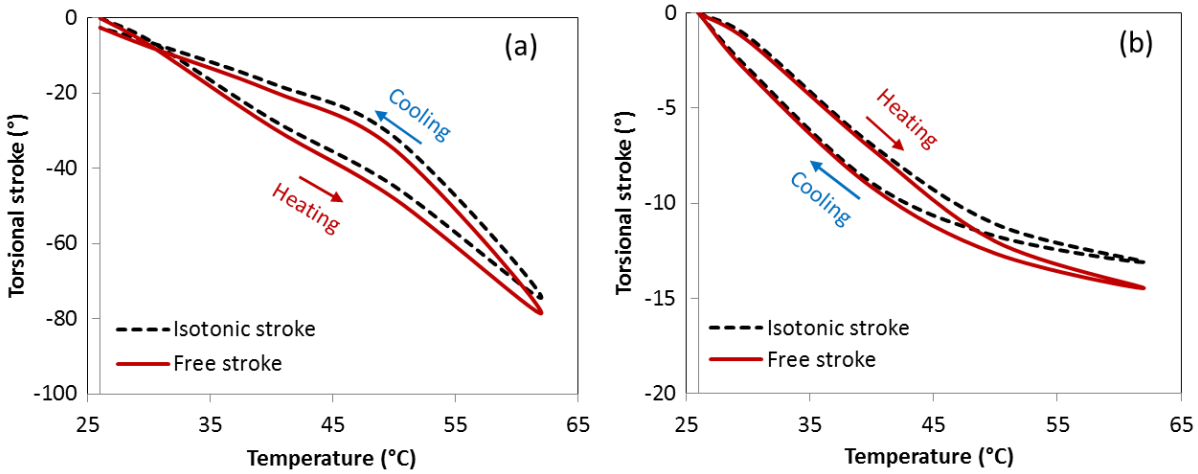


Fig. 9. Torsional stroke of twisted fibres; (a) polyethylene, and (b) polypropylene. (Note that different Y-axis ranges are used for two Fig.s).

Fig. 10 shows the blocked torque generated from twisted polyethylene and polypropylene fibres. The maximum blocked torque of the twisted polyethylene and polypropylene fibres were 614 and 13 µN.m, respectively, when heated from 26°C to 62°C. The large difference in torques reflects the significant variation in torsional stiffnesses of the two fibres. A large hysteresis in blocked torque was shown by the polypropylene fibre during continuous heating and cooling. The hysteresis was smaller in the polyethylene fibres and may demonstrate a degree of viscoelasticity in the materials. However, both the fibres showed high reversibility in torque generation when cooled, and the actuation pattern was reproducible for several heating / cooling cycles.

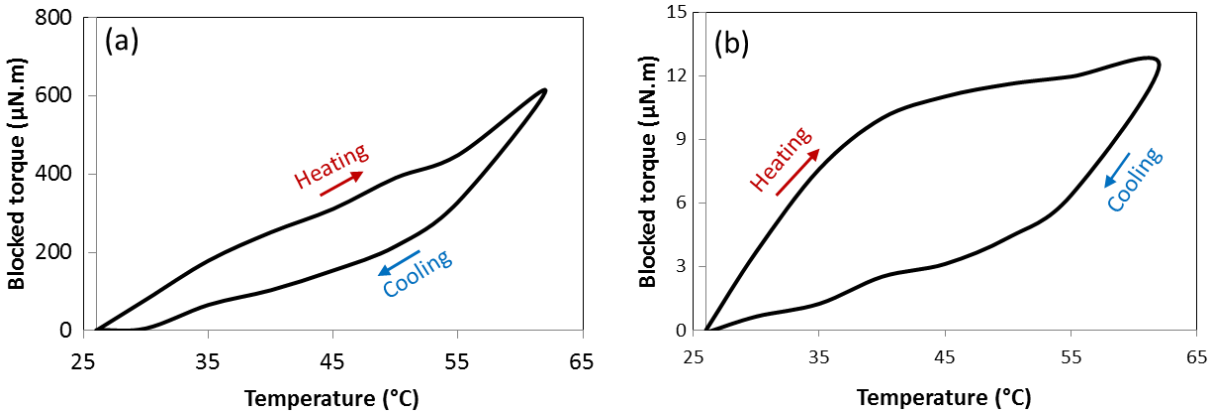


Fig. 10. Blocked torque generated from twisted fibres; (a) polyethylene, and (b) polypropylene. (Note that different Y-axis ranges are used for the two Fig.s).

4. Discussion

4.1. Theoretically predicted results of torsional stroke

The aim of the present study was to determine if the single-helix approximation of the twisted fibre structure could accurately predict the torsional stroke and torque generated during fibre heating. Previous work had demonstrated that the single-helix approximation was able to predict the torsional stroke of twisted polyamide-6 monofilament. This material represented a special case since the length of the twisted fibre was unchanged during heating. Under these conditions the single helix model can be greatly simplified from equation (1) to equation (4):

$$\lambda_n = \frac{1}{\lambda_d} \tag{4}$$

In contrast to polyamide-6, the twisted polyethylene and polypropylene fibres displayed both thermally induced length changes and diameter changes. To account for this additional complexity, the theoretical predictions of torsional stroke of these fibres was conducted by using equation (1). These calculated torsional strokes were calculated using the measured fibre diameter and length expansion ratios (Fig. 8) and plotted together with previously reported torsional stroke of twisted polyamide-6 (840 μm diameter) fibre (Fig. 11) by using the expression of 'final twist / initial twist' (n/n_0). This expression is independent of fabrication variables of twisted fibres such as the number of inserted twist, bias angle and fibre diameter, and only depends on the thermally induced volumetric changes of the samples. Experimentally measured torsional strokes are included for comparison and there is a very good agreement between the measured and calculated values for all three samples. The single-helix theory correctly predicts the dependence of torsional stroke on the volume change and the amount of inserted twist. The theory also predicts the quantitative torsional strokes with high accuracy, supporting the previously considered assumption that the string length remains unchanged in oriented polyamide-6, polyethylene and polypropylene.

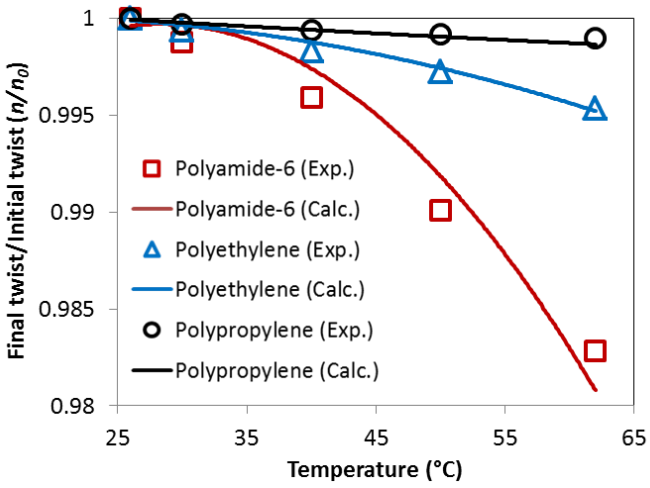


Fig. 11. Torsional stroke of twisted fibres comparing experimentally measured values with predictions from the single helix model.

It is noted that the amount of torsional rotation varied significantly for twisted polyamide-6, polyethylene and polypropylene fibres under the same experimental condition. The predictive single helix model allows an exploration of the reasons for the differences in torsional actuation in these three polymers. Fig. 12 shows calculated torsional strokes expressed as a fractional change in twist for the three polymers prepared with different initial twist bias angles. The analysis used the measured diameter and length expansion ratios and assumed that these parameters were unaffected by the inserted twist. The calculated torsional actuation was little changed for each polymer over a wide range of initial bias angles. It can be concluded that the differences in torsional actuation for the tested polymer fibres can be mainly attributed to their differences in thermal expansion, which is significantly higher in polyamide-6 fibre compared to polypropylene monofilament and ultra-high molecular weight polyethylene braided fibres. This same phenomenon follows a decrease in crystallinity or, conversely, an increase in amorphous fraction. Amorphous polymers are known to show higher thermal expansion coefficients than crystalline polymers [20].

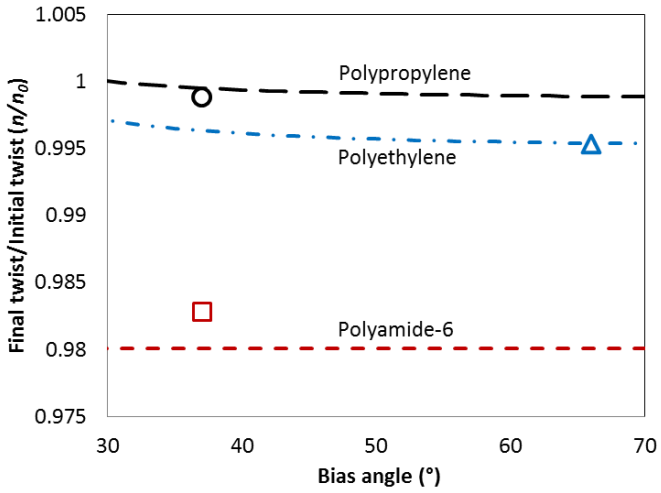


Fig. 12. Torsional stroke of twisted fibres in terms of different initial twist bias angles (dotted lines represent theoretically calculated values and the markers denote experimentally measured results for corresponding bias angles).

4.2. Theoretically predicted results of torque generated

Experimental results of the torque generated by heating twisted polyethylene and polypropylene fibre were significantly different. Theoretical analysis of the torque generated from these fibres was conducted from torsion mechanics [15] denoted in equation (5) and results are plotted together with experimental results in Fig. 13. Previously measured torque generation by twisted polyamide-6 fibre (840 µm diameter) was also included in the plot for comparison.

$$\tau_{blocked} = \Delta n . S'_A \qquad (5)$$

Here, $\tau_{blocked}$ is the torque generated from twisted fibre, Δn represents the calculated free rotation (in radians) for a certain length (l) of twisted fibre and S'_A is the fibre torsional stiffness in the actuated condition. In all cases, there is an excellent agreement between the measured and calculated values, further supporting the analytical approach based on a single-helix. The higher torsional stiffness of the polyethylene fibre results in a generated torque that is similar to that produced by the polyamide-6 twisted fibre, despite showing almost three times smaller torsional stroke.

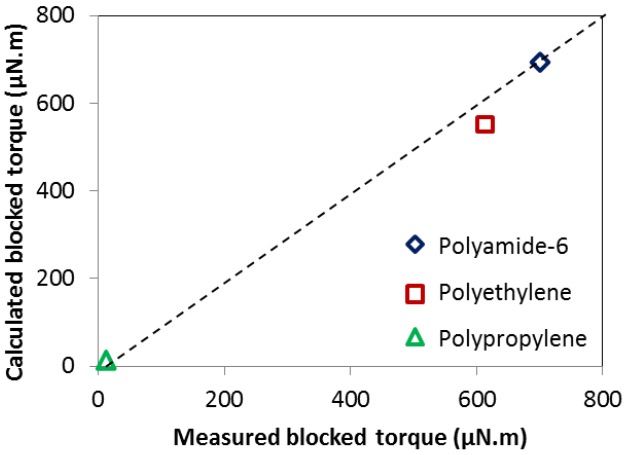


Fig. 13. Measured and calculated blocked torque generated by twisted fibres when heated from 26^{o}C to 62^{o}C.

5. Conclusions

The objective of this work was to experimentally determine the torsional actuation in twisted multifilament polyethylene yarns and monofilament polypropylene fibres and to further evaluate the usability of the previously developed single-helix model for quantitatively predicting torsional stroke and torque. Highly twisted fibres were prepared by using a rotary motor and the torsional actuation tests were conducted over a temperature range of 26 – 62°C. As reported in our previous work, twisted polyamide-6 fibre showed negligible length change with significant diameter expansion when heated from 26 to 62°C. In comparison, both polyethylene and polypropylene fibres showed small length contractions over this temperature range. A very good agreement was found between the experimentally measured and theoretically calculated results showing the validation of the single-helix approximation. The analysis also demonstrated that the fractional degree of untwist in the three polymers was mainly determined by the thermal expansion, which was associated with the degree of crystallinity. Generated blocked torques was also correctly predicted by the single-helix model when combined with the measured fibre torsional stiffness.

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