EFFECT OF MAGNETIC INTENSITY ON DIAMETER OF CHARGED JETS IN ELECTROSPINNING

by

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In the electrospinning process, the rotating charged-jet moves between the permanent magnets, as a result Ampere force is generated. Experiment shows that the magnetic field can decrease fiber size and enhance the uniformity of fiber size.

Key words: *magnetic intensity, electrospinning, charged jet, diameter distribution*

Introduction

Existing nanotechnologies that require aligned nanoparticle arrays include surface-enhanced Raman scattering (SERS) substrates for use in ultrasensitive analytical tools [1], micromechanical sensors [2], and protein separation [3]. Prior studies have shown that magnetic fields can be applied during the electrospinning of polymer nanoparticle systems to improve alignment of the fibers, but not of the nanoparticles within the fibers. Because magnetic nanoparticles (MNP) are superparamagnetic at room temperature when the size decreases to less than 20 nm [4], the nanofibers were magnetized by an external magnetic field due to the addition of MNP. As a consequence, magnetized fibers could be stretched into essentially parallel fibers in a magnetic field over a relatively large area. Yang *et al.* [5] have used this method to fabricate polyvinyl alcohol (PVA) aligned fibers. They all focused on the design and intrinsic essence of magnetic electrospinning.

In this paper, theoretical and experimental analyses for magnetic-electrospinning are presented to explain how to prepare parallel fibers. The theoretical analysis takes into account the effect of magnetic field on the quantity of heat, which plays a pivotal role in determining the diameter of the electrified jet. In the magnetic-electrospinning process, the charged jet lands the gap of the permanent magnets, and a couple of Ampere forces are generated due to the current in the jet. The direction of the couple of Ampere forces is always parallel to the velocity of the charged jet, leading to straightening the whipping circle. Therefore, the straightened circle means less energy waste in the electrospinning process, the saved energy is used to increase the kinetic energy of the moving jet. According to conservation of mass, with the increase of magnetic intensity the radius of the jet becomes much smaller. In addition, the effect of magnetic field on the diameter distribution of electrospun fibers is studied.

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Theoretical analysis

In the electrospinning process, the charged jet lands the gap of the permanent magnets, and a couple of Ampere forces are generated due to the current in the jet [6], as illustrated in fig. 1.

$$F_m = q_e \frac{1}{c} u \times B + \frac{1}{c} J \times B + (\nabla B) M + \frac{1}{c}(P \times B u) + \frac{1}{c}\frac{\partial}{\partial t}(P \times B) \quad (1)$$

where q_e is the electric charge, u – the velocity of the jet, B – the magnetic induction, J – the current, M – the magnetization, P – the polarization, and c – the velocity of light in a vacuum (c = 2.998925 ± 0.00006·10^8 m/s).

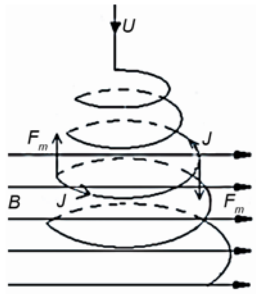


Figure 1. A couple of Ampere forces in the charged jet induced by the magnetic field

$$J = k\left(E + \frac{1}{c} u B\right) + q_e u + \sigma_T \nabla T \quad (2)$$

$$P = \varepsilon_p \left(E + \frac{1}{c} u B\right) \quad (3)$$

$$q_e = \nabla D, \quad D = E + P \quad (4)$$

where k is the electric conduction, E – the electric field, σ_T – known as Peltier and Seebeck coefficient, T – the temperature in Kelvin degrees, ε_P – the material moduli, and $D = E + P$, – the atomic displacement vector.

The current in the jet, under the magnetic field, produces a couple of Ampere forces. The direction of the Ampere force is always parallel to the velocity of the charged jet (fig. 1), leading to straightening the whipping circle. The straightened circle means less energy waste in the electrospinning process, and the saved energy is used to increase the kinetic energy of the moving jet. As a result the stability condition is enormously improved. More kinetic energy of the moving jet means a higher velocity of the jet. According to conservation of mass $r^2 \sim 1/u$, the radius becomes much smaller than that without magnetic field.

In addition, according to the mathematical model of the charged jet under coupled multifield [7], an equation determining the quantity of heat (q) has been written [7]:

$$q = k\nabla T + k_E \left(E + \frac{1}{c} u \times B\right) \quad (5)$$

where k is the heat conductivity and k_E – known as the Peltier and Seebeck coefficient.

Equation (5) shows the effect of magnetic field on the quantity of heat in the charged jet. It can be seen that with increase in the magnetic intensity, the jet will obtain a larger quantity of heat.

Experimental verification

PVA is dissolved in the deionized water with a weight ratio 8%. Fe_3O_4 nanoparticles with an average diameter of 20 nm are dispersed in the PVA solution. The gap of the two permanent magnets is 8 cm. All the experiments are carried out with the same collective distance (10 cm), the same voltage applied (10 kV) and the same flow rate (2 ml/h) at the room temperature (18 °C) and 55% relative humidity. The different magnetic intensities between 0 mT-160 mT are applied.

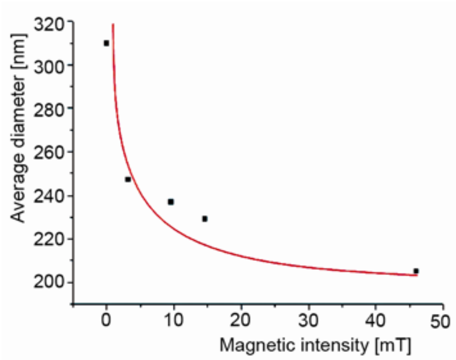
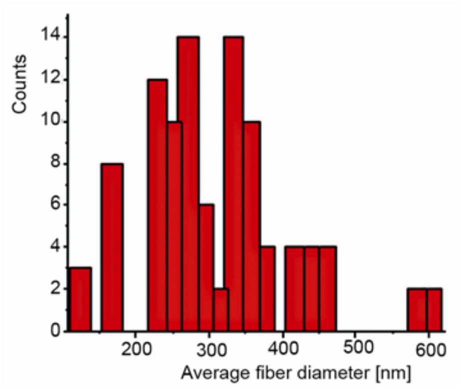


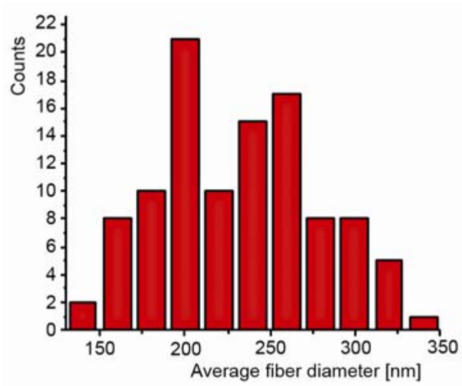
Figure 2. The relationship between the magnetic intensity and diameters of jets

Figure 2 shows the effect of applied magnetic intensity on the diameter of the charged jets. It can be seen that with the increase of magnetic intensity, there has appeared ever-decreasing sizes of the charged jets. This phenomenon can be explained by given theoretical analysis.

Figure 3 shows the electrospun fiber diameter distribution with the different magnetic intensity. It can be seen that the diameter distribution with a magnetic field is more homogeneous than that without a magnetic field. These experimental results also agree with the theoretical predictions. The magnetic field force can decrease the waste of most energy, and the stability condition is enormously improved.



(a) Magnetic intensity = 0 mT



(b) Magnetic intensity = 9.65 mT

Figure 3. The electrospun fiber diameter distribution with the different magnetic intensity

Conclusions

In this paper, the moving behavior of the charged jet in the electrospinng process with a magnetic field is analyzed. The results indicate that the magnetic field produces a couple of Ampere forces. The direction of the Ampere force is always parallel to the velocity of the charged jet, leading to straightening the whipping circle. As a result more energy is used to increase the kinetic energy of the moving jet, and with the increase of magnetic intensity the radius of the jet becomes much smaller. In addition, the electrospun fiber diameter distribution and the relationship between the diameter of the jet and the magnetic intensity are obtained by experiment. The experimental results correspond well to the theoretical analysis and show that the magnetic field can control the diameter of the charged jet and the diameter distribution.

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