Review of Polymer Solutions for Near-Field Electrospinning with Spatial Control

Antonio Osamu Katagiri Tanaka, Héctor Alán Aguirre Soto

Abstract

Near-field electrospinning (NFES) is identified to be a technique able to fabricate polymer nano and micro fibers with accurate placement. In the past years (2006-2019), several polymer solutions have been successfully electrospun into fibers through several variants of the conventional NFES process. Each NFES variant intents to tailor the process parameters in order to improve the fibers' properties. This paper presents a review on the research and related development of electrospun fibers, emphasizing the used polymers, solvents, and fiber characteristics. Relevant summary of polymer solutions and near-field electrospinning processing conditions is provided in this paper.

Keywords: polymer, solvent, near-field electrospinning, NFES, fibers, spatial control

Contents

1. Introduction

Even though electrospinning is an old invention [1], it is currently a trending topic among researchers [2–4]. One of the reasons electrospinning is to be studied is its potential to fabricate polymer nano-fibers from a variety of polymers. The technique allows the production of

Email addresses: `oskatagiri@gmail.com` (Antonio Osamu Katagiri Tanaka), `alan.aguirre@tec.mx` (Héctor Alán Aguirre Soto)

thin continuous fibers with ease, with diameters down to 3 nm in some cases, which is something difficult to achieve by other techniques. Furthermore, the basic setup can be modified with ease to fabricate different fibers with diversified functionalities with different materials. The produced fibers can be aligned or unaligned. Besides, the electrospinning equipment is inexpensive and of small size, compared to the equipment of standard spinning techniques. On the other hand, the understanding of the electrospinning process has improved in the last years [5].

The main components of the electrospinning technique are the fluid control unit (e.g. syringe pump) and a voltage power supply. The process also requires a target electrode or combination of electrodes on which the fibers can be collected. Figure 1 describes a typical near-field electrospinning set-up [5]. Two sub-techniques can be derived from electrospinning depending on the distance between the dispensin g electrode and the collector. The process in which the electrospun jet can be controlled near the tip is called NFES or near-field electrospinning [6]. Moreover, if the distance between the collector and the dispensing needle is greater, the configuration is known as FFES or far-field electrospinning [7]. Near-field electrospinning is considered to be an outstanding technique to fabricate polymer fibers with spatial control and it has suffered several modifications to improve the precision and accuracy of the fiber deposition. This paper intents to collect the NFES variants of electrospunable polymer solutions with spatial control in recent research.

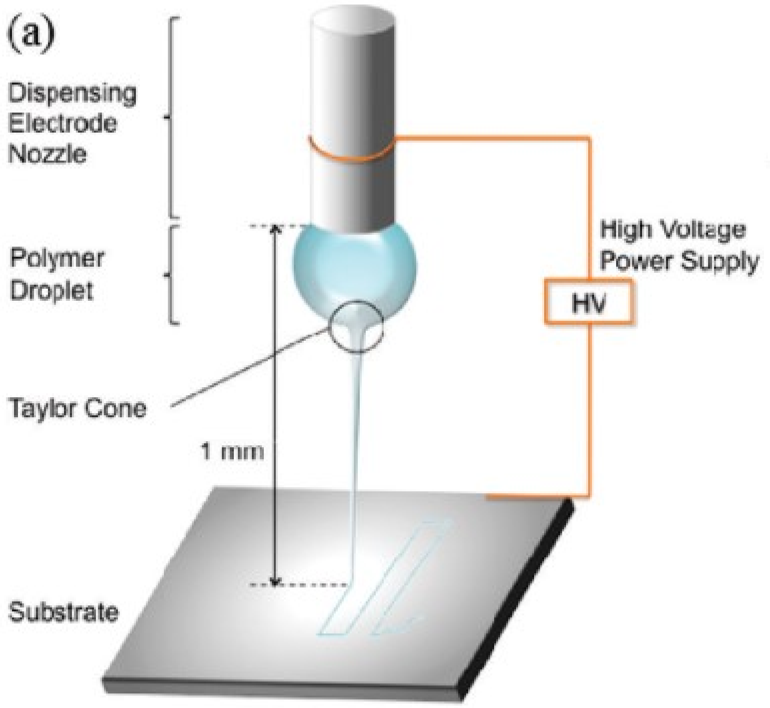

Figure 1: Typical near-field electrospinning set-up [8] .

2. NFES articles' summary

The key advance that allows for lowering of the voltage and attendant increase in patterning control ofNFES is the use of a superelastic polymer ink. Solutions of such a polymer ink contain long entangled polymer chains that promote stretchability and are expected to augment continuity of the electrospun jets. This facilitates the continuous electrospinning of the polymer jet into nanofiber.

The polymer jet does not self-initiate under the influence of the voltage because the electrostatic force cannot overcome the surface tension at the droplet - air interface. Therefore, the electrospinning process was initiated by introducing an artificial instability at the droplet - air interface with a glass microprobe tip (1 to 3 μm tip diameter) that resulted in a very high local electric field, sufficient to overcome the interfacial surface tension, giving rise to the formation of the Taylor cone and initiation of the polymer jet.

Therefore, we believe that 2 wt % PEO solution has the proper balance of viscosity, conductivity, and resistance to hardening that allows for low-voltage continuous electrospinning.

At 300 Vand lower, the perturbation phenomenon was eliminated and straight deposition patterns were obtained (as seen in Figure 4c,d). This could be achieved with slow stage speeds (20-40 mm/s) clearly demonstrating that the low-voltage NFES technique substantially reduces bending instabilities

Another advantage oflower voltage operation lies in reduction of the diameter of the jet, leading to thinner nanofibers. This is most likely due to the lower electrostatic forces at play that reduce the feed rate of the polymer, thus reducing jet thickness. Therefore, the voltage can be manipulated to directly control the thickness of the nanofibers

Further investigation into the effect of voltage on the thickness
of nanofibers reveals an increasing linear trend of average diameter versus voltage as shown in Figure 6. This trend is opposite to that observed in far-field electrospinning

We further demonstrate the ability to integrate low-voltage
NFES "writing" capability with 3D substrates by suspending nanofibers on carbon micropost arrays on a Si substrate. In a typical example, we use posts of a height of40 μm, a diameter of 30 μm, an interpostal distance of 100 μm. [8]

[9]

[10]

[11]

[12]

[13]

[14]

[15]

[16]

[17]

[18]

[19]

[20]

[21]
[22]
[23]
[24]
[25]
[26]
[27]
[28]
[29]
[6]
[30]
[31]

Table 1: Electrospun Polymer Solutions - Solution and Process Parameters

Polymer(s)	Solvent(s)	NFES Variant	Process Parameters and Fiber Characterization	Ref.
Poly(ethylene oxide) (PEO MW = 4 000 000)	Deionized water	Low-Voltage NFES (LV NFES)	**Solution Concentration:** 1, 2, and 3 $wt\%$ PEO **Nozzle:** 27 gauge type 304; stainless steel needle **Solution deposition rate:** lower than $1\mu L/h$ **Nozzle-to-substrate distance:** $1mm$ **Substrate composition:** Pyrolyzed SU-8 carbon and Si **Applied voltage:** polymer jet initiated at 400-600 V and dispensed at 200-400 V **x-y stage velocity:** 10-40mm/s **Fiber Diameter:** 50-425nm **Distance between adjacent fibers:** *Not determined*	[8]
Poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV) with Poly(ethylene oxide) (PEO)	acetonitrile toluene mixture (65/35); acetic acid toluene (17/83); pure toluene	Typical NFES process	**Solution Concentration:** $10mg$ of MEH-PPV in $2mL$ of toluene; $500mL$ of MEH-PPV solution with $250mg$ of PEO in $3.5mL$ of acetonitrile; $500mL$ of MEH-PPV solution with $250mg$ of PEO in $3mL$ of acetic acid / toluene (17 / 83). The resulting MEH-PPV/PEO concentration is 1:100 **Nozzle:** mm-diameter tip Tungsten spinneret in a 26 gauge needle **Solution deposition rate:** $50\mu L/h$ **Nozzle-to-substrate distance:** $500\mu m$ **Substrate composition:** SiO2/Si (oxide thickness = 800 nm) **Applied voltage:** around $1.3kV$ **x-y stage velocity:** $50cm/s$ **Fiber Diameter:** $100nm$ **Distance between adjacent fibers:** around $100\mu m$	[11]

Continued on next page

Table 1 continued

Poly(ethylene oxide) (PEO)	Water	Scanning Tip Electrospinning and NFES	**Solution Concentration:** $7wt\%$ PEO **Nozzle:** Needle outer diameter of $200\mu m$ and inner diameter of $100\mu m$ **Solution deposition rate:** $0.1\mu L/h$ **Nozzle-to-substrate distance:** $500\mu m$ **Substrate composition:** *Not determined* **Applied voltage:** polymer jet initiated at 1.5 kV and dispensed at $600V$ **x-y stage velocity:** $120mm/s$ **Fiber Diameter:** $709\pm131nm$; 49-74nm when applied voltage is $800V$ **Distance between adjacent fibers:** *Not determined* **Notes:** $108m$ yield in $15min$ with a fiber diameter of $709\pm131nm$	[12]
Poly(vinylidine fluorid) (PVDF)	N,N Dimethylformamide (DMF)	Helix Electrohydrodynamic Printing (HE-printing)	**Solution Concentration:** $1.8g$ PVDF in $4.1g$ of DMF and $4.1g$ of acetone. The resulting concentration is 18% PVDF. **Nozzle:** Needle outer diameter of $510\mu m$ and inner diameter of $260\mu m$ **Solution deposition rate:** $400nL/min$ **Nozzle-to-substrate distance:** 10-50mm **Substrate composition:** Poly(dimethylsiloxane) (PDMS) on Ecoflex **Applied voltage:** 1.5–3kV **x-y stage velocity:** 0-400mm/min **Fiber Diameter:** about 1.5-3μm **Distance between adjacent fibers:** *Not determined*	[13]

Continued on next page

Table 1 continued

Polyhedral Oligomeric Silsesquioxane-Poly(Carbonate-Urea)Urethane (POSS-PCU) and Polyhedral Oligomeric Silsesquioxane Poly(Caprolactone-Poly(Carbonate-Urea)Urethane) (POSS-PCL-PCU)	Dimethyl acetamide (DMAC) and 1-Butanol	Electrohydrodynamic 3D Print-patterning or Electrohydrodynamic Jetting	**Solution Concentration:** POSS-PCU and POSS-PCL-PCU used in 20%w/w concentration in DMAC **Nozzle:** needle of 750 μm in diameter **Solution deposition rate:** less than 1$\mu L/min$ **Nozzle-to-substrate distance:** about between 500μm to 2mm **Substrate composition:** *Not determined* **Applied voltage:** 8.0-10.0kV **x-y stage velocity:** 10mm/s **Fiber Diameter:** 5-50μm **Distance between adjacent fibers:** 250μm	[14]
Poly(ethylene oxide) (PEO)	Distilled water	Electrohydrodynamic Writing or Mechano-electrospinning (MES)	**Solution Concentration:** 6wt% PEO **Nozzle:** *Not determined* **Solution deposition rate:** 1200nL/min **Nozzle-to-substrate distance:** 7.5mm **Substrate composition:** *Not determined* **Applied voltage:** polymer jet initiated at 2 kV and dispensed at 0.8-1kV **x-y stage velocity:** around 400mm/s **Fiber Diameter:** 200-350nm **Distance between adjacent fibers:** 5μm	[15]

Continued on next page

Table 1 continued

Poly(ethylene oxide) (PEO)	Deionized water and the ethanol with a volume ratio of 3:1	Airflow-assisted Electrohydrodynamic Direct-writing (EDW)	**Solution Concentration:** $8wt\%$ PEO **Nozzle:** Outer airflow passage diameter: $1mm$ Airflow gas pump pressure: $25kPa$ Inner liquid passage diameter: $0.21mm$ **Solution deposition rate:** $30\mu L/h$ **Nozzle-to-substrate distance:** $2mm$ **Substrate composition:** Silicon **Applied voltage:** about $2kV$ **x-y stage velocity:** 1-$20mm/s$ **Fiber Diameter:** $3.73 \pm 1.37\mu m$ **Distance between adjacent fibers:** $5.13 \pm 6.67\mu m$	[16]
Poly(Vinylidene Fluoride) (PVDF)	Acetone and Dimethyl Sulfoxide (DMSO)	3D Electrospinning	**Solution Concentration:** $17wt\%$ PVDF; $1.7g$ of PVDF, $5g$ of acetone, $0.5g$ of Capstone FS-66, $5g$ of DMSO **Nozzle:** Needle inner diameter of $100\mu m$ **Solution deposition rate:** 14 nL/min **Nozzle-to-substrate distance:** $750\mu m$ **Substrate composition:** A4 size commercial printing paper (Double A) **Applied voltage:** $1.9kV$ **x-y stage velocity:** $10mm/s$ **Fiber Diameter:** *Not determined* **Distance between adjacent fibers:** *Not determined*	[17]

Continued on next page

Table 1 continued

Poly(9-Vinyl Carbazole) (PVK)	Styrene	Typical NFES process	**Solution Concentration:** $3.96wt\%$ PVK in styrene **Nozzle:** Needle inner diameter of $100\mu m$ **Solution deposition rate:** $500nL/min$ **Nozzle-to-substrate distance:** around $2.5mm$ **Substrate composition:** Si/SiO2 **Applied voltage:** 3-$4kV$ x-y stage velocity: $13.3cm/s$ **Fiber Diameter:** $289.26 \pm 35.37nm$ **Distance between adjacent fibers:** $50\mu m$ **Notes:** $15m$ yield in $2min$	[18]
Polystyrene (PS)	1,2,4-Trichloro benzene	Electrohydro-dynamic (EHD) jet printing	**Solution Concentration:** 1 to $5wt\%$ PS **Nozzle:** Glass nozzle inner diameter of $2\mu m$ and outer diameter of $2.66\mu m$ **Solution deposition rate:** Si **Nozzle-to-substrate distance:** **20, 30, 40**μm **Substrate composition:** **Applied voltage:** 500 to $400V$ in $25V$ increments **x-y stage velocity:** 0.01-$10mm/s$ **Fiber Diameter:** about 60-$170\mu m$ **Distance between adjacent fibers:** *Not determined*	[19]
Poly(ethylene oxide) (PEO)	*Not determined*	Typical NFES process	**Solution Concentration:** $3wt\%$ PEO **Nozzle:** *Not determined* **Solution deposition rate:** *Not determined* **Nozzle-to-substrate distance:** $500\mu m$ **Substrate composition:** Si **Applied voltage:** $1000V$ **x-y stage velocity:** $20cm/s$ **Fiber Diameter:** $300nm$ **Distance between adjacent fibers:** $25\mu m$	[20]

Continued on next page

Table 1 continued

Poly(ethylene oxide) (PEO)	Distilled water	Multinozzle NFES	**Solution Concentration:** $5wt\%$ **Nozzle:** four-nozzle and six-nozzle array with needle spacing changes from $1.5mm$ to $3.5mm$ **Solution deposition rate:** 1-$3\mu L/min$ **Nozzle-to-substrate distance:** $2mm$ **Substrate composition:** *Not determined* **Applied voltage:** 1.7-$2.7kV$ **x-y stage velocity:** *Not determined* **Fiber Diameter:** $5.47\mu m$ **Distance between adjacent fibers:** 3-5 mm	[21]
Poly(ethylene oxide) (PEO)	Distilled water	Multinozzle NFES	**Solution Concentration:**$5wt\%$ **Nozzle:** Dual-28G-needle array with needle inner diameter of $0.18mm$ and outer diameter of $0.36mm$; with needle spacing changes from $2.0mm$ to $3.0mm$ **Solution deposition rate:** $0.2\mu L/min$ **Nozzle-to-substrate distance:** 3.0-$4.0mm$ **Substrate composition:** *Not determined* **Applied voltage:** 2.0-$3.0kV$ **x-y stage velocity:** $20mm/s$ **Fiber Diameter:** *Not determined* **Distance between adjacent fibers:** 218-$326\mu m$	[22]

Continued on next page

Table 1 continued

Poly(ethylene oxide) (PEO)	Distilled water	Multinozzle NFES	**Solution Concentration:** 5 $wt\%$ **Nozzle:** Dual-28G-needle array with needle inner diameter of $180\mu m$ and outer diameter of $360\mu m$; with needle spacing changes of $2.0mm$ **Solution deposition rate:** $0.2\mu L/min$ **Nozzle-to-substrate distance:** $4.0mm$ **Substrate composition:** chromium-plated glass **Applied voltage:** $2.5kV$ **x-y stage velocity:** $20mm/s$ **Fiber Diameter:** *Not determined* **Distance between adjacent fibers:** 2.3002-$2.7224mm$	[23]
Poly(ethylene oxide) (PEO)	*Not determined*	Typical NFES process	**Solution Concentration:** $2wt\%$ **Nozzle:** G30 needle with inner diameter of $0.15mm$ **Solution deposition rate:** *Not determined* **Nozzle-to-substrate distance:** 1-$3mm$ **Substrate composition:** Silicon **Applied voltage:** $1250V$ **x-y stage velocity:** *Not determined* **Fiber Diameter:** *Not determined* **Distance between adjacent fibers:** $20\mu m$	[24]

Continued on next page

Table 1 continued

Gelatin (porcine skin)	Acetic Acid and Ethyl Acetate	Typical process	NFES	**Solution Concentration:** $11wt\%$ gelatin, $30wt\%$ water, $35.4wt\%$ acetic acid, $23.6wt\%$ ethyl acetate **Nozzle:** 19G needle tip with outer diameter of $1.08mm$ **Solution deposition rate:** *Not determined* **Nozzle-to-substrate distance:** $1.25mm$ **Substrate composition:** Poly(Dimethylsiloxane) (PDMS) films **Applied voltage:** $1000V$ **x-y stage velocity:** *Not determined* **Fiber Diameter:** around 2-$3\mu m$ **Distance between adjacent fibers:** $40\mu m$	[25]
Poly(ethylene oxide) (PEO)	Water/Ethanol (v/v = 60/40)	Typical process	NFES	**Solution Concentration:** PEO concentrations of 16% adn 18% **Nozzle:** $40\mu m$ **Solution deposition rate:** **Nozzle-to-substrate distance:** $1mm$ **Substrate composition:** Planar silicon **Applied voltage:** $1.7kV$ **x-y stage velocity:** $0.36m/s$ **Fiber Diameter:** $5.15\mu m$ **Distance between adjacent fibers:** *Not determined*	[26]

Continued on next page

Table 1 continued

Poly(ethylene oxide) (PEO)	Water/Ethanol (v/v = 3/1)	Electrohydrodynamic Direct-Write (EDW)	**Solution Concentration:** $14wt\%$ PEO **Nozzle:** Stainless needle with inner diameter of $210\mu m$ and outer diameter of $400\mu m$ **Solution deposition rate:** $50\mu L/h$ **Nozzle-to-substrate distance:** $2mm$ **Substrate composition:** Poly(ethylene terephthalate) (PET) **Applied voltage:** $3kV$ **x-y stage velocity:** $700mm/s$ **Fiber Diameter:** 15-$35\mu m$ **Distance between adjacent fibers:** $70\mu m$	[27]
Poly(ethylene oxide) (PEO)	Deionized water	Mechano-Electrospinning	**Solution Concentration:** $3wt\%$ PEO **Nozzle:** Stainless steel nozzle with inner diameter of $160\mu m$ and outer diameter of $310\mu m$ **Solution deposition rate:** $50nL/min$ **Nozzle-to-substrate distance:** 2-$5mm$ **Substrate composition:** Silicone **Applied voltage:**polymer jet initiated at $2kV$ and dispensed at $1kV$ **x-y stage velocity:** 200-$400mm/s$ **Fiber Diameter:** from 344 ± 32 to $214\pm27nm$ **Distance between adjacent fibers:** *Not determined*	[28]

Continued on next page

Table 1 continued

Poly(co-Glycolic) acid (PLGA)	Dimethyl Carbonate (DMC)	Tethered Pyro-Electrohydrodynamic Spinning (TPES)	**Solution Concentration:** *Not determined* **Nozzle:** nozzle-free **Solution deposition rate:** The drop reservoir is placed directly on a flat substrate **Nozzle-to-substrate distance:** Taylor's cone is focused and put in direct contact with the collector **Substrate composition:** Poly(tetrafluoroethylene) (PTFE) coated glass slide **Applied voltage:** pyro-electric field of between 2.7 $x10^7$ V/m and $5.5x10^7$ V/m **x-y stage velocity:** *Not determined* **Fiber Diameter:** $304.7nm$ **Distance between adjacent fibers:** *Not determined*	[29]
Poly(ethylene oxide) (PEO) with Tetrabutylammonium tetrafluoroborate (TBF) and SU-8 2002	N,N Dimethylformamide (DMF)	Typical NFES process	**Solution Concentration:** SU-8/PEO/TBF blend with $0.75wt\%$ PEO, $1wt\%$ TBF; the blend is diluted with $30vol\%$ DMF $\mu m \mu m$ **Solution deposition rate:** *Not determined* **Nozzle-to-substrate distance:** *Not determined* **Substrate composition:** Brass disk with a diameter of $38mm$ **Applied voltage:** $980V$ **x-y stage velocity:** *Not determined* **Fiber Diameter:** *Not determined* **Distance between adjacent fibers:** *Not determined*	[6]

Continued on next page

Table 1 continued

Poly(ethylene oxide) (PEO)	Water:Ethanol (3:2)	Suspension NFES	**Solution Concentration:** $14wt\%$ PEO **Nozzle:** stainless steel needle (25 G) with inner diameter of $0.25mm$ **Solution deposition rate:** $3nL/s$ **Nozzle-to-substrate distance:** between 0.5 and $10mm$ with $0.5mm$ increments **Substrate composition:** Planar silicon electrodes **Applied voltage:** $1.6kV$ **x-y stage velocity:** 50, 150, and $250mm/s$ **Fiber Diameter:** $300nm$ **Distance between adjacent fibers:** 0.1 and $0.5mm$	[30]
Poly(ethylene oxide) (PEO)	Deionized water	Typical NFES process	**Solution Concentration:** $10wt\%$ PEO **Nozzle:** 32G metal needle **Solution deposition rate:** (Jet impact speed of $5mm/s$) **Nozzle-to-substrate distance:** $0.5mm$ **Substrate composition:** p-type silicon wafer **Applied voltage:** $400V$ **x-y stage velocity:** $5mm/s$ **Fiber Diameter:** **Distance between adjacent fibers:** $50\mu m$	[31]

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum.

3. Polymer Solution and Process Parameters

4. Applications

5. Fiber Characterization

6. Conclusion

References

[1] F. Anton, Process and apparatus for preparing artificial threads (1930). doi:https://patents.google.com/?q=D01D5%2f0076.

[2] Z.-M. Huang, Y. Z. Zhang, M. Kotaki, S. Ramakrishna, A review on polymer nanofibers by electrospinning and their applications in nanocomposites, Composites Science and Technology 63 (15) (2003) 2223–2253. doi:10.1016/S0266-3538(03)00178-7.

[3] D. H. Reneker, A. L. Yarin, Electrospinning jets and polymer nanofibers, Polymer 49 (10) (2008) 2387–2425. doi:10.1016/J.POLYMER.2008.02.002.

[4] J. D. Schiffman, C. L. Schauer, A Review: Electrospinning of Biopolymer Nanofibers and their Applications, Polymer Reviews 48 (2) (2008) 317–352. doi:10.1080/15583720802022182.

[5] Q. Li, Chapter 7: Liquid Crystal-Functionalized Nano- and Microfibers Produced by Electrospinning - Liquid Crystals Beyond Displays: Chemistry, Physics, and Applications, John Wiley & Sons, 2012. doi:9781118078617.

[6] A. Cisquella-Serra, M. Magnani, Álvaro Gual-Mosegui, S. Holmberg, M. Madou, M. Gamero-Castaño, Study of the electrostatic jet initiation in near-field electrospinning, Journal of Colloid and Interface Science 543 (2019) 106–113. doi:10.1016/J.JCIS.2019.02.041.

[7] S. K. Nataraj, K. S. Yang, T. M. Aminabhavi, Polyacrylonitrile-based nanofibers—A state-of-the-art review, Progress in Polymer Science 37 (3) (2012) 487–513. doi:10.1016/J.PROGPOLYMSCI.2011.07.001.

[8] G. S. Bisht, G. Canton, A. Mirsepassi, L. Kulinsky, S. Oh, D. Dunn-Rankin, M. J. Madou, Controlled Continuous Patterning of Polymeric Nanofibers on Three-Dimensional Substrates Using Low-Voltage Near-Field Electrospinning, Nano Letters 11 (4) (2011) 1831–1837. doi:10.1021/nl2006164.

[9] J. Lee, S. Y. Lee, J. Jang, Y. H. Jeong, D.-W. Cho, Fabrication of Patterned Nanofibrous Mats Using Direct-Write Electrospinning, Langmuir 28 (18) (2012) 7267–7275. doi:10.1021/la3009249.

[10] J. Zheng, Y. Z. Long, B. Sun, Z. H. Zhang, F. Shao, H. D. Zhang, Z. M. Zhang, J. Y. Huang, Polymer nanofibers prepared by low-voltage near-field electrospinning, Chinese Physics B 21 (4) (2012) 1–6. doi:10.1088/1674-1056/21/4/048102.

[11] D. D. Camillo, V. Fasano, F. Ruggieri, S. Santucci, L. Lozzi, A. Camposeo, D. Pisignano, Near-field electrospinning of conjugated polymer light-emitting nanofibers, Nanoscale 5 (2013) 11637–11642. doi:10.1039/C3NR03094F.

[12] C. Chang, K. Limkrailassiri, L. Lin, Continuous near-field electrospinning for large area deposition of orderly nanofiber patterns, Appl Phys Lett (2008) 3doi:10.1063/1.2975834.

[13] Y. Duan, Y. Ding, Z. Xu, Y. Huang, Z. Yin, Helix Electrohydrodynamic Printing of Highly Aligned Serpentine Micro/Nanofibers., Polymers 9 (9) (sep 2017). doi:10.3390/polym9090434.

[14] A. Gupta, A. M. Seifalian, Z. Ahmad, M. J. Edirisinghe, M. C. Winslet, Novel Electrohydrodynamic Printing of Nanocomposite Biopolymer Scaffolds, Journal of BIOACTIVE AND COMPATIBLE POLYMERS 22 (2007). doi:10.1177/0883911507078268.

[15] Y. Huang, Y. Duan, Y. Ding, N. Bu, Y. Pan, N. Lu, Z. Yin, Versatile, kinetically controlled, high precision electrohydrodynamic writing of micro/nanofibers, Scientific Reports 4 (1) (2015) 5949. doi:10.1038/srep05949.

[16] J. Jiang, X. Wang, W. Li, J. Liu, Y. Liu, G. Zheng, J. Jiang, X. Wang, W. Li, J. Liu, Y. Liu, G. Zheng, Electrohydrodynamic Direct-Writing Micropatterns with Assisted Airflow, Micromachines 9 (9) (2018) 456. doi:10.3390/mi9090456.

[17] J. Kim, B. Maeng, J. Park, Characterization of 3D electrospinning on inkjet printed conductive pattern on paper, Micro and Nano Systems Letters 6 (1) (2018) 12. doi:10.1186/s40486-018-0074-1.

[18] S.-Y. Min, T.-S. Kim, B. J. Kim, H. Cho, Y.-Y. Noh, H. Yang, J. H. Cho, T.-W. Lee, Large-scale organic nanowire lithography and electronics, Nature Communications 4 (1) (2013) 1773. doi:10.1038/ncomms2785.

[19] C. Song, J. A. Rogers, J.-M. Kim, H. Ahn, Patterned polydiacetylene-embedded polystyrene nanofibers based on electrohydrodynamic jet printing, Macromolecular Research 23 (1) (2015) 118–123. doi:10.1007/s13233-015-3024-2.

[20] D. Sun, C. Chang, S. Li, L. Lin, Near-Field Electrospinning (2006). doi:10.1021/nl0602701.

[21] H. Wang, S. Huang, F. Liang, P. Wu, M. Li, S. Lin, X. Chen, Research on Multinozzle Near-Field Electrospinning Patterned Deposition, Journal of Nanomaterials 2015 (2015) 1–8. doi:10.1155/2015/529138.

[22] Z. Wang, X. Chen, J. Zeng, F. Liang, P. Wu, H. Wang, Controllable deposition distance of aligned pattern via dual-nozzle near-field electrospinning, AIP Advances 7 (3) (2017) 035310. doi:10.1063/1.4974936.

[23] Z. Wang, X. Chen, J. Zhang, Y.-J. Lin, K. Li, J. Zeng, P. Wu, Y. He, Y. Li, H. Wang, Fabrication and evaluation of controllable deposition distance for aligned pattern by multi-nozzle near-field electrospinning, AIP Advances 8 (7) (2018) 075111. doi:10.1063/1.5032082.

[24] J. Xu, M. Abecassis, Z. Zhang, P. Guo, J. Huang, K. Ehmann, J. Cao, Accuracy Improvement of Nano-fiber Deposition by Near-Field Electrospinning, International Workshop on Microfactories IWMF2014 (9th) (2014).

[25] N. Xue, X. Li, C. Bertulli, Z. Li, A. Patharagulpong, A. Sadok, Y. Y. S. Huang, Rapid Patterning of 1-D Collagenous Topography as an ECM Protein Fibril Platform for Image Cytometry, PLoS ONE 9 (4) (2014) e93590. doi:10.1371/journal.pone.0093590.

[26] G. Zheng, W. Li, X. Wang, D. Wu, D. Sun, L. Lin, Precision deposition of a nanofibre by near-field electrospinning, Journal of Physics D: Applied Physics 43 (41) (2010) 415501. doi:10.1088/0022-3727/43/41/415501.

[27] J.-Y. Zheng, H.-Y. Liu, X. Wang, Y. Zhao, W.-W. Huang, G.-F. Zheng, D.-H. Sun, Electrohydrodynamic Direct-Write Orderly Micro/Nanofibrous Structure on Flexible Insulating Substrate, Journal of Nanomaterials 2014 (2014) 1–7. doi:10.1155/2014/708186.

[28] N. Bu, Y. Huang, X. Wang, Z. Yin, Materials and Manufacturing Processes Continuously Tunable and Oriented Nanofiber Direct-Written by Mechano-Electrospinning Continuously Tunable and Oriented Nanofiber Direct-Written by Mechano-Electrospinning (2012). doi:10.1080/10426914.2012.700145.

[29] S. Coppola, V. Vespini, G. Nasti, O. Gennari, S. Grilli, M. Ventre, M. Iannone, P. A. Netti, P. Ferraro, Tethered Pyro-Electrohydrodynamic Spinning for Patterning Well-Ordered Structures at Micro-and Nanoscale, Chem. Mater 26 (2014) 3360. doi:10.1021/cm501265j.

[30] A. R. Nagle, C. D. Fay, Z. Xie, G. G. Wallace, X. Wang, M. J. Higgins, A direct 3D suspension near-field electrospinning technique for the fabrication of polymer nanoarrays, Nanotechnology 30 (19) (2019) 195301. doi:10.1088/1361-6528/ab011b.

[31] D. Shin, J. Kim, J. Chang, Experimental study on jet impact speed in near-field electrospinning for precise patterning of nanofiber, Journal of Manufacturing Processes 36 (2018) 231–237. doi:10.1016/J.JMAPRO.2018.10.011.