2015 Problem 3: Artificial Muscle

Exploration on The Microscopic Essence and Mechanical Properties of Artificial Muscle

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Abstract

In this study, we attach a polymer fishing line to an electric drill and apply tension to the line. As it twists, the fiber forms tight coils in a spring-like arrangement. We then apply heat to the coils, so that the spring-like shape is fixed permanently. When we apply heat again, the coil will contract. We call this the 'artificial muscle'. We experiment on this material to obtain the properties of the artificial muscle under different conditions. Finally we find that the artificial muscle is a result of entropy force and a model of torsion spring.

Introduction

The polymer fishing line is made of nylon. Nylon is a generic designation for a family of synthetic polymers, more specifically aliphatic or semi-aromatic polyamides. Basic properties of Nylon are shown in Table 1. [3]

When the fishing line is tied to the endpoint of an electric drill, it begins to rotate. When temperature increases, the fishing line begins to shrink. [2]

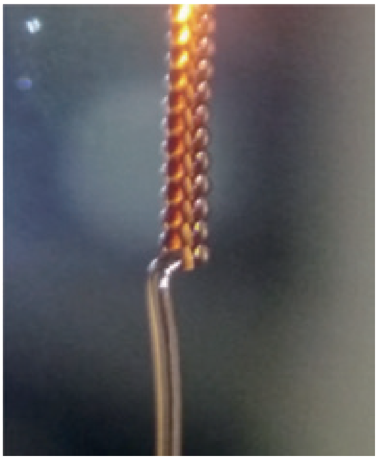

Fig.1. Artificial muscle

Density	1.15g/cm^3
Elasticity modulus	1.4GPa
Coefficient of linear expansion	110~500μm/ m · ºC
Specific heat capacity	1.67~1.70J/g · ºC

Table.1. The properties of Nylon 6

Theoretical background

The Young's modulus of long-chain macromolecule of the polymer has different degree of deformation at variable temperature. We can understand the theory from two aspects. Microscopically, such deformation is the result of entropy force: the coefficient of stiffness is proportional to temperature. Macroscopically, the coefficient of stiffness k is proportional to Young's modulus. [1]

Similarly, the essence of the problem can be seen at two angles. In terms of energy, entropy force is the derivative of the free energy F [1], and the thermal energy is transformed to the mechanical energy of the hanging object. It is at the loss of ordering. And the entropy increases as temperature increases. In terms of force, the shear deformation of torsional spring can change the torsional moment into shear stress along the vertical direction.

First, the problem is analyzed from the microscopic

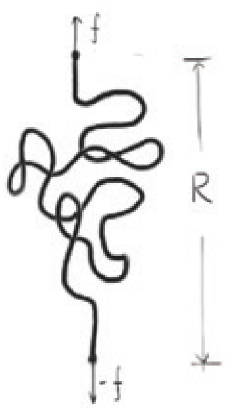

Fig.2. Model of random walk

view. We are familiar with the fundamental law: entropy force is directly proportional to the temperature. Polymer molecule of which the coefficient of stiffness is ***k*** consists of ***N*** segments, each of which has a length of ***a***. We drag the molecule to make the distance between two extreme points change from **0** to ***R*** like figure 2. k_B is the Boltzmann constant. Then we calculate the change of entropy ***S*** by using the random walk method:

$$\Delta S = -\frac{3k_B R^2}{2Na^2} \quad (1)$$

The corresponding change of the free energy at temperature ***T*** is obtained:

$$\Delta F = -T\Delta S = \frac{3}{2}k_B\, T\frac{R^2}{Na^2} \quad (2)$$

The free energy tension equation of the polymer chain takes the form:

$$f = \frac{dF}{dR} = \frac{3k_B T}{Na^2}R \quad (3)$$

then:

$$R = \frac{Na^2}{3k_B T}f \quad (4)$$

where ***R*** represents the elongation.

From the above equation, we find that temperature ***T*** is inversely proportional to the elongation.

Second, the problem is analyzed from the macroscopic view. In homogeneous and isotropic material, the relation between Young's modulus ***G*** and shear modulus ***E*** is expressed as:

$$G = \frac{E}{2(1+v)} \quad (5)$$

where ***υ*** stands for the Poisson's ratio.

The schematic diagram is shown as figure 3. [5] The elongation of micro-line along the axial direction ***dλ*** is:

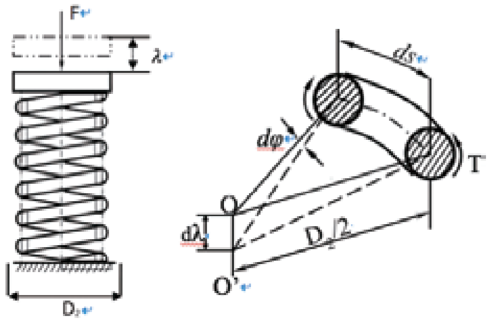

Fig.3. Macroscopic analysis

$$d\lambda = \frac{D_2}{2} d\emptyset = \frac{8FD_2{}^2 ds}{G\pi d^4} \quad (6)$$

where D_2 is the diameter of artificial muscle, d is the diameter of fishing line, F is the force applied to the model of torsion spring.

After integration we get:

$$\lambda = \int_0^t d\lambda = \frac{8FD_2{}^2 n}{G\pi d^4}\int_0^t ds = \frac{8FD_2{}^3 n}{Gd^4} \quad (7)$$

where n stands for the number of laps.

So we can find the relation between free energy F and Young's modulus G :

$$k = \frac{F}{\lambda} = \frac{Gd^4}{8D_2{}^3 n} \quad (8)$$

We combine the two views together. The Poisson's ratio can be regarded as an invariant at the temperature of 200K, so G is directly proportional to E. As a result, when F is kept constant, the elongation is inversely proportional to the temperature.[4]

Fig.4. GZX-9140MBE Electro-thermostatic blast oven

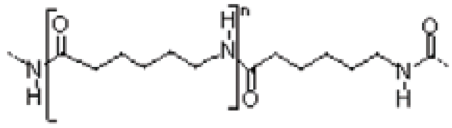

Fig.5. structural formula of Nylon 6

Experiment Verification

In our experiments, we use an electro-thermostatic blast oven to control the temperature (figure 4). The thermal blower has a temperature range of 25ºC-250ºC, and has an incremental step of 1ºC. The temperature of environment is about 30ºC.

Also we prepare an artificial muscle before the experiment. We use the fishing line to produce artificial muscle. The fishing line is made of Polycaprolactam with the trivial name Nylon 6.(figure 5) The diameter of the material is about 0.401mm.

First, we want to verify whether elongation is related to temperature. After the first heating and unwinding, we measure the relation between the elongation and temperature when the temperature increases or decreases. The result is visualized in figure 6.

From figure 6 which describes the relation between elongation and temperature, we can find that the ascending and descending temperature deviate from each other below 65ºC, we guess that when

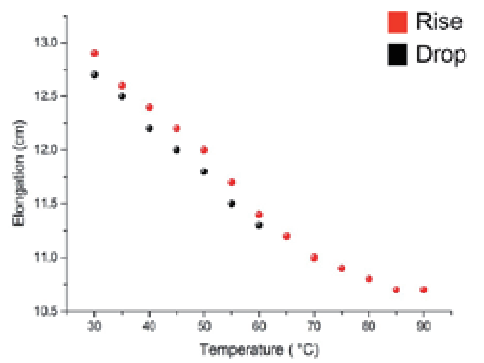

Fig.6. The relation between elongation and temperature

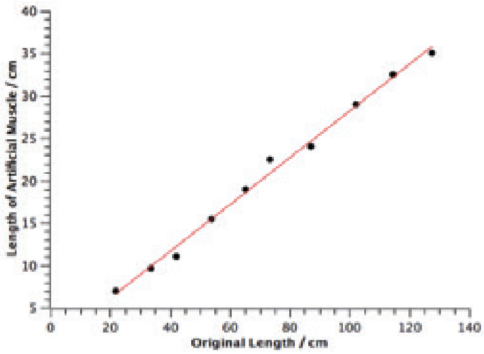

Fig.7. The relation between original length and length of artificial muscle

the temperature is descending, the artificial muscle is thought to be too tight for it to elongate. Then we conclude that the temperature T is inversely proportional to the elongation λ which accords with equation 4: $R = \frac{Na^2}{3k_B T}f$.

In a macroscopic view, the artificial muscle is a model of torsion spring. [4] So next we do an experiment to verify this prediction. Using a fishing line made of Nylon 6, we measure the original length and the fixed load respectively, and after the first heating, we obtain the relation between some parameters.

First, at the fixed load of 153.87g, we measure the length of artificial muscle by varying the original length. Then we heat the artificial muscle at 92℃. We obtained the relationship in figure 7.

The figure shows that the relation between original length of fishing line and length of artificial muscle is linear. Propose that we make an artificial muscle of which the original length is l. Then after producing, the length of artificial muscle L can be expressed like this: $L=\frac{D}{\pi d}\cdot l$, where D is the diameter of artificial muscle and d is the diameter of the fishing line.

Apparently, the coefficient of the formula $\frac{D}{\pi d}$ is constant. Then we conclude that at a fixed load, the diameter of the same fishing line is constant by varying the original length.

Also we measure the coefficient of stiffness of each artificial muscle and obtain figure 8.

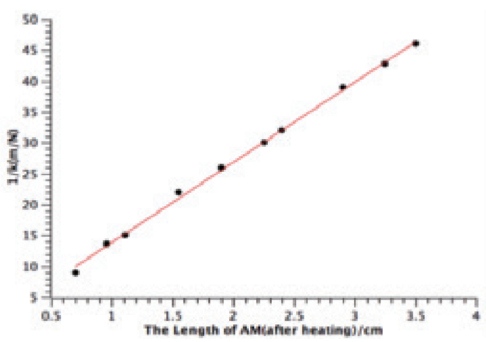

Fig.8. The relation between k and the length

Fig.8 The relation between k and the length $\frac{1}{k}$ is proportional to l(the length of artificial muscle). The relation between the laps of the muscle n and l is: $l = n \cdot d$, where d is the diameter of the fishing line.The conclusion is that at a fixed load, the coefficient of stiffness k is inversely proportional to the laps of the muscle n. It conforms to the macroscopic view.

If we change the independent and dependent variables, we can get other conclusions. So secondly at a fixed original length, we measure the length of artificial muscle by varying the load. We plot the figure which describes the relation between k and D^3.Then we conclude that the coefficient of stiffness k is simply proportional to D^3.

Conclusion

After the above experiments, we obtain the following conclusions. From the microscopic view, it is a model of entropy force. The higher temperature, the larger elongation. From the macroscopic view, it is a model of torsion spring. At a fixed load, the coefficient of stiffness k is inversely proportional to the laps of the muscle n.

Also ***k*** is proportional to the third power of **D**. The above two conclusions verify formula 7. We also find that when temperature is too high, some of artificial muscle will unwind as a result of the growth defect.

References

[1] Introduction to soft matter physics Kunquan Lu, Jixing Lu.

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[4] Shigley, Joseph E.; Mischke, Charles R.; Budynas, Richard G. (2003), Mechanical Engineering Design, New York: McGraw Hill

[5] Spring seal principle, Central South University