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Structure and properties of polypropylene fibers during thermal bonding

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Abstract

The role of fiber morphology in a thermal point-bonding operation was investigated. Polypropylene fibers were spun to produce fibers with a wide range of structure, keeping the diameter same. The fibers were characterized for their structure and properties before and after bonding by differential scanning calorimeter (DSC), thermo-mechanical analysis (TMA), birefringence measurement and tensile testing. The results show that the fiber samples with different morphology vary in their bonding behavior, which in turn determine the fabric properties. Significant changes were observed in fiber structure during thermal bonding. The extent of change taking place during the process was dependent on the initial morphology of the fibers.
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Keywords: Polypropylene; Thermal bonding; DSC; TMA

1. Introduction

Thermal bonding is the most popular method of bonding used in nonwovens production. The main advantages of thermal bonding are low raw material and energy costs, products versatility, smaller space requirements, cleanliness of the process, better product quality characteristics, and increased production rates. Of the several types of thermal bonding such as area-bond calendering, point-bond calendering, through air bonding, ultrasonic bonding and radiant bonding, point-bonding is the most widely used technique [1].

During point-bonding, the bond points and the bridging fibers develop distinct properties, different from those of the virgin fibers, depending on the process variables employed. This change in properties has been suggested by several authors but has not been investigated [2–4]. So far most of the work has been done to study the effects of bonding conditions on fabric properties. Some work [5–7] has been done on the effect of fiber properties on final fabric properties. However, role of fiber morphology in point-bonding and morphological changes taking place in the fibers due to applied heat and pressure in thermal bonding have been analyzed to a limited extent. This has been mainly due to the fact that it is almost impossible to characterize the bond points, and the fibers surrounding the bond without the use of some innovative techniques.

Point bonding is used commercially for a wide range of fibers, from those with a relatively less developed morphology as in spunbonding to those with fairly well developed morphology as in staple

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fiber nonwovens. It is very important to study bonding behavior of the fibers with different morphology and to investigate the changes taking place in fiber structure during the bonding process. In this study, polypropylene fibers with a wide range of crystallinity and orientation were produced and studied for their bonding behavior, and the change in structure and properties during thermal point bonding.

2. Experimental procedure

Fiber grade polypropylene, which had a melt flow rate of 17°/min, supplied by Montell USA was used. The fibers were produced on the Fourne extruder and a spinning setup using a seven-hole die with hole diameter of 0.764 mm and *L*/*D* ratio of five. Extrusion temperature was kept constant at 230°C. Polymer throughput rate and take-up speeds were varied in order to achieve the same diameter for all the fibers. Ambient air was used as the quenching medium. Out of the six samples produced, three were as-spun with no subsequent drawing and three were drawn after spinning. Drawing was done at 140°C on a two-stage conventional drawing machine with heated rolls. The details of all the fiber samples are summarized in Table 1.

The fibers were chopped into staple fibers of length 40 mm for carding. Chopped fibers, with an appropriate level of water and spin-finish, were carded on a Saco-Lowell carding machine to produce webs with basis weight of 40 g/m^2. Carded webs were then bonded at five different bonding temperatures and at a speed of 5 m/min using a Kuster point-bonding calender having 15% bonding area.

Table 1
The details of the fiber samples produced

Sample ID	Spinning speed (m/min)	Draw ratio	Denier	Fiber diameter (μm)
As-spun 1	1000	Undrawn	2.7	20.8
As-spun 2	1500	Undrawn	2.4	19.5
As-spun 3	2000	Undrawn	2.5	19.7
Drawn 1	1000	1.5	2.4	19.9
Drawn 2	1000	2.5	2.7	20.7
Drawn 3	1000	3.5	2.4	19.5

The fiber denier was determined by measuring the mass of a known length of the fiber and then the mass converted to that of 9000 m of length to be expressed as denier. The fiber diameter and birefringence were measured using the optical microscope. Thermal analyses were done using the Mettler thermal analysis system consisting of TC11 controller, DSC25 and TMA 40. The scans were done at heating rates of 10°C/min. Percentage crystallinity of the fibers was calculated from the DSC scans. Bonded and unbonded regions of the bonded fabric were separated using a sharp pair of scissors and then characterized for their structure and properties. The tensile tests for the fibers as well as the fabrics were determined using a United Tensile Tester. For fibers, sample length used was 100 mm with a cross-head speed of 400 mm/min. For fabrics, sample length used was 127 mm with a cross-head speed of 127 mm/min.

3. Results and discussion

Six different fibers with varying structure and properties were produced for this study. As can be seen from the data in Table 1, the diameter of all the fibers was within the targeted range. The fiber diameter was kept same for all the fibers so that variations due to diameter can be reduced and the role of fiber morphology in the bonding process could be analyzed. The DSC scans of the samples (Fig. 1) show that there is an increase in the crystallinity of the fibers with increase in spinning speed or draw ratio as one can expect. This increase in crystallinity is accompanied by an increase in birefringence as well indicating the improvement in the morphology of those fibers (Table 3).

The TMA scans of the fibers are shown in Fig. 2. As shown earlier, the TMA response is very useful in predicting the bonding performance of the fibers in a thermal bonding process [8]. It is obvious from the TMA scans that well-drawn fibers are very stable and do not show any deformation until 150°C. On the other hand, the as-spun fibers start deforming at much lower temperatures. Moreover, the temperature at which the deformation starts decreases with lowering of take-up speeds. The deformation temperature was close to 120°C for as-spun 2 and 3 fibers and was about 75°C for as-spun 1. This phenomenon correlates with

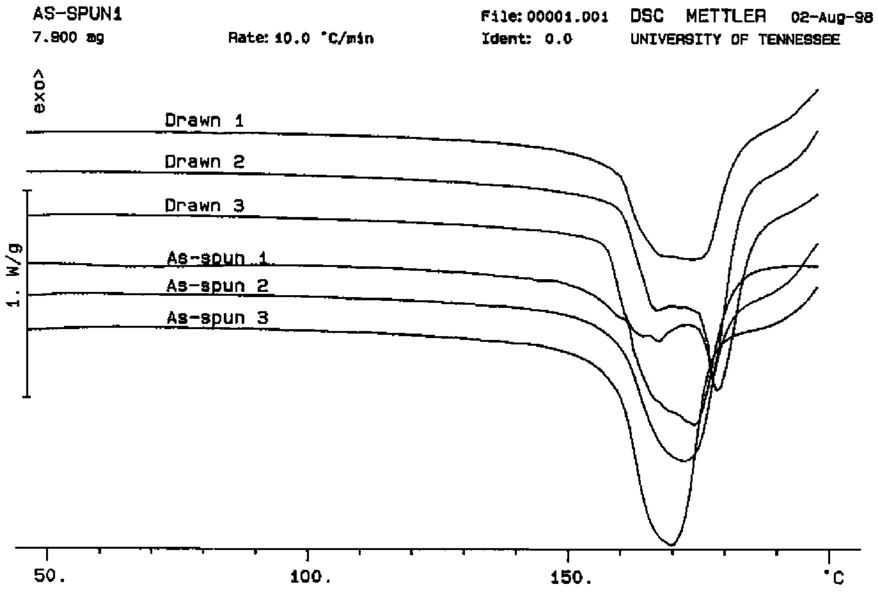


Fig. 1. DSC scans of as-spun and drawn PP fibers.

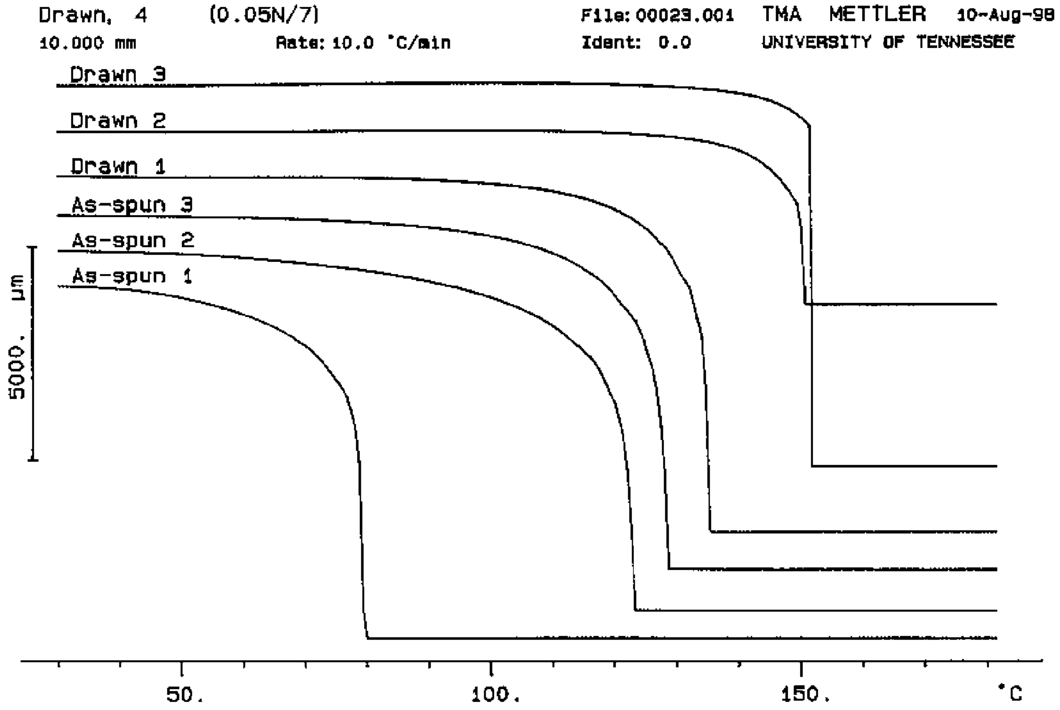


Fig. 2. TMA scans of as-spun and drawn PP fibers at high tension (0.05 N).

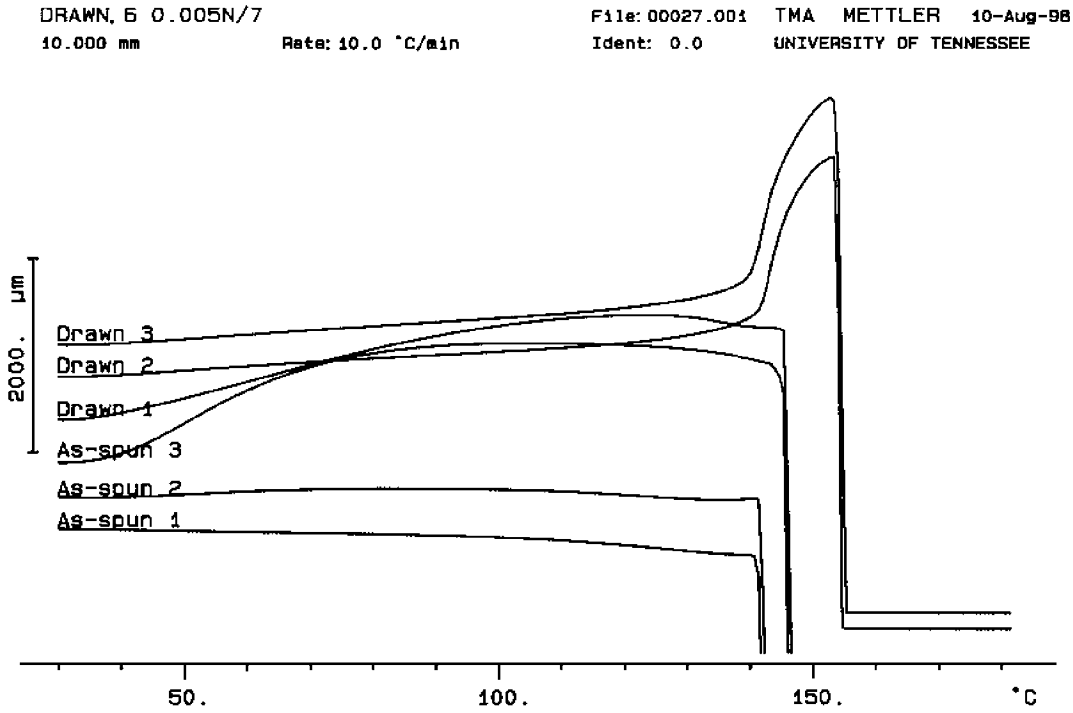


Fig. 3. TMA scans of as-spun and drawn PP fibers at lower tension (0.005 N).

the morphology development in these fibers. The TMA response is consistent with other structural parameters such as crystallinity and orientation of the fibers.

More information about fiber structure can be obtained from TMA scans done at lower tension. Scans done at lower tension show shrinkage behavior before melting and failure (Fig. 3). The extent of shrinkage and the temperature at which shrinkage takes place depend on the orientation and crystallinity of the samples. The shrinkage values and the temperatures of failure are summarized in Table 2. The values indicate a clear trend of increasing values of shrinkage with higher draw down of the fibers, that corresponds to increasing orientation in fibers. The failure temperatures also show a similar trend.

Fiber structural parameters before and after bonding are summarized in Table 3. There is an increase in crystallinity and orientation during the thermal bonding process. A significant change in these parameters has been observed even in unbonded regions. However, it is to be noted that the calendering speeds used were much lower than the commercially practiced ones. These higher residence times may have been

Table 2
Fiber thermo-mechanical properties

Sample ID	TMA shrinkage (%)	TMA failure temperature under low tension (°C)	TMA failure temperature under high tension (°C)
As-spun 1	Nil	142	79
As-spun 2	1	142	124
As-spun 3	12	146	128
Drawn 1	10	146	134
Drawn 2	24	156	150
Drawn 3	27	156	152

Table 3
Birefringence and crystallinity before and after thermal bonding

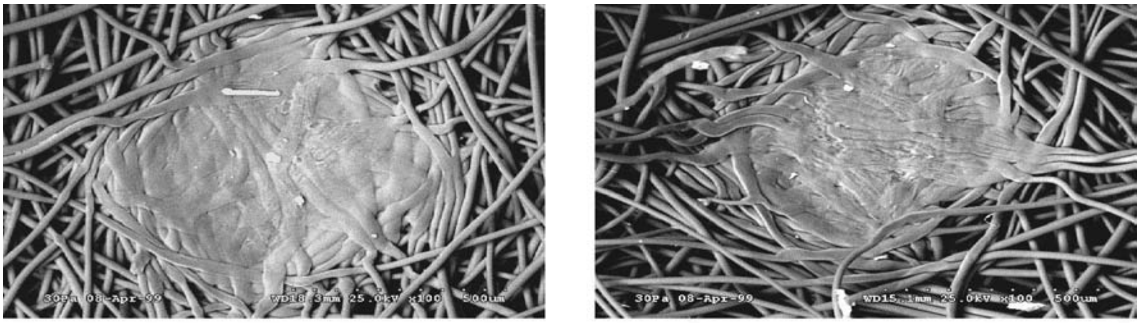
Fiber ID	Birefringence of the fibers ($x \times 10^{-3}$)		Crystallinity (%)		
	Virgin fibers	Fibers in unbonded region	Virgin fibers	Unbonded region	Bonded region
As-spun 1	19.0	23.3	36.7	41.9	50.1
As-spun 2	20.4	23.4	41.3	47.8	55.1
As-spun 3	17.8	25.0	45.0	48.3	58.8
Drawn 1	23.8	26.6	48.9	52.6	53.5
Drawn 2	29.4	29.6	53.7	54.2	54.3
Drawn 3	31.4	30.6	56.4	56.9	56.1

responsible for the changes observed in unbonded regions. In commercial operations, due to higher speeds employed, these changes may not be observable. Increase in birefringence may be attributed to annealing of the fibers at sufficiently high temperatures and under constrained dimensions. Similarly, increase in crystallinity may be attributed to further crystallization that occurs during the bonding process. Here it needs to be mentioned that extent of change in fiber structure depends upon the structure of the original fibers and process variables. The fibers with less developed morphology, such as as-spun 1 fibers, undergo more change in their structure as compared to those with more developed morphology, such as drawn 3 fibers. These changes in fiber structure may be of significant importance when predicting the fabric properties from constituent fiber properties.

The relationship between fiber and fabric tensile properties can be seen from the data in Table 4. Fabric strength and elongation given in the table are the

Table 4
Fiber and fabric tensile properties

Fiber ID	Fiber strength (g/tex)	Fabric strength (g/tex)	Fiber breaking elongation (%)	Fabric breaking elongation (%)
As-spun 1	26	5.4	290	82
As-spun 2	43	5.6	280	73
As-spun 3	58	4.3	190	47
Drawn 1	58	3.3	160	33
Drawn 2	67	1.7	60	14
Drawn 3	77	1.2	25	14



As-spun 1 fibers (x100) **Drawn 1 fibers (x100)**

Fig. 4. SEM photographs of bond points from less drawn and highly drawn fibers.

maximum that could be achieved for a given fiber. Fibers with less developed morphology, i.e. lower molecular orientation and lower crystallinity, showed relatively poor fiber properties but very good fabric properties in terms of strength and toughness. Fracture analysis of the samples showed that the fibers with highly developed morphology tend to form a weak and brittle bond in the fabric, which in turn lead to poor fabric properties. Another important factor which may be responsible for poor fabric properties in the case of highly drawn fibers is the poor load sharing between the fibers due to their lower breaking elongation. SEM photographs of the bond area (Fig. 4) for highly drawn and low-speed spun fibers clearly show the differences. For as-spun fibers with less developed morphology, the fiber melts and flows better forming a good bond. On the other hand, the highly drawn fibers do not melt and flow to form a filmlike bond in spite of the long residence time. This difference in bonding is responsible for the observed variation in their properties.

4. Conclusions

Fibers undergo structural changes in bonded as well as unbonded regions of the bonded fabric during thermal point-bonding process. The extent of change in fiber structure depends upon the structure of original fibers and process variables employed. The fibers with different morphology differ in their bonding behavior. The fibers with high molecular orientation and crystallinity tend to form a weak and brittle bond due to lack of polymer flow. On the other hand, fibers with lower tenacity and higher breaking elongation result in better bonding and higher fabric tensile properties. This is also due to the differences in failure mechanisms in these fabrics, which is a result of differences in bonding.

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