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# FABRICATE WAVY MICRO/NANO FIBER VIA AUXILIARY ELECTRODES

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**ABSTRACT:** Wavy micro/nano fiber is a common phenomenon in traditional electrospinning caused by bending instability. However, using bending instability to fabricate wavy fibers is hard to control the wavelength and amplitude of the wavy fibers. Auxiliary electrodes were developed to control the morphology of the wavy fibers in this paper, when a 4 wt% Poly(ethylene oxide)(PEO) solution was electrospun at 1KV applied voltage in near-field electrospinning, and the collector at relatively low speed, AC current power supplied to auxiliary electrodes, and the amplitude of wavy was increased as increasing the AC current power voltage supplied to the auxiliary electrodes, and the frequencies of the wavy fibers was the same as the frequencies of the AC current power. Therefore, AC current power supplied to auxiliary electrodes can be used to control wavy fibers fabrication.

## INTRODUCTION:

Electrospinning is a simple, economic and versatile technique for fabricating ultrafine fibers with diameters ranging from 5nm to 3 $\mu$ m by many materials, such as polymer, melt, ceramic and so on, for Huang et al,(2003). Since the electrospinning was first studied by Formhuzls, electrospinning has been widely studied by many people from 1990s, for Sun et al,(2013a). Wavy micro/nano fiber is a common phenomenon in traditional electrospinning caused by bending instability, it also appears in the near-field electrospinning when the collector speed is low. Due to their unique structure, wavy fibers have been used for sensors, resonators, for Kong et al,(2003), electromechanical systems, for Motojima et al,(1999), electromagnetic devices, for Zhang et al,(2003), stretchable electronics products, flexible displays, electronic skin, etc, for Huang et al,(2013).

Bending instability was first studied by Reneker in 2000, and they found that during the jet drop from the capillary to the collector, the jet would become instability, which called bending instability. During the electrospinning process, the jet would get coil when it impacted a hard, stationary surface and buckles could account for some of the observed coils. As a result, the helical or wavy fiber would be collected on the collector because of the small bending instability, for Reneker et al,(2000). Yarin has studied the mathematical model about the bending instability in 2001, for Yarin et al,(2001). In 2005, Zhao has demonstrated how the solution concentration effect the morphologies of the fiber, and as the concentration increased, products with a variety of morphologies, including polymer colloids, beaded fibers, smooth fibers, and zigzag ribbons, for Zhao et al,(2005). Han found that, the buckling instability in electrospinning, whose patterns have frequencies of the order of  $10^5$  to  $10^6$  Hz, while the bending loops are formed at the frequencies of the order of  $10^3$  Hz. Meanwhile, the deposited buckling patterns include sinuous, zigzag-like, figures-of-eight, recurring curves, coiled and other structures that resembled many patterns created by uncharged jets as the highly viscous fluids impinging a hard flat surface, for Han et al,(2007). In 2008, Han found a new phenomenon called pendulum-like jet, which due to repulsive Coulomb force between the straight electrified jet and the charges accumulated on the collector, and it has frequencies of the order of  $10$  to  $10^2$  Hz. The zigzag fibers were collected on a static water surface which served as a grounded

electrode, for Han et al,(2008). Near-field electrospinning was first studied by Sun in 2006, which is a new technique to fabricate alignment and straight fiber with a moving collector, for Sun et al,(2006). However, Zheng has found that, during the near-field electrospinning(NFES) in 2010, when the collector speed is slow, the wavy fibers could also be collected on the collector, for Zheng et al,(2010). Xin has built a moving collector with a gas controlled lateral motion in 2012, which had been used to collect buckled fibers, The conditions for making these swinging patterns are reproducible, and the coiling and sinusoidal meanders have been collected. These uniform buckled patterns extend over millimeter distances, for Xin et al,(2012). In 2013, Duan put forward a new method to fabricate wavy fibers, which used Photolithography to generate well-defined patterns, for Duan et al,(2013). In order to get fibers with specific wavy/coiled microstructures, auxiliary electric field, for Deitzel et al,(2001) and patterned collector, for Li et al,(2005) have been used to control fibers deposition process, and Sun has developed a novel electrospinning method for fabricating curled fibers in 2013, called reciprocating-type electrospinning, which combined whipping-based electrospinning and detachment lithography to generate patterned film with high stretchability, for Sun et al,(2013b).

However, those methods as mentioned above to fabricate wavy fibers are too coarse to be used in electronic devices. NFES can deposit high positioning accuracy fibers by shortening the nozzle-to-collector distance, but NFES normally generate straight or uncontrollable wavy fibers, for Duan et al,(2013). Although auxiliary electric field has been used to control the morphology for the fibers in the conventional electrospinning process, for Deitzel et al,(2001; for Bellan et al,(2006; for Grasl et al,(2013; for Arras et al,(2012), and most of them with the help of auxiliary electric field to deposit align fibers.

In this paper, NFES and auxiliary electric field are combined to generate patterned controllable wavy fibers. The NFES is utilized to generate single high positioning accuracy fibers, and the auxiliary electric field is utilized to control the morphology of the deposited fibers. The fibrous morphology could get well controlled by auxiliary electrodes, especially to fabricate the zigzag fibers, which could be used to fabricate the lines of the grating. As we know, most of the grating lines on the grating ruler are fabricated by laser carve, but it's very hard and expensive to fabricate the gratings whose diameter lower than 5 micrometer, for Wang,(2010). However, near-field electrospinning can produce fibers that the diameter rang from 50nm to 3 $\mu$ m, which is very useful to fabricate the grating lines of the grating ruler.

## **EXPERIMENT:**

### **Materials:**

Poly (ethylene oxide) (PEO),  $M_w = 2,000,000 \text{ g} \cdot \text{mol}^{-1}$ , 4 wt% solution in distilled water and under stirring for 4h at room temperature 20°C. PEO was purchased from Aladdin Shanghai China, and the distilled water was purchased from Watsons. The ground collector was made of chromium plating glass, which is the material to fabricate grating.

### **Experiment set up**

The experimental setup(Fig. 1) for NFES was the same as to those used previously, for Sun et al,(2006; for Zheng et al,(2010),and in a constant temperature of 20 $\mu$  room, and the relative humidity about 50%. However, there are two parallel auxiliary electrodes setting on beside the collector, and the upper surface of the collector is overtop than the lower limp of the parallel auxiliary electrodes, meanwhile, the tip of the needle is lower than the coboundary of the parallel

auxiliary electrodes, both of which could avoid the marginal effect of the electric field. The needle size is 30G, whose inner diameter is 0.16mm and the outer diameter is 0.31mm. The collector can move at a constant speed of typically  $V_c = 0 \sim 45\text{mm/s}$  via a motion platform (SURUGA, Japan). The syringe and the accurate syringe pump were installed on an X-Y-Z manual operation accurate platform, which could be easy to adjust the distance between the needle and collector with the help of the microcalliper. The DC power could supply voltage rang from 0~50KV □dong-wen, China□. The auxiliary AC current power voltage supply to auxiliary electrodes could adjust from 0~5KV (Sinusoidal Ac Power (SAP), frequency: 50HZ). The auxiliary electrodes were made of copper foil, and the distance of two auxiliary is 40mm.

### **Characterization:**

Collected solidified fibers were observed with CNC video measuring system (VMS-3020H) and Scanning Electron Microscopy (HITACHI TM3030).

### **RESULT AND DISCUSSION:**

The PEO fibers were collected on the collector which speed were selected from 5mm/s to 20mm/s, and the auxiliary SAP voltage select:0v, 50\*25v, 100\*25v, 150\*25v, 200\*25v for each selected speed. The needle to collector distance is 4mm. and the DC power supply voltage to the needle is 1KV.

During the NFES process, the jet drop from the needle to the motion collector, then nanofiber can be deposited along the track of collector, and the jet stayed straight or was not collected as a regular wavy/coils fiber unless supply the SAP to auxiliary electrodes, as shown in Fig. 2(a). When the SAP voltage was supplied to the auxiliary electrodes, there was a 'alternating electric field' (50HZ) between the auxiliary electrodes, which caused by the auxiliary SAP, and the jet would become swinging when the 'alternating electrical field' force play more important role in the deposition process of nanofiber in NFES process. Therefore, the wavy fibers would be collected on the collector. Meanwhile, the amplitudes of the deposited fibers increased as the SAP voltage increased, which were shown in Fig. 2 (b)-(e). The wavy/zigzag fibers were collected on the motion collector via Auxiliary electrodes, as the Fig. 4(a) shown, the amplitude of the fibers were a linear relation to the voltage of the auxiliary SAP, Thus, the amplitude of the wavy/zigzag fibers can be controlled by the alternating electrical field force. However, as the Fig. 3(a) show to us, the fibers were unsmooth due to the collector motion speed lower than electrospinning rate in NFES process, and the falling jet is in relaxed state that would be disturbed easily by other factors, for Zheng et al.(2010), and as shown in Fig. 3(b), the wavy fibers also unsmooth, just like to the NFES process, the reason why the wavy fibers become unsmooth was during the electrospinning process assisted by SAP, the swinging frequencies of the jet lower than the electrospinning rate.

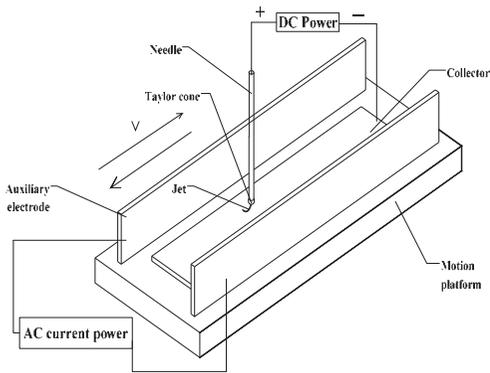


Fig. 1 Schematic representation of the experimental setup.

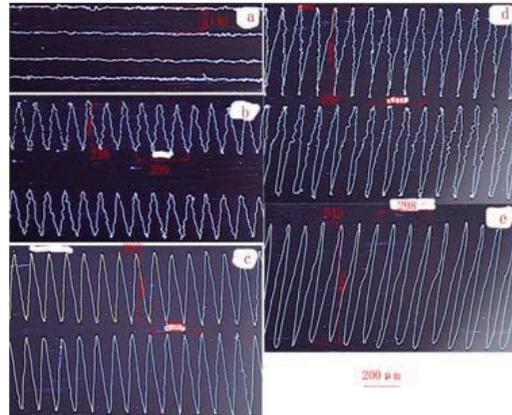


Fig. 2 with the help of the auxiliary electrodes, the fibers were deposited as wavy fibers at the speed of 5mm/s, and the DC power supplied was 1KV. (a)-(e): Comparison of the wavy patterns created by the AC power voltage supplied to auxiliary electrodes each was 0v, 50×25v, 100× 25v, 150×25v,200×25v.

As shown in Fig. 2(b)-(e), the wavelength was measured by three periods, when the collector speed was 5mm/s, and the AC power voltage supplied to auxiliary electrodes was 50×25v, and the average wavelength of one period is 101μm. As shown in Fig. 4(b), under each of the collector speed, the wavelength of wavy fibers didn't change very much when the different AC current voltage supplied to auxiliary electrodes. As shown in Fig. 4(c), the wavelength would liner increased as the collector speed increasing. The frequencies of wavy fibers can be calculated by Eq. (1) and Eq. (2):

$$f = \frac{1}{T} \tag{1}$$

$$\lambda = v \times T \tag{2}$$

Where f is the frequencies of wavy fibers, v is collector speed; T is the period of the wavy fibers; λ is the wavelength of the wavy fibers. And the frequencies of wavy were shown in Fig. 4(c), even though the collector was increased, the frequencies were near to 50HZ, which is the same as to the AC current power frequencies. As a result, it shows that, the collector speed wouldn't affect the frequencies of the wavy fibers, and it could control the wavy fibers frequencies by controlling the AC current power frequencies.

## CONCLUSION:

The wavy micro/nano fibers via auxiliary electrodes in NFES have been studied by experiment. The jet is easily disturbed by many factors when the collector speed and the DC power supplied to electrospinning are lower, and the fibers were deposited on the collector are not straight fibers. When supplied the AC current power to the auxiliary electrodes, the jet became swinging, and the wavy fibers would deposit on the motion collector, meanwhile, the amplitude of the wavy fibers would increase as the AC current power voltage increasing. The frequencies of the wavy fibers also have been studied in this paper, and the collector speed didn't affect the wavy fibers frequencies.

The experiment result shows that the wavy fibers frequencies are the same as the AC current power frequencies. In future, the auxiliary electrodes used for controlling the wavy nanofibers deposit will be realized, and it can fabricate zigzag fibers when supply AC current power. It's an important advantage, which can be used for fabricating super-precise grating encoder.

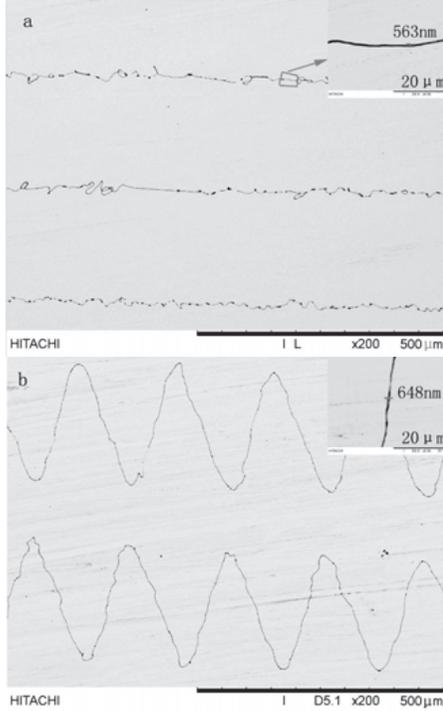


Fig. 3 SEM images of the fibers generated from (a): the AC current voltage is 0v, Collector speed was 5mm/s;(b): the AC Current voltage was 50×25v, collector speed was 5mm/s.

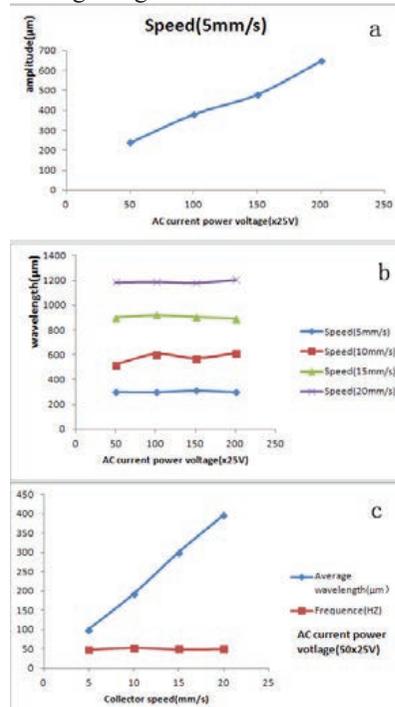


Fig. 4 (a): The relationship between the amplitude and AC current power voltage; (b): the relationship between the wavelength and AC current power voltage; (c): the relationship between the wavelength (frequencies) and collector speed

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