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Nano Bubble Dynamics in Spider Spinning System

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Abstract: A possible mechanism in the spider-spinning process is illustrated and a nanobubble dynamical model is suggested. The spinning system consists of thousands of nano scale spigots and a bubble can be produced at the apex of each nano-spigot. Nano-effect enables the dragline silk to have of extraordinary strength and toughness, while the extremely small surface tension of nanobubbles enables the spider to use an awfully small force during the spinning procedure.

Key words: Nanofiber, nano-effect, nanobubble dynamics, spider

INTRODUCTION

After 400 million years of evolution, Nature endows spiders with genius of spinning flexible, lightweight fibers which have the strongest strength in the world, at least 5 times stronger by weight than steel and have remarkable toughness and elasticity (Bell, 2002; Vollrath, 2006; Vollrath and Knight, 2001). Even in the modern times, it is difficult to synthesize a material having advantages of strength and toughness except carbon nanotube fibers, which is spun from solution in very hot temperature or pressure (Li *et al*., 2004) while the spider silks are produced at room temperature and from aqueous solutions. Spider silk is the only nature material that combines the properties unmatched by any known synthetic high-performance fibers.

Spider silks are protein-based "biopolymer" filaments or threads secreted by specialized epithelial cells as concentrated soluble precursors of highly repetitive primary sequences (Lazaris *et al*., 2002). Though many experiments have been conducted and much research is focused on gene sequencing of spider and developed a bio-mimicry technology (Service, 2002; Gatesy *et al*., 2001; Jin *et al*., 2003) however, theoretical analysis is not yet dealt with and our understanding of the mechanism of spider-spinning is rare and primitive. If the mystery in its mechanism can be solved, then we can apply the mechanism to synthetic high-performance fibers such as electrospun fibers with combination of great strength and stretch. The devised method must be much economical, so this could be the beginning of a new materials revolution (He *et al*., 2008; Liu and He, 2007).

MYSTERY IN SPIDER-SPINNING PROCESS

Spider-spun fiber is of extraordinary strength and toughness comparable to those of electrospun fiber (He *et al*., 2008; Liu and He, 2007), the later needs a very high voltage (from several thousands voltage to several ten thousands voltages) applied to water-soluble protein "soup" that was produced by a spider, furthermore, its mechanical strength dramatically decreases comparable to spider silk.

The distinct character in spider-spinning is that its spigot consists of millions of nano scale spigots (Fig. 1) and a bubble can be produced at the apex of each nano-spigot. Most natural spider silk is only 2.5-4 micrometres in diameter. Consider a dragline silk with diameter of 3 micrometre which consists of many nano scale fibers with diameter of about 20 nanometer. We, therefore, can estimate the number of nano-spigots, which reads

$$n = \left(\frac{3\times 10^{-6}}{20\times 10^{-9}}\right)^2 \approx 2\times 10^4 \quad (1)$$

That means there are tens of thousands of nano-spigots, Each nano-spigot can produce a nano-fibers with diameter of about 20 nm and a dragline silk is made of tens of thousands nano-fibers with diameter of about 20 nm. Similar to the Hall-Petch relationship, the nanofiber strength depends upon fiber diameter in nano-scale (from few nanometers to tens of nanometers) (He *et al*., 2007):

$$\tau = \tau_0 + \frac{k_\tau}{d^\alpha} \quad (2)$$

Where, k_τ, is the fitting parameter (material constant), τ_0 is the strength and surface energy of the bulk material, d is the fiber diameter, $0<d<100$ nm. $\alpha>0$ is scaling exponent.

The nano-effect enables the dragline silk to have of extraordinary strength while have of remarkable toughness (Fig. 2).

Fig. 1: The cribellum plate of a spider consists of thousands of minuscule spigots reproduced with the permission of Dennis Kunkel Microscopy, Inc

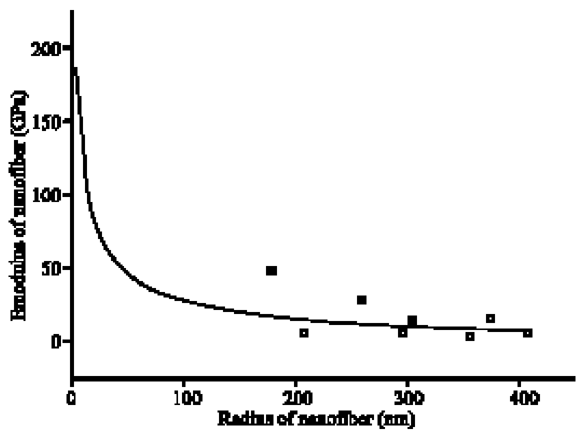

Fig. 2: Elastic modulus of nanofibers (He *et al*., 2007)

It is still an enigma how a spider produces a silk which human needs ten thousands voltage to do. One possible answer is that a spider applies sufficiently the nano-effect of bubble dynamics.

Consider a bubble made by the aqueous fibroin solution and assume that the air pressures inside and outside the bubble are, respectively P_i and P_0, its radius is r.

The pressure difference between the inside and outside of a bubble depends upon the surface tension and the radius of the bubble.

For a bubble with 2 surfaces providing tension, the net upward force on the top hemisphere of the bubble is just the pressure difference times the area of the equatorial circle:

$$F_{upward} = \pi r^2 (P_i - P_o) \quad (3)$$

The surface tension force downward around circle is the surface tension times the circumference:

$$F_{downward} = 2\pi r T \quad (4)$$

the surface tension of the bubble, T, can be expressed as (Brennen, 1995):

$$T = \frac{1}{2} r (P_i - P_0) \quad (5)$$

From Fig. 1, we can see clearly that dragline silk is made of many nano-fibers with diameter of about 20 nm. We have the very reason to assume that a nanobubble can be produced at the apex of each nanospigot with a diameter of about 20 nm. According to Eq. 5, the surface tension of such bubbles is extremely small, it can be easily overcome either by the spider's body weight or tension created by the rear legs.

We assume a spider has weight of $G = 10^{-1}$ kg. In the spinning process, the spider can use its weight to overcome the surface tension of all bubbles produced at apex of nano-spigots, that requires:

$$T = G \quad (6)$$

from which the pressure difference between inside and outside of a bubble can be determined, which reads:

$$\Delta P = P_i - P_0 = \frac{4G}{\pi r} = \frac{4 \times 10^{-4}}{(2 \times 10^{4})(20 \times 10^{-9})} = 1\, N/m^2 \quad (7)$$

Extremely small force is needed in the spider-spinning.

CONCLUSION

Although, the maximal or minimal size of a bubble might depend upon the solution viscosity, the surface tension of bubbles is independent of properties of the spun solutions, such as viscosity, which is the main obstruction in traditional electrospinning (Xu *et al*., 2007). In fact based on the present rather sketchy analysis, it would reveal the reason why dragline silk is of extreme strength, a spider can optimally use the nano-effect in its spinning procedure.

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