2017 International Conference on Education Science and Education Management (ESEM 2017)
ISBN: 978-1-60595-486-8

The Utilization of Experimental Phenomena in the Lessons about Basic Theories in Material Engineering

Man ZHANG[a], Deng-Guang YU[b,*], Xing-Hao LI, Gang-Qiang LIANG, Lin-Bo MA and Yang-Chao DENG

School of Material Science and Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China

[a] ZhMan0225@163.com, [b]ydg017@usst.edu.cn

*Corresponding author

Keywords: Higher Education, Material Processing, Electrospinning, Basic Theory, Scientific Phenomenon.

Abstract. How to give a vivid lesson about basic theory to college students comprises a puzzle to many teachers in high schools. Electrospinning is a very popular nanotechnology for creating polymeric nanofibers and fiber-based nanocomposites, which involves the overlap of multiple disciplines. The basic theories about this material processing method are very complicated, and are difficult to explain clearly to the college students in the classroom lesson. When some phenomena happened during the electrospinning processes were exploited as teaching materials, the students were greatly provoked to know "what", "how" and "why" about this advanced technology. Correspondingly, the lessons about its teaching and explanations became easy. In the field of material science and engineering, the combinations of scientific phenomena with the related theories comprise an effective approach for engineering teaching in higher education.

Background

Electrospinning, electrospraying and e-jetting printing are commonly termed as electrohydrodynamic atomization (EHDA) techniques, which are "top-down" processes for nano fabrications [1-3]. Different with traditional nano fabrication methods, electro-static energy is directly exploited to remove organic solvents from the working fluids for generating solid products during the EHDA processes [4-6]. These advanced material processing processes are very popular with potential applications of their products in a wide range of fields including pharmaceutics, ceramics, cosmetics energy, environmental science and food industries.

One fundamental reason for their popularity is the easy implementation of these processes [7-9]. Shown in Fig. 1a is a common system for carrying out electrospinning. It consists of four components, i.e. 1) a high-voltage power supply, 2) a fluid driving device (syringe pump), 3) a capillary for introducing the sprayed fluid, and 4) a grounded collector [10-12]. The inset of Fig. 1a shows the simple connection of the power supply with the working fluid, i.e. *via* an alligator clip on the spinneret leading the fluid. A typical working process of electrospinning is exhibited in Fig. 1b, during which two related theories are involved, one is indicated in its inset about the formation of Taylor cone, and the other is the bending and whipping processes. Needless to say, in a typical electrospraying process (Fig.1c), the theoretical energy-fluid interactions are similar.

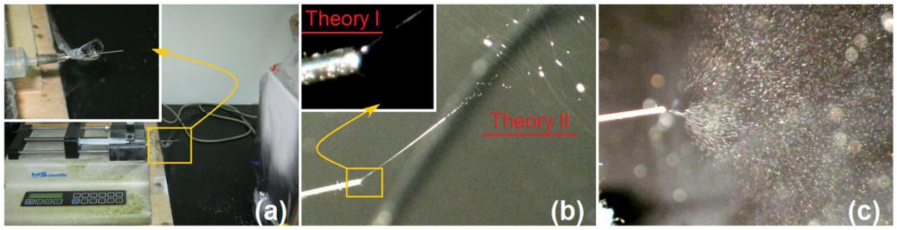

Figure 1. Implementation and Theories about the EHDA Processes. (a) The Typical Components of an EHDA System, the Inset Shows the Connection between the Power Supply with the Working Fluids; (b) A Typical Working Process of Electrospinning, During Which Two Related Theories Are Involved, the Inset Shows an Enlarged Taylor Cone ; (c) A Similar Electrospraying Process.

Basic Theories about Electrospinning

The past two decades has witnessed the great developments of electrospinning in manipulating the working fluids, which has evolved from the common single-fluid process, to double-fluid processes (including coaxial and side-by-side electrospinning), and to multiple-fluid processes (including tri-axial electrospinning and tri-layer side-by-side electrospinning) [13-16]. These techniques permit the creation of new types of sophisticated nanofibers with well-defined microstructures, novel morphologies, and/or new functions [12-15]. However, their working processes are similar, i.e. the formation of Taylor cone, the injection of a straight fluid jet, and the bending and whipping instable region [17,18], shown in Fig. 1b.

During the similar working processes, the involved theories about material science and engineering are also similar. These theories are mainly about the interactions between the working fluids and the electrostatic energies. To be more concrete, one is about the formation of Taylor cone by the working fluid under the electrical field, and the other important one is the solidification of the fluid jets during the bending and whipping processes, which still reflects the interactions between the fluid jets and the electrical fields.

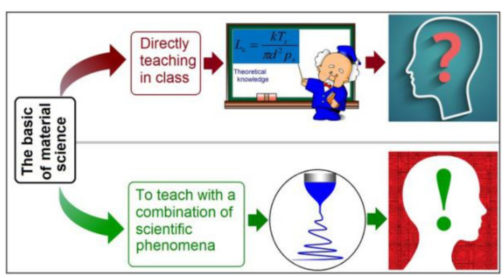

Figure 2. The Combined Strategy for Explaining the Basic Theories of in the Materials Science and Engineering Lessons to the College Students with the Scientific Phenomena as the Vivid Teaching Materials.

When these theories are directly taught to the college students. It is often very hard to explain them in a simple and clear way because the students never see anything about the related contents using their naked eyes. Meanwhile these theories often involve physical variables from different disciplines. The failure in making the students understanding these theories may suppress their learning interests about material science and engineering.

The most important thing for the commissioning of an electrospinning process is the formation of a Taylor cone of the viscous fluid under the electrical fields. The basic theory can be described according to the following equation (1) [19]:

$$V_c \sim \sqrt{\frac{\gamma d^2}{\varepsilon R}} \qquad (1)$$

The critical voltage applied to the fluid (V_c) to initiate the formation of the compound Taylor cone and straight cone-jets can be estimated, where V_c is the critical voltage for a jet emanating from the meniscus tip, d is the electrode separation, ε is the permittivity, γ is the surface tension, and R is the principal curvature of the liquid meniscus.

The second theory involved in the electrospinning process is the effective evaporation of solvent from the working fluid jets, which can be described using the equation about Knudsen layer. Knudsen layer is also termed as evaporation layer. It is a thin layer of vapor near a liquid or solid, which is named after Danish physicist Martin Knudsen [20]. The Knudsen layer thickness (L_c) can be estimated according to the following equation [21]:

$$L_c = \frac{kT_s}{\pi d^2 p_s} \tag{2}$$

where ps is the saturated pressure, Ts is the temperature, d is the solvent molecular diameter, and k is the Boltzmann's constant.

The Utilization of Scientific Phenomena in the Explanations of Basic Theories

Shown in Fig. 3a is a schematic diagram about the formation of Taylor cone, which is mainly a balance between the electrical force (*E*) and the surface tension of the working fluid (γ). When the applied voltage reaches the critical value V_c, a straight fluid jet is emitted from the tip of the Taylor cone. To keep a stable and robust process, it is a common sense that the semi-vertical angle of the Taylor cone (θ), i.e. the sharpness of the hyperboloid, should lie between the range 32º < 46º. Within the suitable range and according to Eq. (1), some parameter can be exploited to manipulate the electrospinning processes. For example, Fig. 3b and 3c show the digital pictures of the Taylor cones and straight fluid jets under the same applied voltage but with different working distance. When a spacing of the spinneret and the collector was fixed at 20 cm, the height of Taylor cone (T1) and the length of straight fluid jet (S1) were 1.4 mm and 7.3 mm, respectively, which could be estimated *via* the 2.5 mm diameter of spinneret (Fig. 3b). In contrast, when a spacing of the spinneret and the collector was fixed at 12 cm, the height of Taylor cone (T2) and the length of straight fluid jet (S2) were changed to 0.7 mm and 4.2 mm, respectively (Fig. 3b).

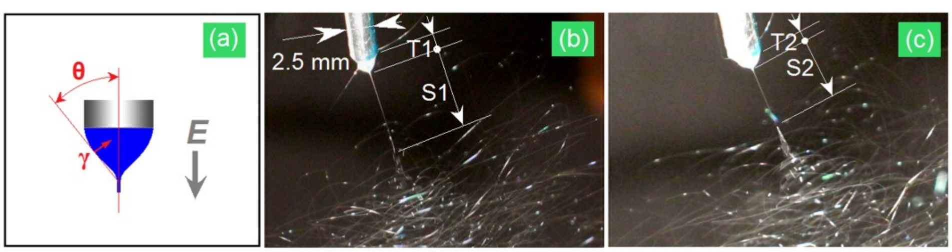

Figure 3. The Utilization of Scientific Phenomena as Teaching Materials in Explaining the Formations of Taylor Cones and Straight Fluid Jets. (a) A Schematic Diagram about the Taylor Cone; (b) A Digital Picture of the Taylor Cone Initiated at A Working Distance of 20 cm; and (c) A Digital Picture of the Taylor Cone Initiated at A Working Distance of 12 cm.

According to Eq.(1), these phenomena are easy to be elaborated. When the electrode separation *d* increased, the initiated voltage V_c should be correspondingly increased for a stable spinning process. When a fixed voltage *V* was similarly applied on the fluids that had a different distance from the collector, the longer the distance, the larger the value of V_c and the smaller the *V* over the V_c. Thus the smaller electrical forces were exerted on the fluids, resulting in a longer Taylor cone and a longer straight fluid jet. These phenomena can impressed the students a lot, which were not only utilized to explain the basic theory to them, but also greatly encourage them to do further self-learning about this advanced technology.

Shown in Fig. 4a is a schematic diagram about the Knudsen layer on a fluid jet in the instable region [22]. From Fig.4b to 4e are SEM images of the solidified nanofibers fabricated under different working temperatures of 20, 30, 40 and 50 °C, respectively. From these morphology, an interesting phenomenon is observed that the diameter of nanofibers first decreased and later slightly increased when the working temperature gradually elevated.

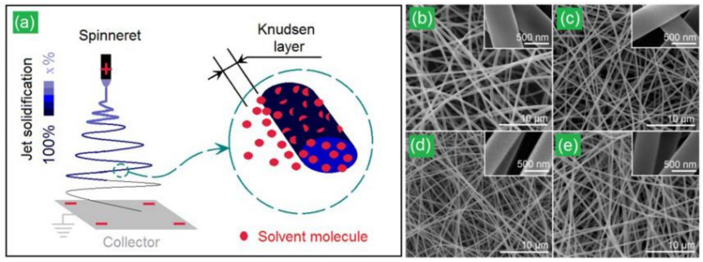

Figure 4. The Utilization of Scientific Phenomena as Teaching Materials in Explaining the Solidification of Fluid Jets during the Bending and Whipping Processes. (a) A Schematic Diagram about the Knudsen Layer on A Fluid Jet in the Instable Region; (b) to (e) are SEM Images of the Solidified Products Fabricated under Temperatures of 20, 30, 40 and 50 °C, respectively [22].

As evidently seen from the Eq.(2), the elevation of temperature will result in a thicker Knudsen layer. However, the increase in temperature will simultaneously increase the saturated pressure and consequently result in a thinner Knudsen layer. Thus, there is a balance between these two physical variables. They simultaneously imposed on the electrospinning processes. At the earlier stage, the increase of T_s is faster than p_s and thus a thicker Knudsen layer can be maintained for drawing the fluids at a relatively longer time period, which in turn result in the downsizing of nanofibers' diameters. However, at the later stage, the increase of T_s is slower than p_s and thus a thinner Knudsen layer is generated, which result in a shorter drawing time period of the fluids before their solidification, and thus in turn result in the increase of nanofibers' diameters. These phenomena not only make the students to grasp the theory deeply, but also promote them to do analysis on the engineering problems using the related theories. Certainly, the phenomena occurred at the processes of advanced technologies are first-rate teaching materials [23, 24].

Summary

In this investigation, different scientific phenomena happened during the electrospinning processes were exploited as teaching materials to explain the related theories about materials science and engineering to the college students. The traditional manner about teaching material theories to the students in the classroom lesson is often obscure. The effective introductions of scientific phenomena can make the teaching processes more vivid. What is more, the reasonable usage of scientific phenomena can impress the students for grasping the related knowledge, can encourage them to do self-learning, and also can hasten them to utilize the learned theories for analyzing some engineering problems.

Acknowledgements

The financial supports from the following projects are appreciated: the Shanghai Education Science Research Project (C17058), the 2016 key project on teachers teaching development in USST (CFTD17017Z), the National Natural Science Foundation of China (No. 51373101), the 2017 Graduate curriculum reform project in USST, and the College Student Innovation Project of USST (Nos. XJ2017282, SH2017189-190-191).

References

[1] U.E. Illangakoon, D.G. Yu, B.S. Ahmad, N.P. Chatterton, G.R. Williams, 5-Fluorouracil loaded Eudragit fibers prepared by electrospinning, Int. J. Pharm., 495 (2015) 895-902.

[2] G.Z. Yang, J.J. Li, D.G. Yu, M.F. He, J.H. Yang, G.R. Williams, Nanosized sustained-release drug depots fabricated using modified tri-axial electrospinning, Acta Biomater., 53 (2017) 233-241.

[3] D.G. Yu, K. White, N. Chatterton, Y. Li, L. Li, X. Wang, Structural lipid nanoparticles self-assembled from electrospun core-shell polymeric nanocomposites, RSC Adv., 5 (2015) 9462-9466.

[4] D.G. Yu, J.J. Li, M. Zhang, G.R. Williams, High-quality Janus nanofibers prepared using three-fluid electrospinning, Chem. Commun., 53 (2017) 4542-4545.

[5] D.G. Yu, X.Y. Li, X. Wang, J.H. Yang, S.W.A. Bligh, G.R. Williams, Nanofibers fabricated using triaxial electrospinning as zero order drug delivery systems, ACS Appl. Mater. Interfaces, 7 (2015) 18891-18897.

[6] Y.H. Wu, D.G. Yu, X.Y. Li, A.H. Diao, U.E. Illangakoon, G.R. Williams, Fast-dissolving sweet sedative nanofiber membranes, J. Mater. Sci., 50 (2015) 3604-3613.

[7] G. Chen, Y. Xu, D.G. Yu, D.F. Zhang, N.P. Chatterton, K.N. White, Structure-tunable Janus fibers fabricated using spinnerets with varying port angles, Chem. Commun., 51 (2015) 4623-3626.

[8] D.G. Yu, C. Yang, M. Jin, G.R. Williams, H. Zou, X. Wang, S.W.A. Bligh, Medicated Janus fibers fabricated using a Teflon-coated side-by-side spinneret, Colloid. Surface. B, 138 (2016) 110-116.

[9] H.F. Wen, C. Yang, D.G. Yu, X.Y. Li, D.F. Zhang, Electrospun zein nanoribbons for treatment of lead-contained wastewater, Chem. Eng. J., 290 (2016) 263-272.

[10] C. Yang, D.G. Yu, D. Pan, X.K. Liu, X. Wang, S.W.A. Bligh, G.R. Williams, Electrospun pH-sensitive core-shell polymer nanocomposites fabricated using a tri-axial processes, Acta Biomater., 35 (2016) 77-86.

[11] M. Jin, D.G. Yu, X. Wang, C.F.G.C. Geraldes, G.R. Williams, S.W.A. Bligh, Electrospun contrast agent-loaded fibers for colon-targeted MRI, Adv. Healthcare Mater., 5 (2016) 977-985.

[12] M. Jin, D.G. Yu, C.F.G.C. Geraldes, G.R. Williams, S.W.A. Bligh, Theranostic fibers for simultaneous imaging and drug delivery, Mol. Pharm., 13 (2016) 2457-2465.

[13] X. Wang, X.Y. Li, Y. Li, H. Zou, D.G. Yu, J.S. Cai, Electrospun acetaminophen-loaded cellulose acetate nanofibers fabricated using an epoxy-coated spinneret, E-polymers, 15 (2015) 311-315.

[14] X. Wang, D.G. Yu, X.Y. Li, S.W.A. Bligh, G.R. Williams, Electrospun medicated shellac nanofibers for colon-targeted drug delivery, Int. J. Pharm., 490 (2015) 384-390.

[15] Y.H. Wu, C. Yang, X.Y. Li, J.Y. Zhu, D.G. Yu, Medicated nanofibers fabricated using NaCl solutions as shell fluids in a modified coaxial electrospinning, J. Nanomater., 2016 (2016) Article ID 8970213.

[16] Y.H. Wu, D.G. Yu, J.J. Li, Q. Wang, H.P. Li, X.Y. Li, Medicated multiple-component polymeric nanocomposites fabricated using electrospraying, Polym. Polym. Compos., 25 (2017) 57-62.

[17] B. Sanchez-Vazquez, A.J. Amaral, D.G. Yu, G. Pasparakis, G.R. Williams, Electrosprayed Janus particles for combined photo-chemotherapy, AAPS PharmSciTech, 2016 (2016) 1-9.

[18] Y.H. Wu, H.P. Li, X.X. Shi, J. Wan, Y.F. Liu, D.G. Yu, Effective utilization of the electrostatic repulsion for improved alignment of electrospun nanofibers, J. Nanomater., 2016 (2016) Article ID2067383.

[19] L.Y. Yeo and J.R. Friend, Electrospinning carbon nanotube polymer composite nanofibers, J. Exp. Nanosci., 2 (2006) 177-209.

[20] Anonymity, https://en.wikipedia.org/wiki/Knudsen_layer), 28-Feb-2017.

[21] A. Gusarov and I. Smurov, Gas-dynamic boundary conditions of evaporation and condensation: Numerical analysis of the Knudsen layer, Phys Fluids., 14 (2002) 4242-455.

[22] G.Z. Yang, H.P. Li, J.H. Yang, J. Wan and D.G. Yu, Influence of working temperature on the formation of electrospun polymer nanofibers. Nanoscale Res. Lett., 12 (2017) 1-10.

[23] Y. Xu, J.J. Li, D.G. Yu, G.R. Williams, J.H. Yang, X. Wang, Influence of the drug distribution in electrospun gliadin fibers on drug-release behavior, Eur. J. Pharm. Sci., 2017, Doi: 10.1016/j.ejps.2017.06.017.

[24] D.G. Yu, D. Pan, X. Wang, J.Q. Luo, G.R. Williams, Cultivating undergraduate student's creativity by sharing scientific research experiences of academic staff -- with electrospinning as an example to illustrate how to nurture teaching from scienfific researches, J. University of Shanghai for Science and Technology, 38 (2016) 179-183.