Analysis of micro-failure behaviors in artificial muscles based on fishing line and sewing thread

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Abstract. The aim of the present study was to discuss a new and effective method for testing artificial muscles based on micro-failure behaviors analysis. Thermo-mechanical actuators based on fishing line and sewing thread, also, the capability of responding to ambient temperature variations producing a large amount of shrinkage ratio of a resulting variation in longitudinal length. The minimum micro-failure value is 0.02μm and the maximum value is 1.72μm with nylon twist pattern. The discovery of an innovative effective testing of artificial muscles based on polymeric fibers specimens on micro-failure, rupture, slippage, etc. This research finds out a micro-failure behavior analysis of thermo-mechanical actuators based on fishing line and sewing thread. The specimens show large deformations when heated together with warping performance in terms of shrinkage of energy and densities. With the purpose of providing useful analysis data for the further technology applications, we attempt micrometre-sized artificial muscles which were also tested was readily accessible and also can be applied to other polymeric fibers. Effective use of this technique achievement relies on rotate speed, temperature and tensile direction. The results of the tensile testing experiments were outstanding with respect to some important issues related to the response of micro-structure, twisted polymeric fibers and shrinkage ratio.

1. Introduction

Artificial muscle is a generic term used for advanced materials that can be expanded and rotated by external stimulus (such as voltage, pressure or ambient temperature) [1]. However, performance, stability and the cost have restricted their manufacture and application. When the sufficient thin metallic nano-wires has been made by specimen, we found the mechanical properties of their intrinsic bond strength. Seyed M. Mirvakili, et al. found that up to 49% upon heating for tensile tested thermal
expansion [2-5]. Up to 29% linear actuation is reaching 840 kJ/m$^3$ (528 J/kg$^{-1}$) and 1.1 kW/kg$^{-1}$ (operating at 0.1 Hz, 4% strain) [6]. In this work, we introduced a method for the specimens’ micro-structuring twist spun with spun angle to explore micro-failure. These nylons average from 44.9 $\mu$m to 45.3 $\mu$m in diameter with an inserted twist of 300 turns/m. As with all fishing line and sewing thread materials, one outstanding method of approach is viable for their production: twisting. Nylon has been twisted and heated from fishing line and sewing thread to stretch with fixed angle, as described in the supplementary materials. Nylon is a general term for synthetic polymer, especially refers to aliphatic or semi-aromatic polyamides. They can be melt-processed into fibers, films or shapes [7]. The minimum micro-failure value is 1.06 $\mu$m and the maximum value is 3.68 $\mu$m with axial direction view of the nylon cross-section area (as shown in Figure 1a, Figure 1b).

Here we demonstrated large-stroke and high-work-capacity artificial muscle that provides millions of twist coils. These materials have demonstrated significant micro-failure when patterned in such a way as to convert into twist. In the present work we reported, for the first time, that artificial muscle micro-failure was analyzed using twist due to predict intrinsic bond strength. Also, the diameter of the material is measured by electron microscopy (as shown in Figure 1c). The twist-spun polymeric fibers confine this actuating in fishing line and sewing thread and provide the mechanical strength and enable large-stroke twist or torsional and tensile testing actuation. Dispersed carbon nano-tubes sheets have been applied for actuating materials to provide cantilever deflections [8-10].

The degree of nylon filament winding determines the range of overall volume changes. Twine exhibits a large volumetric shrinkage when heated (a Tm of 50%, between 25°C and 80°C), and is very effective in micro-actuators since the thermal time constants are small [10]. We hope the artificial muscles can be applied by people who require abrasive resistance in prosthetic limbs, robotic exoskeletons and other medical devices. In addition, the application areas and opportunities for polymer muscles are vast when otherwise made to change in volume [12].

Fishing line and sewing thread share many properties with their micro-structure, such as the surface-area-to-volume ratio, and also provide cheap and easy machining property. As such, if once a particular phase has been formed, one of twisting of coiling twisting could generate micro-failure. The resultant polymer fibers twisting could be used as a heat template (Tm).
Figure 1. Micro-failure image of nylon 66. a) strands of nylon maintaining after ambient temperature heat start up; b) axial direction view of the nylon cross-section area; c) nylon twist-spun with spun angle spun angle $\alpha$ of 43°.

Based on the mono-filament winding method of winding around the center of the shaft, we measured the angle of winding and deflection (as shown in Figure 1c). Also, the rotation angle of nylon is 43°. As of 2014, the existing of most powerful artificial muscle fibers offered a hundredfold increase in power over equivalent lengths of natural muscle fibers [13]. Artificial muscles can be separated into several major groups based on their actuation mechanism, such as electric field actuation, ion-based actuation, pneumatic actuation and thermal actuation. For instance, the linear diameter of nylon mono-filament fishing line and sewing thread are 0.42mm, 0.54mm, 5.34mm and 5.63mm.

The polymer fibers which are finer than hair could give humanoid robots more life-like external expressions. Metal nano-wires are twisted to form yarns strong are from 0.4 to 1.1GPa, normalized to yarn length and torsional rotation was 12deg/mm $^{-1}$ [14]. We attempted our study from low-cost and high-bond strength polymeric fibers, most often those used as fishing line and sewing thread (as shown in Table 1).

Table 1. Summary of the polymer fibers found to be most useful for coiled tensile testing. The tensile testing calculated results are given in Figure 2.

| Material                        | Linear Diameter | $K^a$ Value | Twist to coil |
|---------------------------------|-----------------|-------------|---------------|
| Nylon                           | 0.42 mm         | 9.8 N/m     | 300 turns/m   |
| mono-filament fishing line and  | 0.54 mm         | 11.33 N/m   | 300 turns/m   |
| sewing thread                   | 5.34 mm         | 7.4 N/m     | 300 turns/m   |
|                                 | 5.63 mm         | 6.2 N/m     | 300 turns/m   |

$^a$Hooke's law: $F=K \cdot \Delta L$, where $K$ is a constant factor characteristic of the spring, its stiffness.
Figure 2. Thermomechanical analysis (TMA) of nylon mono-filament fishing line and sewing thread.

Figure 2 depicts that tensile tests direct correspondence between the variable force $F$ from 12N to 140N and the variable length $L$ from 2cm to 40cm. The tensile test measured is the degree of nylon fibers twist determines the range volume change that is converted to twine angle.

2. Experimental

Coiled and several-nylon actuators fibers were made by twisting nylon mono-filaments such as fishing line and sewing thread. The specimens were applied to the twisted nylon mono-filaments during the twisting process before coiling start up. After the specimens were coiled and heated (from 25$^\circ$C to 80$^\circ$C), nylon 66 appeared to show micro-failure in diameter (as shown in Figure 3). Then by lowering the tensile testing, the nylon 66 twisted to coil is 300 turns/m. Depending on the diameter of the mono-filaments and structure, the nylon structure of K value is stretched under loads of around 6.2 to 11.33N/m (as shown in Table 1; main text).

The resulting coil wires are twisted to form a fishing line and sewing thread (as shown in Figure 1c). Longer samples can be obtained by passing longer fishing lines and nanowires during the experiment. The nylon weights are determined by a balance with a resolution of 1μg.

Figure 3. Micro-structure force and potential energy vary in entropy.
The nano-fibers’ internal stress changes over time at constant temperature, and its deformation remains constant. (as shown in Figure 3). Stress relaxation proceeds slowly at ambient temperature but in case of heating, it will considerably shorten the time of the last stresses to 0. Stress reduction causes the fishing line and sewing thread to become a "spring-type" eternally. Also, due to the tensile and rotational effects of gravity, the fishing line and the sewing thread become spring.

Macro-molecule chains generate large increase in enthalpy and entropy. The fishing line and sewing thread internal energy will thus increase. Then internal energy releases heat and the polymeric fibers twisting and coiling attain the lowest potential energy. Heat-Shrinkage versus temperature trace on a graph is shown in Figure 4.

![Heat-Shrinkage graph](image)

**Figure 4.** Heat-Shrinkage versus temperature trace on a graph.

The structure and micro-structure of the polymer fibers were characterized by the test parameters in the experiment.

3. **Results and discussion**

As known to all, the artificial muscle technologies have comprehensively applied in bio-mimetic machines, medicine, industrial actuators and powered exoskeletons, etc. Haines et al. suggested that the twist-aligned polymer nanofibers in a helical experimental model should be improved in terms of heating and torque direction and by adding micro-fixtures in the fixed nylon fibers [15]. In the horizontal direction, the material is contracted and stretched by stretching and heating to change the material's performance. When the nylon is coiled, the specimens have changed coil length from 25°C (ambient temperature) to 80°C (as shown in Figure 5b).
Figure 5. Tensile testing of nylon 66. a) Ambient temperature 25°C; b) heat temperature from 25°C to 80°C.

The artificial muscles are powered by ambient temperature changes; Figure 3 depicts tensile tests from 25°C (ambient temperature) to 80°C. Nylon 66 diameter is 5.46mm, and the shrinkage ratio around a Tm of 50% of deformation in length, which resulted from a heat temperature increases twist model volume caused by external micro-force in diameter, a change in length and twisting.

Artificial muscles increase in diameter occurs due to the polymer fibers interior macro-molecule chains shrinkage and coiling. During the heating process, the artificial muscle materials were contracted and its micro-structure changed. The lowest law of energy principle that increases in internal energy is equal to the total heat added. Artificial muscles lessen internal energy achieve steady state. Under the condition of external heating, the materials would yield shrinkage performance and the surface energy would change too (as shown in Figure 4). Artificial muscles with heat contractility and electrical contractility are sensitive to change in the external environment. It is found that the effect of rotation and temperature changes the performance of flexure and deformation of mono-filament materials during the experiment.
Figure 6. Artificial muscles increase in diameter. a) Before heating; b) After heating (The temperature error is ±2°C).

4. Conclusions
This article investigates a micro-failure behaviors analysis of thermo-mechanical actuators based on fishing line and sewing thread. These micro-failure behaviors have the capability of responding to ambient temperature variations producing a large amount of shrinkage ratio of a resulting variation in longitudinal length. The minimum micro-failure value is 0.02μm and the maximum value is 1.72μm with nylon twist pattern (as shown in Figure 1c).

(1) Heat setting is the process of internal material stress release, making the artificial muscle of K factor (as shown in Table 1: main text), thermal shrinkage and other performance more superior.

(2) Artificial muscles increase in diameter because of interior macro-molecule chains’ shrinkage and coiling.

(3) In artificial muscles, the greater the diameter, the smaller the coiling, and also better water absorbing.

(4) Artificial muscles with heat conductivity, electrical conductivity are sensitive to change in the external environment.

Future work should investigate some possible micro-critical changes such as: twist failure, surface stress, heat treatment temperature (Tm), or effect of twist strain on the performance and on the energy density, dynamic behaviors, etc. Future work should also address other unexplored areas such as mechanical-medicine cross research, fatigue lifetime, or effect tensile testing of hygroscope on the specimen performance.

5. Acknowledgements
This research is funded and instrument support by Faculty of Materials Science and Engineering, Harbin University of Science and Technology, China. The innovation project grant from Jiabin Science Laboratory, China. The authors wish to express Harbin University of Science &Technology and Jiabin Science Laboratory researcher gratitude for the generous support.
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