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2014

Chanthakulchan, A., Parkhi, A. A., Koomsap, P., & Supaphol, P. (2014). Environmental Effects in Fiber Fabrication Using Electrospinning-Based Rapid Prototyping. Proceedings of the 1st International Conference on Progress in Additive Manufacturing (Pro-AM 2014), 428-433.

<https://hdl.handle.net/10356/84262>

https://doi.org/10.3850/978-981-09-0446-3_016

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ENVIRONMENTAL EFFECTS IN FIBER FABRICATION USING ELECTROSPINNING-BASED RAPID PROTOTYPING

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ABSTRACT:

Rapid prototyping has been well accepted in medical applications due to its ability to create a stacked of layers rapidly in a control fashion. Both commercial and in-house development RP techniques have been applied for this purpose. Currently, an electrospinning-based rapid prototyping (ESRP) is being developed for scaffold fabrication, and presented in this paper is the investigation on the effect of environment on the fabrication process. Experiments were conducted to investigate the fabrication in open and closed environments as well as the influence of humidity. According to the statistical analyses of the results, the environment has the effects on the fiber creation.

INTRODUCTION

Scaffold is a necessary vehicle for regeneration of tissue or organ in tissue engineering. It works as a biological substrate for growing and preventing cells during transplantation (Yeong et al., 2004). Several techniques have been used to fabricate the scaffold. Electrospinning is one of conventional techniques that are used for this purpose. Electrospinning produces the scaffold from a continuous fine fiber that is drawn from a polymer solution in a metallic needle by an electric field (Owida et al., 2011). A high DC voltage is applied in the process to create the electric field between the needle and a collector. After an electrostatic force at the needle tip overcomes the surface tension, the polymer solution jets towards the collector (Park et al., 2008). The jet comes out straight for a certain distance before it starts bending and becomes uncontrollable. Therefore, the deposition of the fiber on the collector is unpredictable.

Attempts have been made in order to keep the jet straight during the deposition either by prolonging the straight part of the trajectory (Edwards et al., 2010; Kim and Kim, 2006), or by shortening the distance between the needle tip and the collector to be within the straight part of the trajectory (Sun et al., 2006; Chang et al., 2008). Electrospinning has also been combined with rapid prototyping (RP) that allows a pattern to be created in a control fashion, for scaffold fabrication (Park et al., 2008; Chen et al., 2009; Owida et al., 2011; Mota et al., 2011). The electrospinning has been used to create fine fiber while RP has been used to achieve controllable shape.

Besides, an in-house RP technique, called electrospinning-based rapid prototyping (ESRP), is currently being developed (Chanthakulchan et al., 2014). It is an attempt to integrate electrospinning with rapid prototyping to achieve the fabrication of a scaffold with a controllable pattern of fine fibers. ESRP follows RP process of FDM for a layer construction but instead of

using extrusion process for fiber creation, electrospinning is applied to generate electrostatic force to draw a continuous fiber from a liquid solution. Near-field deposition which a standoff distance between the needle and the platform is set within the range of the straight jet is applied to avoid uncontrollable flight trajectory. The pattern creation is done by controlling the movement of the platform instead of controlling the movement of the needle as being done in FDM. The fabrication is repeated layer after layer until the final layer is constructed. Figure 1 illustrates the example of scaffolds created by ESRP.

Presented in this paper is an experimental investigation of the environmental effects on the ESRP process. Two sets of experiments were conducted to investigate the fabrication in open and closed environments as well as the influence of humidity. The next section presents the experimental setup, followed by two experiments and the results. Conclusions are addressed at the last section.

Figure 1. Forty five-layer scaffold fabricated by ESRP

EXPERIMENT SETUP

Material Preparation

In this research, Polycaprolactone (PCL) with Mn 80,000 to 90,000 g/mol from Sigma Aldrich Chemistry was used as the polymer material for the process. N-Dimethylformamide (DMF) was used as a solvent. The solution of 10% weight of PCL in DMF was prepared for the experiments. PCL and DMF were weighted on a digital scale. Both substances were mixed together on a hot-plate stirring machine at temperature of 80°C about 15 minutes.

Machine Setup

The size of the needle was fixed at 20 gauge which the inner diameter is about 610 μm . An aluminum foil was placed on the collector platform. The positive charge line of the power supply was connected to the needle tip while the ground line was connected to the collector. The speed of the collector was fixed at 200 mm/s with acceleration and deceleration of 50 mm/s².

Evaluation Method

A portable digital microscope with MicroCapture software was used to capture the images of the fabricated scaffolds. The resolution of the magnified images was about 10.638 μm per pixel. Each sample was measured for fibers' diameter, and fibers' straightness.

EXPERIMENTS AND RESULTS

Investigation of surrounding environment effects to fiber fabrication

The electrospinning process is normally sensitive to the surrounding environment due to the very thin fiber creation. Therefore, this experiment aimed to investigate the effects of surrounding

environment to the fiber fabrication. Two sets of samples were fabricated. One was in open environment and another was in closed environment. Each set had six 30x40 mm samples: three for 0° pattern which fibers were laid along x-axis and another three for 90° pattern which fibers were laid along y-axis. The gaps between any pair of fibers were set 1 mm apart. The relative humidity was in the range of 55% to 65% for open environment and 50% to 60% for closed environment. The applied voltage of the process was set at 3.2 kV. The distance between the needle tip and the collector or standoff distance (SOD) was set at 5 mm.

Five fibers were randomly selected from each sample. For the diameter measurement, each fiber was measured at the head, the middle and the tail. The average was calculated for the fiber's diameter. The straightness of the fiber was determined from the deviation of points on the center lines of the fiber from a reference line. Six values were measured and used to calculate a standard deviation, representing the straightness error of the fiber.

Tables 1 and 2 present the average diameters, and straightness errors of fibers fabricated with both 0° and 90° patterns under two environments. The fibers obtained from 0° pattern were smaller than 90° pattern under both environments. That was due to the present of vibration at different magnitudes when the machine moved along the two axes (Chanthakulchan et al., 2014). The fibers created in closed environment were also smaller than in open environment. Two-way ANOVA were conducted to confirm the effects of the environment and the lay-down pattern to the diameter. According to the ANOVA result, shown in Figure 2, the null hypotheses which fibers have the same diameter under both environments and also with two different lay-down patterns could be rejected with 95% confidence interval because p-values of both factors were less than 0.05, but the null hypothesis of their interaction could not be rejected. Therefore, the environment and fiber pattern had effects to the fiber diameters, but their interaction could not be concluded to have the effect.

For the straightness errors, the closed system yielded lower errors for both average values and standard deviations. The differences resulted from lay-down pattern was also observed. However, the two-way ANOVA shown in Figure 3 indicated that the null hypothesis that the errors are similar for both environments was marginally rejected while the null hypotheses for lay-down pattern and for the interaction between the two factors could not be rejected. Therefore, the environment had slight influence on the straightness.

Table 1. Averages of diameter, and straightness for fabricated fibers in open environment

Pattern	Diameter (μm)		Straightness Error (μm)	
	Average	SD	Average	SD
0°	155.80	8.44	36.73	13.19
90°	170.29	10.15	46.21	18.46

Table 2. Averages of diameter, and straightness for fabricated fibers in closed environment

Pattern	Diameter (μm)		Straightness Error (μm)	
	Average	SD	Average	SD
0°	150.73	8.31	32.69	10.60
90°	164.25	12.97	35.38	14.15

Figure 2. Two-way ANOVA on diameter versus environment and pattern

Figure 3. Two-way ANOVA on straightness error versus environment and pattern

Although the environment did not influence the results much according to the statistically analysis, the closed system did provide more consistent outcomes. Therefore, it is recommended that the fabrication should be conducted in the closed environment.

Investigation of standoff distance and relative humidity effects to fiber fabrication

This experiment was conducted to investigate the effects of standoff distance (SOD) and relative humidity (RH) to the fibers' size. As the electrospinning jet is formed the Taylor's cone at the needle tip and pulled to be the fiber, the straight jet occurs during a certain distance before bending. SOD was studied in order to investigate the effect to the fibers' size. Moreover, the relative humidity was taken into the study for checking the fiber fabrication effect. Two sets of 40x40 mm samples were created. The first set was conducted in the RH range of 50% to 60%. Another set was conducted in the RH range of 60% to 70%. The SODs were varied at three levels: 5 mm, 8 mm and 10 mm and the applied voltages were set at 3.2, 3.7 and 3.8 kV accordingly. The diameters of fibers were measured from three fibers in each sample. The head, the middle and the tail of each fiber were measured. The averages were calculated from the measurement values.

Table 3 presents the average diameters of the fibers fabricated at different SODs under two RH ranges. The diameter was decreased when the SOD increased for both RH ranges. The diameters of 5 mm and 10 mm in SOD for 60-70%RH range were smaller than 50-60%RH range. In contrast, the diameter of 8 mm SOD in the range of 60-70%RH was larger than the range of 50-60%RH. Two-way ANOVA was conducted to check the effects of SOD and relative humidity. The ANOVA results are shown in Figure 4. Only the null hypothesis that SOD has no effect to the diameter size could be rejected with 95% confidence interval while the null hypotheses for both the relative humidity and the interaction between the two factors could not be rejected. Therefore, the SOD affects the diameter of fibers. However, it could not be concluded that the relative humidity has the effect to fiber diameter.

For PLC in DMF solution, the SOD affects the fiber fabrication. If the distance between needle tip and collector (SOD) is increased, the size of fiber diameter will be decreased. While the jet comes out from the needle tip, Taylor's cone is formed and pulled down as the fiber. The fiber is pulled toward the collector. When it is far from the cone, the size is reduced due to the stretchiness.

Table 3. Averages of fiber diameters from different SODs and humidity ranges

SOD (mm)	RH Range			
	50-60%		60-70%	
	Average (μm)	SD (μm)	Average (μm)	SD (μm)
5	169.28	14.70	168.87	12.61
8	134.87	22.10	152.07	20.81
10	122.46	17.67	109.93	13.28

CONCLUSIONS

The experiments were conducted to investigate the effects of fiber fabrication with the developing electrospinning-based rapid prototyping. The surrounding environment was studied. The results recommended the process to be conducted in a closed environment for consistency. The standoff distance and relative humidity of the environment were investigated. The fiber could be fabricated in all conditions. The results, however, showed the different in the fiber diameter.

Figure 4. Two-way ANOVA on diameter versus relative humidity and standoff distance

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