EFFECT OF TEMPERATURE ON THE BUBBLE-ELECTROSPINNING PROCESS AND ITS HINTS FOR 3-D PRINTING TECHNOLOGY

by

Yuting ZUO[a,b*] ***and Hongjun LIU***[a,b*]

[a] School of Materials Science and Engineering, Lanzhou University of Technology, Lanzhou, China
[b] State Key Laboratory of Advanced Processing and Recycling of Non-Ferrous Metals, Lanzhou University of Technology, Lanzhou China

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The temperature will significantly affect the surface tension of a bubble. By suitable control of the inside and outside temperature of the spun bubble, the surface tension can be vanished entirely. This zero-tension phenomenon is extremely helpful in the bubble electrospinning process. An experiment is designed to study the effect of the inside and outside temperature on the nanofibers diameter, and the theoretical prediction agrees well with the experimental data. This paper sheds a bright light on controlling the spinning process by temperature and hinting at a new trend in the 3-D printing technology.

Key words: *bubble-electrospinning, temperature, nanofibers, 4-D printing, fractal rheological model*

Introduction

Nanofibers are defined as ductile fibers with properties that their micro partners do not have, *e.g.*, high surface energy, high permeability, good thermal property, and electronic property, these special properties are also called as nanoeffect of the nanofibers [1].

Nowadays, nanofibers can be comprehensively applied to various fields, *e.g.*, biotechnology, environment, energy, medical treatment, filtration, senor, and other industries. In recent decades, nanotechnology has been attracting more and more attention from both academic and industrial communities, and it is one of the most important issues to produce nanofibers industrially.

As a simple and straightforward fabrication process, electrospinning is widely adopted in producing nanofibers [2-6], whereas its low output has dramatically hindered its industrial applications. To get rid of the shortcoming of the electrospinning, the bubble electrospinning was appeared as the most promising technology for mass-production of various functional nanofibers [7-13]. It is a milestone in both spinning technology and nanotechnology.

The bubble electrospinning [7-13] is to use an electrostatic force to overcome the surface tension of a polymer bubble, and the temperature inside and outside of the bubble will affect the surface tension greatly. As a result, it will also affect the spinning process and fibers morphology. In this paper, we will study the effect of temperature on the nanofibers diameter.

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* Corresponding autothors, e-mails: 2452767789@qq.com, liuhongjun@lut.edu.cn

Experiment

The experimental set-up is illustrated in fig. 1, where a water bath controls the temperature of the input air. A long snake-like tube is immersed into the water bath, where the temperature is kept unchanged. The temperature inside the bubble is controllable, and the environment temperature is not controlled in our experiment.

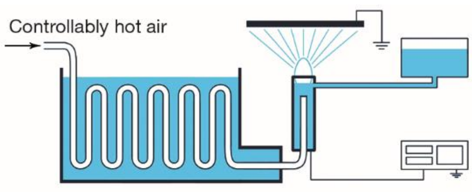

Figure 1. The bubble electrospinning set-up; the inside temperature is controlled by the water-bath

In our experiment, polyvinyl alcohol (PVA) and pure water are used to prepare for a PVA solution with a concentration of 8% as a traditional way. The distance between the receptor and the solution's surface is 25 cm, the voltage is 20 kV, the humidity is controlled between 55% and 65%, and the temperature of the water-bath is set as 30 °C, 50 °C, 70 °C, and 90 °C, respectively, and the environmental temperature is 15 °C and 25 °C, respectively.

Figures 2 and 3 show the SEM illustrations of the nanofibers under the environment temperature of 15 °C and 25 °C, respectively. Figure 4 shows the effect of the temperature inside and outside of the bubble on the nanofibers diameter.

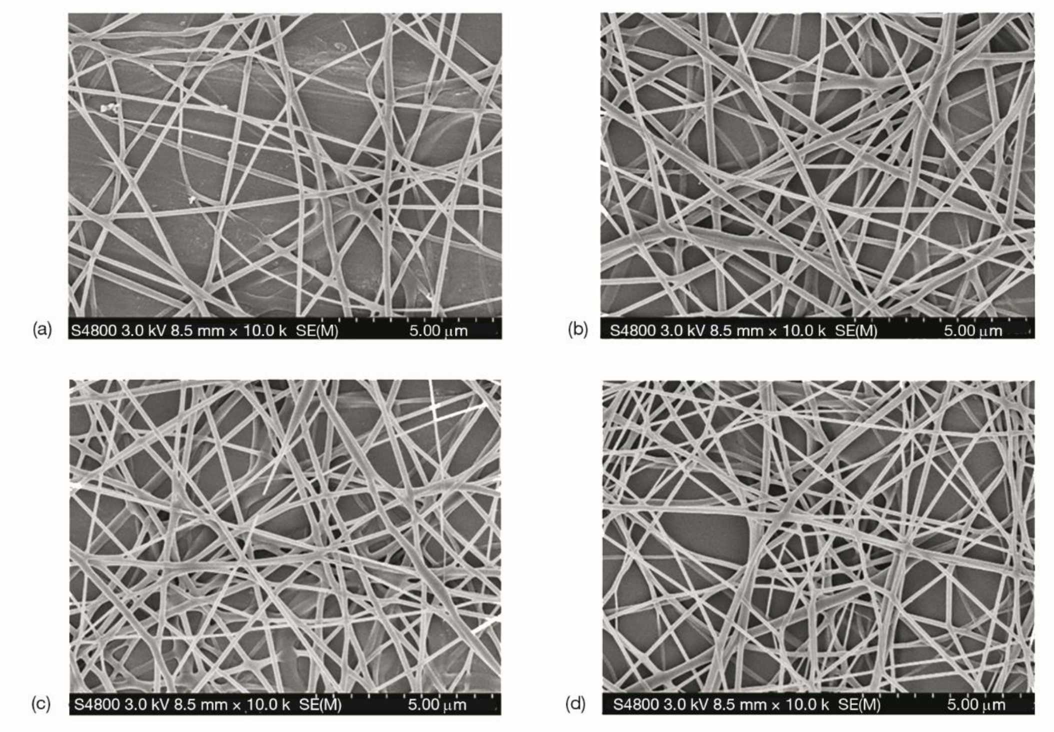

Figure 2. The SEM illustrations of nanofibers under the environmental temperature of 15 °C; the inside temperature is (a) 30 °C, (b) 50 °C, (c) 70 °C, and (d) 90 °C

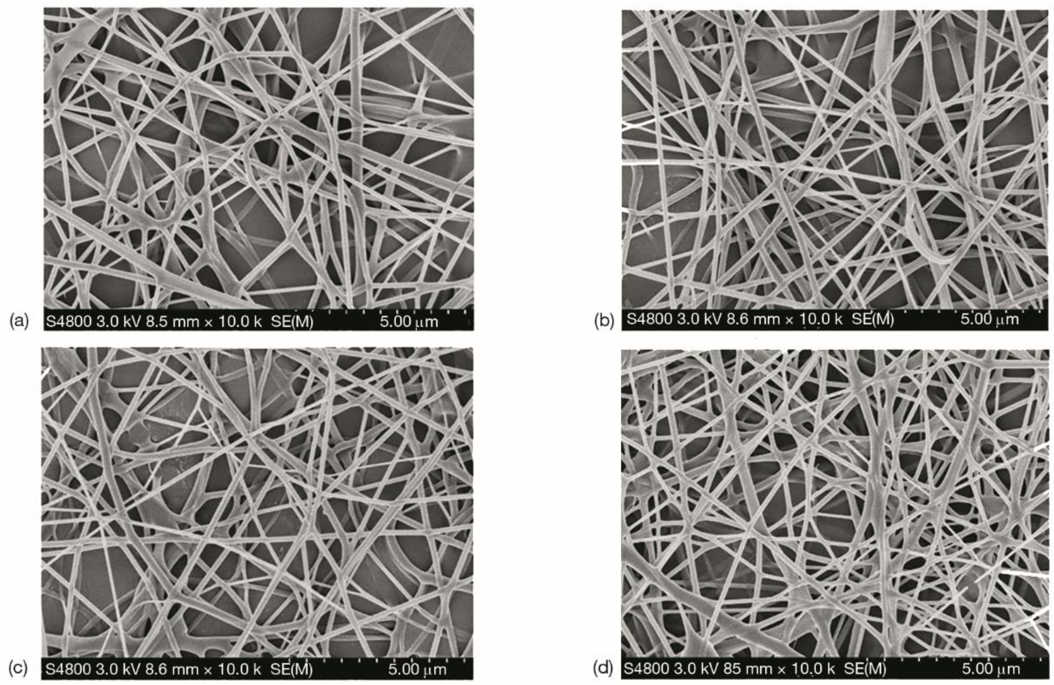

Figure 3. The SEM illustrations of nanofibers under the environmental temperature of 25 °C; the inside temperature is (a) 30 °C, (b) 50 °C, (c) 70 °C, and (d) 90°C

Theoretical analysis

The surface tension of a sphere bubble can be expressed:

$$\sigma = \frac{1}{4} r (P_i - P_o) \tag{1}$$

where σ is the surface tension, r – the radius of the bubble, and P_i and P_o – the pressure of the inside and outside of the bubble, respectively.

According to the state equation of an ideal gas, we have:

$$\frac{P_i}{\rho_i} = \mathrm{R} T_i \tag{2}$$

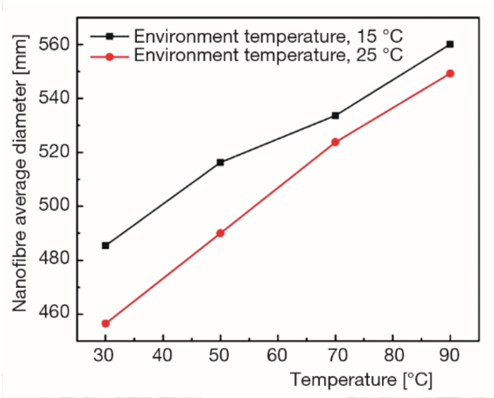

Figure 4. Effect of the temperature inside and outside of the bubble on the nanofibers diameter

and

$$\frac{P_o}{\rho_o} = \mathrm{R} T_o \tag{3}$$

where T_i and T_o are inside and outside temperature of the bubble, respectively, ρ_i and ρ_o – the densities of the inside and outside air, respectively, and R – is the universal gas constant.

After a simple calculation, we have:

$$\sigma = \frac{1}{4} r\mathrm{R}(T_\mathrm{i}\rho_\mathrm{i} - T_\mathrm{o}\rho_\mathrm{o}) \tag{4}$$

By suitable choice of the temperature inside and outside of the bubble, we can have the following relationship:

$$T_\mathrm{i}\rho_\mathrm{i} - T_\mathrm{o}\rho_\mathrm{o} = 0 \tag{5}$$

That means that the bubble surface tension becomes zero, and any small external force can break the bubble.

According to eq. (4), for a fixed environment temperature, a higher T_i implies a higher surface tension. That means we require a higher external force to break the bubble. In our experiment, the external force is produced by the electrostatic field, and it is kept unchanged.

In the spinning process, the total energy produced by the electrostatic field is kept unchanged, that is:

$$E_1 + E_2 = E \tag{6}$$

where E_1, E_2, and E are the energy needed to overcome the surface tension of the bubble, the kinetic energy of the moving jet, and the total energy produced by the electrostatic field, respectively.

A higher T_i implies a higher E_1 to overcome the surface tension of the bubble, as a result, we have a lower velocity of the moving jet. According to the mass conservation of the moving jet, we have:

$$\pi r^2 u\rho = Q \tag{7}$$

where r, ρ, u, and Q are moving jet radius, density, velocity, and flow ratio, respectively.

Equation (7) implies a lower velocity leads to a larger radius, this theoretical prediction agrees well with the experimental observation as given in fig. 4.

When T_i is a constant, according to eq. (4), a higher T_o results in a lower surface tension. By a similar analysis as above, a higher T_o implies a smaller nanofiber. This prediction also sees a good agreement with the experimental data, see fig. 4.

Discussion and conclusion

In this paper, we predict a zero-tension of the bubble wall, which is extremely helpful in controlling the bubble electrospinning process. The zero-tension phenomenon might be used for an ultra-viscous solution.

In the 3-D printing process [14-17], the paste is always a high viscosity, and a coaxial nozzle, fig. 5, might be a new trend in the 3-D printing technology.

In the coaxial nozzle, the air with controllable temperature is put into the center tube, and a bubble is formed at the nozzle. By suitable control of the temperature, the printed bubble has zero surface tension, that means any a small force can push the bubble for printing purpose. As the bubble's surface tension can be exactly controlled with respect to time, this coaxial nozzle 3-D printing technology can be developed into the 4-D printing technology in the near future.

This paper finds a zero-tension phenomenon of a spun bubble in the bubble electrospinning process, *e.g.*, a suitable choice of the inside and outside temperature of the bubble, its surface tension can vanish completely. This zero-tension phenomenon is extremely helpful in controlling the spinning process. Both the theoretical analysis and experimental data imply that a higher inside temperature results in a larger diameter of the nanofibers, while a higher environment temperature leads to smaller nanofibers. The finding is extremely helpful in designing an experimental set-up.

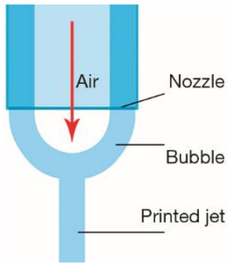

Figure 5. A coaxial nozzle in the 3-D printing technology

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