Rapid fabrication of poly(ε-caprolactone) nanofibers using needleless alternating current electrospinning

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ABSTRACT: Poly(ε-caprolactone) (PCL) biopolymer nanofibers and micro-fibers have been fabricated for the first time at the rates up to 14.0 g per hour using a needleless and collectorless alternating current electrospinning technique. By combining the ac-voltage, "green" low toxicity glacial acetic acid (AA) as the solvent and sodium acetate (NaAc) as an additive, beadless PCL fibers with diameters tunable from 150 nm to 2000 nm, varying surface morphology and degree of self-bundling are obtained. In this new approach, the addition of NaAc plays a crucial role in improving the spinnability of PCL solution and fiber morphology. NaAc reveals the concentration-dependent effect on charge transfer and rheological properties of the PCL/AA precursor, which results in broader ranges of spinnable PCL concentrations and ac-voltages suitable for rapid manufacturing of PCL-based fibers. © 2015 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2016**, *133*, 43232.

INTRODUCTION

Poly(ε-caprolactone) (PCL) is a biodegradable and biocompatible polymer that has been proven suitable for a number of biomedical applications. PCL is frequently used for tissue engineering scaffolds, absorbable sutures, contraceptive devices, and long-term drug delivery systems.[1–3] When formed into microscale to nanoscale fibers, PCL and its blends with other synthetic and natural biopolymers have been frequently found advantageous to other PCL formations for the mentioned applications.[4–6]

PCL microfibers and nanofibers are commonly produced by various electrospinning techniques using a suitable PCL/solvent system. Most previous studies on electrospun PCL fibers utilized capillary needle and needleless high-voltage direct current (dc) electrospinning and organic solvents with varied levels of toxicity.[7,8] Alternatively, acetic acid (AA) was proposed in several studies as a moderately good, "green" PCL solvent due to its chemical stability and because it can be removed from the prepared fibers and fibrous constructs without leaving potentially harmful residues.[9–13] Yet, the available experimental data on the electrospinning of PCL/AA precursor system are scarce and somewhat contradictory. For example, Moghe et al.[9] obtained good quality PCL nanofibers (100–900 nm diameter) at the rate up to 0.06 g/h using a capillary needle dc-electrospinning of 10–20 wt % PCL dissolved in glacial AA with the addition of

pyridine (0.1–5 wt %). If pyridine was not added, only beaded PCL fibers were obtained in that range of PCL concentrations. Van Der Schueren et al.[10] found that PCL nanofibers can be electrospun from acetic/formic acid mixtures within a narrow range of PCL concentrations (13–17 wt %). Luo et al.[8] reported only the droplet formation when PCL was dc-electrospun from a 10 wt % PCL/AA solution. It was suggested that AA alone may not be a good solvent because of its low dielectric constant. Similarly, Dias et al.[11] observed little fiber formation in a capillary needle dc-electrospinning process with 11 wt % PCL solution in AA alone, but good nanofibers were prepared at up to 0.35 g/h rate at this PCL concentration in AA with a 2 wt % addition of trimethylamine. On contrary, Kanani and Bahrami[12] reported the formation of beadless PCL nanofibers and microfibers when using 15 wt % and 20 wt % PCL, respectively, in glacial AA as a sole solvent. Ferreira et al.[13] prepared good quality PCL microfibers (1.0–3.0 μm in diameter) from 20 wt % and 23 wt % PCL solutions in glacial AA using a needle dc-electrospinning at 0.3 mL/h flow rate (0.06–0.08 g/h fiber production rate). However, it was noted that the increase of PCL concentration to 26 wt % or the flow rate to 2 mL/h (~0.4 g/h fiber production rate) led to fused fibers.

In this study, PCL nanofibers and microfibers were fabricated for the first time at rates up to 14.0 g/h from PCL/AA precursor solution, a nearly two orders of magnitude increase when
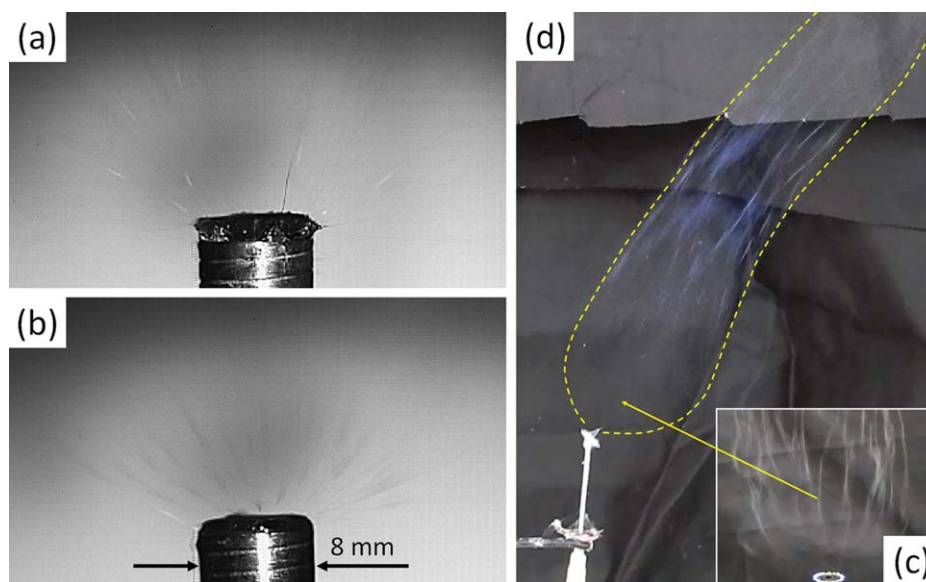
Figure 1. High-speed camera images of the polymer jets emitting from the electrode surface at 38 kV rms ac-voltage for (a) 20% and (b) 10% PCL solution; (c) the formation of a flow of partially bundled fibers, and (d) slowly propagating flow of polymer fibers. Striped line indicates the boundary of the flow. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

compared to the needle dc-electrospinning in PCL/AA system, using an uncommon high-voltage, needleless alternating current (ac) electrospinning method. The latter method has recently emerged as an effective approach to significantly increase efficiency of the polymer nanofiber manufacturing process.[14] Furthermore, by introducing sodium acetate trihydrate (NaAc) as a new additive to PCL/AA system, better control of fiber morphology and dimensions and a broader range of spinnable polymer concentrations were achieved.

EXPERIMENTAL

Materials

PCL with an average molecular weight of 80,000 [M_n], density 1.145 g/mL, melting point 60°C from Sigma Aldrich, was dissolved in glacial acetic acid (Sigma Aldrich) at various PCL/AA concentrations (5–20 wt %) to test ac spinnability and prepare fibers. NaAc with an average molecular weight of 136.089 [M_n] from LACHEMA was used at various percentages to determine its effect on ac-spinnability of PCL/AA solution and fiber quality.

Alternating Current Electrospinning

The ac-electrospinning device was based on a type VTS-38 instrument voltage transformer (CPB Intra, Czech Republic) operated in inverse mode. One end of the high-voltage winding was connected through a 20 MOhm resistor to a metallic rod of 8 mm in diameter with a concave top (this rod served as a jet generating electrode), and another end was grounded. The output ac-voltage was controlled by a variable transformer connected to the low-voltage winding of the instrument transformer. Additional details on the ac-electrospinning process can be found in Pokorny et al.[14] For the spinnability testing, 0.2–0.3 mL of the polymer solution was placed on the top of the metallic rod. Once the ac-voltage was supplied the generated flow of fibers was carried away by corona wind, and grounded

fiber collector was not necessary (Figure 1). The fibers could be collected directly from the propagating flow as clumps with a nonconductive stick or accumulated as layers on flat paper sheets and then used for characterization. A series of PCL/AA precursor solutions with varied PCL concentrations (5–20 wt %) and NaAc salt additions (up to 15 wt %) were tested for spinnability at ac-voltages in the range of 15–38 kV rms voltage.

Characterization of Precursors and Fibers

Viscosity of PCL solutions was determined using a HAAKE RotoVisco 1 from Thermo Scientific paired with Rheowin 4 Job and Data Manager Software. The RotoVisco was programmed to calibrate the zero point before each sample test. Once calibrated a drop of the solution was placed on the RotoVisco platform, and the viscosity values were recorded over a 120-s time period at 1000 rpm. The viscosity graphs and recorded values were stored within the Rheowin 4 Data Manager and could be exported for further analysis.

Electrical conductivity was measured using the WTW inoLab pH/Cond 720 instrument. The meter was calibrated according to the WTW inoLab 720 instruction manual. The AutoRead function was used to obtain at least five stabilized values for each sample.

The size, shape, surface morphology, and arrangement of the ac-electrospun PCL fibers were investigated using scanning electron microscopy (VEGA3 SEM, Tescan, Czech Republic). The samples were sputter-coated with a few nm of gold to prevent charging. SEM imaging was done in secondary electron mode at an accelerating voltage of 30 kV.

Fourier-transform infrared spectra (FTIR, Vertex 70 spectrometer, Bruker Optics) were acquired in transmission mode by placing fibrous specimens across a 6-mm diameter aperture. In all cases, the FTIR spectra represented an average of 32 scans recorded with a resolution of 2 cm^{-1} for each sample.
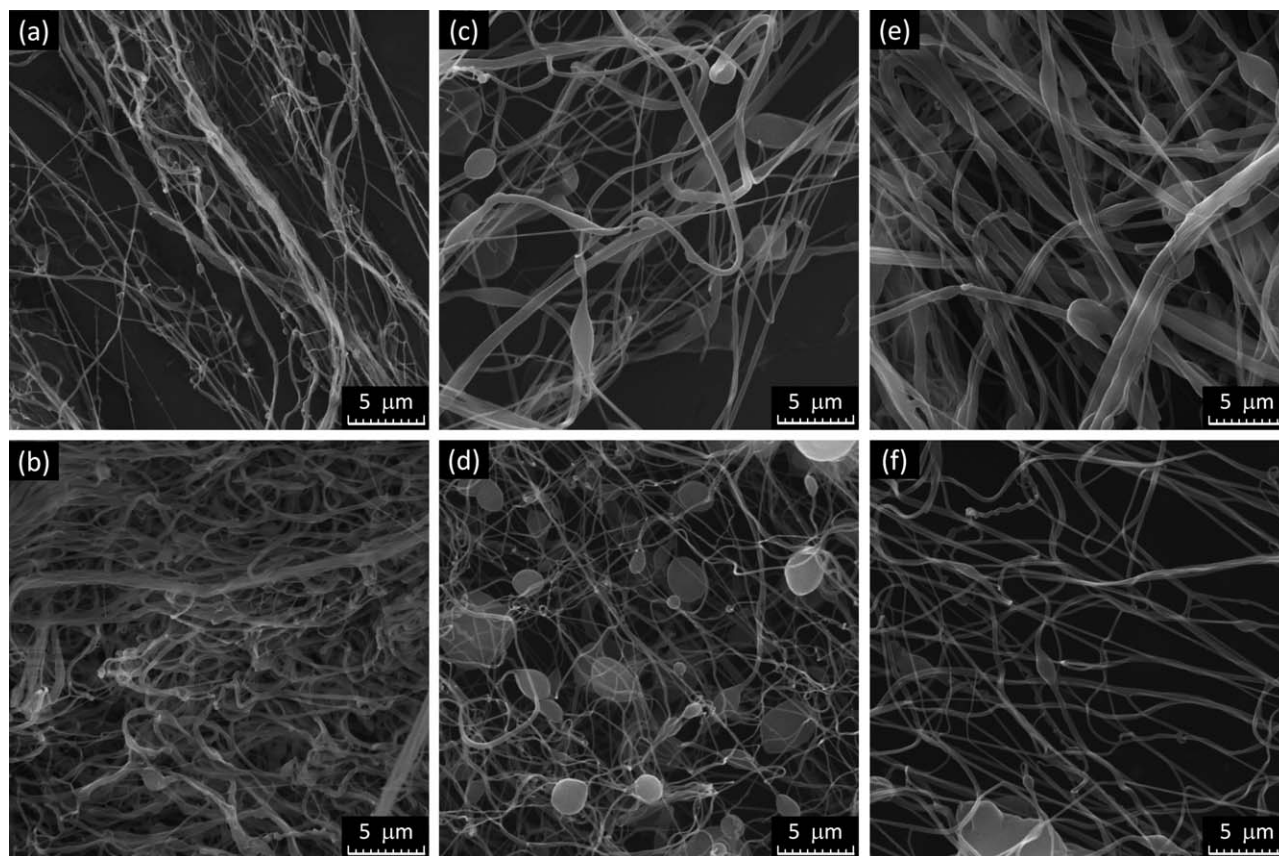
Figure 2. SEM images of the PCL fibers AC-electrospun from: 15 wt % PCL/AA solution at (a) 20 kV and (b) 38 kV; 10 wt % PCL/AA solution at (c) 20 kV and (d) 38 kV; and 10 wt % PCL/AA solution with 0.1 wt % sodium triacetate (NaAc) addition at (e) 20 kV and (f) 38 kV.

RESULTS AND DISCUSSION

PCL/AA Precursor Spinnability

The spinnability of PCL/AA solution depended strongly on the precursor concentration, ac-voltage, and the presence of NaAc salt. In a typical process, no electrospinning was observed when ac-voltage was below 19 kV rms. Without NaAc, the PCL/AA precursor was ac-spinnable and formed fibers between 20 kV and 38 kV rms ac-voltage (upper limit for the used ac-electrospinning setup) with 10 wt % and 15 wt % PCL solutions. However, the 20 wt % PCL solution was not spinnable and only resulted in some electrospraying at 38 kV. However, when NaAc salt was present even at 0.1–0.2 wt % concentrations, all tested PCL/AA/NaAc precursor solutions became ac-spinnable in the range of PCL concentrations of 5–20 wt % and above 19 kV rms ac-voltage. High-speed videos indicated the development of multiple continuous jets generated from the surface of the precursor layer [Figure 1(a,b)]. Despite the periodic character of the electric field, none or very little interruption of the polymer jet generation was observed. Jets formed from PCL/AA/NaAc with lower PCL concentrations exhibited some bending instability near the electrode surface [Figure 1(b)], whereas this common effect of dc-electrospinning was not observed in the 20 wt % PCL solution [Figure 1(a)].[15] Regardless of the polymer concentration and ac-voltage, the generated polymers jets formed slowly moving (0.5 ± 0.2 m/s) flows of fibers and fibrous strands carried away by corona wind [Figure 1(c,d)].[14,16]

Fiber Morphology Characterization

Figure 2 shows how the changes in ac-voltage and PCL concentration, as well as NaAc salt addition, effect the PCL fiber formation. Without NaAc, PCL fibers electrospun from 15 wt % PCL/AA precursor at 20 kV rms ac-voltage display rather small, 120–240 nm, diameters and the presence of microbeads [Figure 2(a)]. Increasing voltage led to a higher rate of fiber production and formation of fibrous bundles and strands due to more interaction between the fibers in a denser fibrous flow with a low residual electric charge [Figure 2(b)]. PCL fibers produced from the 10 wt % PCL solution at 20 kV show noticeable variations in the fiber diameters (150–1000 nm) and a large fraction of beads and droplets [Figure 2(c)]. Increasing voltage in this case resulted in smaller fiber diameters and their more uniform size distribution, but did not reduce the droplet fraction [Figure 2(d)]. However, the addition of just 0.1 wt % NaAc salt to this precursor significantly reduced the droplet fraction and made the effect of voltage on the fiber diameter more pronounced [Figure 2(e,f)], although very little change in the viscosity and electrical conductivity of the precursor solution was registered.

Further investigation of the effect of NaAc salt addition showed that sustainable high-rate ac-electrospinning of PCL microfibers and nanofibers can be achieved at 2 wt % NaAc in PCL/AA/NaAc precursor solution. The electrical conductivity of this precursor solution was 12 ± 2 μS/cm and changed little with the polymer concentration. Figure 3 shows representative SEM
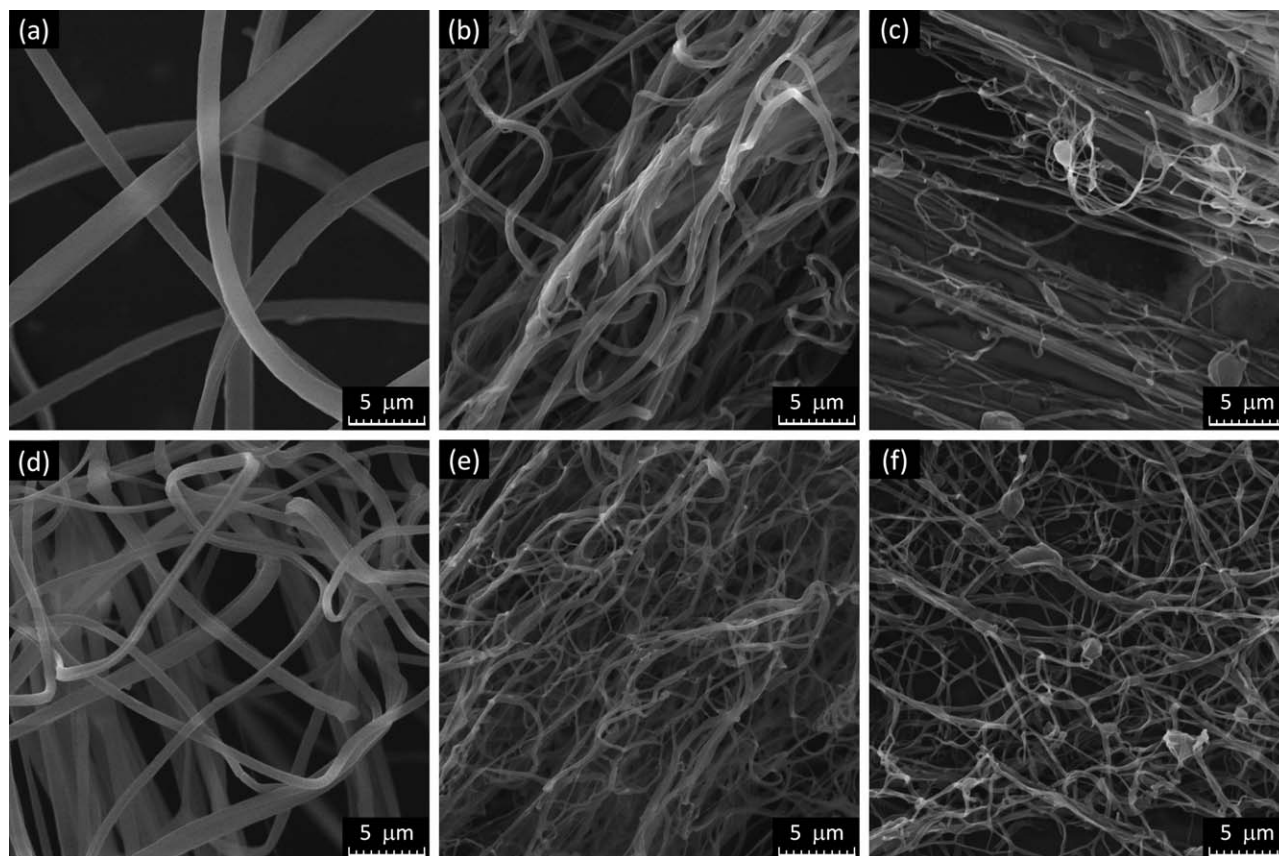
Figure 3. SEM images of PCL fibers AC-electrospun from PCL/AA/2 wt % NaAc solutions at 20 kV and 20 wt % (a), 15 wt % (b); 10 wt % (c) PCL concentration; and at 38 kV and 20 wt % (d), 15 wt % (e); and 10 wt % (f) PCL concentration.

images of PCL fibers prepared in the range of PCL concentrations 10–20 wt % at 20 kV and 38 kV rms ac-voltages. Still, a few droplets can be seen in PCL fibers prepared from 10 wt % PCL/AA/NaAc solution. The 5 wt % PCL solution with and without salt was not spinnable at all tested voltages.

PCL fibers prepared from 20 wt % PCL precursor solution had the diameters of 1530 ± 470 nm and 720 ± 190 nm when prepared at 20 kV and 38 kV, respectively, and revealed partially ribbon-like shapes [Figure 3(a,d)]. Occasional ribbon-like fiber shapes have been observed in other ac-electrospun salt-loaded polymer microfibers prepared from a relatively high-viscosity precursor.[17] Such fiber shapes can develop due to rapid solvent evaporation leading to the formation of a hollow polymer tube with solidified shell, which eventually collapse into a flat ribbon.[18,19] When compared with PCL fibers prepared without NaAc salt addition, fibers prepared from 15 wt % and 10 wt % PCL/AA/NaAc precursor solutions at 20 kV become more bundled and uniform, perhaps due to the increased fiber generation rate and interaction of fibers in the propagating flow [Figure 3(b,c) vs. Figure 2(a,c)]. The fiber diameters in this case were 490 ± 190 nm and 270 ± 70 nm, respectively. However, there was little difference in fiber diameter (230 ± 70 nm) and arrangement between the PCL fibers prepared at 38 kV from the 15 wt % PCL/AA precursor with and without NaAc addition [Figure 3(e) vs. Figure 2(b)]. Similar effect was noticed for fibers prepared at 38 kV from 10 wt % PCL/AA/NaAc precursor

solution with 2 and 0.1 wt % NaAc addition [Figure 3f vs. Figure 2(f)].

The observed trends can be associated with the dominating effect of ac-voltage and polymer concentration on the fiber's diameter and morphology, while the NaAc salt addition seems to determine the balance of forces in the polymer layer on the electrode surface and the efficiency of continuous polymer jets generation. It cannot also be excluded that better quality of PCL fibers prepared from 10 wt % PCL/AA/NaAc precursor solution can be reached by adding more salt as noted by Moghe et al.[9] All tested precursors with 15 ± 5 wt % PCL concentration demonstrated good spinnability with the up to 15 wt % NaAc addition, but large amounts of salt may not be practical. Aside the increasing electrical conductivity and viscosity of the precursor solution, adding more NaAc led only to some variations in the fiber assembling in the propagating flow and resulting fibrous sheets and other constructs. At room temperature, the precursors solidified at 15 wt % NaAc salt addition.
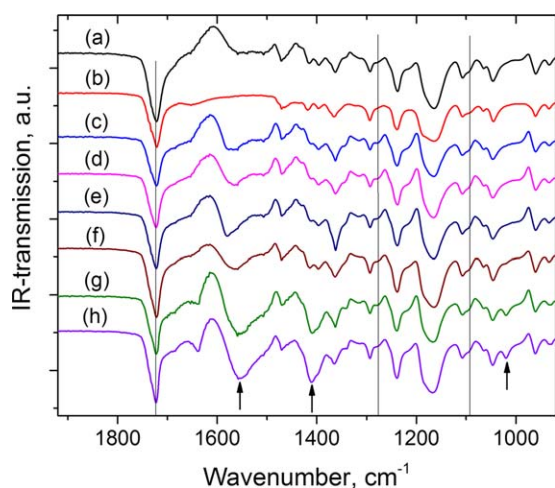
FTIR Spectroscopy
Analysis of FTIR spectra of the ac-electrospun randomly packed fibrous PCL samples shows no dependence of their structure and composition on the ac-voltage and PCL concentration. The absorption bands of NaAc become visible in FTIR spectra when the NaAc/PCL weight ratio reaches 0.2 (e.g., when 2 wt % NaAc is added to 10 wt % PCL solution in AA). This indicates that
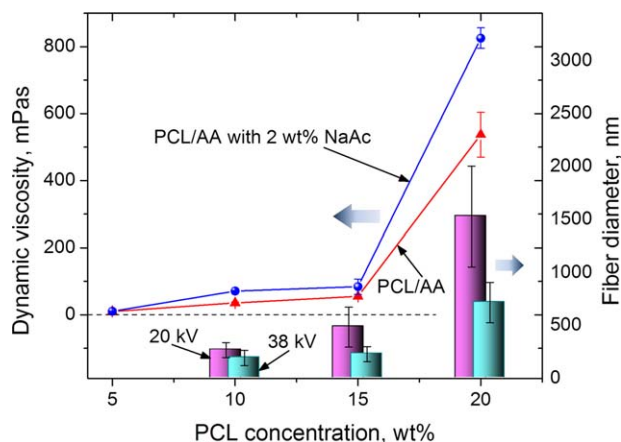
NaAc is present in as prepared PCL fibers. Figure 4 provides an example of FTIR spectra of PCL fibers prepared from 15 wt % PCL/AA precursor solution without and with addition of 2 and 11 wt % of NaAc. FTIR spectra of the source PCL polymer [Figure 4(a)] and the needle dc-electrospun PCL fibers [Figure 4(b)] are shown for the comparison. All ac-electrospun PCL samples demonstrate good crystallinity (characteristic position of C=O stretching band at 1722 cm^{-1}).[20,21] However, this band is a little more asymmetric than the one in the source PCL because of increased contribution from the amorphous phase usually characterized by C=O band position at 1737 cm^{-1}. The dc-electrospun PCL sample revealed the most asymmetry of the C=O band at 1722 cm^{-1} along with a slightly stronger absorption at 1090 cm^{-1} (characteristic band in amorphous PCL) and less visible band at 1285 cm^{-1} (crystalline PCL phase). These results indicate that the ac-electrospinning provides more favorable conditions for the crystallization of PCL fibers when compared to dc-electrospinning, perhaps due to a longer time available for the fiber drying in the propagating flow.

Effects of Salt Addition and Precursor Viscosity

The effects of PCL concentration and 2 wt % NaAc addition on the PCL/AA solution viscosity and the resulting fiber diameters for different ac-voltages are summarized in Figure 5. Viscosity data points correspond to the average viscosity of the samples measured over a time period of 120 s. Viscosity of PCL/AA solution increased from ~10 mPa s at 5 wt % PCL concentration to 35 mPa s and 55 mPa s at 10 and 15 wt % PCL, respectively, and sharply raised to 537 ± 67 mPa s at 20 wt % PCL concentration. Adding NaAc salt did not change the viscosity of 5 wt % PCL/AA solution, but for other PCL concentrations the viscosity increased by a factor 1.5–2.0, reaching 825 mPa s in 20 wt % PCL/AA/NaAc precursor solution. It was noted that viscosity of the latter solution dropped sharply with increasing shear rate, which indicated shear-thinning behavior of this non-

Figure 5. Dynamic viscosity of PCL/AA solution as the function of PCL concentration, without and with addition of 2 wt % sodium triacetate. The lines are shown to guide the eye. Bar graph shows the average diameters of PCL fibers ac-electrospun from the PCL/AA/NaAc precursor. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Newtonian fluid. For example, the viscosity of 20 wt % PCL/ AA/NaAc precursor solution dropped below 500 mPa s at 4300 s^{-1} shear rate, and when coupled with the effect of salt, this can result in the observed good spinnability and fiber formation. This phenomenon was not observed in 20 wt % PCL/ AA solution without salt addition, which was not spinnable, and for lower PCL concentrations.

The electrical mobility of polymer molecules is expected to reduce under the ac-field conditions and hinder the charge transfer,[22] which could explain a rather high-threshold ac-voltage required to initiate the process and lack of spinnability of 20 wt % PCL/AA precursor solution. Salt addition increases the number of ions and electric conductivity, which could stimulate the alignment of PCL molecules and charge transfer in the electrified fluid, thus improving the conditions for electrospinning. Additionally, in the case of 20 wt % PCL/AA/NaAc precursor solution, high shear rate and, consequently, gradual reduction in the magnitude of viscosity can be beneficial for achieving the polymer jet initiation and stable fiber generation process. Furthermore, it has been observed that there is a polymer concentration-dependent time delay between the application of ac-voltage and the initiation of the electrospinning process. This time delay can be associated with the establishing of an optimal state of the polymer solution in the ac-field. For example, high-speed video analysis revealed that this time delay was 20 ms in 5 wt % PCL/AA solution with 2 wt % NaAc, but it reached 120 ms in 20 wt % PCL/AA solution with 2 wt % NaAc, and then stable fiber generation was observed through the entire process. It should be noted that the time delay can vary for the different shapes and dimensions of the jet generating electrode in the experimental setup.

CONCLUSIONS

The results of this study demonstrated that PCL polymer fibers with diameters in the range of 150–2000 nm can be fabricated at the production rates up to 14 g/h from low toxicity glacial

Figure 4. FTIR spectra of (a) source PCL polymer, (b) dc-electrospun 20 wt % PCL/AA at 15 kV, and ac-electrospun 15 wt % PCL/AA at (c) 20 kV, (d) 38 kV, (e) 2 wt % NaAc and 20 kV, (f) 2 wt % NaAc and 38 kV, (g) 11 wt % NaAc and 20 kV, (h) 11 wt % NaAc and 38 kV. Arrows indicate the absorption bands of NaAC. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

acetic-acid-based precursor solutions using an uncommon needleless ac-electrospinning technique. High productivity and simplicity of the ac-electrospinning combined with the absence of need in a grounded collector make this process a viable alternative to other polymer nanofiber fabrication methods. A new additive, sodium triacetate (NaAc), was tested and found to play a crucial role in improving the spinnability of PCL/AA solutions and the fiber morphology. PCL nanofibers (150–300 nm) were consistently ac-electrospun from as low as 10 wt % PCL/AA precursor solutions with up to 2 wt % NaAc (Newtonian fluid), and microfibers were prepared from 20 wt % PCL/AA solutions with 2 wt % NaAc (non-Newtonian fluid). The presence of salt can attenuate the effects of the reduction of the electrical conductivity and charge mobility in the polymer solution under ac-field and achieve better control of fiber morphology and dimensions in a broader range of polymer concentrations and process parameters. Furthermore, AA can dissolve many drugs and is miscible with polar solvents, which may allow easier blending of PCL with medications as well as with synthetic and natural hydrophilic polymers, and therefore aid in the technological advancement of commercial electrospinning of PCL-based multipurpose nanofibers and nanofibrous constructs.

ACKNOWLEDGMENTS

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