DAUGHTER JET CASCADES PRODUCED BY REPELLING OF MICRO/NANO SURFACE CHARGES

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We demonstrate that when a charged polymer jet is accelerated by an electrostatic field, its diameter tends to micro/nano scale, and its surface can eject one or more daughter charged jet due to the growing Coulomb force acting on its surface. Sub-daughter jets are formed when the Coulomb force overcomes the surface tension of the daughter charged jet, as a result, we can observe a multi-stage cascade, which is received as superfine fibers, the diameter of the minimal fiber reaches as small as 4 nanometers (40 angstroms).

(Received October 8, 2012, Accepted April 29, 2013)

Keywords: Electrospinning, daughter cascade, nanofiber , Coulomb force, Mass conversation

1. Introduction

Any charged surfaces are subjected to an electronic force, when two surfaces tend to micro/nano scales, according to Coulomb's law, its repelling force increases greatly. Electrospinning(McKee, 2006) uses an electrical charge to eject a charged jet, which is accelerated and becomes thinner to form superfine fibers typically on the micro or nano scale. Attempts to understand the process have mostly focused on fabrication of smooth nanofibers. However, the effect of surface charge on morphology of micro/nano fibers has not been caught much attention yet. Here we show a daughter jet cascade in the electrospinning process.

2. Experimental details

Materials: Polyvinyl alcohol (PVA) with a degree of 1750±50 and wood ashes were dissolved into distilled water with the temperature 16.2^0C and the humidity 43%. Then the mixture was stirred with the aid of electromagnetic stirrer at 90^0C for 4 hours to get a homogeneous and transparent solution, and cooled to the room temperature before the experiment. The solution concentration is 10% and the ash concentration is 1%.

Instrumentation: The solution was placed in a 10 mL syringe. The needle tip with a diameter 0.7mm was connected to a DC high-voltage generator via an alligator clip. A piece of aluminum foil, placed 10cm before the needle tip, was served as the collector for the electrospun fibers depositing. And the voltage applied was maintained at 20 kV.

3. Results and discussion

A hierarchical fiber cascade obtained by the electrospinning is illustrated experimentally in Fig.1, where we also obverse many spots on the fibers' surface. The phenomenon can be explained using force balance and mass conversation.

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3.1. Coulomb force

Consider a curve with length *dl* as illustrated in Fig. 2. It is repelled outward by the other charge on the circle:

$$dF_e = k\frac{(\sigma dl)(\sigma rd\theta)}{(r + r\cos\theta)^2 + (r\sin\theta)^2} \tag{1}$$

where σ is the surface charge per length , r is the radius of the jet, k is a constant.
Integrating Eq.(1) results in

$$F_e = \int_0^{2\pi} k\frac{\sigma^2 rdl}{(r + r\cos\theta)^2 + (r\sin\theta)^2} d\theta \tag{2}$$

The Coulomb force acting the surface per length reads

$$f_e = \frac{F_e}{dl} = k_e \frac{\sigma^2}{r} \tag{3}$$

where k_e is a constant.

The spots are formed due to the Coulomb force, which repels the whole jet surface simultaneously, and many protruding cones are formed on the surface, but generally only one cone can eject its daughter jet on a close region, because the characteristic diameter scale is reduced greatly between adjacent cascades, and the other un-ejected cones become spots. The formed cones result in an unsmooth surface, remarkably increase the surface-to-volume ratio.

3.2 Mass conservation

During the electrospinning process, the charged jet follows the mass conservation, that requires(He, et al., 2007; He, et al. 2008)

$$\pi r^2 \rho u = Q \tag{4}$$

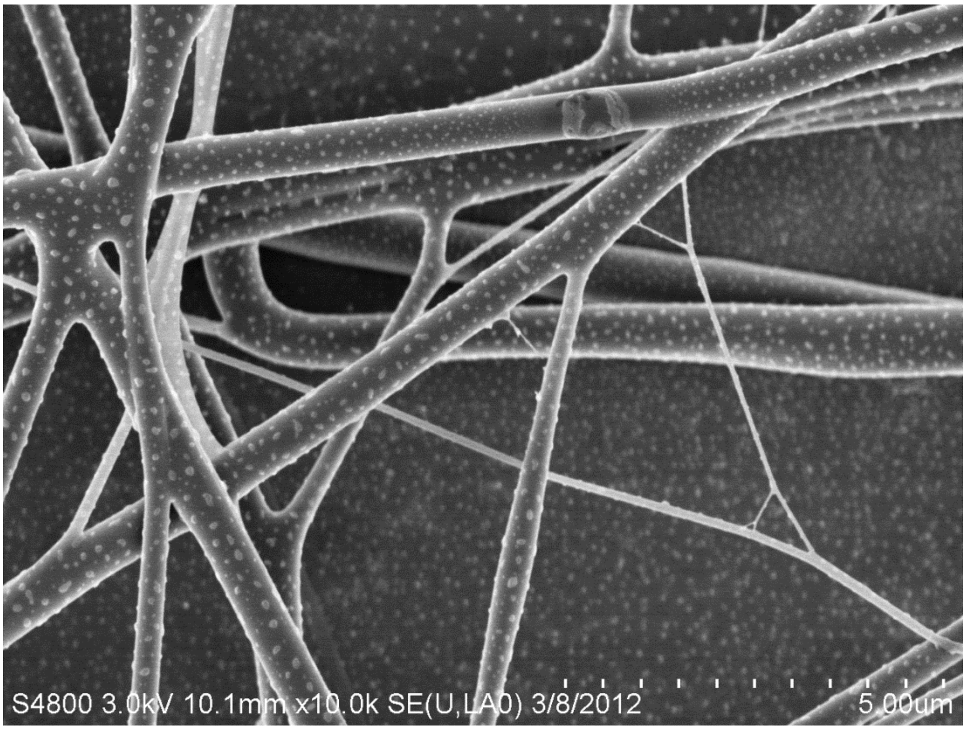
where *Q* is the mass flow rate, ρ is density, *u* the velocity of the jet.
Generally the flow rate and density keep unchanged in the experiment, we, therefore, have

$$r^2 u = C \tag{5}$$

where C is a constant.

A higher electrostatic field leads to a higher jet velocity and smaller jet radius. When the radius reduces to micro/nano scales, the Coulomb force due to the surface charges increases remarkably (see Eq.(3)) :

On a macro scale, the Coulomb force can be ignored, but when the radius of the jet becomes smaller, the Coulomb force might be large enough to relax the jet surface. The coupling of surface charge and the Coulomb force creates a tangential stress, extruding the surface to form a cone, this can greatly affect the electronic force acting on the jet surface. Once the electric force exceeds the critical value needed to overcome the surface tension of the cone, a daughter charged jet is ejected, see Fig.1. A similar phenomenon occurs in a daughter jet, and a sub-daughter jet can be ejected, thus a hierarchical jet cascade is formed, an event that typically occurs within milliseconds.



Original SEM illustration

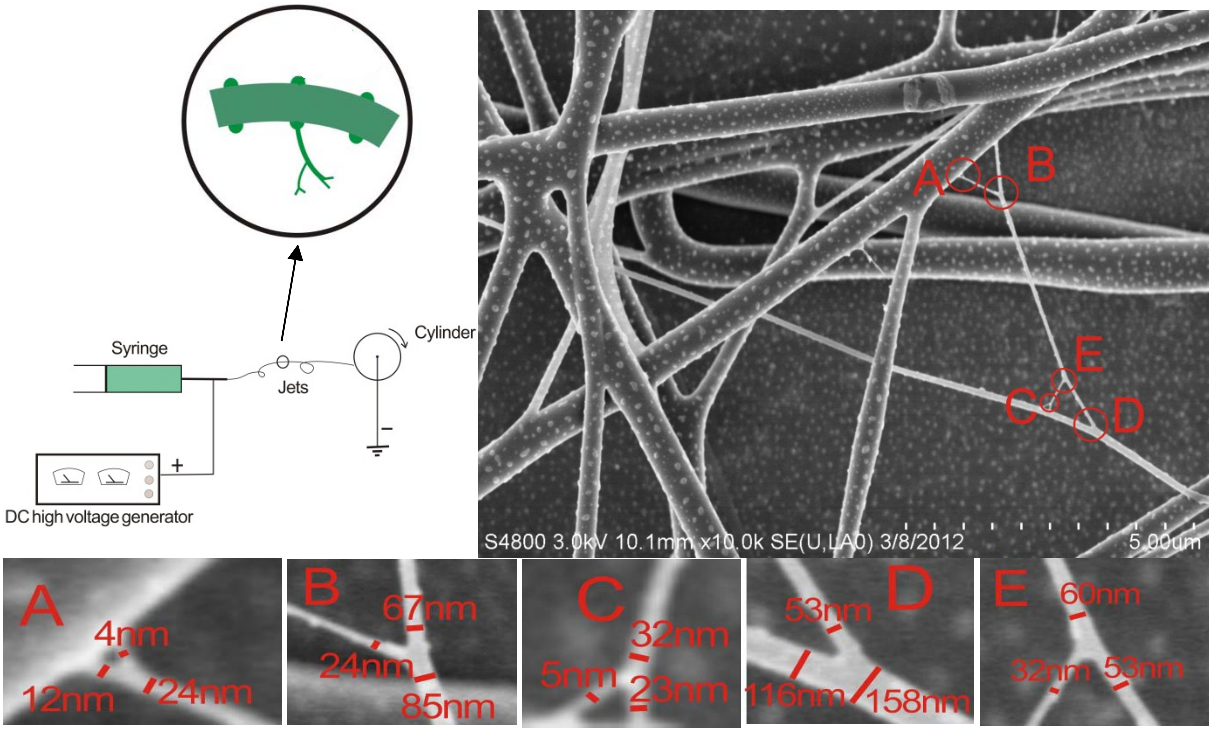


Fig.1 A hierarchical fiber cascade by the electrospinning. The top left is an experimental setup; the top right is the SEM image ; (A-E)two-stage cascade.

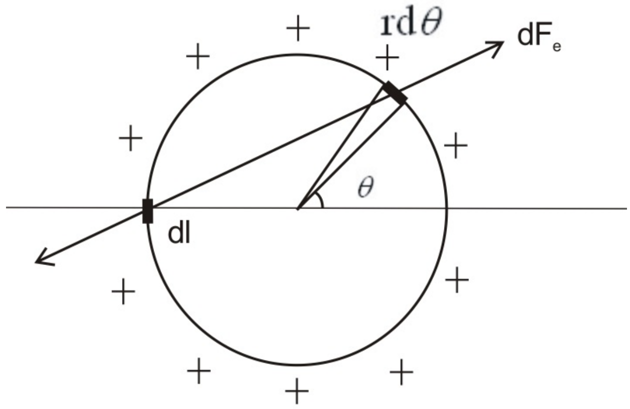


Fig. 2 The Coulomb force acting the surface.

4. Conclusions

The diameter of the obtained fibers in last cascade can reach as small as several nanometers, 4 nanometers in Fig. 1a, and 5 nanometers in Fig.1 c, which might be a minimum in artificial fibers because a macromolecule usually ranges from about 10 to 1000 nanometers.

Acknowledgement

The work is supported by PAPD (A Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions), National Natural Science Foundation of China under Grant No.10972053.

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