Fiber and Web Formation of Melt-Blown Thermoplastic Polyurethane Polymers

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ABSTRACT: The goal of this research was to determine the fiber and web properties of melt-blown (MB) thermoplastic polyurethane (TPU) polymer as dependent on the MB processing conditions. The relationships between the MB fiber properties and the MB process conditions, such as the die-to-collector distance and the velocity of the MB TPU fiber in the spin line, were measured and estimated on the basis of the air velocity and air temperature, respectively. Consequently, this study provided fundamental guidelines of heat, air flow, and distance conditions of the MB process for the production of commercially acceptable MB TPU nonwovens. More specifically, the essential insight into the MB process was fundamentally valid for the MB TPU process; however, the inherent heat sensitivity of the TPU polymer brought more complexity at fiber and web formation than the conventional polyolefin MB process. © 2007 Wiley Periodicals, Inc. J Appl Polym Sci 105: 3723–3727, 2007

Key words: elastomers; fibers; polyurethanes; processing

INTRODUCTION

The concept of the melt-blown (MB) process was first introduced in 1956 through a Naval Research Laboratory project initiated by Wente to produce filters composed of microfibers for collect radioactive particles from the atmosphere during the early years of the cold war.[1–12] Zhao[2] reported that only 20 U.S. Patents were granted from the 1950s to the 1970s related to MB technologies and products, but the numbers of patents have increased remarkably to 64 and 236 during the 1980s and 1990s, respectively. The most important advantage of the MB process is that, fundamentally, all thermoplastics polymers can be processed by MB technology.[3,4,8] Recently, elastomers, including thermoplastic polyurethanes (TPUs), have been a focus of MB research because of their unique properties, including high elasticity in all directions, good shore hardness for a given modulus, high abrasion/chemical resistance, excellent mechanical/elastic properties, low stress relaxation, and resistance to long-term cyclic flex failure.[11–19]

Even though many processing methods, such as melt spinning, injection molding, coating, film blowing, melt blowing, and sealing, work well with TPU materials, the consumption of TPU elastomers is still much less than conventional polyurethanes, which must be solvent-spun to produce fibers. Because of their tendency to snap back during attenuation of the spin line, the melt-spinning process of elastic fibers is more difficult than that of other polymers. This is even more challenging with the MB process because the filaments are attenuated by aerodynamic skin friction and form drag, and the filaments may be discontinuous and are not positively held by a take-up spindle or nip while in flight to the collector.[5,6] However, the fact that TPUs can be melt-spun into fibers makes them much more versatile for replacing natural rubber thread, solvent-spun polyurethane, and other more conventional materials for use in biomedical devices, implants, medical applications, and protective clothing. Furthermore, the products of MB TPU webs with average fiber diameters in the range of 2–6 μm provide high filtration and barrier protection with additional advantages.[3–7]

Although numerous studies have been performed to determine the relationships between the MB process and the product parameters of polyolefin polymers, additional studies are needed to understand the melt blowing of TPUs and to make further improvements in MB TPU web performance properties.[12,13]

Therefore, in this research, we concentrated on the fiber- and web-formation process of the MB TPU process. For this purpose, fiber diameter, fiber orientation, and fiber entanglement of MB TPU, depending on the die-to-collector distances (DCDs), were studied. Air temperature and air velocity were also determined to examine the relation between MB TPU fibers and process variables.[20–22]

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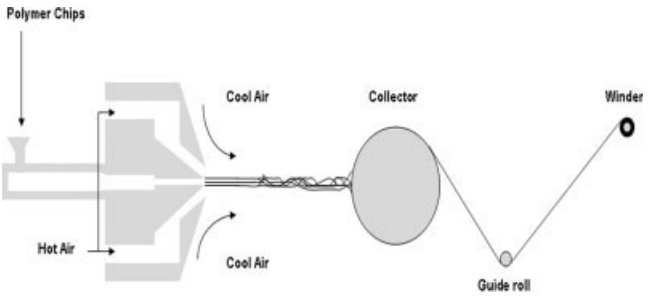

Figure 1 Schematic diagram of the 20-in. Accurate MB Products line.

EXPERIMENTAL

Polymers and MB processing conditions

ESTANE 58280 (TPU_{280}), a polyether-based TPU, was obtained from Noveon, Inc. (Cleveland, OH). It is moderately breathable and highly elastic and is designed to provide good adhesion for a mold on substrate. It is also designed to provide toughness, dynamic flexibility, vibration damping, and a surface with abrasion, scratching, oil, and grease resistance. Furthermore, TPU_{280} was designated to compete with Lycra fiber.[23]

For the MB process, the die geometry, which is consisted of a 60° nose tip, 30 holes/in., a hole diameter of 0.368 mm, an air gap, and a setback of 0.762 mm, was prepared. A schematic diagram of the 20-in. MB pilot line is shown in Figure 1.

Air temperature and speed were measured by a Series 471 digital thermo-anometer produced by Dwyer (Chicago, IL), and the die temperature was measured by an IR thermometer MX2 provided by Rasytek (Santa Cruz, CA). The TPU fiber velocity and temperature during the MB process were calculated on the basis of a polypropylene (PP) fiber velocity and air velocity spin line study by Breese and Qureshi.[12,13]

Furthermore, the morphological change of MB TPU_{280} fibers and the orientation of fiber bundles on the MB TPU_{280} webs with different DCDs was investigated, for this purpose, MB TPU_{280} webs were collected at different DCDs with a high collector speed of 100 m/min, a polymer throughput rate of 0.14 g/h/min, and die and air temperatures were set at 216 and 240°C, respectively.

Characterizations

The microstructures of achieved MB TPU webs were examined by optical microscopy (YS1-T Nikon, El Segundo, CA) and scanning electron microscopy (Hitachi S-3500, Tokyo, Japan). The fiber bundle size and orientation of MB TPU webs with different DCDs were studied by an image analysis technique with WebPro version 2.1 (Knoxville, TN). About 100 images were taken from two different angles for each sample. Then, the average fiber bundle diameter, fiber bundle diameter distribution, mean of the fiber bundle orientation, and machine direction and cross direction (MD/CD) ratio was determined for each specimen.

RESULTS AND DISCUSSION

Fiber- and web-formation studies

The MB TPU fiber/web formation of TPU_{280} were studied at different MB processing conditions. Die temperature, air temperature, air speed, DCD, and throughput are considered major influence factors for MB products. The die temperature showed only minor differences across the transverse direction, and the measured air temperature by the Series 471 digital thermo-anometer produced by Dwyer without polymer extrusion also did not show any major differences across the die, but air temperature dramatically decreased with increasing distance from the die. The air temperature was set on 240°C in the air manifold, but the air temperature rapidly decreased to below 100°C very near the die exit. The air temperature and velocity profiles are shown Figure 2. The air temperature decreased from 240 to 71°C in the first 6 cm from the die, and the air temperature from 6 to 20 cm decreased moderately from 71 to 51°C. After 51 cm, the decrease in the air temperature was minimal.

On the other hand, the air velocity was measured at 50 cm from the die without polymer extrusion with 60% opening of the air valve, and on the basis of the experimental study of the MB PP process, air velocity was calculated with mathematical models. For the fiber- and web-formation study of the MB TPU process, the sigmoidal curve of logged data fit was used on MB PP experimental data sets.[12,13]

Figure 3 shows the air velocity (y) profiles of MB PP process, depending on the distance from the die

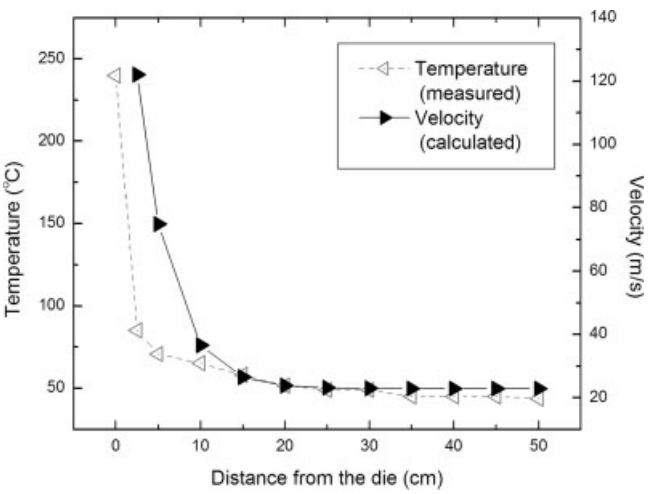

Figure 2 Air temperature and velocity profiles at various DCDs.

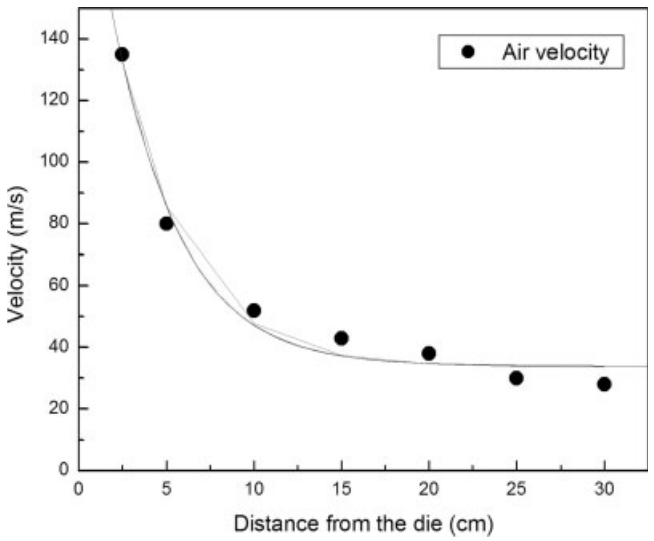

Figure 3 Air velocity profiles at various DCDs.

(x). The Boltzmann fitting model[eq. (1)] showed 98.8% accuracy with the MB PP experimental data sets and was interpreted as the best fitting model for the MB process:

$$y = \frac{A_1 - A_2}{1 + e^{(x-x_o)/dx}} + A_2 \quad (1)$$

where A_1 is equal to 1622.44, A_2 is equal to 33.83, x_o is equal to −7.47, and d_x is equal to 3.68.

For the MB TPU study, the air velocity was measured 30 cm from the die. After that, on the basis of eq. (1), the velocity of air near the die was assumed.

On the other hand, the relationship between air velocity (y) and fiber velocity (z) was introduced as a second degree of polynomial regression on the basis of the experimental PP study and as presented in eq. (2):

$$z = A + B1y + B2y^2 \quad (2)$$

where A is equal to −10.66, $B1$ is equal to 1.64, and $B2$ is equal to −0.01. The regression model fit with 99.9% accuracy with the experimental PP data sets.

During the MB process, fiber velocity is determined by air velocity. The air speed continuously decreased from the die, but the fiber speed started at nearly zero at the die exit and then abruptly increased because of the difference between the higher speed of air and the lower speed of the fiber. Because the air and fiber speeds were identical at 4–6 cm from the die, the fiber speed also continuously decreased with air velocity.

With eq. (2), the air and fiber velocity of MB TPU process assumed under MB PP and TPU fiber velocity showed similar tendencies at extremely high air velocities. Figure 4 shows the calculated MB TPU air/fiber velocity at 60% opening of the air valve and experimental PP air/fiber velocity.

The MB TPU fiber reached a maximum speed of 55 m/s 3 cm from the die and, after that, decreased

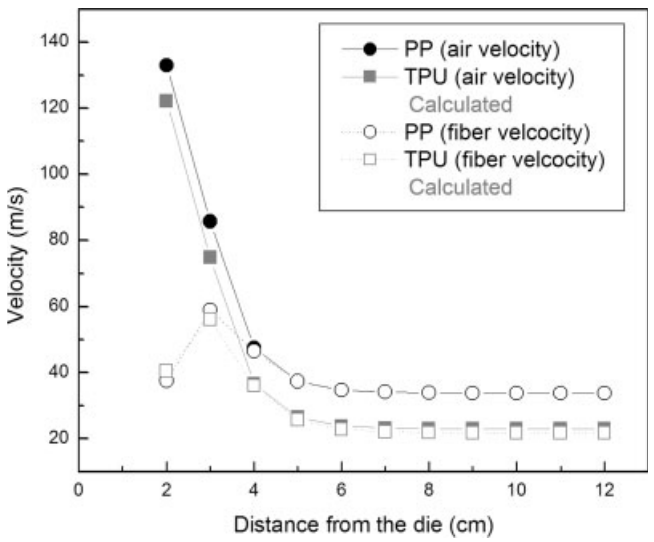

Figure 4 Air/fiber velocity of the MB PP and TPU processes at various DCDs.

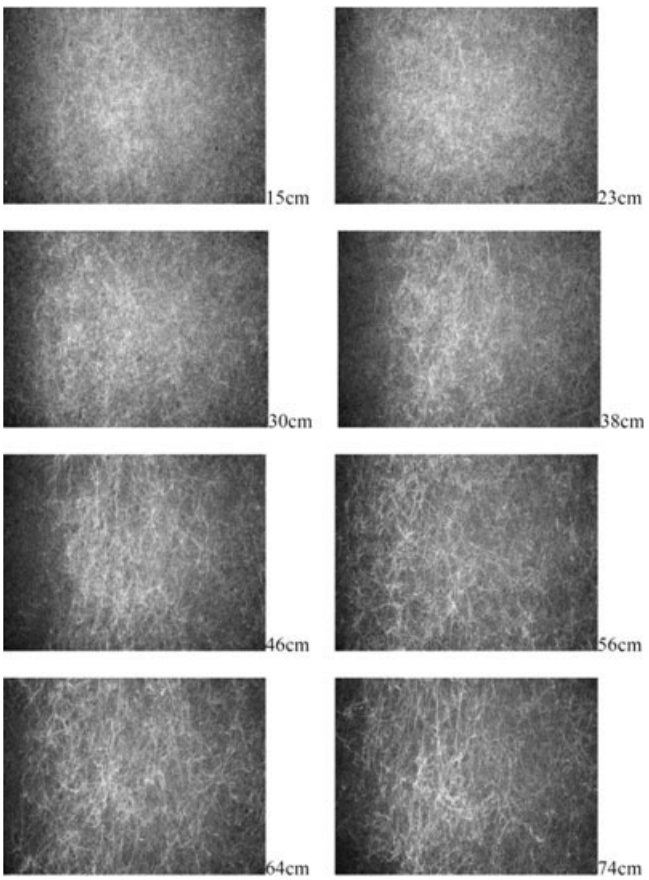

Figure 5 MB TPU fibers collected at various DCDs at the maximum speed (100 mpm) of the collector.

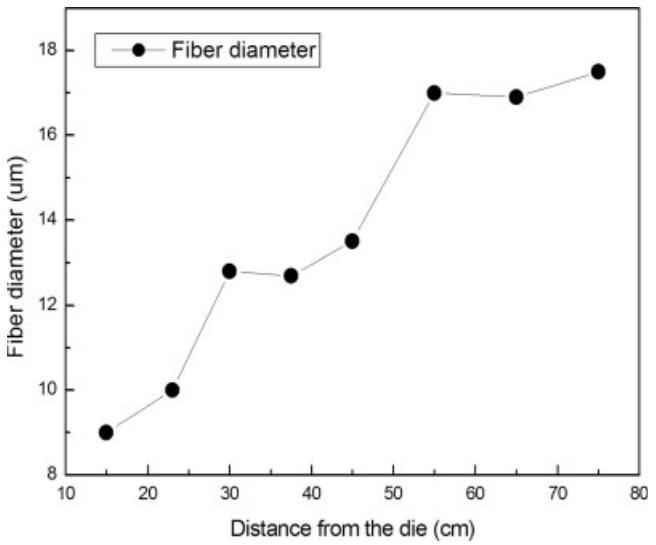

Figure 6 Fiber diameters of MB TPU_{280} webs collected at various DCDs.

with air speed; at 4 cm from the die, the velocity of the TPU fibers were identically matched with air velocity.

Figure 5 shows the MB TPU_{280} fibers captured on Kraft paper at the high speed (100 mpm) of the collector with different distances from the die. The TPU_{280} fibers were captured at 15, 23, 30, 38, 46, 56, 64, and 74 cm from the die.

Generally, the air velocity near the die was much higher than the collector speed, which caused fiber fly and made the web structure unstable. However, the fiber entanglements increased with increasing DCD at certain levels and decreased again. However, the fiber orientation of the MB TPU webs showed minor differences depending on the DCD.

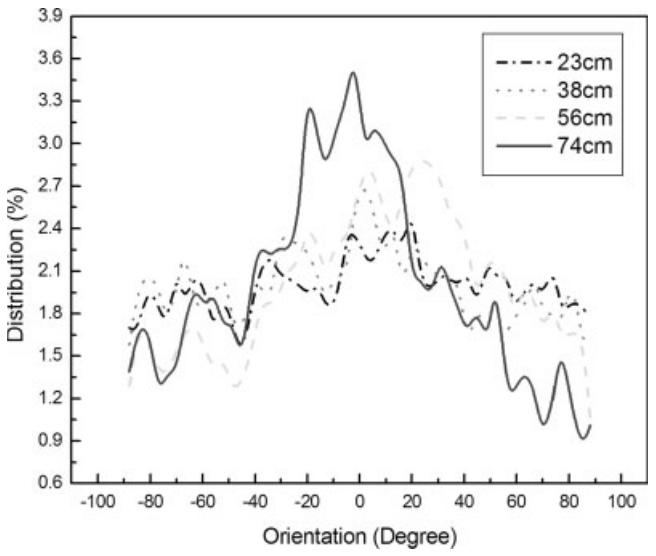

Figure 7 Distribution of the fiber bundle orientation of MB TPU_{280} collected at various DCDs.

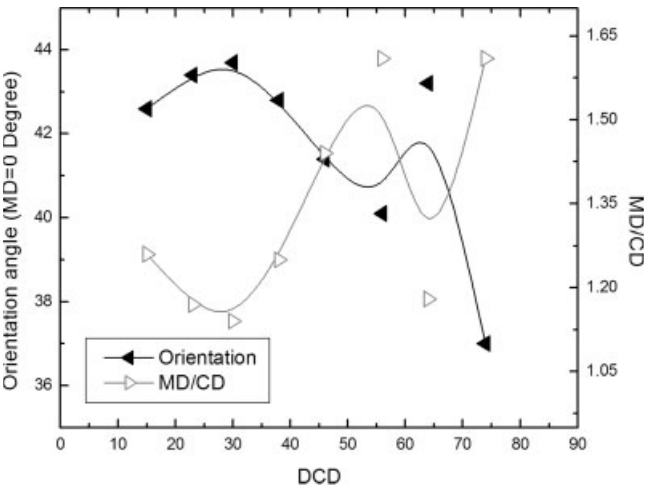

Figure 8 Orientation of the fiber bundle and MD/CD ratio of MB TPU_{280} collected at various DCDs.

Figure 5 also shows that the fiber entanglements were smaller at lower DCD than at higher DCD. However, the fiber entanglements very close to the die were not determined in this study due to excessive air turbulence and sticking of the fiber to the Kraft paper. The profiles of the MB TPU fiber diameter implied that smaller fiber diameters could be achieved near the die and that these fiber diameters increased with DCD, although the fiber bundle size could have been different from the single fiber diameters size because of the increase in fiber entanglements with increasing DCD.

Figure 6 shows the change in fiber diameters with increasing DCD. Unlike in the PP experimental study of Breese, the fiber diameters of MB TPU webs continuously increased with increasing DCD, instead of decreasing. Thus, the TPUs exhibited fundamentally different fiber diameter attenuation during the MB process. This may have been due to the differences in the thermal and elastic relaxations of TPU_{280} compared to PP.[12,13]

Figures 7 and 8 show the orientation distribution of fiber bundles with different DCDs and MD/CD ratios of the fiber bundles, respectively. The fiber bundles of the MB TPU_{280} web were generally more unidirectional in MD rather than isodirectional with increasing DCD, and the orientation of the webs was more randomly distributed near the die. The general MD/CD ratio initially showed a moderate decrease with increasing DCD, but it increased rapidly after 30 cm of DCD.

CONCLUSIONS AND RECOMMENDATIONS

MB TPU webs with small fiber diameters were obtained from TPU_{280}. Overall, the basic MB process was fundamentally valid for the MB TPU process. However, the MB TPU process was more compli-

cated than the MB PP process because the web structures and properties of MB TPUs were very sensitive to MB process conditions, especially the die/air temperature and DCD. The fiber- and web-formation studies of TPU_{280} proposed that the fiber diameters of the MB TPU fibers increased with increasing DCD and that the MB TPU fibers were less entangled at shorter DCDs; however, the orientation of fibers was more highly oriented with increasing DCD instead of being randomly distributed. These results correlated and contrasted with conventional polyolefin MB nonwovens, respectively.

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