

Nano and Submicrometric Fibers of Poly(D,L-Lactide) Obtained by Solution Blow Spinning: Process and Solution Variables

Juliano E. Oliveira,^{1,2} Eduardo A. Moraes,^{2,3} Rodrigo G. F. Costa,^{2,3} André S. Afonso,^{2,3} Luiz H. C. Mattoso,² William J. Orts,⁴ Eliton S. Medeiros⁵

¹Departamento de Engenharia de Materiais (DEMA), Universidade Federal de São Carlos (UFSCAR), Rodovia Washington Luis, Monjolinho, 13.565-905 São Carlos, SP, Brazil

²Laboratório Nacional de Nanotecnologia para o Agronegócio (LNNA), Embrapa Instrumentação Agropecuária (CNPDIA), Rua XV de Novembro, 1452 Centro, 13.560 970 São Carlos, SP, Brazil

³Departamento de Química (DQ), Universidade Federal de São Carlos (UFSCAR), Rodovia Washington Luis, Monjolinho, 13.565-905 São Carlos, SP, Brazil

⁴United States Department of Agriculture (USDA), Western Regional Research Center (WRRC), Bioproduct Chemistry and Engineering (BCÉ), Albany, California 94710

⁵Departamento de Engenharia de Materiais (DEMAT), Cidade Universitária, Universidade Federal da Paraíba (UFPB), 58.051-900 João Pessoa, PB, Brazil

Received 4 July 2010; accepted 24 February 2011

DOI 10.1002/app.34410

Published online 12 July 2011 in Wiley Online Library (wileyonlinelibrary.com).

ABSTRACT: Nano and submicrometric fibers of poly(D,L-lactide) (PDLLA or PLA) were spun from solutions using a solution blow spinning (SBS) apparatus. Fiber morphology and diameter were investigated by scanning electron microscopy as a function of polymer concentration, feed rate, and air pressure. A more systematic understanding of the SBS process parameters was obtained, and a quantitative relationship between these parameters and average fiber diameter was established by design of experiments and response surface methodology. It was observed that polymer concentration played an important role in fiber diameter, which

ranges from 70 to 2000 nm, and its distribution. Lower polymer concentration tended to increase the formation of bead-on-string structures, whereas smooth fibers were formed at higher concentrations. Fiber diameter tended to increase with polymer concentration and decrease with feed rate. Based on these results, optimal conditions could be obtained for solution-blow spun fibers. © 2011 Wiley Periodicals, Inc. *J Appl Polym Sci* 122: 3396–3405, 2011

Key words: nanofiber; imaging; nanotechnology; biodegradable; biofibers

INTRODUCTION

Recently, a novel technique named solution blow spinning (SBS) was introduced.¹ This technique uses conceptual elements of electrospinning, solution, and melt spinning to produce micro and nanofibers of polymers with diameters ranging from a few tenths of nanometers to several micrometers. Therefore, offering several advantages over electrospinning such as low cost and higher rate of fiber production.^{1,2} Moreover, fibers produced by SBS are equivalent to electrospun ones and are at least one or two orders of magnitude smaller in diameter than those

produced by conventional fiber production methods like solution and melt spinning.^{3–9}

SBS depends on a certain arrangement of concentric nozzles in which the polymer solution is extruded through the inner nozzle, while a high pressure gas (air, nitrogen, argon, etc.) is released from the outer nozzle. A polymer solution is forced through the inner nozzle at a constant feed rate, resulting in the formation of a drop at the tip of the inner nozzle, which is stretched by the high pressure stream of compressed gas flowing through the outer nozzle. The compressed air exiting the nozzle causes the surface of the drop to shape into a cone similar to Taylor's cone in electrospinning. When a critical air pressure is exceeded, a jet erupts from the apex of this cone and is accelerated toward the collection target. As this jet travels through the surrounding environment, the solvent evaporates leaving behind polymer fibers, which can be collected on virtually any target, from human skin to nonmetallic collectors such as woven fabrics, and even

Correspondence to: E. S. Medeiros (eliton@ct.ufpb.br or eliton_s@yahoo.com).

Contract grant sponsors: MCT/FINEP, CNPQ, CAPES, and EMBRAPA/LABEX.

human skin.² This highlights an advantage over traditional electrospinning, which depends on a voltage differential between the polymer output and the target.

SBS has been successfully applied to produce micro and nanofibers of several polymers, including poly(lactic acid) (PLA) that belongs to the family of aliphatic polyesters commonly made from α -hydroxy acids, including polyglycolic acid or polymandelic acid, which are known to be biodegradable and compostable.^{10–16} PLA is a thermoplastic, high-strength, high-modulus polymer made from renewable resources with many applications in packaging and biocompatible/bioabsorbable medical devices.^{10,13,14} In addition to this, it has been successfully studied by several researchers throughout the world to produce nanofibers by electrospinning.^{17–23} These nanofibers, obtained by electrospinning or SBS from PLA, have numerous potential applications, such as in biomimetic scaffolds for tissue engineering,^{24–27} drug carriers,^{28–33} sensors,³⁴ biosensors,³⁵ and nanocomposites.^{36–41} However, solution blow spun nanofibers does not use high voltage that can be an advantage in the simultaneous spinning of living cells and other biomaterials, such as proteins, vitamins, and hormones.

In the present work, we report the results on SBS of PLA though a systematic investigation of the effect of variation of the process parameters that ultimately govern fiber formation including feed rate, polymer concentration, and air pressure.

EXPERIMENTAL

Preparation and characterization of the solutions

Poly(D,L-lactide) PDLLA ($M_w = 75,000$ g/mol) pellets were obtained from Biomater (São Carlos, Brazil). Chloroform and acetone were purchased from Synth (São Paulo, Brazil) and used as solvents to prepare solutions with different PDLLA concentrations, whereby weighed amounts of PDLLA and chloroform : acetone 3 : 1 (v/v) were mixed and vigorously stirred for several hours until complete dilution. A factorial experiment was designed to investigate and identify the significance of three processing parameters—feed rate (X1), air pressure (X2), and polymer concentration (X3)—on average fiber diameter as shown in Table I. The experiment was performed for at least three levels of each factor to fit a quadratic model that resulted in 27 possible combinations of factor setting.

TABLE I
Experimental Design (Coded and Uncoded Values) for the Solution Blow Pinning of PDLLA Fibers

Coded and uncoded values						
Experiment	X1	X2	X3	Feed rate ($\mu\text{L}/\text{min}$)	Air pressure (MPa)	Polymer concentration (wt %)
1	-1	-1	-1	20	0.2	4
2	0	-1	-1	80	0.2	4
3	1	-1	-1	120	0.2	4
4	-1	0	-1	20	0.3	4
5	0	0	-1	80	0.3	4
6	1	0	-1	120	0.3	4
7	-1	1	-1	20	0.4	4
8	0	1	-1	80	0.4	4
9	1	1	-1	120	0.4	4
10	-1	-1	0	20	0.2	6
11	0	-1	0	80	0.2	6
12	1	-1	0	120	0.2	6
13	-1	0	0	20	0.3	6
14	0	0	0	80	0.3	6
15	1	0	0	120	0.3	6
16	-1	1	0	20	0.4	6
17	0	1	0	80	0.4	6
18	1	1	0	120	0.4	6
19	-1	-1	1	20	0.2	8
20	0	-1	1	80	0.2	8
21	1	-1	1	120	0.2	8
22	-1	0	1	20	0.3	8
23	0	0	1	80	0.3	8
24	1	0	1	120	0.3	8
25	-1	1	1	20	0.4	8
26	0	1	1	80	0.4	8
27	1	1	1	120	0.4	8

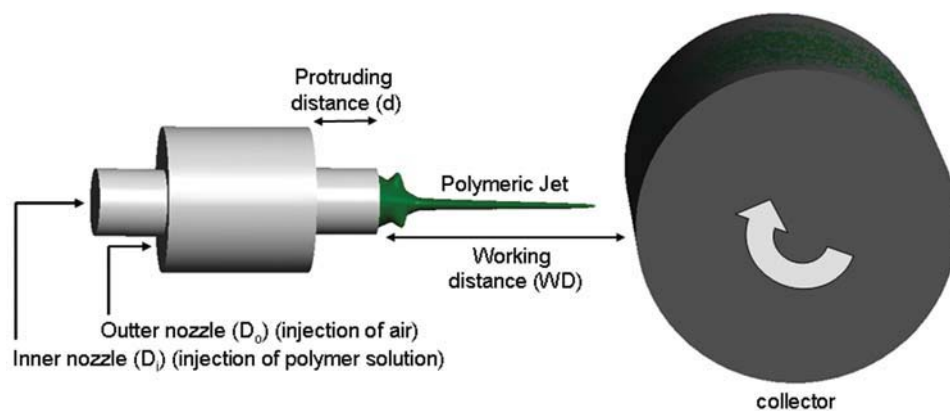


Figure 1 Schematic representation of the solution blow spinning apparatus used fiber preparation. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Solution properties such as surface tension (γ) and shear viscosity (η) were measured at ambient temperature using a Kibron Microtrough X pressure sensor and an Anton Paar Physica MCR rheometer, respectively.

SBS of the PDLLA solutions

The solution blow spinning (SBS) system consisted of a source of compressed air, equipped with a pressure regulator, a 10-mL glass syringe, a syringe pump (KD Scientific, USA) to control the injection rate (β) of the polymer solutions, a spinning apparatus that consisted of a setup with concentric nozzles (see Fig. 1), and a collector with a controllable rotation speed.² A series of experiments were performed by varying processing parameters using polymer solutions of poly(D,L-lactide) (PDLLA) in a chloroform : acetone mixture.

Processing variables were tested to determine their effect on fiber diameter and morphology. Process conditions, that is, feed rate (β), air pressure (p), and polymer concentration were investigated using a fixed working distance of 12 cm, a length of the protruding inner nozzle of 2 mm, and ratio diameter between the concentric nozzles of 0.5 for all experiments (Table I).

Morphological studies

Morphology of PDLLA fibers was observed by a Zeiss DSM960 scanning electron microscope (SEM), after being gold-coated with a sputter coater. Diameters of electrospun fibers were measured with an image analyzer (Image J, National Institutes of Health, USA). For each experiment, average fiber diameter and distribution were determined from about 100 random measurements of fiber diameters for each SEM micrograph representative of fiber morphology.

Statistical treatment

A Box–Behnken design of experiments was realized using three factors (air pressure, feed rate, and concentration). For application of response surface methodology to optimize the process, sequential experiments were carried out. These experiments were planned according to the modified central composite design. This type of design defines the minimum number of experimental combinations in the experimental domain to be explored to obtain the maximum information for adjusting the proposed model. For a quadratic model, experiments must be performed for at least three levels of each factor. These levels are best chosen and equally spaced. The three factors and three levels resulted in 27 possible combinations of factor settings. The coded and uncoded variables are listed in Table I. Pareto Chart was also chosen due to its capability to verify interactions among the various factors and its influence on the average fiber diameter. The software Statistica 7.0 (StatSoft, USA) was used to carry out experimental designs and data analyses.

RESULTS AND DISCUSSION

Solution characterization

In SBS, similar to electrospinning, solution viscosity plays an important role in determining the range of concentrations from which continuous fibers can be obtained. Above a critical concentration, continuous fibrous structure is obtained, and its morphology is affected by solution concentration. Formation of continuous fiber can be attributed to extensive chain entanglements in polymer solution.⁴² However, as reported by Regev et al.,⁴³ if the extensional viscosity is not sufficiently high throughout the length of the spun jet, the

viscoelastic jet will generally split into single droplets. Moreover, Yu et al.⁴⁴ showed by extensional rheology measurements that the elasticity of the polymeric solution, or its extensional viscosity, is not necessarily related to polymer entanglements in solution. According to them, uniform fibers can be obtained by any sufficiently strong elastic response of the solution, even for polymer solutions in dilute regime.

Figure 2 shows the change in solution viscosity with increasing concentration of PDLLA in chloroform : acetone 3 : 1 (v/v). PDLLA viscosity increased rapidly at $\sim 7\%$ (w/v), indicating that an extensive chain entanglement occurred around this concentration. Another change in the viscosity at $\sim 2.5\%$ (w/v) indicated the onset of the dilute regime for this polymer solution. Surface tension increased from 26 (solvent) to 34 mN m⁻¹ (polymer solutions). As in the electrospinning process,⁴⁵⁻⁴⁷ the lower surface tension and higher evaporation rate of the solvent diminish the formation of beads. The SBS process requires a high evaporation rate of the solvent, and consequently a low surface tension in order for the fibers to reach the target already in the dry state. Otherwise, a net of interconnected fibers is formed, and, in the worst case, a continuous film can be produced. Literature reported⁴⁶⁻⁴⁹ that surface tension has the effect of decreasing the surface area per unit mass of a fluid. In the case of SBS, due to Rayleigh instability, there is a greater tendency for solvent molecules to segregate when there is a high concentration of free solvent molecules. A higher viscosity or lower surface tension means a decrease

in the segregation of solvent molecules and thus a better interaction between solvent molecules and polymer chains. Therefore, when the solution is stretched under the influence of drag forces, due to the air exiting, the spinning nozzle, solvent molecules will not tend to agglomerate with entangled polymer chains, reducing the tendency of bead formation. From Figures 3-5, it is observed that the formation of beaded fibers occurs when the dilute solution regime is approached.

Effect of feed rate on fiber morphology

An increase in feed rate (Fig. 3) has been found to increase fiber diameter and its distribution, but the effect may become parabolic at lower concentrations. The optimal feed rate can be expected to narrow fiber size distribution and reduce fiber diameter, because when feed rate is equivalent to the rate at which the jet carries the solution away, the conic shape at the nozzle exit remains stable, unlike in the case of nozzle blocking (high feed rate) or jet instability (low feed rate). High feed rates may cause nozzle obstruction, in which a pendant droplet accumulating at the tip begins to solidify, sealing the nozzle by solidified polymer residue. Jet instability occurs when the solution is dragged to the collector faster than the feed rate [Fig. 3(a)]. Higher feed rates would naturally increase fiber productivity at least in cases when nozzle blocking would not occur. Moreover, the optimal value of this parameter is strongly affected by the viscosity of the solution, which in turn is dependent on polymer molecular weight and concentration.

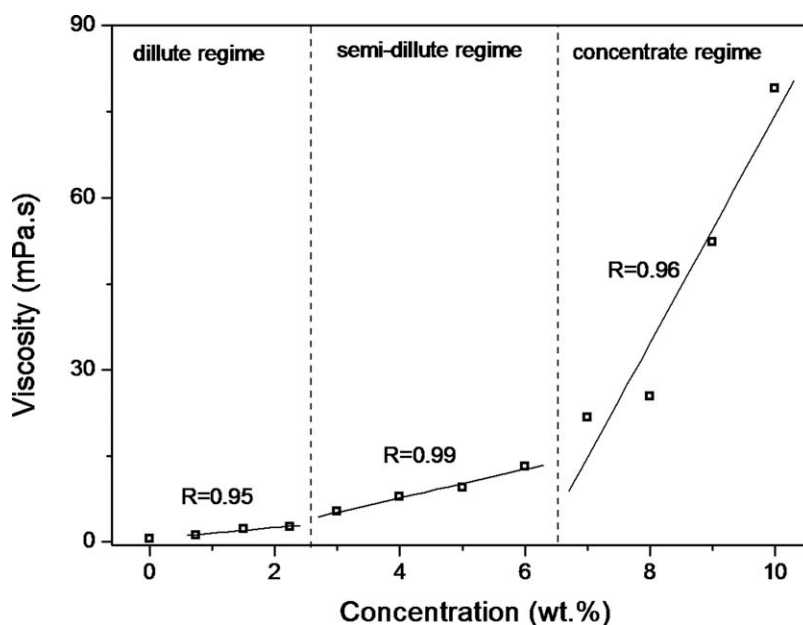


Figure 2 Dependence of specific viscosity, measured at 10^0 s^{-1} shear rate, on the concentration of the polymer solutions.

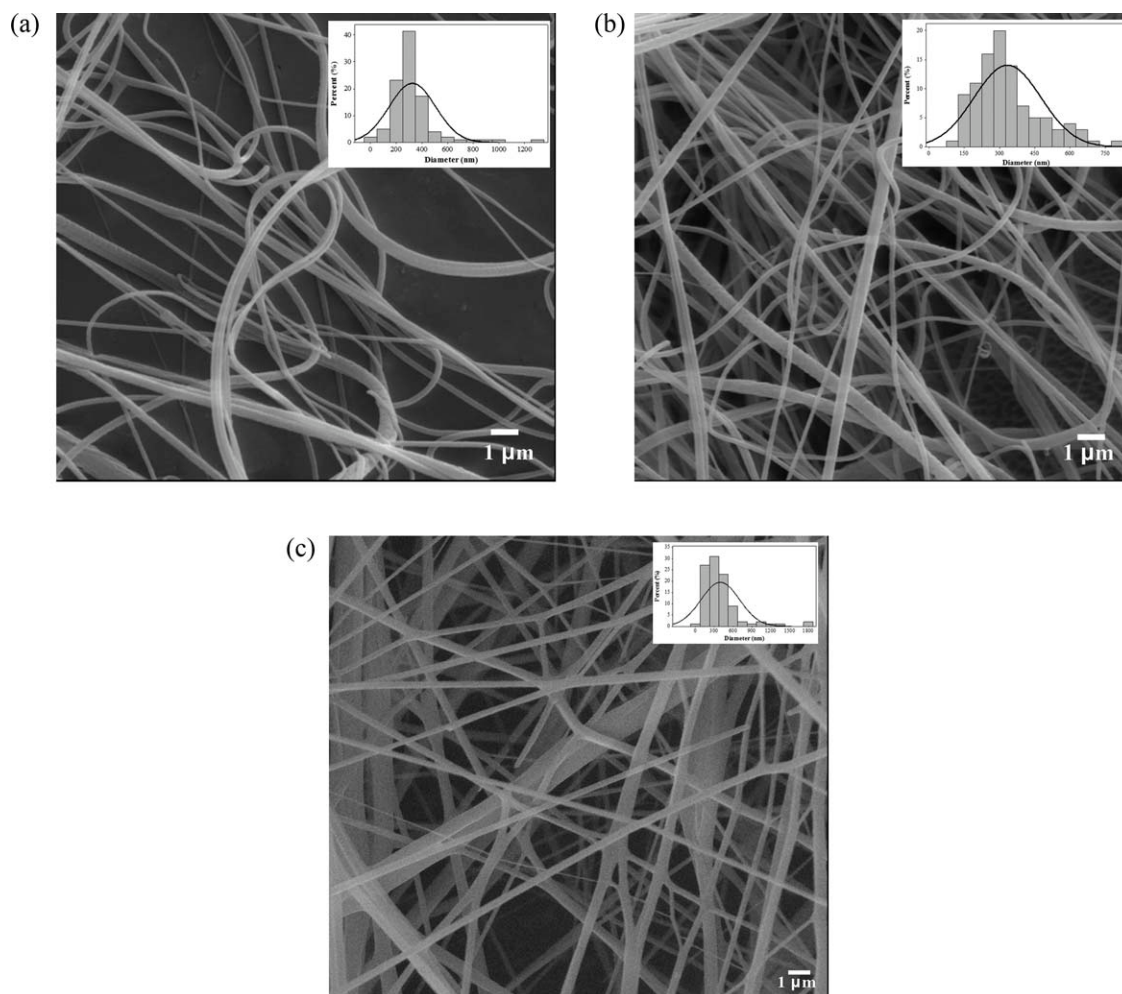


Figure 3 SEM of structures obtained by SBS of PDLLA solutions at different feed rates: (a) 20; (b) 80; and (c) 120 $\mu\text{L}/\text{min}$. Inset: fiber diameter distribution.

Effect of air pressure on fiber morphology

A paraboliclike dependence between fiber diameter and pressure, at lower air pressures, and linear dependence at high air pressures was found. This occurs because the air flow surrounding the surface of the jet exiting the nozzle does not allow an accumulation of solvent molecules immediately above the jet surface, therefore promoting a high evaporation rate. This occurs because the boundary layer at the evaporation surface decreases with flow velocity, reducing solvent diffusion in the stagnant layer. Then, at high air pressures, solvent evaporation rate is increased. As a consequence, fiber diameter also decreased. Moreover, as discussed later in the Pareto chart (Fig. 6), the quadratic and linear interactions between air pressure, feed rate, and polymer concentration play important roles in fiber formation by SBS. In this study, the quadratic interaction between the feed rate and air pressure was more important than the effect of the isolated variables, because this combined effect is responsible for jet formation caus-

ing drag and lift forces that stretch the jet to form fibers. The reduction in pressure (Fig. 4) increased the fiber diameter and its distribution and also affected negatively the spinning process, that is, nozzle blocking seemed to be slightly higher in trials using reduced air pressure.

Effect of polymer concentration

In the current experiments, polymer concentration was the most important parameter determining fiber morphology. The effect of concentration and thus viscosity can be summarized as follows: (1) at low viscosities small fibers with beads are formed [Fig. 5(a)] and (2) with increasing viscosity, fibers become thicker while the beads become fewer and merge into the thickening of fibers, leading finally to a smooth fiber morphology [Fig. 5(b)]. Higher viscosity might favor the occurrence of new morphologies like branched or bundled fibers [Fig. 5(c)]. Moreover, the dependency between viscosity

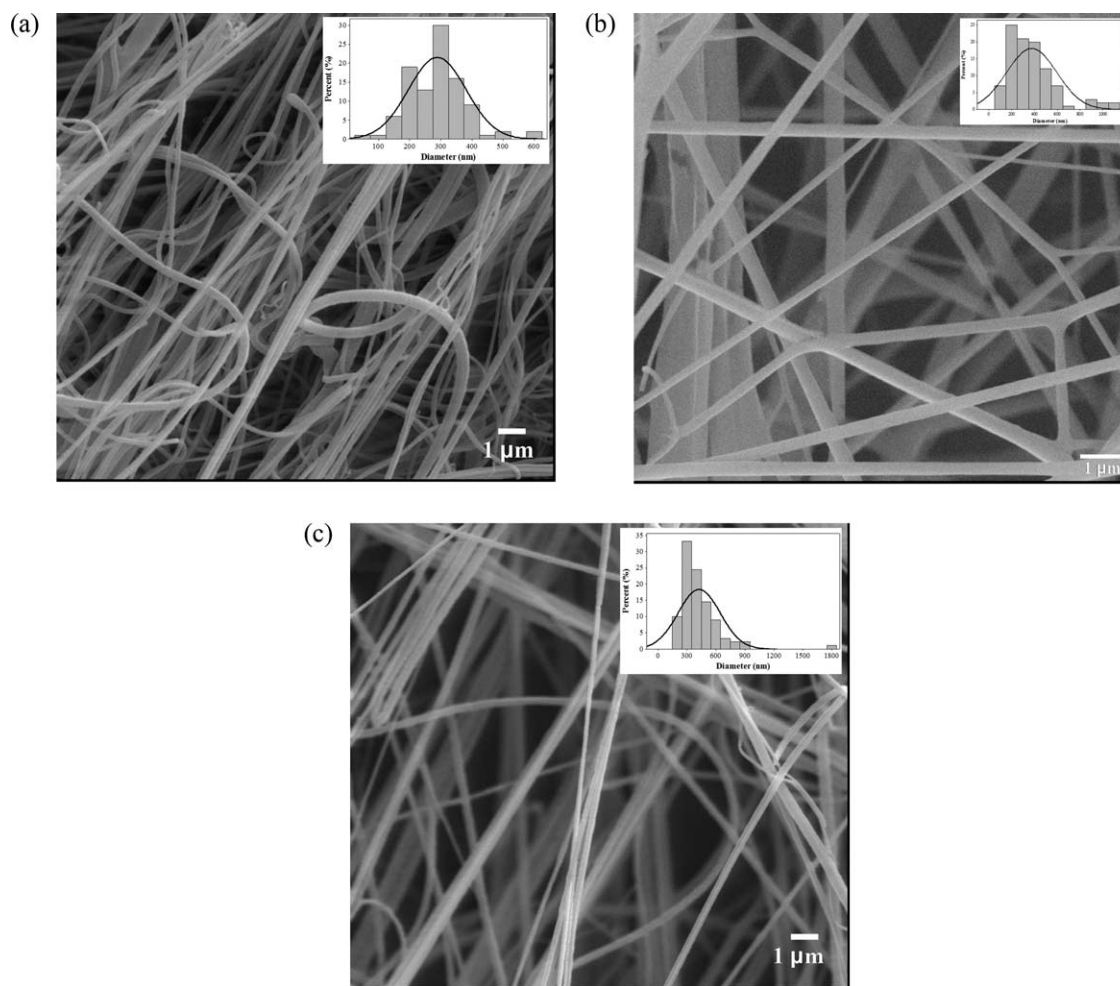


Figure 4 SEM of structures obtained by SBS of PDLLA solutions at different air pressures: (a) 0.4 MPa; (b) 0.3 MPa, and (c) 0.2 MPa. Inset: fiber diameter distribution.

(or the concentration) and the fiber diameter was noted to increase, that is, smaller diameters obtained at lower viscosities are related to the higher mobility of polymer chains in the jet during the spinning process. In the case of the PDLLA fibers studied here, generally low (4 wt %) or high (8 wt %) concentrations are considered advantageous to obtain narrower fiber diameter distributions. A parabolic dependency curve between viscosity and fiber density was also obtained. Moderate viscosity was associated with the highest density, which is probably at least partly due to homogeneous mass flow observed.

Viscoelasticity of fluid jets is a key element in several process such as melt blow spinning⁵⁰ and electrospinning.^{44,51,52} In SBS, the fluid jet travels in straight paths due to drag air forces, and, in this regime, it undergoes almost pure extensional deformation that can trigger the elastic response of the fluid and causes a increase in the elastic stresses in the polymeric jet. Therefore, this elastic response can exceed the effects of Rayleigh instability, and the

increase in elasticity of solutions allows the formation of fibers with more uniform diameters.

Optimization studies for process parameters in SBS

The standardized effects of the independent variables and their interactions on the dependent variable were investigated by preparing a Pareto chart (Fig. 6).

The length of each bar in the chart indicates the standardized effect of that factor quadratic (Q) or linear (L) and the quadratic pressure interactions on the response.⁵³ The fact that the bar for polymer concentration quadratic and linear— $X3(L)$ and $X3(Q)$ and feed rate quadratic [$X1(Q)$ —are outside the reference line in Figure 6 indicated that these terms contributed more effectively to the prediction of average diameter fibers. The negative coefficients for the model components— $X1(Q)X2(Q)$, $X2(Q)X3(Q)$, $X2(Q)X3(L)$, $X2(L)$, $X1(L)X2(Q)$, and $X2(Q)$ —indicated a decreasing in the average diameter of the

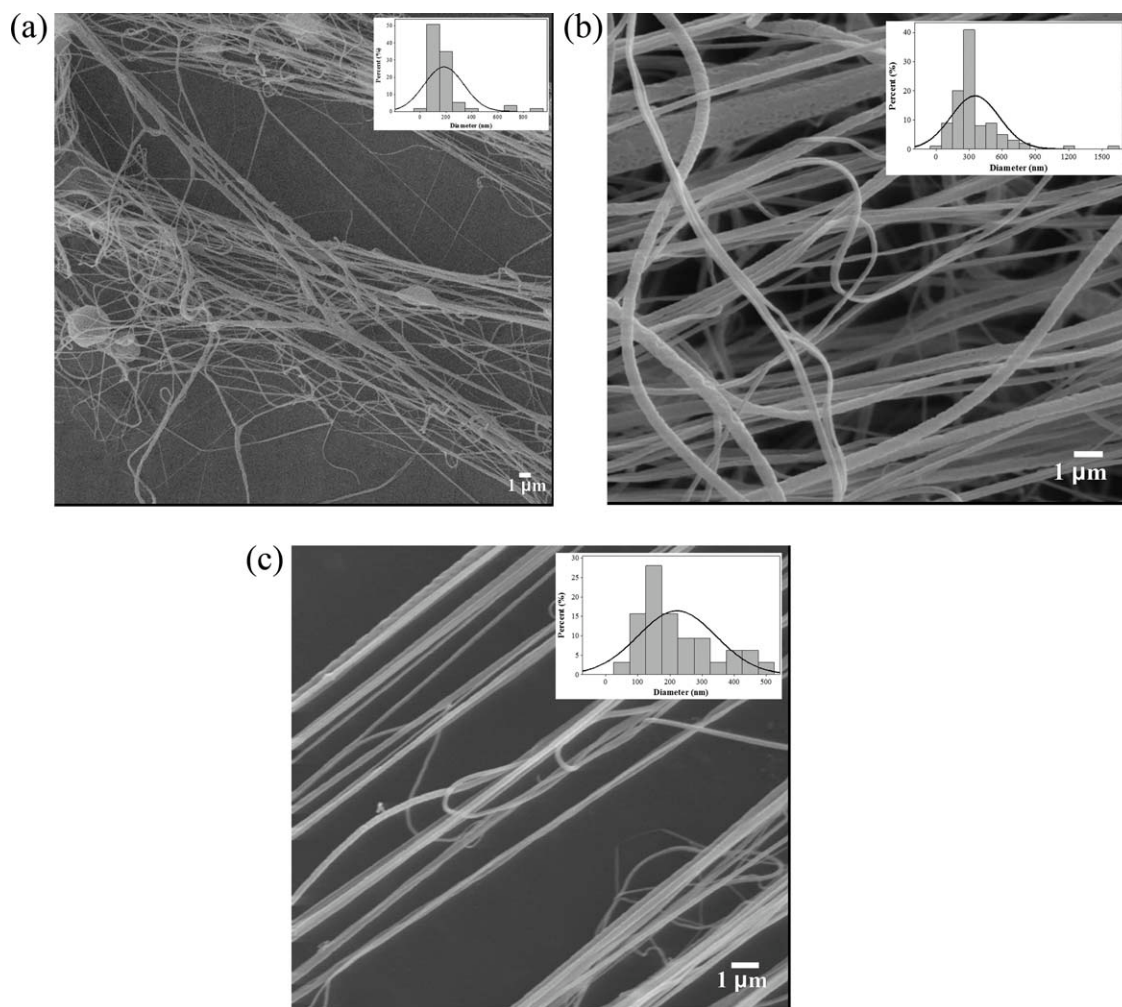


Figure 5 SEM of structures obtained by SBS of PDLLA solutions at different concentrations: (a) 4, (b) 6, and (c) 8% by weight. Inset: fiber diameter distribution.

fibers, while positive coefficients for the model components— $X3(L)$, $X3(Q)$, $X1(Q)$, and $X1(L)$ —showed an increasing in the average diameter of fibers.

Physically, this occurs because an increase in polymer concentration increases viscosity and chain entanglements and, therefore, makes the solution stretching to form fibers (spinning) more difficult. This behavior was found to be similar to electrospinning of several polymers.^{42–46} The increase in air pressure, that is, the physical force that acts directly on the stretching of the solution drops, as expected, resulted in a tendency in reducing fiber diameter. A similar behavior was observed by Medeiros et al.¹ in a first work with SBS of PMMA fibers.

Figure 7 shows the response surfaces of average fiber diameter, in nanometer, as a function of polymer concentration and feed rate at a constant air pressure. In addition, comparison of the three response surfaces shows the effect of air pressure.

The response surfaces indicate that the resulting fiber diameter is very responsive to the changes in

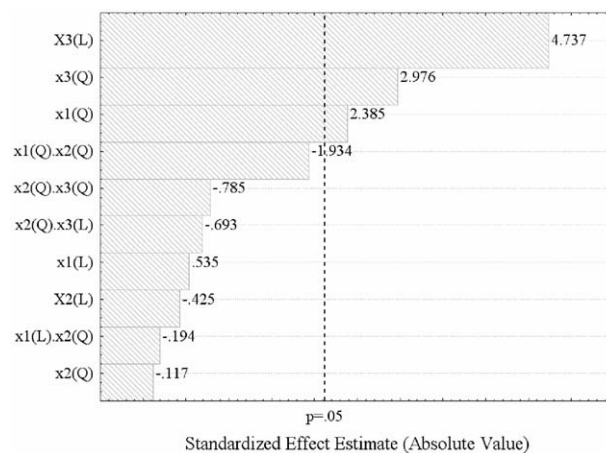


Figure 6 Pareto chart showing the standardized linear (L) and quadratic (Q) effects of independent variables ($X1$ is feed rate, $X2$ is air pressure, and $X3$ is polymer concentration) and their interaction on the fiber diameter.

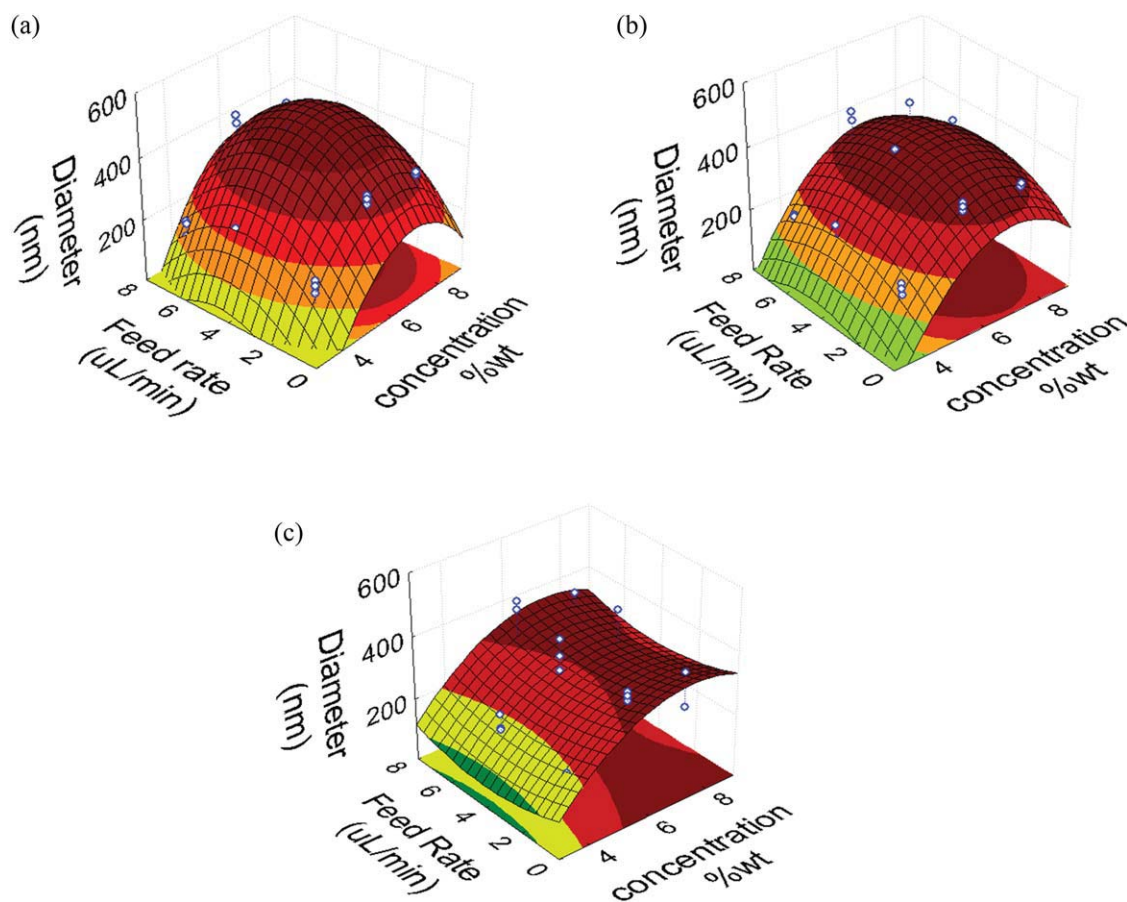


Figure 7 Response surfaces of average fiber diameter as a function of polymer concentration and feed rate at (a) 0.2, (b) 0.3, and (c) 0.4 MPa. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

concentration as expected and previously mentioned in studies with electrospinning.^{17,54–56} It is also responsive to changes in feed rate, but its effect depends on solution concentration and air pressure. For instance, at an air pressure of 0.2 MPa [Fig. 7(a)], fiber diameter is more sensitive to the changes in feed rate. Moreover, at 0.3 and 0.4 MPa air pressure [Fig. 7(b,c)], response surfaces suggest that feed rate has very little and almost no effect on fiber diameter formation, respectively. Actually, pressure effect is relative to other physical constraints involved; at low pressures, there is not enough stretching and thus thicker fibers are produced. However, when the pressure is too high, other effects such as jet instability caused by turbulence at the nozzle exit takes place; as a consequence, fiber diameters range from very low to very high, therefore broadening the fiber diameter distribution curve.

The average diameters of PDLLA fibers as a function of the experimental variables (feed rate, air pressure, and polymer concentration) are listed in Table II. It is observed that fibers with narrower diameter distribution can be obtained at intermediate concentrations and higher air pressures. That is,

process conditions can be chosen according to the statistical model described in this study to obtain tailor-made structures. But it should be noted that the model might be valid only to the experimental conditions (i.e., polymer-solvent system) listed in this study, and it might have to be regenerated for any other conditions, but we are currently testing other polymer/solvent systems to investigate whether or not the same behavior can be extended to these systems.

CONCLUSIONS

In this work, the effects of process variable and solution parameters on the morphology of individual solution blow spun PDLLA nanofibers were investigated. We have found that the morphology of the nano and submicrometric fibers produced is influenced strongly by parameters such as feed rate of the polymer solution, air pressure, and solution properties such as concentration and viscosity. Analysis of the abovementioned parameters suggests that fibers ranging from 70 to 1800 nm in diameter can be obtained over the process conditions in this study. Solution concentration plays one of the most

TABLE II
Average Diameter of PDLA Fibers

Feed rate ($\mu\text{L min}^{-1}$)	Air pressure (MPa)	Polymer concentration (wt %)	Average diameter (nm)
20	0.2	4	184
80	0.2	4	183
120	0.2	4	125
20	0.2	6	354
80	0.2	6	388
120	0.2	6	426
20	0.2	8	222
80	0.2	8	609
120	0.2	8	288
20	0.3	4	145
80	0.3	4	180
120	0.3	4	172
20	0.3	6	325
80	0.3	6	334
120	0.3	6	398
20	0.3	8	322
80	0.3	8	405
120	0.3	8	306
20	0.4	4	167
80	0.4	4	228
120	0.4	4	164
20	0.4	6	340
80	0.4	6	288
120	0.4	6	289
20	0.4	8	332
80	0.4	8	274
120	0.4	8	378

important roles in fibers morphology. Lower concentration tends to facilitate the formation of beaded structures, while fiber diameter tends to increase with increasing polymer concentration and to decrease with air pressure. Lower concentration gives lower standard deviation of fiber diameter regardless of air pressure or feed rate over the range of process conditions. Therefore, to obtain thinner fibers with diameter in the nanoscale, it is better to spin at lower concentrations. But this will bring spindle-like beaded structure. Fibers with uniform diameter and narrower distribution can be obtained at intermediate concentrations and higher air pressures. That is, process conditions can be chosen according to the model in this study to obtain tailor-made structures of PDLA. Moreover, we show that to accurately predict fiber diameter, a combination of variables may have to be taken into account instead of each variable separately.

References

- Medeiros, E. S.; Glenn, G. M.; Klamczynski, A. P.; Orts, W. J.; Mattoso, L. H. C., Solution Blow Spinning, US Patent, 0062.08, 2010.
- Medeiros, E. S.; Glenn, G. M.; Klamczynski, A. P.; Orts, W. J.; Mattoso, L. H. C. *J Appl Polym Sci* 2009, 113, 2322.
- Eling, B.; Gogolewski, S.; Pennings, A. J. *Polymer* 1982, 23, 1587.
- Fisher, R. J.; Denn, M. M. *AICHE J* 1976, 22, 236.
- Jin, H. J.; Kaplan, D. L. *Nature* 2003, 424, 1057.
- Kase, S.; Matsuo, T. *J Polym Sci Part A: Gen Pap* 1965, 3, 2541.
- Katayama, K.; Amano, T.; Nakamura, K. *Kolloid-Zeitschrift Zeitschrift Polym* 1968, 226, 125.
- Smith, P.; Lemstra, P. J. *J Mater Sci* 1980, 15, 505.
- Yoshino, K.; Nakajima, S.; Fujii, M.; Sugimoto, R. *Polym Commun* 1987, 28, 309.
- Auras, R.; Harte, B.; Selke, S. *Macromol Biosci* 2004, 4, 835.
- Cooper-White, J. J.; Mackay, M. E. *J Polym Sci Part B: Polym Phys* 1999, 37, 1803.
- Desantis, P.; Kovacs, A. J. *Biopolymers* 1968, 6, 299.
- Drumright, R. E.; Gruber, P. R.; Henton, D. E. *Adv Mater* 2000, 12, 1841.
- Garlotta, D. *J Polym Environ* 2001, 9, 63.
- Mikos, A. G.; Thorsen, A. J.; Czerwonka, L. A.; Bao, Y.; Langer, R.; Winslow, D. N.; Vacanti, J. P. *Polymer* 1994, 35, 1068.
- Tsuji, H.; Ikada, Y. *Polymer* 1995, 36, 2709.
- Gu, S. Y.; Ren, J. *Macromol Mater Eng* 2005, 290, 1097.
- Mo, X. M.; Xu, C. Y.; Kotaki, M.; Ramakrishna, S. *Biomaterials* 2004, 25, 1883.
- Ramdhanie, L. I.; Aubuchon, S. R.; Boland, E. D.; Knapp, D. C.; Barnes, C. P.; Simpson, D. G.; Wnek, G. E.; Bowlin, G. L. *Polym J* 2006, 38, 1137.
- Yang, F.; Murugan, R.; Wang, S.; Ramakrishna, S. *Biomaterials* 2005, 26, 2603.
- You, Y.; Lee, S. J.; Min, B. M.; Park, W. H. *J Appl Polym Sci* 2006, 99, 1214.
- Zhou, H. J.; Green, T. B.; Joo, Y. L. *Polymer* 2006, 47, 7497.
- Zong, X. H.; Kim, K.; Fang, D. F.; Ran, S. F.; Hsiao, B. S.; Chu, B. *Polymer* 2002, 43, 4403.
- Ko, E. K.; Jeong, S. I.; Rim, N. G.; Lee, Y. M.; Shin, H.; Lee, B. K. *Tissue Eng A* 2008, 14, 2105.
- Xin, X. J.; Hussain, M.; Mao, J. J. *Biomaterials* 2007, 28, 316.
- Boland, E. D.; Pawlowski, K. J.; Barnes, C. P.; Simpson, D. G.; Wnek, G. E.; Bowlin, G. L. *Polym Nanofibers* 2006, 918, 188.
- Luu, Y. K.; Kim, K.; Hsiao, B. S.; Chu, B.; Hadjiargyrou, M. *J Controlled Release* 2003, 89, 341.
- Xu, X. L.; Chen, X. S.; Wang, Z. F.; Jing, X. B. *Eur J Pharm Biopharm* 2009, 72, 18.
- Peng, H. S.; Zhou, S. B.; Guo, T.; Li, Y. S.; Li, X. H.; Wang, J. X.; Weng, J. *Colloids Surf B: Biointerfaces* 2008, 66, 206.
- Chen, C.; Lv, G.; Pan, C.; Song, M.; Wu, C. H.; Guo, D. D.; Wang, X. M.; Chen, B. A.; Gu, Z. Z. *Biomed Mater* 2007, 2, L1.
- Buschle-Diller, G.; Cooper, J.; Xie, Z. W.; Wu, Y.; Waldrup, J.; Ren, X. H. *Cellulose* 2007, 14, 553.
- Kim, K.; Luu, Y. K.; Chang, C.; Fang, D. F.; Hsiao, B. S.; Chu, B.; Hadjiargyrou, M. *J Controlled Release* 2004, 98, 47.
- Kenawy, E. R.; Bowlin, G. L.; Mansfield, K.; Layman, J.; Simpson, D. G.; Sanders, E. H.; Wnek, G. E. *J Controlled Release* 2002, 81, 57.
- Picciani, P. H. S.; Soares, B. G.; Medeiros, E. S.; de Souza, F. G.; Wood, D. F.; Orts, W. J.; Mattoso, L. H. C. *Macromol Theory Simul* 2009, 18, 528.
- Li, D. P.; Frey, M. W.; Baeumner, A. J. *J Membr Sci* 2006, 279, 354.
- Xiang, C. H.; Joo, Y. L.; Frey, M. W. *J Biobased Mater Bioenergy* 2009, 3, 147.
- Kim, H. W.; Lee, H. H.; Chun, G. S. *J Biomed Mater A* 2008, 85, 651.
- McCullen, S. D.; Stevens, D. R.; Roberts, W. A.; Clarke, L. I.; Bernacki, S. H.; Gorga, R. E.; Lobo, E. G. *Int J Nanomed* 2007, 2, 253.
- Cui, W. U.; Li, X. H.; Zhou, S. B.; Weng, J. *J Biomed Mater Res A* 2007, 82, 831.

40. Kim, H. W.; Lee, H. H.; Knowles, J. C. *J Biomed Mater A* 2006, 79, 643.
41. Zhou, H. J.; Kim, K. W.; Giannelis, E.; Joo, Y. L. *Polym Nano-fibers* 2006, 918, 217.
42. Ko, F. A. A.; Lam, H.; MacDiarmid, A. G. In *Wearable Electronics and Photonics*; Tao, X., Ed.; CRC Press: Cambridge, 2005; Chapter 2.
43. Regev, O.; Vandebril, S.; Zussman, E.; Clasen, C. *Polymer* 2010, 51, 2611.
44. Yu, J. H.; Fridrikh, S. V.; Rutledge, G. C. *Polymer* 2006, 47, 4789.
45. Fong, H.; Chun, I.; Reneker, D. H. *Polymer* 1999, 40, 4585.
46. Thompson, C. J.; Chase, G. G.; Yarin, A. L.; Reneker, D. H. *Polymer* 2007, 48, 6913.
47. Zhang, C.; Yuan, X.; Wu, L.; Han, Y.; Sheng, J. *Eur Polym J* 2005, 41, 423.
48. Ramakrishna, S.; Fujihara, K.; Teo, W.-E.; Lim, T.-C.; Ma, Z. *An Introduction to Electrospinning and Nanofibers*; Singapore, World Scientific Publishing Co., 2005.
49. Wei, W.; Yeh, J.-T.; Li, P.; Li, M.-R.; Li, W.; Wang, X.-L. Wiley Subscription Services, Inc., A Wiley Company; p3005.
50. Baldi, F.; Franceschini, A.; Ricco, T. *Rheol Acta* 2007, 46, 965.
51. Han, T.; Yarin, A. L.; Reneker, D. H. *Polymer* 2008, 49, 1651.
52. Shenoy, S. L.; Bates, W. D.; Frisch, H. L.; Wnek, G. E. *Polymer* 2005, 46, 3372.
53. Bas, D.; Boyaci, I. H. *J Food Eng* 2007, 78, 836.
54. Yordem, O. S.; Papila, M.; Menciloglu, Y. Z. *Mater Design* 2008, 29, 34.
55. Sukigara, S.; Gandhi, M.; Ayutsede, J.; Micklus, M.; Ko, F. *Polymer* 2004, 45, 3701.
56. Gu, S. Y.; Ren, J.; Vancso, G. J. *Eur Polym J* 2005, 41, 2559.