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Implementation of hands-on nanofabrication projects into undergraduate mechanical engineering design courses

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Abstract

Substantial progress has been made in nanotechnology in the last two decades, which has noticeably shaped today's engineering activities and people's life and will significantly influence the entire society in the near future. Today's undergraduate engineering education needs to represent such a trend in order to nurture next generation labor force with well-prepared knowledge and skills. This paper is to introduce our recent efforts to implement hands-on design projects on scalable nanofabrication devices into existing mechanical engineering design courses to improve nanoscale science and engineering education for undergraduate students. The background of nanotechnology and specific scale-up nanofabrication methods were introduced. Rational development of the hand-on design projects on mass nanofabrication was given. Two sample design projects were described and discussed in detail, which have been successfully implemented in our mechanical engineering senior design courses in the past three years. Results of the design projects were provided and justified. Suggestions for future development and conclusion on the study were made.

1. Introduction

1.1 Central role of mechanical design in undergraduate mechanical engineering education

Mechanical engineering (ME) is one of the oldest and broadest disciplines of engineering that involves the production and utilization of heat and mechanical power for the design, production, and operation of machines and tools.[1] Broadly speaking, mechanical engineers employ the core principles of physics, materials science along with a variety of tools to analyze, design, manufacture, and maintain all mechanical systems such as manufacturing plants, machinery, transport systems, heating and cooling systems, space station, aircrafts, robots, medical devices, etc. Education and training of qualified new generation of mechanical engineers familiar with contemporary mechanical sciences will positively influence the innovation competency and quality of people's life of a nation. Undergraduate education in ME covers broad fields such as engineering mechanics, materials science, thermal science, machine design, etc., which has been accredited by the Accreditation Board for Engineering and Technology (ABET) to ensure similar course requirements and standards from one university to the other.[2] In undergraduate students' education in ME, mechanical design occupies the central position because mechanical design oriented courses are targeted to educate and train students to develop comprehensive capability and skills of utilizing all the mechanical engineering principles to design and manufacture new mechanisms and mechanical systems. Thus, the quality and broadness of mechanical design courses directly influences the ME education and students' career development.

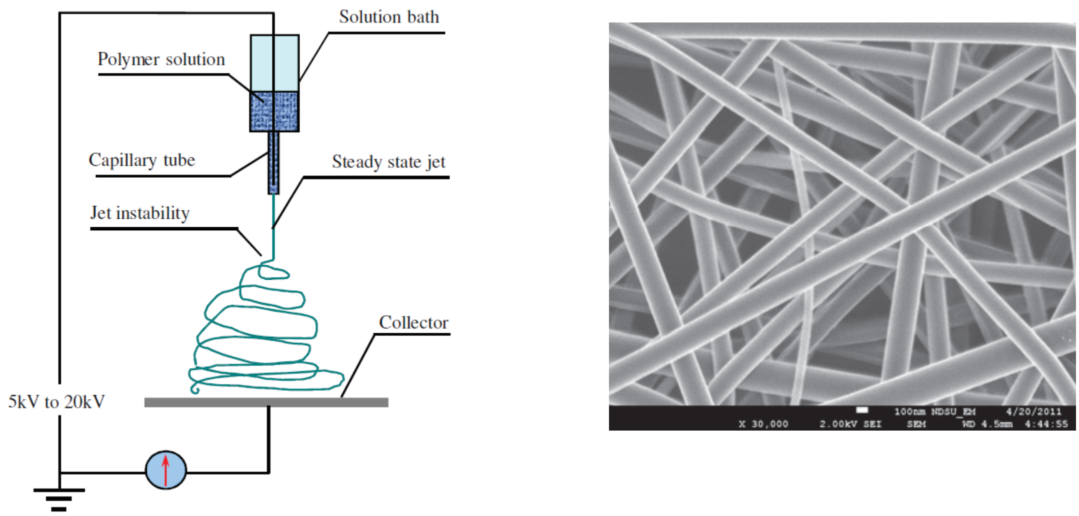
The ME Department at North Dakota State University (NDSU) offers four required core mechanical design courses at the junior and senior levels, i.e., two introductory machine design courses (ME 442/443 Machine Design I & II), followed by two design project courses (ME 461/462 Design Project I & II). The ME 442/443 courses are instructed by conventional lecturing along with one or two semester course projects, through which students learn the fundamental knowledge of machine design process, material selection, and strength, deformation and life time analysis of machine parts (ME 442), and design of common machine parts (ME 443). In contrast, the ME 461/462 courses are design project oriented, mimicking the real-world machine designs in industry. During the course of ME 461/462, typically 3-5 students form a design group to conduct a specific design project under mentoring of one or two faculty members. Therein, the ME 461 focuses on project plan, budgeting, conceptual and final designs; the follow-up ME 462 focuses on revised design and budgeting, prototype fabrication of the final design that is accomplished in ME 461. At the end of each semester, each group is required to present its design project progress and outcomes along with a comprehensive project report on the detailed design process and results of the individual design project.

After the ME 461/462, each involved student group is expected to learn substantial hands-on design and manufacturing experiences through a detailed design and prototype manufacturing process along with close interaction with the faculty mentor(s). These design projects are formulated by the faculty mentors from industrial sponsors or spinoffs of research projects. The *relatively flexible, independent, and self-consistent nature* of the senior design projects provide the opportunities to formulate new design project modules to incorporate new developments of contemporary sciences and technologies into the engineering education and training for undergraduate students, especially in the emerging engineering and technologies. Thus, *the existing senior design courses in the ME major provide an excellent carrier to implement hands-on machine design project modules for scalable nanofabrication to improve the undergraduate students' nanoscale science and engineering education and training.*

1.2 Scalable nanofabrication and nanoscale science and engineering education for undergraduate students

It has been generally accepted and validated by experiments and theoretical modeling that materials at nanoscale (e.g., quantum dots, nanowires, etc.) exhibit unique physical and chemical properties that are not observed and achieved in their bulk counterparts such as the noticeably enhanced mechanical strength/stiffness, thermal and electrical conductivities, catalytic activity, etc.[3-5] Nanotechnology is defined as the technology which manipulates matter with at least one dimension in the range of 1-100 nanometers, which also normally includes the technologies relating submicron materials. Nanotechnology as emerging technology has been developing very fast in every branch of science and engineering in the last two decades; nanotechnology has been dramatically shaping broad sectors of the society and everyone's life such as use of high-capacity flash memory cards, smart phones, Li ion rechargeable batteries in portable electronics, power tools and electrical vehicles, high-efficiency LED lights, clay nanocomposites, etc. In general, nanomaterials can be classified as zero-dimensional (0D) (e.g., quantum dots, nano clusters, nanoparticles, etc.), one-dimensional (1D) (e.g., nanotubes, nanowires, nanofibers, nanorods, etc.), and two-dimensional (2D) nanomaterials (e.g., biological membranes, graphene nanosheets, etc.). To date, a significant number of nanomaterials in each category have been synthesized and characterized in laboratories, some of which exhibit excellent performance with very promising future for use in structural materials, bioengineering, energy harvesting, conversion and storage, and environmental protection. For a newly available nanomaterial with promising commercial applications, it is crucial to identify feasible, robust routes to guarantee economic, safe, continuous and scalable nanofabrication techniques for low-cost, mass production.

In academia, on the one side, it is of critical importance and also challenge to discover new types of nanomaterials with controllable high-performance in resolving some particular outstanding engineering problems and related low-cost, continuous, scalable nanofabrication techniques. On the other side, it is equally important to educate and train new generation engineering students to get familiar with the fundamental concepts and principles of nanoscale science and engineering and learn specific low-cost mass nanofabrication techniques. These students will be the next generation engineers and researchers trained with cutting-edge nanoscience and nanotechnology, who will design, manufacture and operate nanostructured devices and systems in the near future. Among a variety of 0D-2D nanomaterials reported in the literature, continuous nanofibers of various materials produced by electrospinning[6-10] and other recently developed techniques (e.g., solution blowing) represent a new class of low-cost 1D nanomaterials with fast expanding applications.[11] The typical diameters of these nanofibers are in the range of a few nanometers to micrometers. Scale-up techniques for mass production of continuous nanofibers have evolved very fast from the essential multi-nozzle electrospinning to the contemporary needleless and solution blowing techniques. Besides, the ongoing worldwide intensive studies on electrospun nanofibers have tremendously expanded the high-performance applications of continuous nanofibers due to their unique continuity, high specific surface area, controllable geometries and material properties, and very low cost in fabrication.



(*a*) (*b*)

Figure 1. (*a*) Schematic of electrospinning setup and (*b*) polyacrylonitrile (PAN) nanofibers with the diameter around 300 nm produced by electrospinning (from author's ongoing research)

Electrospinning is one of the most successful processes suitable for low-cost fabrication of continuous nanofibers, which is based on the principle of electrified jetting from polymer solution or melt.[6-10] To date, electrospinning has been widely used to produce a variety of continuous nanofibers and nanowires of natural and synthetic polymers and polymer-derived carbon, ceramics, metals, metal oxides, etc.[11-21] Figure 1(*a*) shows the schematic setup of a conventional needle-based electrospinning process. In a typical solution-based electrospinning process, under the action of electrostatic force (on the induced charges) on the polymer solution, a droplet forms from the capillary tube and deforms into a Taylor cone.[22-24] When the electrostatic force overcomes the surface tension of the Taylor cone, a charged thin jet is ejected, elongated and accelerated in the electrostatic field. After a variety of jet destabilizations and solvent evaporation (drying), the ultra-thinned jet is finally deposited on the collector to form a nonwoven nanofiber mat [See Fig. 1(1b)]. To date, over three hundred synthetic and natural polymers have been produced by electrospinning.[11,12,19,20,25-29] These low-cost, continuous nanofibers have found very promising applications in protective clothing,[30] gas/liquid filtration,[11] templates for synthesizing metallic and polymer nanotubes,[11,31,32] precursors for fabricating carbon nanofibers,[33-35] nanofiber composites,[36-38] and so on.

However, the productivity of conventional electrospinning as shown in Fig. 1(*a*) is very low, typically a few gram of nanofibers per day, which could not satisfy any realistic industrial applications. The technological bottleneck for scalable, continuous nanofiber fabrication was overcome by a research group at Technical University of Liberec, Czech, by utilizing free-jetting of a thin liquid layer formed on a rotating drum,[39-42] i.e., needleless electrospinning, as illustrated in Fig. 2, which paves the way for low-cost massive production of continuous nanofibers for industrial applications.

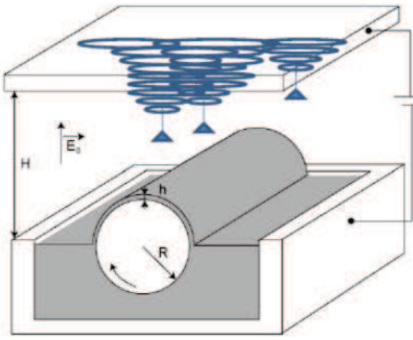


Figure 2. Concept of needleless electrospinning: Multiple jets ejaculating from a thin layer of polymeric solution on a rotating drum under high DC electrostatic field.[39-42]

Compared to other nanofabrication methods such as chemical vapor deposition (CVD) for growth of carbon nanotubes (CNTs), needleless electrospinning is suited for formulating self-consistent, interdisciplinary hands-on ME design projects with substantial ME oriented design and analysis components. To mention a few, such a prototype needleless electrospinning device is a typical electrohydrodynamic system, consisting of 15-30 components depending on targeted functions. The designed system includes a few core sub-systems: the high DC electrical field generation system, microfluidic delivery system, nanofiber collecting system, among others. Obviously, such design projects are a combination of conventional mechanical design and contemporary nanomaterial manufacturing. With the purpose to improve undergraduate’s nanoscale science and engineering education through hands-on senior design projects, several hands-on design projects have been successfully formulated and implemented into ME senor design courses at NDSU in the past three years, which will be introduced in Section 2. The outcomes and suggestions of these projects will be discussed in Section 3. Conclusions of the study will be made in consequence.

2. Formulation and implementation of hands-on nanofabrication design projects

2.1 Design of needleless electrospinning machines for mass production of continuous nanofibers

Two two-semester hands-on design projects on design and manufacturing of needleless electrospinning machines for mass production of continuous nanofibers have been successfully implemented in the ME Department at NDSU.[43,44] Both design projects were based on the fundamental needleless electrospinning concept as shown in Fig. 2. Of these, one design was a preliminary design project to design and manufacture a lab needleless electrospinning machine for scale-up production of nanofibers as shown in Figs. 3 and 4. The second was to scale down the machine dimensions and integrate remote control function in order to satisfy the design constraints of special nanofiber fabrication process in inert gas (Ar) environment that was provided within the glove box. These two design projects consisted preliminarily of the following design and nanofabrication components, which carried the purpose of simultaneously improving the nanoscale science and engineering education and training for the ME senior students as well as modern device and machine designs within the two-semester duration:

- Conceptual design to select proper needleless electrospinning method for mass production of nanofibers of particular materials, liquid delivery and control method, nanofiber collection and drying method, etc.
- Preliminary design to select proper machine geometries, high-voltage DC electric field generation system, liquid delivery and control system, nanofiber collection and drying mechanisms, etc.
- Detailed design to design and select all the system parts, scaling analysis of process parameter and design parameters for system and process optimization, electrostatic field, liquid delivery rate, nanofiber productivity, etc. The process also includes substantial computational electrostatics, microfluidics, and finite element analysis.
- Prototype manufacturing and testing of design model for mass production of continuous nanofibers.
- Morphology and structural characterization of fabricated nanofibers by optical and electron microscopes (e.g., scanning electron microscopy-SEM).
- Correlations of the process parameters (e.g., polymer concentration, electrical voltage, drum rotating speed, etc.) to the nanofiber productivity and properties (e.g., fiber diameters, morphology, etc.) (See Fig. 5 for example)
- Design progress report and presentation per semester based on the course requirement.

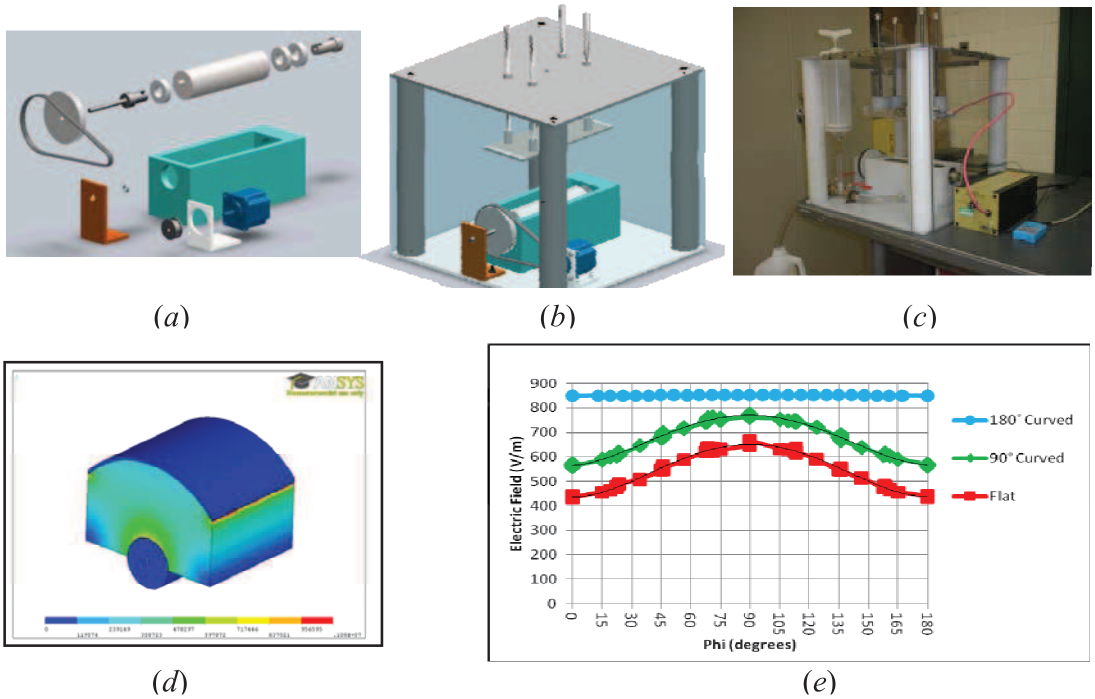


Figure 3. Design process of a needleless electrospinning device.[43] (*a*) Exploded diagram of the bin assembly for free-surface jetting, (*b*) 3D Pro-E drawing of the needleless electrospinning device, (*c*) prototype of the designed device, (*d*) 3D electrostatic field by using multiphysics field modeling based on commercial finite element analysis package-ANSYS™, (*e*) scaling analysis of the near-surface electrostatic field on a varying curvature of the collecting plate (top) (Designed and manufactured by an ME senior design group mentored by the author and Dr. I. S. Akhatov.)

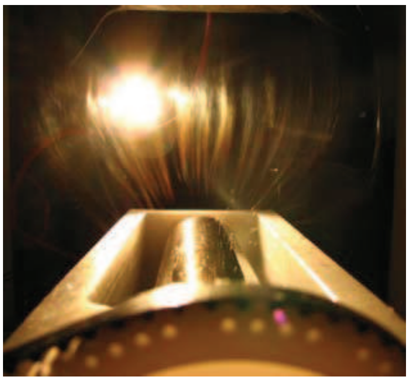


Figure 4. Close-up view of multiple jets ejaculating from the polymer-solution-wetted rotating drum of a prototype needleless electrospinning device as shown in Fig. 3(*c*)[43]. [Designed and manufactured the above ME senior design group with the author and Dr. I. S. Akhatov as mentors]

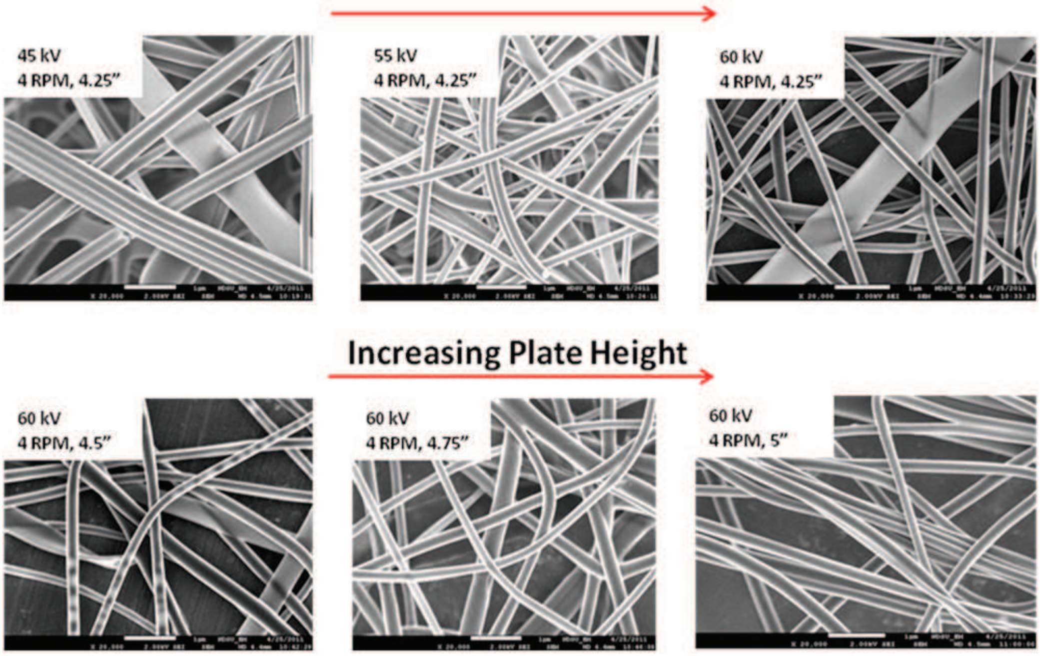


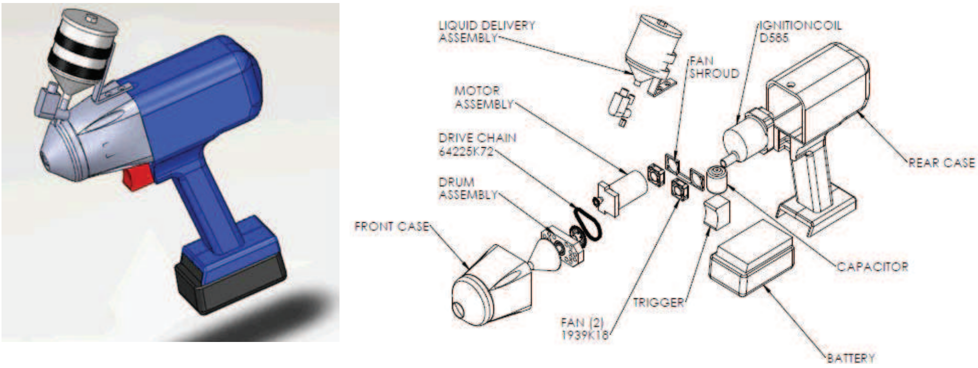
Figure 5: Effects of electrical voltage and plate height (i.e., distance between the drum surface and the nanofiber collection plate) on the diameter and morphology of polyethylene oxide (PEO) nanofibers[43] (Obtained by the above ME senor design group at NDSU with the author and Dr. I. S. Akhatov as the mentors)

2.2 Design of portable needleless electrospinning machines for on-site mass production of continuous nanofibers

Parallel to the above design projects, we also focus on the portability of electrospinning machines for the purpose of in situ mass production of nanofibers for some special applications, such as on-site wound dressing for curing burn wounds, poison spraying for plants, etc. In this case, the design process is still similar to the projects above. However, new and existing conceptual needleless electrospinning methods need to be further identified, compared and evaluated by the involved ME undergraduate students in order to effectively diminish the device dimensions and maintain the productivity, controllability, and quality of mass fabrication of nanofibers. So far, one ongoing senior design project mentored by the author has started such process as shown in Fig. 6. In this case, an innovative needleless electrospinning mechanism was extended and utilized in this project. Therefore, the design group has experienced how to identify and evaluate new conceptual fabrication methods for device design, fabrication, and evaluation, which results in new knowledge and skills in machine design and nanofabrication.

2.3 Other hands-on design projects on nanofiber fabrication and applications

Due to the unique features and superior advantages of electrospun nanofibers, there have been a significant number of research papers in the literature on nanofiber fabrication and advanced applications. Some of the new methods could be furthered for potential industrial applications. Thus, new design projects could be further formulated to extend the current hands-on design projects of nanofiber fabrications for use to improve the nanoscale science and engineering education for undergraduate students while maintaining the core part of the conventional mechanical design courses. Those design projects could be special nanofiber fabrication methods such as solution-blowing method, needleless melt spinning, melt force spinning, etc. and could also be particular applications of continuous nanofibers such as testing machines for nanofiber-based air/liquid filters.[46]



(*a*) (*b*)

Figure 6. Design of a portable electrospinning device for wound dressing. (*a*) 3D isometric drawing and (*b*) exploded drawing of the device assembly[45] [designed by an ongoing ME senior design group at NDSU with the author as the mentor]

3. Discussions

Since implementation of these projects, four group students (14 ME senor students) have been successfully involved. The outcomes are encouraging and significant, and gave great feedbacks for the instructor to shape the project modules. First, all the involved students were highly motivated and satisfied with the projects since all such design project modules have substantial difference from traditional machine design projects which only include the mechanical components. Also, all these design projects are interdisciplinary-oriented involving electrostatics, electrohydrodynamics, microfluidics, solid mechanics, electronics, system engineering, electron microscopy, etc. In addition, at the beginning of each project, all the students have been exposed to the instructor's research facilities on electrospinning and nanofibers with the assistance of skillful graduate students. The involved students can stay in the instructor's electrospinning laboratory, observe the electrospinning process, and interact with the instructor and graduate students on electrospinning and any outstanding questions regarding the design project. Also, the instructor introduced the fundamental concepts and principles of nanostructured materials and nanofabrication and the potential applications of nanofibers to the involved students, which greatly helps to build up students' interest and background in the nanofabrication device projects. Therefore, such efforts greatly enhance students' learning in nanoscale science and engineering.

With the instructor' and students' efforts, all the students were satisfied with their nanofabrication design project. As evidenced, all the design projects had the final grades higher than the average (all groups got "A" in continuously two semesters except for one group with "B" in one semester). The students found these hands-on nanofabrication machine design projects are “unique”, “interesting”, “cool”, “the nanofabrication project deepens their understanding in nontraditional mechanical design”, etc., letting them learn substantial unique nontraditional skills and knowledge relating nanofibers, nanoscience and nanomanufacturing. Furthermore, by analyzing the student evaluations made by other peer students who were enrolled in the same ME 461/462 courses, it was found that except for some particular reasons induced by personal rehearsal in the semester presentation, all comments on the nature of the design project such as novelty, design methodology, etc., are positive with the marks of 8.5-10 out of 10. This indicates the majority of the ME senior students are interested in the nanofabrication machine design projects.

Furthermore, it can be found that the above design projects on nanofiber fabrication machines are comprehensive and interdisciplinary, which combines the conventional mechanical design and contemporary cutting-edge nanoscale science and engineering. Through these hands-on design projects, the involved ME undergraduates have learned substantial practical knowledge and skills of nanoscale science and engineering. More importantly, these design projects have built the seamless connection between nanofabrication and conventional manufacturing, which places the seemingly abstract nanoscience and nanoengineering in a practical hands-on way that the students can fell, touch, measure and directly operate. Such a process would attract more and more undergraduate students in this emerging field. Besides, the involved students have also experienced quite a few pieces of equipment relating nanofiber fabrication and characterization such as SEM, which also benefit their future career development in the field relevant to nanoscale science and engineering. In addition, these successful design projects also allow the author to formulate standard design project modules for expanding these projects to research border students at NDSU and other universities.

4. Concluding remarks

This paper has introduced the author’s and his colleagues’ ongoing activities on implementation of hands-on nanofabrication projects into traditional mechanical design courses. Several successful design projects have been introduced and discussed. Such an effort would be greatly beneficial to undergraduate’s nanoscale science and engineering education and training in the mechanical engineering major, and it also helps to naturally extend conventional mechanical design to contemporary machine and device design for advanced nanomanufacturing. Design project modules will be formulated to standardize the process in the near future.

Bibliography

1. http://en.wikipedia.org/wiki/Mechanical_engineering.
2. http://www.asme.org/groups/centers-committees/public-affairs-and-outreach/accreditation-board-for-engineering-and-technology
3. A. S. Edelstein and R. C. Cammarata, Nanomaterials: Synthesis, Properties and Applications, Institute of Physics Publishing, Bristol, UK, 1996.
4. W. A. Goddard III, D. W. Brenner, S. E. Lyshevski, and G. J. Iafrate, Handbook of Nanoscience, Engineering and Technology, CRC Press, New York, 2003.
5. M. J. Jackson, Micro and Nanomanufacturing, Springer, 2007.
6. D. H. Reneker and I. Chun, “Nanometre diameter fibres of polymer, produced by electrospinning,” Nanotechnology **77**, 216-223 (1996).

7. J. Doshi and D. H. Reneker, "Electrospinning process and applications of electrospun nanofibers," J. Electrostatics **35** (1995) 151-160.
8. D. H. Reneker, A. L. Yarin, E. Zussman, and H. Xu, "Electrospinning of nanofibers from polymer solutions and melts," Adv. Appl. Mech. **41**, 43-195 (2007).
9. D. H. Reneker and A. L. Yarin, "Electrospinning jets and polymer nanofibers," Polymer **49**, 2387-2425 (2008).
10. Y. Dzenis, "Spinning continuous fibers for nanotechnology," Science **304**, 1917-1917 (2004).
11. Z. M. Huang, Y. Z. Zhang, M. Kotaki, and S. Ramakrishna, "A review on polymer nanofibers by electrospinning and their applications in nanocomposites," Compos. Sci. Tech. **63**, 2223-2253 (2003).
12. D. Li and Y. N. Xia, "Electrospinning of nanofibers: reinventing the wheel?"Adv. Mater. (Weinheim, Germany) **16**, 1151-1170 (2004).
13. Z. L. Wang (ed.), Nanowires and Nanobelts: Materials, Properties and Devices, volume 2: Nanowires and Nanobelts of Functional Materials, Springer, New York (2003).
14. S. Guceri, Y. G. Gogotsi, and V. Kuznetsov (ed.), Nanoengineered Nanofibrous Materials, Kluwer Academic Publishers, Boston (2003).
15. G. Cao, Nanostructures and Nanomaterials: Synthesis, Properties and Applications, Imperial College Press, London, U.K. (2004).
16. S. Ramakrishna, K. Fujihara, W. E. Teo, T. C. Lim, and Z. Ma, An Introduction to Electrospinning and Nanofibers, World Scientific, Singapore (2005).
17. I. S. Chronakis, "Novel nanocomposites and nanoceramics based on polymer nanofibers using electrospinning process-A review," J. Mater. Processing. Tech. **167**, 283-293 (2005).
18. R. Ramaseshan, S. Sundarrajan, R. Jose, and S. Ramakrishna, "Nanostructured ceramics by electrospinning," J. Appl. Phys. **102**, 111101 (2007).
19. A. Greiner and J. H. Wendorff, "Electrospinning: A fascinating method for the preparation of ultrathin fibers," Angew. Chem. Int. Ed. **46**, 5670-5703 (2007).
20. A. L. Andrady, Science and Technology of Polymer Nanofibers, Jon Wiley & Son, New York (2008)
21. A. Baji, Y. W. Mai, S. C. Wong, M. Abtahi, and P. Chen, "Electrospinning of polymer nanofibers: Effect on oriented morphology, structures and tensile properties," Compos. Sci. Tech. **70**, 703-718 (2010).
22. G. Taylor, "Electrically driven jet," Proc. Roy. Soc. Lond. A **313**, 453-475 (1969).
23. A. F. Spivak and Y. A. Dzenis, "A condition of the existence of a conductive liquid meniscus in an external electric field," J. Appl. Mech. **66**, 1026-1028 (1999).
24. A. L. Yarin, S. Koombhongse, and D. H. Reneker, "Taylor cone and jetting from liquid droplets in electrospinning of nanofibers," J. Appl. Phys. **89**, 3018-3026 (2001).
25. C. B. Huang, S. L. Chen, C. L. Lai, D. H. Reneker, H. Y. Qiu, Y. Ye, and H. Q. Hou, "Electrospun polymer nanofibres with small diameters," Nanotechnology **17**, 1558–1563 (2006).
26. C. B. Huang, S. L. Chen, C. L. Lai, D. H. Reneker, H. Qiu, Y. Ye, and H. Q. Hou, "Electrospun polymer nanofibres with small diameters," Nanotechnology **17**, 1558 (2006).
27. Y. Z. Zhang, J. Venugopal, Z. M. Huang, C. T. Lim and S. Ramakrishna, "Crosslinking of the electrospun gelatin nanofibers," Polymer **47**, 2911-2917 (2006).
28. S. H. Tan, R. Inai, M. Kotaki and S. Ramakrishna, "Systematic parameter study for ultra-fine fiber fabrication via electrospinning process," Polymer **46**, 6128-6134 (2005).
29. W. E. Teo and S. Ramakrishna, "A review on electrospinning design and nanofibre assemblies," Nanotechnology **17**, R89-R106 (2006).
30. P. Gibson, H. Schreuder-Gibson, and D. Rivin. "Transport properties of porous membranes based on electrospun nanofibers," Colloids Surfaces A –Physicochem. Eng. Asp. **187**, 469-481 (2001).
31. M. Bognitzki, H. Q. Hou, M. Ishaque, T. Frese, M. Hellwig, C. Schwarte, A. Schaper, J. H. Wendorff, and A. Greiner, "Polymer, metal, and hybrid nano- and mesotubes by coating degradable polymer template fibers (TUFT process)," Adv. Mater. **12**, 637-640 (2000).

32. W. X. Liu, M. Graham, E. A. Evans, and D. H. Reneker, "Poly(meta-phenylene isophthalamide) nanofibers: Coating and post processing," J. Mater. Res. **17**, 3206-3212 (2002).
33. J. Sutasinpromprae, S. Jitjaicham, M. Nithitanakul, C. Meechaisue and P. Supaphol, "Preparation and characterization of ultrafine electrospun polyacrylonitrile fibers and their subsequent pyrolysis to carbon fibers," Polym. Int. **55**, 825-833 (2006).
34. K. S. Yang, D. D. Edie, D. Y. Lim, Y. M. Kim, and Y. O. Cho, "P reparation of carbon fiber web from electrostatic spinning of PMDA-ODA poly(amic acid) solution," Carbon **41**, 2039-2046 (2003)
35. C. L. Lai, Q. H. Guo, X. F. Wu, D. H. Reneker, and H. Q. Hou, "Growth of carbon nanostructures on carbonized electrospun nanofibers with palladium particles," Nanotechnology **19**, 195303 (2008).
36. J. S. Kim and D. H. Reneker, "Mechanical properties of composites using ultrafine electrospun fibers," Polym. Compos. **20,** 124-131 (1999).
37. Y. Dzenis, "Structural nanocomposites," Science **319**, 419-420 (2008).
38. X. F. Wu, Fracture of Advanced Composites with Nanostructured Interfaces: Fabrication, Characterization and Modeling, VDM Publishing House, Germany (2009).
39. A. Sarkar and D. Lukas, "Physical principles of needleless electrospinning," 6^{th} Int. Conf.-TEXSCI, June 5-7, Czech Republic (2007).
40. D. Lukas, A. Sarkar, and P. Pokorny, "Self-organization of jets in electrospinning from free liquid surface: A generalized approach," J. Appl. Phys. **103**, 084309 (2008).
41. D. Lukas, A. Sarkar, L. Martinova, K. Vodsed'alkova, D. Lubasova, J. Chaloupek, P. Pokorny, P. Mikes, J. Chvojka, and M. Komarek, "Physical principles of electrospinning (Electrospinning as a nano-scale technology of the twenty-first century)," Textile Progress **41**, 59-140 (2009).
42. S. Petrick and M. Maly, "Production nozzle-less electrospinning nanofiber technology," Liberc, Czech Republic (2009).
43. B. Bakke, B. Dagen, W. Melby, and J. Weyer, Design of a needleless electrospinning device for mass-production of nanofibers (Final Report of Senior Design), Department of Mechanical Engineering, North Dakota State University (2011).
44. W. J. Li, S. Shahukhal, and Y. Zhao, Design of a novel needleless electrospinning device for low-cost, mass production of continuous silicon nanowires for use in vehicle Li-ion battery electrodes (Final Report of Senior Design), Department of Mechanical Engineering, North Dakota State University (2012)
45. D. Gillard, N. Reilly, and M. Vetter, Design of a portable medical mini-device for wound dressing (Final Report of Senior Design), Department of Mechanical Engineering, North Dakota State University (2013).
46. N. Grobe, K. Sieberg, C. Splettstoeszer, and C. Strand, Design and filtration evaluation of high-grade air filters made of hybrid renewable nonwoven micro/nanofiber fabrics (Final Report of Senior Design), Department of Mechanical Engineering, North Dakota State University (2012).