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THERMO-MECHANICAL BEHAVIOUR OF COILED MONOFILAMENT POLYMER FIBERS

Sarah Silveira Mendes
Luiz Carlos da Silva Nunes
Universidade Federal Fluminense, Department of Mechanical Engineering, Rua Passo da Pátria 156, Departamento de Engenharia Mecânica, Laboratório de Mecânica Teórica e Aplicada, Bloco E, sala 210, Niteroi, Brazil
smendes@id.uff.br , luizcsn@id.uff.br

Abstract. In this work, the thermo-mechanical behavior of coiled nylon fishing lines was investigated. In the experimental procedure, a polyamide coiled line (0.8 mm of diameter) was pre-stretched holding the distance between its ends constant and was subjected to different temperatures (range from 30ºC to 120ºC). Under this temperature condition, the homochiral coiled fiber of nylon fiber tends to contract upon being heated and expanded upon being cooled. During tests, the reaction force was monitored using a cell load and images of coiled line were captured every 5 seconds. The Digital Image Correlation software was used to attain the displacement fields. The rotation and the deformation of the specimens were estimated with these displacement fields. The pitch angle of the coiled fiber was measured using the ImageJ software. The helical spring theory together with the experimental data was used to describe the termo-mechanical behavior of coiled fiber. Different tests were performed considering coiled fibers with 20 mm length and three values of nominal tension of manufacture, 10,35 MPa, 16,35 MPa and 20,35 MPa. The rotation of these coiled lines was inversely proportional to the initial size of the specimens, and the deformation was not affected by it. The torsional stiffness, deformation and force were proportional to the value of the spring index.

Keywords: artificial muscle, polymeric actuator, fishing line, DIC method

1. INTRODUCTION

Actuators are a category of smart materials capable of changing its geometry or volume when an external stimulus is applied, such as voltage, pressure or temperature (Ionov, 2014; Jani, 2014). Smart materials have become a popular topic due to the demand for muscle-like materials able to reproduce nature mechanism therefore replace the muscular tissue when it fails or aid when powerless (Mirfakhrai, 2007). In other areas, actuators are being developed to substitute conventional electric motors and hydraulic actuators since they potentially ease space and weight (Kim, 2015). Such technology is also a humongous assistance to medical implants and human assist devices likewise to minimize intrusive surgical and diagnostic devices (Majidi, 2014; Madden, 2004).

Nowadays, new polymer actuators presenting similar strains and higher stresses than natural muscles have been invented. They operate using electrostatic forces, electrostriction, ion insertion and molecular conformation changes (Mirfakhrai, 2007; Yang, 2016). Other smart materials capable of being used as artificial muscles were tested (Chen, 2015; Chun, 2014; Kwon, 2015; Mirvakili, 2014) but none of them have shown the possibilities displayed by the artificial muscle studied by Haines et al. (2014). The recent discovery of thermo-active coiled artificial muscle from nylon by Baughman *et al.* 2014 has shown a new outlook in the studies of polymer based actuators. Made of common low cost fishing line, these actuators have shown the capability of actively contract and expand after suffering a twist followed by coiling into helical spring. This semicrystalline polymer displays a large stiffness throughout a large range of temperature (Haines, 2014), actuation energy densities up to 2.6 kJ/kg, low hysteresis, repetitive behavior (Haines, 2014), power densities over 5.3 kW/kg, with strokes as high as 50% (Aziz, 2015).

Several researches have conducted experimental characterization on this nylon based actuator and described the method of production used to produce this helical spring (Kianzad, 2015; Aziz, 2015; Cherubini, 2015; Moretti, 2015; Yang, 2016). Its thermal driven behavior consists in not only on its entropic elasticity but also the string interactions between the polymer chains, which are highly aligned along the axis of the fibers and contract when the temperature is increased (Yuan, 2014). The diameter of the fiber expands with the rise of the temperature and there is a contraction of the fiber as a repercussion of its structure (Haines, 2014). Moretti *et al.* 2015 and Cherubini *et al.* 2015 developed an apparatus to conduct isothermal and isometric tensile tests, which revealed important aspects of this

actuator response some of which are repeatability, predictability, hysteresis and stored elastic energy. The elastic modulus and the tensile stroke were investigated by Kianzad *et al.* (2016); demonstrating an important behavior of the actuator: as the temperature rise from -40°C to 200°C, the elastic modulus decrease from ~155 MPa to 35 MPa and the thermal contraction detected is ~2% from -40 °C to 20 °C, meanwhile between 100 °C and 160 °C the contraction is 10%. The torsional stroke and torque generated was studied by Aziz *et al.* (2015). And Yue *et al.* (2015) studied the effective Young's modulus of the muscle. Yuan *et al.* 2014 developed a multi-scale modeling framework aiming to predict the behavior and analyze the effect of a wide range of factors by evaluating the actuator response.

Applications of this actuator were also demonstrated, for instance, Kim *et al.* 2015 used thermal energy generate a large torsional stroke in the nylon actuator, which turns the rotor of an electric generator. Cho *et al.* 2016and Yip *et al.*, 2015 employed the nylon artificial muscle in a robotic finger and in a robotic arm, respectively, with the purpose of examining their controllability and optimal structure.

In summary, there are no studies exhibiting the influence of the length of the actuator and the weight used during production in the torsion and the vertical deformation of the fiber. Specifically, in this work it will be analyzed the behavior of homochiral nylon coiled fibers with 0,8 mm diameter and 20 mm length fabricated using three different stresses, 10,35 MPa, 16,35 MPa and 20,35 MPa, submitted to pre-deformation of 50% and then a thermal cycle (heating, from 30° to 120°C, followed by cooling from 120°C to 40°C). Before the temperature cycle the actuator was submitted to a thermic treatment and a thermic training cycle.

2. EXPERIMENTAL PROCEDURE

2.1 Helical springs

In order to establish the behavior of the coiled fiber when submitted to a heat cycle is relevant to associate the actuator behavior during the cycle with helical springs when deformed. When a helical spring, with a large spring index, with ends free to rotate is deflected from the state in the Fig. 1 b) to the state in the Fig. 1 c) the initial pitch angle α_o decreases to a final pitch angle α. The spring index (C) is calculated by 2r/d, as shown in Fig. 1 a).
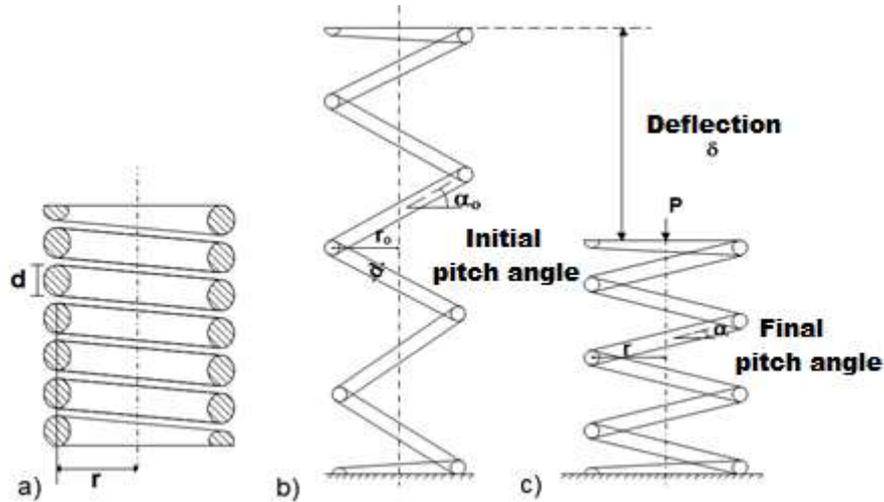

Figure 1: Helicoidal spring with large index. (a) Undeformed spring; (b) Deformed spring

From the elastic theory (Wahl, 1994) the twist $\Delta\Theta$ in the wire per unit length, as the spring deflects from a pitch angle α_o to a pitch angle α is given by the Eq. (1)

$$\Delta\theta = \frac{sen(\alpha)cos(\alpha)}{r} - \frac{sen(\alpha_o)cos(\alpha_o)}{r_o} \qquad (1)$$

The twist $\Delta\Theta$ when multiplied by the torsional rigidity GI_p, for round wire, will yield the twisting moment m_t. Since m_t is given by $m_t = P\ r\ cos\ (\alpha)$ (Wahl, 1994). Thus

$$P\ r\ cos(\alpha) = GIp(\Delta\Theta) \qquad (2)$$

That can be written as the equation (3)

$$GIp = \frac{P\, r \cos(\alpha)}{\Delta\theta} \qquad\qquad (3)$$

Where G = modulus of rigidity and I_p = polar moment of inertia of wire cross section.

2.2 Muscle Fabrication Process

The specimens were manufactured using nylon thread of the brand Ekilon Crystal with a diameter equal to 0.80 mm. One of the ends of the fiber was attached to a drill (motor) and the other was fixed to a weight. The end attached to the weight was prevented from rotating when the drill was turned on in a counter-clockwise direction, in order to produce homochiral actuators (Haines, 2014; Aziz 2015). As the twist is inserted in the fiber and it reaches its limits of torsion small spirals are formed along the fiber's length. This method of fabrication was introduced by Haines et al. (2014).

Immediately after manufacture, the specimens were subjected to a heat treatment to maintain spiral shape obtained in the manufacture. In this treatment, the bodies, fixed to an apparatus to prevent the spirals if unravel, were subjected to a temperature of 120ºC in an oven for 1 hour.

The specimens were subjected, after 24 hours of the heating treatment, to a heating and cooling cycle. The heating cycles were conducted by heating the fiber strained in 50% from the room temperature ~25ºC to 120ºC, followed by a cooling cycle until the chamber reached the room temperature. Than the same heating and cooling cycle was conducted with the fiber on its original length. These training cycles were performed six times in each specimen before the tests.

2.3 Experimental Setup

Experiments were conducted using an in-house-produced heating chamber fabricated from balsa wood and tempered glass. The heating process was operated through Dekel DK-1160 blower. The nylon fiber was positioned in the heating zone to evaluate its behavior during heating and cooling cycles. It was coupled to a fixed base and a portable digital dynamometer from Instrutherm DD-500 with resolution of 0,1 Kgf, being that their data were stored in a computer. The front part of the apparatus was manufactured of tempered glass aiming to capture images of the body using a camera CCD (charged couple device) with high resolution from Sony model XCD-SX900 (1280 x 960 pixels) and pixel size from 4,65µm x 4,65µm with lenses C-Mount 10xZoom fixed at a constant distance from the apparatus. The temperature during the tests was controlled with the aid of 2 K-type thermocouples connected to the thermometer TD 880 of Icel Manaus and the data was stored in the computer. In Fig. 2 an overview of the test bench configuration is given.
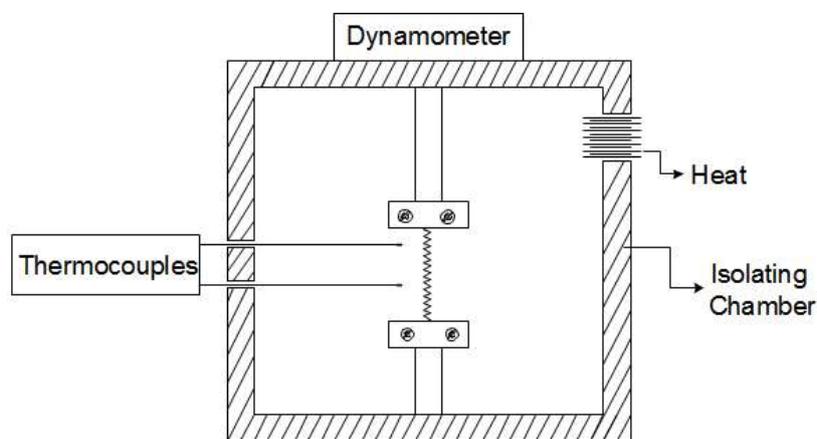

Figure 2: Experimental setup.

The nominal tensions used during the production of the twisted nylon fibers are shown in the Tab. 1. The nominal tension was calculated by the cross section area divided by the height used. The tests were performed with one initial length of the specimen, also shown in Tab. 1. Each type of body was tested 5 times.

Table 1. Properties of the specimens tested.

Nominal tension during fabrication (MPa)	Initial size without deformation (mm)	Deformation applied (%)	Spring index
10,35 MPa	20	50	2,11
16,35 MPa	20	50	1,83
20,35 MPa	20	50	1,78

Initially in the experimental procedure all bodies were deformed 50% the ambient temperature of 25ºC, inside the apparatus. The temperature of the camera was raised from ambient temperature to 120ºC by the blower. To obtain a similar behavior of the blower and a similar rate of increase of temperature for all tests, the interval between tests was 1 hour. During the test, the high-resolution camera captured images every 5 seconds of the twisted nylon fiber.

Captured images were processed using a program of digital images correlation, aiming to obtain the fields of displacement of the bodies during the thermal cycle. With the generated displacements fields the deformation and rotation of the fibers were obtained. Therefore the bodies were submitted to a white paint in all its extension followed by the application of black spray thus generating a random pattern. This program consists in the comparison of images before and after a deformation being imposed on a body. More information about the method can be found at Schreier *et al.* 2009. In this work the sub-reference image had 21 x 21 pixels and the sub-image search 51 x 51 pixels. The captured images were also used to measure the angle pitch of the bodies every 10ºC.

3. RESULTS AND DISCUSSION

The experimental results of the coiled fibers are presented in this section. The specimens tested had 20 mm of initial length (30 mm final length) and fabricated with nominal tension of 10.35 MPa, 16.35 MPa and 20.35 MPa. In Fig. 4 the results for the deformation versus temperature of the specimens are shown during heating (Fig. 4- a)) and during cooling (Fig.4-b)) and the rotation $\left(-\frac{\partial u}{\partial y}\frac{180}{\pi}\right)$ versus temperature of the specimens are shown during heating (Fig. 4- c)) and during cooling (Fig.4-d)). The longitudinal deformation and rotation were obtained with the fields of displacement of the correlation of Digital Images and the first is given by the ratio of deflection δ by the length of the specimens. The changes observed in the temperature range of 80ºC to 90ºC were studied by Haines *et al.* (2014) and explained as due to variation on this same temperature range of a modest thermal expansion negative ($<4.0\times10^{-5}$ K^{-1}) for a large thermal expansion negative ($> 3.7\times10^{-4}$ K^{-1}) in nylon. It was also shown by Haines *et al.* (2014) that this thermal contraction can be increased by 50% in a coiled nylon fiber.
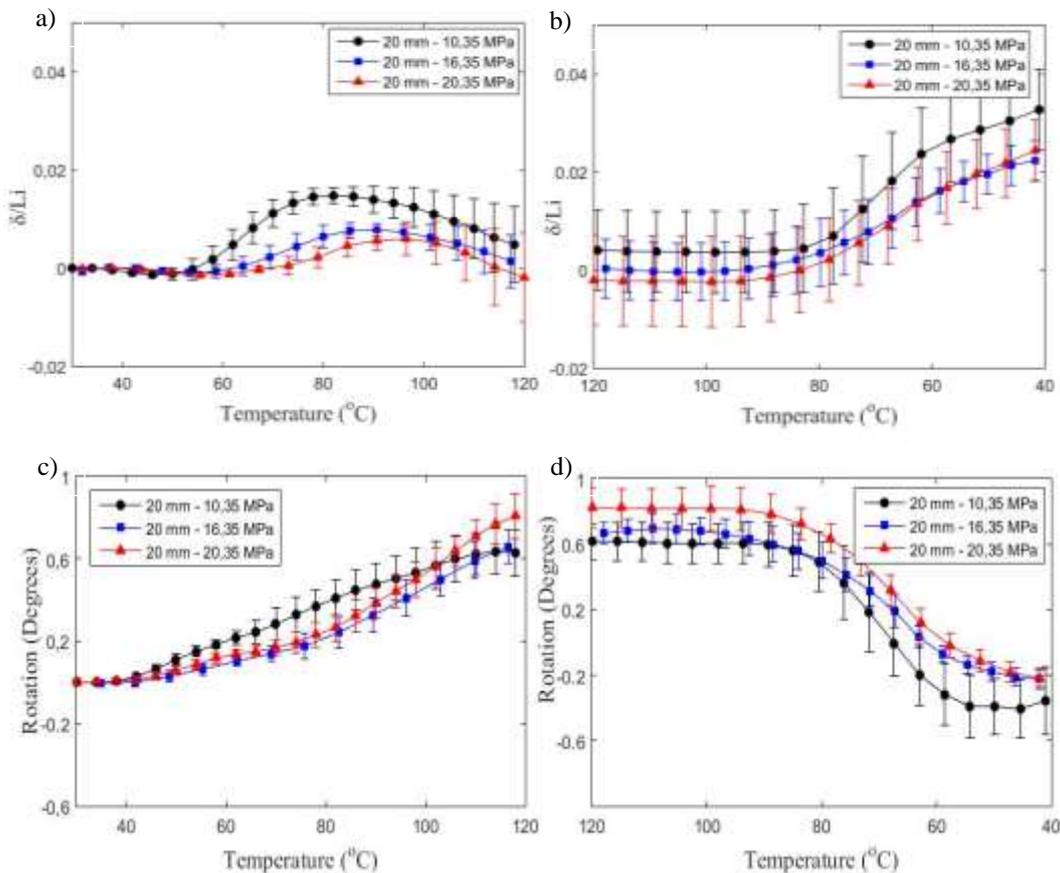

Figure 4: (a) Deformation versus Temperature during heating; (b) and during cooling; (c) Rotation versus Temperature during heating; (d) and during cooling.

The measurements of the pitch angle α, executed in intervals of 10ºC, are shown in Fig. 5. The angle value is inversely proportional to the increase of the temperature during the heating process, Fig. 5 a), and during the cooling process, Fig. 5 b). There is instability in the angle in the range of 100ºC up to 120ºC during the heating and cooling process due to the rapid increase of temperature. The coils did not return to its initial pitch angle after the thermal cycle. This result indicates that, although the training was performed, a small residual deformation is stored in the imposed condition. Furthermore, the effects of boundary conditions need to be considered.
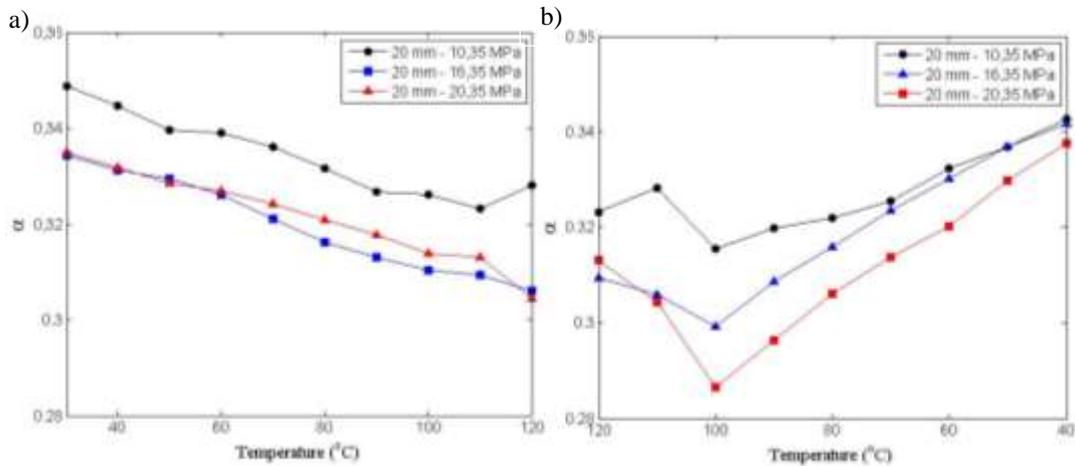

Figure 5: Alfa versus Temperature (a) during heating; (b) and during cooling.

As explained in the section 2.1, when a helical spring is deflected from the initial pitch angle $α_o$ to a final pitch angle $α$, the twist $\Delta\Theta$ in the wire per unit is given by Eq. (1). Fig. 6 shows the linear proportion found in the relation of the twist $\Delta\Theta$ versus the product of the radius projected in the spring base and the cosine of the pitch angle during heating (Fig.6 a)) and cooling (Fig.6 b)). This data was analyzed with the software MatLab and the resulting parameters of this linear proportion are summarized in Tab. 2.
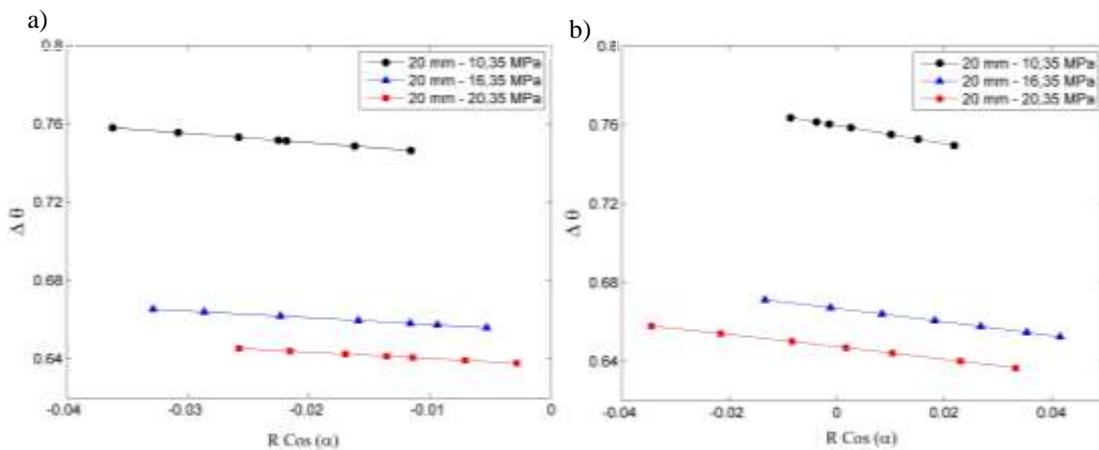

Figure 6: a) Δθ versus R.cos(α) during heating 30ºC until 100ºC, b) Δθ versus R.cos(α) during cooling 100ºC until 40ºC

Table 2. Parameters of the specimens tested obtained using MatLab.

	Nominal tension during fabrication (MPa)	Equation	Coeficient β (modulus)
Heating	10,35 MPa	$\Delta\Theta = -0,4731\ R\cos(α) + 0,7409$	0,4731
	16,35 MPa	$\Delta\Theta = -0,3435\ R\cos(α) + 0,6541$	0,3435
	20,35 MPa	$\Delta\Theta = -0,3277\ R\cos(α) + 0,6368$	0,3277
Cooling	10,35 MPa	$\Delta\Theta = -0,4616\ R\cos(α) + 0,7597$	0,4616
	16,35 MPa	$\Delta\Theta = -0,3406\ R\cos(α) + 0,6668$	0,3406
	20,35 MPa	$\Delta\Theta = -0,3139\ R\cos(α) + 0,6473$	0,3139

The measured loads obtained with the aid of the cell load are shown in Fig.7 a), during heating and Fig.7 b), during cooling. Evidently, the induced force of coiled fibers is dependent on the nominal stress imposed during fabrication. Reaction forces on the order of 6N were obtained for an initial pre-stretch of 50% at room temperature (~ 25 ℃). At temperatures above the glass transition temperature (89℃), the reaction forces altered because of the axial deformation and untwisting/twisting of the coiled fibers, which are directly associated with the effects of thermal softening and thermal expansion. During the cooling process (Fig.7 b)), a saturated state occurs at temperature between 120 ℃ to 100 ℃. In this circumstance, the static equilibrium is reached.
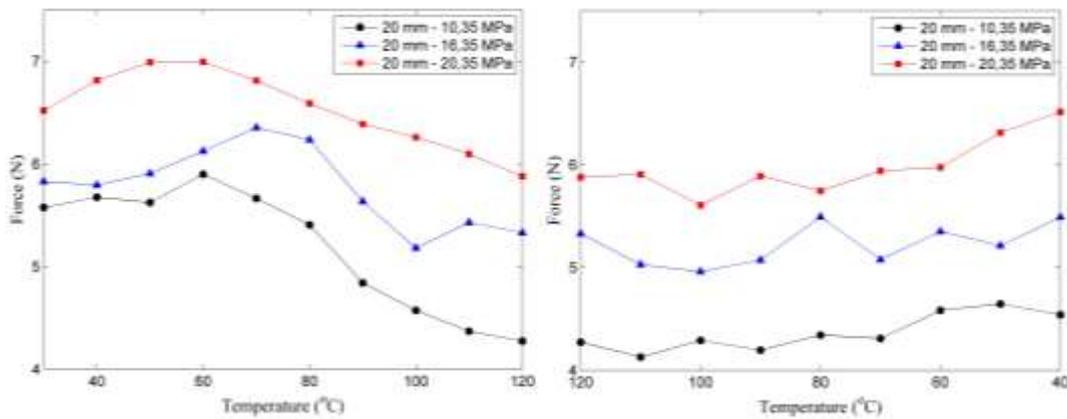
Figure 7: Force versus Temperature (a) during heating; (b) and during cooling.

According to Eq. 3, the ratio of the values of the measured forces by the coefficients β (Tab.2) is equivalent to the torsional rigidity GI_p. Fig. 8 presents the experimental data of the torsional rigidity during heating (Fig. 8 a)) and cooling (Fig.8 b)). As the temperature increases, the specimens undergo a small increase followed by a decrease in the value of GI_p.

As noted by Kianzad et al. (2015), the modulus of elasticity of nylon decreases by the increase of temperature, from 155 MPa at a temperature of -40℃ to 35 MPa at 200 ℃. Similarly, Haines et al. (2014) found that the thermal contraction of a monofilament nylon 6.6 in the temperature range of 20℃ to 240℃ increases from 4% to 34% after being coiled. This variation in the cross section of the material modifies its polar moment of inertia. Hence, it is expected that both values of the polar moment of inertia and the torsional rigidity decrease as the temperature increases.

The results obtained in Fig. 8 also indicate that the spring index C is inversely proportional to the torsional rigidity. According to Haines et al. (2014), the variation of the spring index involves modification in the reaction force and the course of action of the actuator. Actuators with spring index close to 1 have greater stiffness and are able to endure and operate under high tensions. The specimens fabricated with 20.35 MPa of nominal tension presented the lowest spring index, 1.78, and higher torsional rigidity.
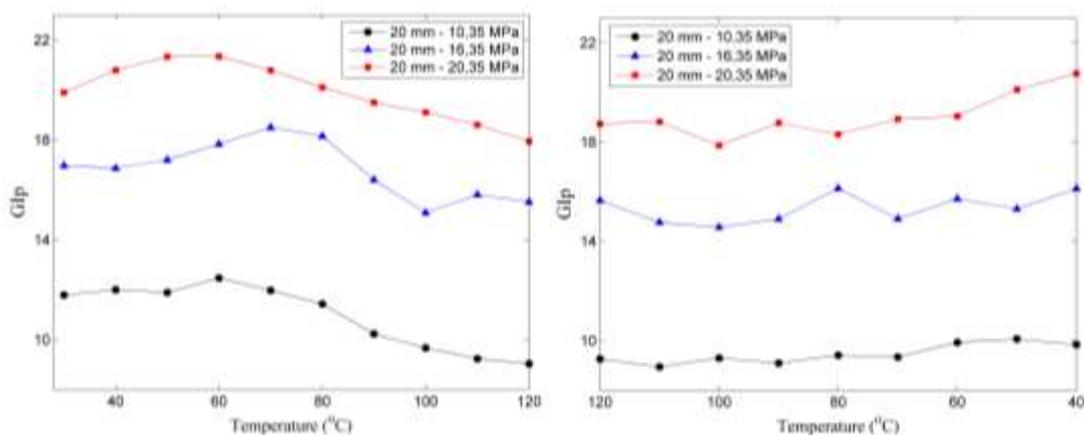
Figure 8: Torsional rigidity versus Temperature (a) during heating; (b) and during cooling.

4. CONCLUSIONS

The objective of this study was to research a new category of thermo-mechanical actuators manufactured from monofilament nylon fishing. The specimens, manufactured with nylon 0.8 mm in diameter, were tested with one length, 20 mm; and were manufactured with three different nominal tensions, 10.35 MPa, 16.35 MPa and 20.35 MPa. Images of the actuators were acquired during the test and through post-processing of these images, with the method of Digital Correlation of Images (DIC), it was obtained the fields of displacement of the body. These were used to provide the longitudinal deformation and rotation. The method of correlation of Digital Images has the advantage of generating these fields of displacement of the material without the need to be in contact with the specimen.

The association of the behavior of the actuator with the deflection of coil springs made it possible to analyze the variation of the angle of rotation of the coils during the thermal cycles. From this, the torsional rigidity was calculated. The values obtained are consistent with published studies on the topic relating to the behavior of the cross section and the rigidity module of nylon during heating and cooling.

In this preliminary study it was observed that the deformation in the specimens is proportional to the spring index of the coiled fiber. No relations were found between with the index of spring and the rotation and longitudinal deformation

5. ACKNOWLEDGEMENTS

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