Effect of Melt Jet Spinning Process on Poly(lactic acid) Disposable Nonwoven Fabric Production

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(Received May 29, 2021; Revised October 4, 2021; Accepted November 5, 2021)

Abstract: In the light of marine microplastic pollution and mounting environmental degradation, this research proposes biodegradable poly(lactic acid) (PLA) nonwoven fabric produced by novel melt jet spinning technology under various process conditions. In the study, the die temperature was varied at 210, 230, and 250 °C and the die-to-collector distance was varied between 30, 60, 90, and 120 cm. The performance metrics included fiber diameter, fiber crystallinity, fabric weight, air permeability, and contact angle. The results revealed that the optimal die temperature was 250 °C. At 250 °C, the fibers were of fine size with high crystallinity, independent of collector distances. Specifically, the die-to-collector distance, given the optimal die temperature, had negligible effect on the fiber diameter and crystallinity. On the other hand, the collector distance played a role in the nonwoven fabric characteristics. The collector distance was positively correlated with the elongation at break and air permeability but inversely correlated with the fabric density and tensile strength. The fabric contact angles were found to be in the range of 124-130 °, indicating the hydrophobicity of PLA nonwoven fabric. Essentially, the novelty of this research lies in the use of biodegradable PLA polymers, as opposed to conventional petroleum-based non-biodegradable polymers; and melt jet spinning technology to realize fine microfibers (1-10 µm).

Keywords: Disposable nonwoven fabric, Poly(lactic acid), Melt jet spinning, Die-to-die collector, Air permeability

Introduction

Non-biodegradable petroleum-based nonwoven fabric is conventionally used in a variety of applications due to versatility, affordability, light weight, biocompatibility, and ease of fabrication [1]. In the medical setting, the conventional nonwoven fabric is the key component in surgical face masks, adult diapers, and disposable surgical caps.

Nonwoven fabric is machine-made matrices of fibers of nanometer to micrometer in diameter [2,3]. Specifically, nonwoven fabric is a fabric-like material made from elongated fibers, bonded together by chemical, mechanical, or thermal treatment [4]. The conventional nonwoven fabrics are produced from petroleum-based non-biodegradable polymers such as polypropylene (PP) or poly(ethylene terephthalate) (PET).

With the exponential growth in nonwoven products, it leads to the environmental pollution due to the conventional nonwoven fabric is non-biodegradable and a source of microplastics in the oceans. As a result, it makes environmental and economic sense to replace the non-biodegradable petroleum-based polymers with biodegradable ones, such as poly(lactic acid) or polyhydroxyalkanoates [5].

Of particular interest is poly(lactic acid) (PLA), which is a biobased, biodegradable, and biocompatible polymer. PLA is derived from natural resources such as corn, sugarcane, cassava, and other biomass products and wastes [6-9]. The intermediate product from biodegradation of PLA is lactic acid, which is unharmful to the human health, and the final products are CO₂ and H₂O [10]. In addition, PLA fabrics have been increasingly used in textile, food packaging, and biomedicine due to the comparably good physical, mechanical, and barrier properties [11-13].

At present, nonwoven fabrics are manufactured using melt spinning process. Unlike the melt spinning process whose fiber sizes are relatively large, the proposed melt jet spinning technology is a novel production process of nonwoven microfibers. In melt jet spinning, the polymer pellets are melted by screw-rotating melt extruder outfitted with a nozzle of three spinnerets. Through the nozzle, the melted polymer is blown by hot air to fabricate the micro-size fibers. By comparison, the melt jet spinning is more energy efficient, highly productive, and compatible with commercial grade polymers [14]. Nevertheless, the performance of the melt jet spinning is subject to multiple factors, including polymer flow rate, nozzle temperature, air pressure, and collector distance.

Feng reported the experimentally fabrication of PLA nonwoven fabrics using the conventional melt spinning method under different die-to-collector distances and documented that the PLA fibers become smaller with the increase in the collector distance, which in turn reduces the fiber strength [15]. Development of the cotton candy method
to efficiently fabricate polypropylene (PP) microfibers was reported by Wongpajan et al. [14]. The experiments were carried out under various process conditions by varying the air pressure, nozzle temperature, and collector distance. The results showed that the diameter of PP microfibers decreases with increasing the air pressure and nozzle temperature, while the fiber diameter remains unchanged with the increase in the collector distance.

Due to increasing environmental degradation and marine microplastic problems, this research proposes biodegradable PLA nonwoven fabrics produced by novel melt jet spinning technology for disposable nonwoven fabric application, including surgical face masks, adult diapers, and disposable surgical caps. The nonwoven fabric was fabricated under various process conditions where the die temperature was varied between 210, 230, and 250 °C and the die-to-collector distance between 30, 60, 90, and 120 cm. The optimal process condition for fabrication of medical nonwoven fabric was subsequently determined. The performance metrics under study were fiber diameter, fiber crystallinity, fabric weight, tensile properties, contact angle and air permeability.

Experimental

Materials and Nonwoven Fabric

Poly(lactic acid) pellets were of Ingeo biopolymer 6100D, with a melt flow index of 24 g/10 min and a density of 1.24 g/cm$^3$ (NatureWorks LLC). The PLA pellets were first oven-dried at 80 °C for 8 h prior to processing. PLA nonwoven was fabricated by a melt jet spinning machine outfitted with a die of three 0.4 mm spinnerets and a hot air outlet at the center.

In the experiment, the die temperatures were varied at 210, 230, and 250 °C with an air pressure of 0.5 MPa. Previous researches showed that a die temperature below 210 °C gave rise to excessive elongational viscosity, rendering fiber formation impossible, while that above 250 °C led to insufficient elongational viscosity to maintain a continuous jet, resulting in droplets of the polymer melt [16]. The screw speed was maintained at five rounds per minute (rpm) with a constant hot air temperature of 600 °C. The collector rotated at 0.5 m/min with left-right motion of 25 rpm. The distance between the die and the collector (die-to-collector distance) was varied between 30, 60, 90, and 120 cm. Figure 1 illustrates the schematic of the melt jet spinning for manufacture of biodegradable PLA nonwoven fabric.

Analytical Methods

Melt flow rate (MFR) analysis was first performed to determine the suitability of experimental die temperatures (210, 230, and 250 °C) with the PLA polymers. MFR was used to measure of the ability of the material melting to flow under pressure (load 2.16 kg). Besides, MFR was a key factor of melt jet spinning technology and played a crucial role in fiber formation.

Analysis of fiber size and fiber crystallinity (i.e., thermal property analysis) were carried out to determine the optimal die temperature for PLA nonwoven fibers using melt jet spinning. In fiber size analysis, the field emission scanning electron microscope (FE-SEM; JSM-7610FPlus, JEOL, Japan) with an accelerating voltage of 15 kV was used for morphology imaging. In SEM analysis, the nonwoven fabric specimens were formed at 210, 230, and 250 °C, given 60 cm die-to-collector distance [14], were gold-sputtered prior to analysis. ImageJ image processing was used to measure the fiber diameter and the size distribution.

Differential scanning calorimetry (DSC 8000, Perkin Elmer, Germany) was used to characterize fiber crystallinity whereby 5-10 mg of nonwoven fabric specimens were heated from 30 to 250 °C at a heating rate of 10 °C/min and left to cool down to room temperature. The crystallinity ($\%X_c$) of PLA fibers was calculated by [17]

$$\%X_c = \frac{\Delta H_m - \Delta H_{cc}}{\Delta H_0} \times 100$$  \hspace{1cm} (1)

where $\%X_c$ is the crystallinity of polymer (%), $\Delta H_m$ is the enthalpy of melting, $\Delta H_{cc}$ is the enthalpy of cold crystallization, and $\Delta H_0$ is the theoretical melting enthalpy of PLA with 100% of crystallinity (i.e., 93.1 J/g).

The fabric weight, tensile properties, air permeability and contact angle of PLA nonwoven fabrics were subsequently determined to investigate the effect of different die-to-collector distances (30, 60, 90, and 120 cm) on these performance metrics, given the optimal die temperature. The fiber temperature at the collector was measured using an infrared thermometer (Proskit Infrared Thermometer MT-4606, -50 to 380 °C).

In PLA nonwoven fabric weight analysis, the specimens were 1×10 cm in dimension for each of different collector distances (30, 60, 90, and 120 cm), given the optimal die temperature, and the results were on the average. It was measured in grams per square meter (g/m$^2$) or GSM.

Tensile properties were carried out by Instron universal testing machine (model 5569, Instron, USA) at room temperature, and the results were on the average.
temperature. The grip distance was set at 25 mm with a testing speed of 50 mm/min according to the standard measurement (ASTM D 3822 01).

The air permeability of nonwoven fabric specimens of 30, 60, 90, and 120 cm collector distances, given the optimal die temperature, were determined by air permeability tester (TexTest FX3300) with an air pressure of 196 Pa according to the standard measurement (ASTM737). The specimens were 20×20 cm in dimension. The contact angle was measured using a contact angle meter (DataPhysics Instrument, OCA 15EC) whereby 0.5 µl of deionized water droplets were dripped on the nonwoven fabric specimens and the contact angle was measured.

**Results and Discussion**

**Effect of Die Temperature**

Figure 2 illustrates the linear relationship between the MFR of PLA and die temperature. The MFR of PLA at 210, 230, and 250 °C die temperatures were 21, 35, and 54 g/10 min respectively, indicating a positive correlation between MFR and die temperature.

Figure 3 depicts the FE-SEM images (a-c) and illustrates the size distribution by fiber diameters (d-f) of PLA nonwoven fabric of 210, 230, and 250 °C die temperatures, respectively, given the die-to-collector distance of 60 cm. The fiber size became smaller with the increase in die temperature, corresponding to the increase in MFR. The finer fiber size was also attributable to lower viscosity of polymers, as evidenced by higher MFR, which is beneficial for hot air blowing, enabling the fibers to be drawn. In Figure 3(d) and (e), the fibers were of large diameters (5-32 µm) and the distribution of fiber sizes was wide. At 250 °C die temperature, the fibers were of fine diameters (1-10 µm) and the distribution was narrow. The results were attributable to the low viscosity and high flow rate of PLA at high temperatures.

![Figure 2. Melt flow rates (MFR) of PLA pellets under variable die temperatures.](image)

![Figure 3. FE-SEM images of PLA nonwoven fabric, fiber diameters, and size distribution under variable die temperatures, given the die-to-collector distance of 60 cm; (a, d) 210 °C, (b, e) 230 °C, and (c, f) 250 °C.](image)

![Figure 4. DSC thermograms of PLA fibers under different die temperatures, given 60 cm die-to-collector distance.](image)

Figure 4 illustrates the DSC thermograms of PLA fibers under the die temperatures of 210, 230, and 250 °C, given the die-to-collector distance of 60 cm. Table 1 presents the glass transition temperature \(T_g\), crystallization temperature \(T_c\), crystalline melting temperature \(T_m\), and crystallinity \(\%X_c\) of PLA fibers under experimental die temperatures. The crystallinity \(\%X_c\) was positively correlated with the
die temperature. In other words, the crystallinity of PLA fibers increases with increasing die temperature. The crystallinities of the fibers at 210 and 230 °C were insignificantly different (29.2 % and 29.6 %). At the higher die temperature, the $T_g$, $T_cc$, and $T_m$ shifted to the lower temperatures due to the thermal degradation of the PLA molecular chains during melt spinning at 250 °C. The weight-average molar mass reduction due to PLA degradation with increasing the melt process temperature was reported [18]. The reduction of the chain length during melt processing promoted successive crystallizability of PLA. Consequently, the degree of crystallinity increased as a result of the shorter molecular chain. It was easier to crystallize at 210 ºC or 230 ºC.

**Effect of Die-to-collector Distance**

This section describes the effect of variable die-to-collector distances (30, 60, 90, and 120 cm) on the fabric weight of PLA nonwoven fabrics produced by melt jet spinning at 250 °C die temperature (i.e., optimal die temperature). The fabric weight of PLA nonwoven fabric at 30, 60, 90, and 120 cm were 61, 55, 50, and 49 g/m$^2$, respectively (Figure 5). The fabric weight of PLA nonwoven fabric decreases as the collector distance increases from 30 to 60 cm. The fibers were not mechanical, or chemical entangled at the longer distance. They would lose packing and would fall out of the collector. Therefore, the difference

| Die temperatures (°C) | $T_g$ (°C) | $T_{cc}$ (°C) | $T_m$ (°C) | $\Delta H_{cc}$ (J g$^{-1}$) | $\Delta H_m$ (J g$^{-1}$) | $X_c$ (%) |
|-----------------------|------------|--------------|------------|-----------------|-----------------|--------|
| 210                   | 73.0       | 103.2        | 182.2      | 22.4            | 49.6            | 29.2   |
| 230                   | 71.8       | 104.3        | 179.7      | 22.6            | 50.2            | 29.6   |
| 250                   | 68.7       | 94.2         | 177.9      | 19.2            | 50.7            | 33.9   |

Table 1. DSC analysis results of PLA fibers at various die temperatures, given 60 cm die-to-collector distance

| Die-to-collector distance (cm) | Fiber temperature (°C) |
|-------------------------------|------------------------|
| 30                            | 47.7 ±0.48             |
| 60                            | 37.1 ±0.35             |
| 90                            | 29.2 ±0.18             |
| 120                           | 28.1 ±0.43             |

Table 2. Temperatures of PLA nonwoven fabric at the collector, given 250 °C die temperature

![Figure 5](image1.png)

**Figure 5.** Fabric weight of PLA nonwoven fabric under different die-to-collector distances, given 250 °C die temperature.

![Figure 6](image2.png)

**Figure 6.** FE-SEM images of PLA nonwoven fabric, fiber diameters, and size distribution under different die-to-collector distances, given 250 °C die temperature; (a, e) 30, (b, f) 60, (c, g) 90, and (d, h) 120 cm.
between fabric weights when the collector distance of more than 60 cm was not significant. The fiber temperatures upon impact with the collector decrease as the collector distance increased, causing the fibers to be loosely packed (Table 2).

Figure 6 illustrates the FE-SEM images of PLA nonwoven fabric, fiber diameters, and size distribution associated with different die-to-collector distances: 30, 60, 90, and 120 cm, given 250 °C die temperature. The fibers became decreasingly entangled as the collector distance increased. The decreased entanglement was attributable to weaker air strength emitting from the die as the collector distance increased. The longer distance caused the reduction of fibers temperature and air blown pressure. Then, the fibers are solidified and decreasingly entangled. However, the die-to-collector distance has no effect on the fiber size. This could be attributed to lower fiber temperatures at the collector (28.1-47.7 °C), vis-à-vis the glass transition temperatures \((T_g)\) of PLA (68.7-70.1 °C). In addition, the fibers were of fine sizes with narrow size distribution. Bhat reported the critical distance of die-to-collector distance (DCD) of 35 cm for the polyethylene melt blown nonwovens production. After 35 cm of the DCD, the change of fiber diameter was small. This distance was acceptable as an optimum DCD for melt blown studied of polyethylene nonwovens [19]. Lee and Wadsworth reported that no effect on fiber diameter was observed for the DCD over 30 cm. The reason could be because the web structure of fabric cannot be formed due to the flying of fibers when the DCD increased more than 35 cm. As the DCD, increased the fiber had more time to cool down and resulting in a web structure with less interfiber adhesion and a weaker entanglement [20].

Figure 7 illustrates the DSC thermograms of PLA fibers of different die-to-collector distances (30, 60, 90, and 120 cm), given 250 °C die temperature. Table 3 tabulates \(T_g\), \(T_{cc}\), \(T_m\), and %Xc of PLA fibers of different collector distances. The die-to-collector distance had no effect on \(T_g\), \(T_{cc}\), \(T_m\), and fiber crystallinity. The finding could be attributed to a rapid decrease in fiber temperatures subsequent to jetting from the die.

Figure 8 illustrates the tensile properties of PLA nonwoven fabric associated with variable die-to-collector distances given 250 °C die temperature. The tensile strength of PLA nonwoven fabric at 30, 60, 90, and 120 cm distances were 0.24, 0.20, 0.20, and 0.18 MPa, respectively, and elongation at break of PLA were at 86, 112, 124, and 132 %, respectively. The effect of increasing the distance resulted in lower tensile strength and higher elongation at break. PLA nonwoven fabrics produced by melt jet spinning process using air pressure and hot air to blow while the polymer melts from the die. Therefore, as the die-to-collector distance increased, the air pressure decreased and the fibers cooled down before reaching the collector, causing, the fiber would be less entanglement and loosely-packed. The effect of fiber disorganized arrangement in fiber web, fiber slippage, and less bonding strength between individual fibers may have resulted in a decrease in their mechanical properties [15].

Figure 9 compares the contact angles of PLA nonwoven fabric associated with variable die-to-collector distances (30, 60, 90, and 120 cm), given 250 °C die temperature.
60, 90, and 120 cm), given 250 °C die temperature. The contact angles were in the range of 124-130 °, indicating the hydrophobicity of the PLA nonwoven fabric, given that a contact angle above 90° indicates hydrophobicity [21,22]. The collector distance had negligible effect on the contact angle of the fabric due to nearly identical fiber diameters (1-10 µm) under different collector distances. Fine fiber sizes contributed to larger contact angles. Since the collector distance has no effect on the fiber diameter, the contact angles remained relatively constant [23].

Figure 10 illustrates the air permeability and fabric weight of PLA nonwoven fabric under different die-to-collector distances, given 250 °C die temperature.

| Die-to-collector distance (cm) | T_g (°C) | T_x (°C) | T_m (°C) | δH_x (J g⁻¹) | δH_m (J g⁻¹) | X_c (%) |
|-------------------------------|----------|----------|----------|---------------|---------------|---------|
| 30                            | 69.2     | 99.9     | 178.6    | 20.0          | 52.0          | 34.4    |
| 60                            | 68.7     | 94.2     | 177.9    | 19.2          | 50.7          | 33.9    |
| 90                            | 69.0     | 97.5     | 178.4    | 19.5          | 51.1          | 34.0    |
| 120                           | 68.7     | 97.7     | 177.9    | 17.2          | 48.9          | 34.1    |

Table 3. DSC analysis results of PLA fibers under different die-to-collector distances, given 250 °C die temperature

Figure 10. Air permeability and fabric weight of PLA nonwoven fabric under different die-to-collector distances, given 250 °C die temperature.

60, 90, and 120 cm), given 250 °C die temperature. The contact angles were in the range of 124-130 °, indicating the hydrophobicity of the PLA nonwoven fabric, given that a contact angle above 90° indicates hydrophobicity [21,22]. The collector distance had negligible effect on the contact angle of the fabric due to nearly identical fiber diameters (1-10 µm) under different collector distances. Fine fiber sizes contributed to larger contact angles. Since the collector distance has no effect on the fiber diameter, the contact angles remained relatively constant [23].

Figure 10 illustrates the air permeability and fabric weight of PLA nonwoven fabric of different die-to-collector distances, given 250 °C die temperature. The air permeability of PLA nonwoven fabric at 30, 60, 90, and 120 cm distances were 237, 306, 360, and 479 l/s/m², respectively. The longer collector distance resulted in the lower fabric weight, which in turn improved the air permeability of PLA nonwoven fabric. The increase in the air permeability at longer collector distance was attributed to loosen packing structure of PLA fabric which could be confirmed from the decrease of fabric weight (Figure 5 and 10). However, the fabric weights at collector distances of 90 and 120 cm were not different but the air permeability at 120 cm was highest which might be due to high porosity from loose packing of fibers in the fiber web. At longer distance the process air pressure decreased which resulted in less entanglement and loose packing of fibers in which a lower porosity was used to arrive at a higher bulk density leading to high air permeability [24].

Conclusion

This research proposed biodegradable PLA nonwoven fabric produced by novel melt jet spinning technology for medical applications. In the study, the experiments were carried out under various process conditions whereby the die temperature was varied at 210, 230, and 250 °C and the die-to-collector distance was varied between 30, 60, 90, and 120 cm. The optimal die temperature for PLA was 250 °C. At the optimal die temperature, the fibers were of fine size (1-10 µm in diameter) with high crystallinity, independent of collector distances (30, 60, 90, and 120 cm). In other words, the die-to-collector distance, given the optimal die temperature, had negligible effect on the fiber diameter and crystallinity. On the other hand, the collector distance played an important role in the characteristics of PLA nonwoven fabric. Specifically, under the optimal die temperature, the PLA nonwoven fabric had lesser fabric weight and tensile strength with the increase in die-to-collector distance, consequently improving elongation at break and the air...
permeability. Besides, the contact angles of 124-130° indicated the hydrophobicity of PLA nonwoven fabrics. In essence, the biodegradable PLA nonwoven fabric produced by melt jet spinning holds great potential as a substitute for conventional petroleum-based non-biodegradable nonwoven fabric.

**Acknowledgments**

The authors would like to express sincere gratitude to Thailand’s Ministry of Higher Education, Science, Research and Innovation for the grant under the Talent Mobility Program, and the Research and Researchers for Industries (RRi) Project (Code: NRCT5-RRI63007-P09).

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