

Continuous Dual-Track Fabrication of Polymer Micro-/Nanofibers **Based on Direct Drawing**

Dave Jao and Vince Z. Beachley*

Department of Biomedical Engineering, Rowan University, Glassboro, New Jersey 08028, United States

Supporting Information

ABSTRACT: This manuscript proposes a continuous and straightforward method for fabricating suspended micro- and nanodiameter polymer fibers using an automated single-step drawing system. Termed track spinning, the system is based on a simple manual fiber drawing process that is automated by using two oppositely rotating tracks. Fibers are continuously spun by direct contact of polymer solution coated tracks followed by mechanical drawing as the distance between the tracks increases. The device can draw single or multifilament arrays of micro- and nanofibers from many kinds of polymers and solvent combinations. To demonstrate, fibers were pulled from polymer solutions containing polyvinyl acetate (PVAc)



and polyurethane (PU). Fiber morphology was smooth and uniform, and the diameter was sensitive to draw length and polymer solution/melt properties. Polymer nanofibers with diameters as small as 450 nm and length of 255 mm were produced. The track spinning method is able to form fibers from high viscosity solutions and melts that are not compatible with some other nanofiber fabrication methods. Further, the setup is simple and inexpensive to implement and nozzleless and does not require an electric field or high-velocity jets, and the tracks can be widened and patterned/textured to enhance fiber yield and manufacturing precision.

ver the past two decades, the fabrication of polymer nanofibers has found many potential applications in tissue engineering scaffolds,¹⁻⁷ composite materials, drug delivery, fabrics, filters,^{8–10} fuel cells,¹¹ packaging,¹² sensors, and optical devices. Polymer nanofibers exhibit many favorable and unique features such as a high surface area to volume ratio and flexibility in surface functionalities and, theoretically, can obtain mechanical properties superior to larger fibers.^{13,14} The motivation to develop processes that can fabricate exceptionally strong and stiff polymer nanofibers has attracted much interest in recent years.

The most popular nanofiber fabrication method is electrospinning, which is joined by several other manufacturing spinning, which is joined by several other manufacturing techniques such as blow/jet spinning,^{15–19} centrifugal spinning,^{20–22} hand spinning (Figure 1A,B),^{23,24} forcespinning,^{25,26} microfluidic spinning,²⁷ magnetospinning,^{28,29} melting spinning,³⁰ pull spinning,³¹ rotary jet spinning,^{32–34} touch spinning,³⁵ spinneret-based tunable engineered parameters technique (STEP),^{36,37} and spun-wrapped aligned nanofiber (SWAN),³⁸ or any combination of these techniques.^{39–41} Despite the versatility and popularity of electrospinning, the technique remains limited in both throughput and the range of materials used. Most notably, electrospinning has been highly limited for making nanofibers comprised of polymers that have poor solubility in solvents or high electrical resistivity, such as polyolefins (e.g., polyethylene and polypropylene).^{42,43} Furthermore, high-voltage electrical fields and sensitivity to solution conductivity and environmental conditions challenge existing

systems. Many of the other techniques listed share similar limitations, and most are not optimized for aligned fiber orientations or compatible with essential postdrawing processing.⁴⁴ Therefore, there is a need for alternative methods and devices for manufacturing nanofibers composed of a wide range of materials.

In this work, we report a new automated fiber drawing device for producing micro- and nanoscale fibers termed "track spinning". Track spinning automates a simple mechanical process, which can lead to lower product costs and better process control compared to many other nanofiber fabrication techniques. Moreover, polymer fibers can be pulled from high viscosity solutions or melts, with little restriction to specific polymer and solvent properties.⁴⁵⁻⁴⁷ The approach can continuously produce linearly aligned fiber networks with integrated postdraw processing and control over fiber placement in secondary assembly.

The capability and feasibility of the track spinning process were demonstrated by producing fibers from 10%, 20%, and 30% wt./vol. solutions of polyvinyl acetate (PVAc, 170 kDa) dissolved in dimethylformamide (DMF) and 7%, 10%, and 13% wt./vol. solutions of thermoplastic polyurethane (PU) dissolved in DMF. The experimental setup for track spinning is

Received: March 7, 2019 Accepted: April 25, 2019 Published: May 3, 2019



Figure 1. (A) Photograph of handspinning. Polymer solution being pressed with the thumb and index finger. (B) Polymer solution being drawn and pulled apart producing uniaxially aligned fibers. (C) Photograph of tracks coming in contact (touching) and separating with the track-spinning apparatus. (D) Diagram of the automated setup showing fiber formation as tracks "touch" and separate when polymer solution is placed on moving tracks. (E) Schematic illustration of fibers pulled from polymer solution at different cycles as polymer solvent evaporates.

shown in Figures 1 and 2. This custom track spinning apparatus consists of two angled rotating tracks (that touch at the top), with a stepper motor powering each track, and a polymer solution dispenser located above the tracks. After polymer solution or melt comes into contact with both tracks at the top of the apparatus, it is manually pulled and elongated to a wide range of fiber lengths and diameters as the gap between the tracks increases. New fibers are continuously spun by continuous rotation of the tracks. The apparatus is easily adjusted to change: (1) the angle (deg) of the tracks, (2) the vertical collection distance from the point of track-track contact to the collection tray (mm), and (3) the track speed. These adjustments can be tuned to control fiber processing parameters including the final fiber length and the fiber draw rate (mm/s). For this study, the tracks were fixed at an angle of 40°, and the track speed was adjusted to fix the fiber draw rate at 6.26 mm/s. To dispense the polymer solution between the two tracks, 1.5 mL of solution was pumped through a 21-gauge stainless steel needle onto the rotating tracks. Track spun fibers were deposited onto a 20 cm wide acrylic collection tray in an aligned configuration at various vertical collection distances measured from the point of contact between the tracks (initial fiber formation) and the collection tray (Figure 2C). A similar device with wider tracks and another with a patterned array of silicone posts were assembled to produce 3-dimensional arrays of aligned fibers between two tracks.

Aligned fiber arrays were manufactured using varying solution concentrations in combination with sequential vertical collection distances. All polymer and solution combinations investigated produced micron diameter fibers initially, but nanofibers with diameters as low as 450 nm were obtained by postdrawing the fiber to lengths as long as 255 mm. Optimizing parameters and extending the geometry of the device could facilitate reduction of fiber diameters further into the nanometer diameter range. The collected fibers were flexible and easily removed from the collecting rack without tearing.

As the angled rotating tracks were brought into contact (similar to pushing two plates together),^{23,24} the polymer solution on the tracks (Figure 1D) was compressed and spread uniformly over the two surfaces. As the angled tracks moved down and separated (similar to pulling two plates apart) the polymer solution present on the tracks was subject to a mechanical force. Fibers did not form between the tracks immediately but stretched across the gap between the tracks around the fourth cycle (Figure 1E). Initial fiber formation was observed after the third cycle when sufficient solvent

Letter



Figure 2. (A) Photograph of the spinning apparatus with collection rack and adjustable stage placed between two rotating tracks. (B) Schematic illustration of the setup used in the solution pulling method for making aligned nanofibers. Draw ratio and draw rate can be independently controlled by modifying the track angle and track speed using this adjustable track system. (C) Photograph of track spun fibers proceeding down the tracks and being deposited on the collection rack. (D) Suspended fiber arrays collected over the gap between the two plates are shown adhered to SEM stubs.

evaporation had occurred, and polymer solution properties favored the formation of semisolid fiber bridges between the tracks. As the tracks continued to cycle, greater amounts of fibers begin to be drawn from semisolid fiber bridges that subsequently solidified via rapid solvent evaporation as they traveled down the device.

Fibers were easily drawn to centimeter scale lengths from each listed concentration of PVAc and PU solution and collected on a frame (Figure 2C). At all concentrations tested, no beading or wavy morphology was observed. The final diameters of the collected fibers were on the order of hundreds of nanometers to several micrometers. The relationships of fiber diameter versus solution concentration and fiber length for PVAc and PU are shown in Figure 3. For both polymers, the fibers obtained from higher concentration solutions had larger fiber diameters, and fibers drawn to longer lengths had reduced fiber diameters.

Suspended fibers with lengths up to 255 mm and diameters in the sub-1000 nm range were obtained from the lowest concentration polymer solutions. The systematic relationship of fiber diameter versus concentration and length suggests that fiber diameter can be controlled by setting appropriate processing parameters.

To assess the uniformity of fibers produced by the track spinning system, fiber diameters at different regions along the

span of fibers were compared. Samples were analyzed from PVAc and PU fiber arrays at two different concentrations for two different collection distances. As depicted in Figure 4A,B, samples were taken at the middle (Mid), quarter (Qtr), and end (End) regions of each fiber array and imaged with SEM. The resulting diameter measurements (n = 15 different fibers)exhibited similar morphology with almost the same average diameter throughout the fiber length, except at the end sections. As expected, the Ends of fibers, near the track attachment, had a larger diameter than the Mid and Qtr sections of the fiber. The percent difference in diameter between the Mid and Qtr sections was less than 2% for all conditions measured, and the difference between the average Mid/Qtr section and far End was between 5 and 20%. As mentioned above, the fiber filament formed at the End points of the track was significantly larger (irregular) than the Mid and Qtr sections due to the fibers anchoring closer to the surface of the polymer solution on the track, while the fibers formed between Ends had a much narrower size distribution due to the constant, even drawing of the track system.

Track spinning also proved to be compatible with naturally derived solvent-based polymer solutions and polymer melts. Polystyrene (PS) dissolved in D-limonene, a chemical found in the peels of citrus fruits, at 15% wt./vol. readily formed 255 mm long fibers with diameters in the range of 0.90–4.16 μ m (Figure



Figure 3. (A) Diameter vs collection length (see Figure 2B) relationship for PVAc fibers made from polymeric solutions in DCM at concentrations of 10%, 20%, and 30% drawn to various lengths. (B) SEM images of PVAc fibers collected from 10%, 20%, and 30% solution concentrations at a collection length of 73, 146, and 218 mm (n = 15, SEM scale bar = 20 μ m). (C) The diameter–concentration relationship for PU fibers made from polymeric solutions in DCM at concentrations of 7%, 10%, and 13% drawn to various lengths. (D) SEM images of PU fibers collected from 7%, 10%, and 13% solution concentrations at a collection length of 73, 146, and 218 mm (n = 15, SEM scale bar = 20 μ m).

5E). Polycaprolactone (PCL) was melt track spun by enclosing an entire device in an oven at a temperature of 70 °C. PCL was melted on an aluminum plate in the oven and applied onto the track with a spatula. Three different molecular weights of polycaprolactone (55 kDa, 100 kDa, and 114 kDa) were drawn to 109 mm, resulting in fibers with increasing diameters of 9.97 μ m, 23.83 μ m, and 40.77 μ m, respectively (Figure 5A–D). Viscosity had an inverse relationship with fiber diameter as higher molecular weight polymer formed higher viscosity melts and resulted in larger fibers. This mirrors the data collected for PVAc and PU solutions where higher polymer concentrations formed higher viscosity solutions and resulted in larger fibers. Melt track spinning at a single uniform temperature in an oven was not an ideal environment for forming long small diameter fibers. The high temperatures required at the initial stages of fiber formation promoted drooping and breakage at the later stages of drawing. However, the feasibility of melt track spinning was demonstrated by this experiment, and it is expected that appropriate variable temperatures at different stages of track spinning could optimize the approach.

These results report on a rapid and simple method to fabricate PVAc, PU, PS, and PCL micro-/nanofibers from various

polymer solutions and melts by using an automatic one-step drawing device. From the initial experimental data, track spinning has the potential to be employed in the fabrication of fibers with diameters ranging from hundreds of nanometers to tens of micrometers. While many of the fiber diameters reported in this manuscript are in the micron scale, fibers as small as 500-800 nm were consistently obtained under specific processing parameters (Figure 5F). We expect that nanoscale diameter polymer fibers could be manufactured from a wide variety of polymers with optimization of processing parameters and tuning of the track spinning method. Under all of the reported processing conditions, fibers were well-defined with highly uniform length and smooth surface morphologies. Changes in the operating parameters can be modified to produce fibers with a targeted fiber diameter. The data would suggest that viscosity and drawing length had significant effects on the diameter of fabricated fibers. Another very important parameter in fiber manufacture is the draw rate, which can be tightly controlled in track spinning dependent on the speed and angle of the tracks. In both simulation and experimental data related to dip drawing and handspinning methods, other groups have reported a rapid decrease in the fiber diameter with an increase in draw rate.^{24,48}



Figure 4. (A) Schematic illustration of the fiber fabrication process via track spinning at varying fiber lengths. Samples were collected at different points along the fiber length to analyze for fiber uniformity. (B) A photograph corresponds to the illustration with the fiber imaged at the middle (Mid), quarter (Qtr), and end (End) portion of a fiber array. (C) Representative SEM images of PVAc track spun fibers from 10% and 20% polymer concentrations at collection length of 109 mm. (D) Representative SEM images of PU track spun fibers from 7% and 10% polymer concentrations at collection height of 182 mm. (SEM scale bar = $10 \,\mu$ m). (E,F) Shows the diameter uniformity of PU and PVAc at collection lengths of 109 mm and 182 mm, respectively. (E) Table showing PVAc fiber uniformity for two fiber lengths at 10% and 20% polymer concentrations. (F) Table showing PU fiber uniformity for two fiber lengths at 7% and 10% polymer concentrations. For each condition, different fibers in an array were measured at Mid, Qtr, and End (n = 15).

Since track spinning was invented by mimicking dipping drawing and handspinning, it is expected that similar draw rate relationships could be observed. This thought leads to the question of what the maximum fiber length is for any given fiber diameter under optimum conditions (draw rate and solution concentration) and what limiting factors lead to fiber breakage. In analyzing this question, it is essential to consider whether the limiting factor for maximum fiber length is the fiber formation and postdrawing process or subsequent fiber fracture caused by external forces generated by the vibration of the track, interference from outside air flow, or even breakage under the fiber's own weight.

Track spinning has several advantages in comparison with other nanofiber fabrication methods: (a) the technique does not require high-voltage electric fields or high-velocity parts, (b) fixation of fibers at both ends allows for added control over fiber postprocessing and placement/assembly into structures, (c) the apparatus is inexpensive and straightforward to implement, (d) uniform fiber diameters can be manipulated by altering the

process variables, (e) fiber fabrication is independent of solution conductivity and compatible with high viscosity solutions and melts, and (f) fibers are simultaneously created and postdrawn in one process. The most significant improvement of track spinning, when compared to manual dip drawing, is that it is capable of fabricating highly aligned nanofibers continuously. Even when attempted sequentially, single probe drawing can become a very tedious fabrication procedure. There are many reports on using variations of the dip drawing approach to fabricate high-quality ultradrawn nanofibers from a polymer solution, heated gel, or melt using a sharp tungsten tip, a platinum or silica rod,^{49,50} a tipless atomic force microscope (AFM) cantilever,^{51,52} glass micropipettes,⁵³ or a metal syringe needle.48,54 However, all these approaches have very low production rates. In contrast, track spinning produces a continuous supply of polymer without requiring an incremental process. Another considerable advantage of track spinning is related to solution viscosity limitations known to be a significant factor in other nanofiber fabrication techniques. Many polymer



Figure 5. (A) Photograph of the track spinning apparatus in a gravity convection oven. (B-D) Representative SEM images of PCL melt spun fibers from three different molecular weights (55 kDa, 100 kDa, and 114 kDa) at final length of 109 mm. (E) SEM images of PS track spun fibers from 15% polymer concentration at collection length of 255 mm. (F) SEM image of nanoscale diameter PVAc fibers (500–800 nm) track spun from a 10% concentration solution to a final length of 255 mm.



Figure 6. (A) Photograph of a 3D spinning system (8 cm track width) scaled up from a 2D track (0.6 cm track width) for high output of aligned fibers. (B) Photographs of a collected array of aligned PS fibers on racks using the 3D and 2D spinning system for the same amount of time. (C) Photograph of a 3D spinning system with a patterned array of bristles on the track for patterned and precision drawing of fibers. (D) Photographs of the patterned 3D spinning system drawing and stretching an array of aligned PVAc fibers.

materials are not practical for electrospinning and centrifugal spinning due to high viscosity and if feasible require voluminous solvent waste. For example, ultrahigh-molecular-weight polyethylene (UHMWPE), which forms a highly viscous solution in organic solvent, has only been reported electrospun from a dilute 1% polymer solution using very high voltage of greater than 35 kV at high temperature (130 °C).^{55,56} In contrast, track spinning relies on a strong direct mechanical force capable of

pulling fibers from solutions with a wide range of low to high viscosity. Manual dip drawing of UHMWPE⁵⁷ (and by extension track spinning) provides an effective and scalable route to form fibers from highly viscous solutions. The technique can also be used for the fabrication of composite fibers that contain magnetic or conductive nanoparticles since nanofibers can be spun without magnetic and electrical inference.⁵⁸ Additionally, a variety of other fillers that may alter solution viscosity and conductivity could be track spun into well-aligned nanofibers with improved thermal, electrical, and mechanical properties.^{57,59}

Due to its simplicity, it is possible to build a custom track spinning setup in a laboratory without highly specialized training or equipment, and we expected that track spinning is well suited for scalable manufacturing. The approach is inexpensive and versatile with interchangeable tracks, and the track can be disposable or lined as a single-use device for specific applications. Track modifications, such as widening the track, can be employed to address production rate limitations by drawing large multifilament arrays of nanofibers from polymer solutions or melts (Figure 6A). This is demonstrated by comparing two PS nanofiber arrays produced in the same amount of time using an 8 cm vs 0.6 cm wide track spinning device (Figure 6B). Manufacturing precision could be enhanced with patterned/textured track configurations that could fix fiber location and provide a site for precise volume solution/melt droplet application (Figure 6C,D).

Since the formed fibers are inherently fixed to tracks at both ends, track spinning enables automated assembly of higherorder structures and offers integrated drawing (initial fiber fabrication) with optional postprocessing steps, such as postdrawing and temperature treatments. Postprocessing techniques, such as postdrawing at different ratios/rates, and different temperatures for different processes can also be adjusted and used in successive steps to engineer nanofibers with a particular property or to align particles, such as carbon nanotubes and silver nanoparticles, inside the fibers. After fabrication and postprocessing, there is potential to integrate the automated track transport of fibers into assembly processes such as thin composite film and staple yarn fabrication.

ASSOCIATED CONTENT

S Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsmacro-lett.9b00167.

Materials and Methods: polymer solution preparation, device design, polymer melt track spinning, and fiber characterization; Results: fiber characterization, fiber morphology, and fiber uniformity (PDF)

AUTHOR INFORMATION

Corresponding Author

*E-mail: beachley@rowan.edu.

ORCID [©]

Vince Z. Beachley: 0000-0001-8793-433X

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was made possible by funding from United States Army Research Laboratory (W911NF-17-2-0227) and the National Science Foundation (NSF1561966 & NSF1653329).

REFERENCES

(1) Beachley, V.; Katsanevakis, E.; Zhang, N.; Wen, X. A novel method to precisely assemble loose nanofiber structures for regenerative medicine applications. *Adv. Healthcare Mater.* **2013**, *2* (2), 343–351.

(2) Brennan, D. A.; Conte, A. A.; Kanski, G.; Turkula, S.; Hu, X.; Kleiner, M. T.; Beachley, V. Mechanical Considerations for Electrospun Nanofibers in Tendon and Ligament Repair. *Adv. Healthcare Mater.* **2018**, *7*, 1701277.

(3) Beachley, V.; Wen, X. Fabrication of nanofiber reinforced protein structures for tissue engineering. *Mater. Sci. Eng., C* **2009**, *29* (8), 2448–2453.

(4) Beachley, V.; Wen, X. Polymer nanofibrous structures: Fabrication, biofunctionalization, and cell interactions. *Prog. Polym. Sci.* 2010, 35 (7), 868–892.

(5) Zhao, Y.; Qiu, Y.; Wang, H.; Chen, Y.; Jin, S.; Chen, S. Preparation of nanofibers with renewable polymers and their application in wound dressing. *Int. J. Polym. Sci.* **2016**, 2016, 1.

(6) Bienek, D. R.; Hoffman, K. M.; Tutak, W. Blow-spun chitosan/ PEG/PLGA nanofibers as a novel tissue engineering scaffold with antibacterial properties. *J. Mater. Sci.: Mater. Med.* **2016**, *27* (9), 146.

(7) Kumbar, S.; James, R.; Nukavarapu, S.; Laurencin, C. Electrospun nanofiber scaffolds: engineering soft tissues. *Biomed. Mater.* **2008**, 3 (3), No. 034002.

(8) Zander, N. E.; Gillan, M.; Sweetser, D. Recycled PET nanofibers for water filtration applications. *Materials* **2016**, *9* (4), 247.

(9) Wang, Z.; Ma, H.; Chu, B.; Hsiao, B. S. Fabrication of cellulose nanofiber-based ultrafiltration membranes by spray coating approach. *J. Appl. Polym. Sci.* **2017**, DOI: 10.1002/app.44583.

(10) Liu, C.; Hsu, P.-C.; Lee, H.-W.; Ye, M.; Zheng, G.; Liu, N.; Li, W.; Cui, Y. Transparent air filter for high-efficiency PM 2.5 capture. *Nat. Commun.* **2015**, *6*, 6205.

(11) Kenry; Lim, C. T. Nanofiber technology: current status and emerging developments. *Prog. Polym. Sci.* 2017, 70, 1–17.

(12) Wang, H. s.; Chen, D.; Chuai, C. z. Mechanical and barrier properties of LLDPE/chitosan blown films for packaging. *Packag. Technol. Sci.* 2015, 28 (10), 915–923.

(13) Tan, E.; Lim, C. Mechanical characterization of nanofibers-a review. *Compos. Sci. Technol.* **2006**, *66* (9), 1102–1111.

(14) Yao, J.; Bastiaansen, C.; Peijs, T. High strength and high modulus electrospun nanofibers. *Fibers* **2014**, *2* (2), 158–186.

(15) da Silva Parize, D. D.; Foschini, M. M.; de Oliveira, J. E.; Klamczynski, A. P.; Glenn, G. M.; Marconcini, J. M.; Mattoso, L. H. C. Solution blow spinning: parameters optimization and effects on the properties of nanofibers from poly (lactic acid)/dimethyl carbonate solutions. *J. Mater. Sci.* **2016**, *51* (9), 4627–4638.

(16) Sinha-Ray, S.; Sinha-Ray, S.; Yarin, A. L.; Pourdeyhimi, B. Theoretical and experimental investigation of physical mechanisms responsible for polymer nanofiber formation in solution blowing. *Polymer* **2015**, *56*, 452–463.

(17) Liu, R.; Xu, X.; Zhuang, X.; Cheng, B. Solution blowing of chitosan/PVA hydrogel nanofiber mats. *Carbohydr. Polym.* **2014**, *101*, 1116–1121.

(18) Liu, F.; Avena-Bustillos, R. J.; Woods, R.; Chiou, B. S.; Williams, T. G.; Wood, D. F.; Bilbao-Sainz, C.; Yokoyama, W.; Glenn, G. M.; McHugh, T. H. Preparation of zein fibers using solution blow spinning method. *J. Food Sci.* **2016**, *81* (12), N3015–N3025.

(19) Sett, S.; Stephansen, K.; Yarin, A. Solution-blown nanofiber mats from fish sarcoplasmic protein. *Polymer* **2016**, *93*, 78–87.

(20) Marano, S.; Barker, S. A.; Raimi-Abraham, B. T.; Missaghi, S.; Rajabi-Siahboomi, A.; Craig, D. Q. Development of micro-fibrous solid dispersions of poorly water-soluble drugs in sucrose using temperaturecontrolled centrifugal spinning. *Eur. J. Pharm. Biopharm.* **2016**, *103*, 84–94. (21) Zhang, X.; Lu, Y. Centrifugal spinning: an alternative approach to fabricate nanofibers at high speed and low cost. *Polym. Rev.* **2014**, *54* (4), 677–701.

(22) Lu, Y.; Li, Y.; Zhang, S.; Xu, G.; Fu, K.; Lee, H.; Zhang, X. Parameter study and characterization for polyacrylonitrile nanofibers fabricated via centrifugal spinning process. *Eur. Polym. J.* **2013**, *49* (12), 3834–3845.

(23) Lee, H.; Watanabe, K.; Kim, M.; Gopiraman, M.; Song, K.-H.; Lee, J. S.; Kim, I. S. Handspinning enabled highly concentrated carbon nanotubes with controlled orientation in nanofibers. *Sci. Rep.* **2016**, *6*, 37590.

(24) Watanabe, K.; Kim, B. S.; Enomoto, Y.; Kim, I. S. Fabrication of uniaxially aligned poly (propylene) nanofibers via handspinning. *Macromol. Mater. Eng.* **2011**, *296* (6), 568–573.

(25) Padron, S.; Fuentes, A.; Caruntu, D.; Lozano, K. Experimental study of nanofiber production through forcespinning. *J. Appl. Phys.* **2013**, *113* (2), No. 024318.

(26) Wiraputra, I. G. P. A. E.; Fauzi, A.; Zulfi, A.; Munir, M. M. The Design of Mini-Rotary Forcespinning System for Nanofiber Synthesis. *Procedia Eng.* **2017**, *170*, 24–30.

(27) Cheng, J.; Jun, Y.; Qin, J.; Lee, S.-H. Electrospinning versus microfluidic spinning of functional fibers for biomedical applications. *Biomaterials* **2017**, *114*, 121–143.

(28) Tokarev, A.; Trotsenko, O.; Griffiths, I. M.; Stone, H. A.; Minko, S. Magnetospinning of Nano-and Microfibers. *Adv. Mater.* **2015**, 27 (23), 3560–3565.

(29) Li, J.-T.; Jia, X.-S.; Yu, G.-F.; Yan, X.; He, X.-X.; Yu, M.; Gong, M.-G.; Ning, X.; Long, Y.-Z. Fabrication of Continuous Microfibers Containing Magnetic Nanoparticles by a Facile Magneto-Mechanical Drawing. *Nanoscale Res. Lett.* **2016**, *11* (1), 426.

(30) Sweetser, D. M.; Zander, N. E. Parameter Study of Melt Spun Polypropylene Fibers by Centrifugal Spinning; Army Research Lab: Aberdeen Proving Ground, MD, 2014.

(31) Deravi, L. F.; Sinatra, N. R.; Chantre, C. O.; Nesmith, A. P.; Yuan, H.; Deravi, S. K.; Goss, J. A.; MacQueen, L. A.; Badrossamy, M. R.; Gonzalez, G. M.; et al. Design and fabrication of fibrous nanomaterials using pull spinning. *Macromol. Mater. Eng.* **201**7, 302 (3), 1600404.

(32) Badrossamay, M. R.; McIlwee, H. A.; Goss, J. A.; Parker, K. K. Nanofiber assembly by rotary jet-spinning. *Nano Lett.* **2010**, *10* (6), 2257–2261.

(33) Ren, L.; Pandit, V.; Elkin, J.; Denman, T.; Cooper, J. A.; Kotha, S. P. Large-scale and highly efficient synthesis of micro-and nano-fibers with controlled fiber morphology by centrifugal jet spinning for tissue regeneration. *Nanoscale* **2013**, *5* (6), 2337–2345.

(34) Rogalski, J. J.; Bastiaansen, C. W.; Peijs, T. Rotary jet spinning review-a potential high yield future for polymer nanofibers. *Nanocomposites* **2017**, *3* (4), 97–121.

(35) Tokarev, A.; Asheghali, D.; Griffiths, I. M.; Trotsenko, O.; Gruzd, A.; Lin, X.; Stone, H. A.; Minko, S. Touch-and Brush-Spinning of Nanofibers. *Adv. Mater.* **2015**, *27* (41), 6526–6532.

(36) Nain, A. S.; Phillippi, J. A.; Sitti, M.; MacKrell, J.; Campbell, P. G.; Amon, C. Control of Cell Behavior by Aligned Micro/Nanofibrous Biomaterial Scaffolds Fabricated by Spinneret-Based Tunable Engineered Parameters (STEP) Technique. *Small* **2008**, *4* (8), 1153–1159.

(37) Nain, A. S.; Wang, J. Polymeric nanofibers: isodiametric design space and methodology for depositing aligned nanofiber arrays in single and multiple layers. *Polym. J.* **2013**, *45* (7), 695.

(38) Ye, Z.; Nain, A. S.; Behkam, B. Spun-wrapped aligned nanofiber (SWAN) lithography for fabrication of micro/nano-structures on 3D objects. *Nanoscale* **2016**, *8* (25), 12780–12786.

(39) Mahalingam, S.; Edirisinghe, M. Forming of polymer nanofibers by a pressurised gyration process. *Macromol. Rapid Commun.* **2013**, *34* (14), 1134–1139.

(40) Senthilram, T.; Mary, L. A.; Venugopal, J. R.; Nagarajan, L.; Ramakrishna, S.; Dev, V. R. G. Self crimped and aligned fibers. *Mater. Today* **2011**, *14* (5), 226–229.

(41) Liu, Y.; Zhang, X.; Xia, Y.; Yang, H. Magnetic-field-assisted electrospinning of aligned straight and wavy polymeric nanofibers. *Adv. Mater.* **2010**, *22* (22), 2454–2457.

(42) Shen, S.; Henry, A.; Tong, J.; Zheng, R.; Chen, G. Polyethylene nanofibres with very high thermal conductivities. *Nat. Nanotechnol.* **2010**, *5* (4), 251.

(43) Shrestha, R.; Li, P.; Chatterjee, B.; Zheng, T.; Wu, X.; Liu, Z.; Luo, T.; Choi, S.; Hippalgaonkar, K.; de Boer, M. P. Crystalline polymer nanofibers with ultra-high strength and thermal conductivity. *Nat. Commun.* **2018**, DOI: 10.1038/s41467-018-03978-3.

(44) Brennan, D. A.; Jao, D.; Siracusa, M. C.; Wilkinson, A. R.; Hu, X.; Beachley, V. Z. Concurrent collection and post-drawing of individual electrospun polymer nanofibers to enhance macromolecular alignment and mechanical properties. *Polymer* **2016**, *103*, 243–250.

(45) Hosseini Ravandi, S.; Hassanabadi, E.; Tavanai, H.; Abuzade, R. Mechanical properties and morphology of hot drawn polyacrylonitrile nanofibrous yarn. *J. Appl. Polym. Sci.* **2011**, *124* (6), 5002–5009.

(46) Qu, Y.; Nguyen-Dang, T.; Page, A. G.; Yan, W.; Das Gupta, T.; Rotaru, G. M.; Rossi, R. M.; Favrod, V. D.; Bartolomei, N.; Sorin, F. Superelastic Multimaterial Electronic and Photonic Fibers and Devices via Thermal Drawing. *Adv. Mater.* **2018**, *30*, 1707251.

(47) Nakata, K.; Fujii, K.; Ohkoshi, Y.; Gotoh, Y.; Nagura, M.; Numata, M.; Kamiyama, M. Poly (ethylene terephthalate) Nanofibers Made by Sea–Island-Type Conjugated Melt Spinning and Laser-Heated Flow Drawing. *Macromol. Rapid Commun.* **2007**, *28* (6), 792– 795.

(48) Lee, H.; Inoue, Y.; Kim, M.; Ren, X.; Kim, I. Effective Formation of Well-Defined Polymeric Microfibers and Nanofibers with Exceptional Uniformity by Simple Mechanical Needle Spinning. *Polymers* **2018**, *10* (9), 980.

(49) Tätte, T.; Hussainov, M.; Paalo, M.; Part, M.; Talviste, R.; Kiisk, V.; Mändar, H.; Põhako, K.; Pehk, T.; Reivelt, K.; et al. Alkoxide-based precursors for direct drawing of metal oxide micro-and nanofibres. *Sci. Technol. Adv. Mater.* **2011**, *12* (3), No. 034412.

(50) Xing, X.; Wang, Y.; Li, B. Nanofiber drawing and nanodevice assembly in poly (trimethylene terephthalate). *Opt. Express* **2008**, *16* (14), 10815–10822.

(51) Nain, A. S.; Amon, C.; Sitti, M. Proximal probes based nanorobotic drawing of polymer micro/nanofibers. *IEEE Trans. Nanotechnol.* **2006**, *5* (5), 499–510.

(52) Ondarcuhu, T.; Joachim, C. Drawing a single nanofibre over hundreds of microns. *EPL* **1998**, *42* (2), 215.

(53) Nain, A. S.; Wong, J. C.; Amon, C.; Sitti, M. Drawing suspended polymer micro-/nanofibers using glass micropipettes. *Appl. Phys. Lett.* **2006**, *89* (18), 183105.

(54) Bajakova, J.; Chaloupek, J.; Lukáš, D.; Lacarin, M. In Drawing– The production of individual nanofibers by experimental method, *Proceedings of the 3rd International Conference on Nanotechnology-Smart Materials*; NANOCON'11, 2011.

(55) Park, J. H.; Rutledge, G. C. Ultrafine high performance polyethylene fibers. J. Mater. Sci. 2018, 53 (4), 3049–3063.

(56) Ma, J.; Zhang, Q.; Mayo, A.; Ni, Z.; Yi, H.; Chen, Y.; Mu, R.; Bellan, L. M.; Li, D. Thermal conductivity of electrospun polyethylene nanofibers. *Nanoscale* **2015**, *7* (40), 16899–16908.

(57) Ma, J.; Zhang, Q.; Zhang, Y.; Zhou, L.; Yang, J.; Ni, Z. A rapid and simple method to draw polyethylene nanofibers with enhanced thermal conductivity. *Appl. Phys. Lett.* **2016**, *109* (3), No. 033101.

(58) Al-Oqla, F. M.; Sapuan, S.; Anwer, T.; Jawaid, M.; Hoque, M. Natural fiber reinforced conductive polymer composites as functional materials: A review. *Synth. Met.* **2015**, *206*, 42–54.

(59) Shanker, A.; Li, C.; Kim, G.-H.; Gidley, D.; Pipe, K. P.; Kim, J. High thermal conductivity in electrostatically engineered amorphous polymers. *Science advances* **2017**, *3* (7), No. e1700342.