Thermal Bonding of Polypropylene Nonwovens: Effect of Bonding Variables on the Structure and Properties of the Fabrics

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ABSTRACT: Properties of the point-bonded nonwoven fabrics are dependent on the bonding conditions, in addition to those of the polymer/fiber. Thermally bonded carded webs were produced and characterized to investigate the role of bond area, bond size, and bonding temperature on the structure and properties of point-bonded nonwoven fabrics. It was observed that the bond strength increases with bond area and bond size. The effects of bond area and bond size on fiber morphology were negligible. Significant morphological differences were observed in the bonded and the unbonded regions of the thermally bonded webs. To see how the staple fiber studies relate to the behavior of continuous filaments, similar sets of samples were produced and characterized by using the spunbond system. The observed trends for properties with respect to bonding conditions were similar for spunbond samples. © 2004 Wiley Periodicals, Inc. J Appl Polym Sci 92: 3593–3600, 2004

Key words: poly(propylene) (PP); fibers; thermal properties; WAXS; structure-property relations

INTRODUCTION

Thermal bonding is the most popular method of bonding used in nonwovens manufacture. It offers high production rates because bonding is accomplished at high speed with heated calender rolls or ovens. Thermal bonding process has been used successfully with a number of thermoplastic fibers. Among the various types of thermal bonding, point bonding is the most widely used technique.[1]

Nonwoven fabric properties are determined by the polymer/fiber type, the characteristics of bond points, and, in particular, by the stress–strain relationship of the bridging fibers. During point bonding, the bond points and the bridging fibers develop distinct properties. Among those that influence the properties are the bond area and bond size, which also affect the final fabric properties such as the strength and stiffness.[2] Effect of fiber morphology on the structure and properties of thermal-bonded polypropylene nonwovens has been extensively studied.[3–7] Limited research has been done to understand how the bond-area and bond-size variables affect the final properties of the thermal point-bonded fabric. This has been mainly due to the fact that it is hard to produce such samples, and moreover, it is a tedious and strenuous procedure to characterize the bond points and the fibers surrounding the bond.

Because thermal point bonding process has so many advantages, it is important to determine how variables such as bond area and bond size along with bonding temperature affect the final properties of the web. In this regard, the main objectives of this research were as follows: (1) to examine the changes taking place in the fibers in the bonded region, unbonded region, and bond vicinity during thermal bonding; (2) to understand the failure behavior of thermally point-bonded fabrics; and (3) to be able to suggest optimum processing conditions for thermal bonding based on variables such as bond area, bond size, and bonding temperature. A series of samples produced under various bonding conditions were thoroughly characterized. Studies were done with both staple and spunbond fibers.

EXPERIMENTAL

Materials and processing

Polypropylene staple fibers produced at Fiber Visions, Inc. (Covington, CA) were carded and then calendered at their laboratories. Bonding was carried out by using different sets of pattern rolls, to obtain a range of bond areas and bond sizes (Table I) so that a comparison could be made. The effective bond areas used varied from 10.8 to 23.2%. The bonding temperature varied from 144 to 172°C in increments of 4°C for different

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TABLE I
Details of Nonwoven Samples Produced from PP Staple Fibers

Sample series	Bond area (%)	Bond size (mm × mm)	Area of the individual bond (sq mm)
I	10.8	0.51 × 0.98	0.50
II	23.2	0.56 × 1.02	0.57
III	15.2	0.51 × 0.99	0.50
IV	18.8	0.63 × 1.34	0.84
V	19.9	0.76 × 1.45	1.10

fabrics. The nip pressure of 3.15 kg/cm^2 was kept constant for all the samples, and production speed of the samples was 76.2 m/min.

Spunbond studies were carried out by using a 35 MFR PP provided by Exxon Mobil (Baytown, TX). The Spunbond fiber webs were prepared at Kimberly Clark (Roswell, GA) and calendered at Fiber Visions (Covington, GA). A total of six series of samples was produced at temperatures varying from 120 to 160°C in increments of 10°C. Bonding was carried out by using different sets of pattern rolls, as used for carded webs.

Characterization of the webs

Fiber diameter and birefringence were measured by using an optical microscope with a compensator. Bonded and unbonded regions were carefully separated from the web by using a pair of sharp scissors and were analyzed for crystal size. Crystal size was measured by using the Rigaku WAXD system in transmission mode. Crystal size was calculated by using the Scherrer equation from the measured full-width half-maximum intensity of reflection peaks in the equatorial scans.[8] Equatorial scans were obtained from $2\theta = 10°$ to 30° in steps of 0.01° and a dwell time of 4 s. Duco cement, which does not show any diffraction pattern, was used as glue for sample preparation. The Rigaku WAXD system was operated at 35 kV and 30 mA.

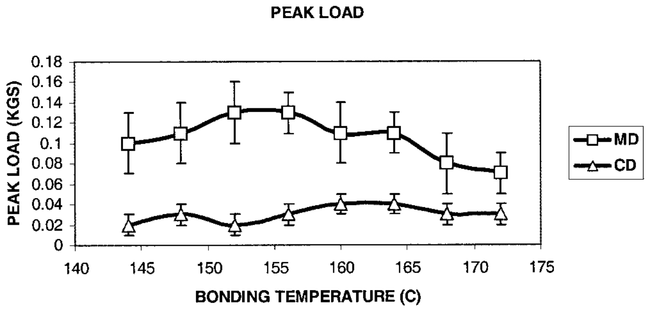


Figure 2 Peak load versus bonding temperature for Set I in MD and CD.

A single bond-strip tensile test developed earlier[3] to estimate the bond strength and the degree of load sharing between the fibers during tensile deformation was used. A tiny strip of size 80 × 5 mm was cut from the web. The strip was cut in the middle in the width direction from two sides to leave only one bond uncut in the middle of the strip. The strip was then subjected to a conventional tensile test. The test was conducted on a United Tensile Tester with a gauge length of 2.54 cm (1 in.) and an extension rate of 1.27 cm/min (0.5 in./min). A total of 20 tests were done for each sample. Also, tensile strip test was done as described in ASTM D1117-80 for fabrics. A gauge length of 12.7 cm (5 in.), width of 2.54 cm, and an extension rate of 12.7 cm/min were used for samples in both the machine and the cross direction.

Tear strength was determined by using the Elmendorf tear tester. INDA standard test 100.1 (ASTM D5734) was the method used to measure the tear strength. Measurements were taken along the machine and cross directions. Bending length was determined by using the FRL cantilever tester. Stiffness measurements for the fabrics were conducted as per the INDA standard test 90.1 (ASTM D5732). Fabrics were cut to 25.4 × 2.54 cm (10 × 1 in.) strips along the machine direction and five strips were measured for each fabric. Scanning electron microscopy (SEM) images of the tested samples were taken by using a

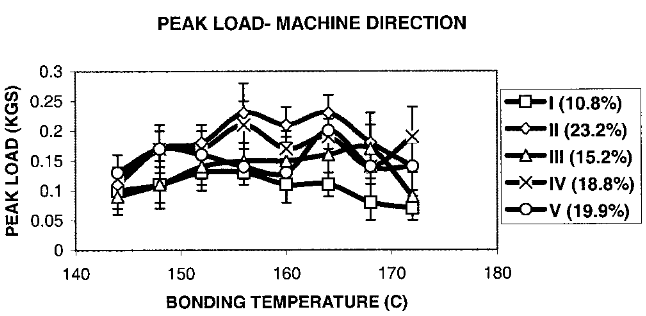


Figure 1 Peak load from single bond-strip test (MD) versus bonding temperature for staple fiber webs.

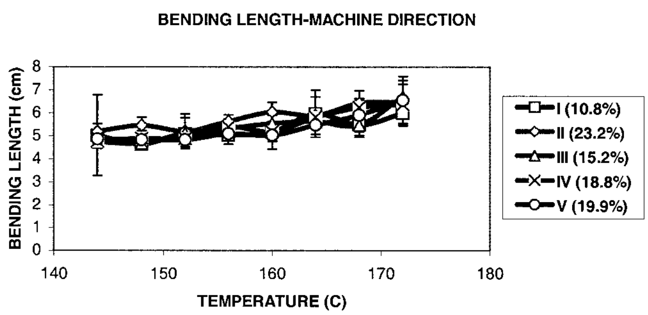


Figure 3 Bending length (MD) versus bonding temperature for staple fiber webs.

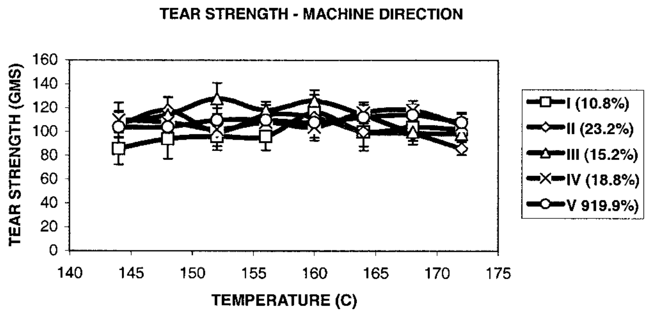


Figure 4 Tear strength versus bonding temperature.

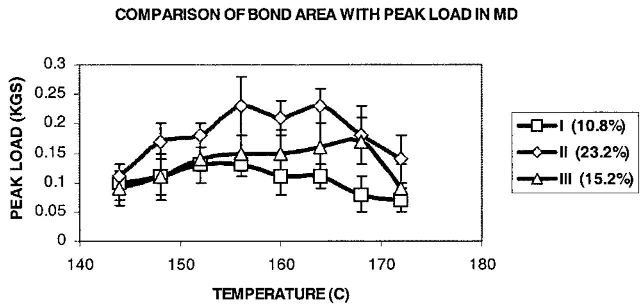


Figure 5 Comparison of bond area with peak load for staple fiber webs.

Hitachi S-3500N electron microscope. Back-scattered images with 30 Pa gas were taken to minimize the problems due to static charge generation.

RESULTS AND DISCUSSION

Staple fiber studies

Effect of bonding temperature

The single bond tensile-strength values of the webs bonded over a range of bonding temperatures for all the different bond areas are shown in Figure 1. From the data, it is obvious that with an increase in bonding temperature, the web strength increases up to a maximum and then decreases with a further increase in temperature. This observation is consistent with findings from earlier studies in comparable systems.[3,7] The maximum strength values observed, and the temperature at which they happen, are slightly different for different bond areas. The details are discussed in the following sections. It is also observed that, overall, the fabrics were not random. The tensile data in the two directions compared in Figure 2 clearly indicate that there is a large difference between the values of peak loads in the two directions. The difference in peak load between the two directions is larger at lower temperatures. With an increase in bonding temperature, the difference decreases, largely due to a drop in the strength values in the machine direction (MD). This change in values with bonding temperature is attributable to a change in failure mechanism, as discussed later. Bending length values increase slightly with an increase in bonding temperature (Fig. 3), indicating that the fabric becomes stiffer with higher bonding temperature, which is consistent with what can be expected. Tear-strength (Fig. 4) values show smaller changes, but the indication is that overall there is a decrease in tear strength with bonding temperature, due to the reduced mobility of the fibers. Here, we can observe that the values in the cross direction (CD) are higher than in the MD along the range of bonding temperature studied.

Fiber morphology tests were done by birefringence and X-ray diffraction to see the effect of bond area and bond size. Fiber diameter and fiber birefringence in the unbonded regions remained the same for all the samples, indicating the changes taking place during bonding in these cases were minimal. However, the crystal sizes (Table II) showed differences in the bonded and unbonded regions, with the values being higher in the bonded areas, and crystal size increasing with bonding temperature. In the unbonded areas, crystal sizes were in the same range for all the process conditions investigated.

Effect of bond area

The effect of bond area was analyzed by using three sets of samples, which vary in bond area, but have

TABLE II
Effect of Bonding Temperature on Crystal Size

Bonding temperature (°C)	Crystal size (A°) (unbonded area)	Crystal size (A°) (bonded area)
144	106	156
148	107	171
156	106	170
160	102	171
168	110	163
172	108	179

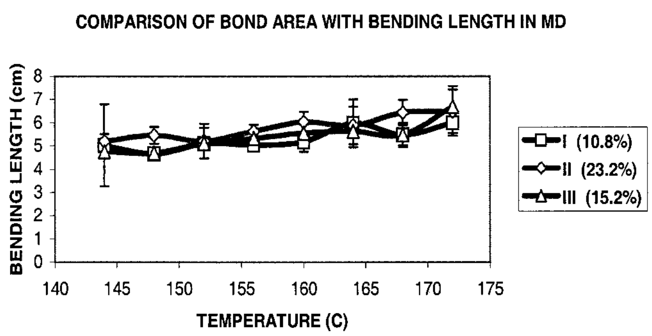


Figure 6 Comparison of bond area with bending length for staple fiber webs.

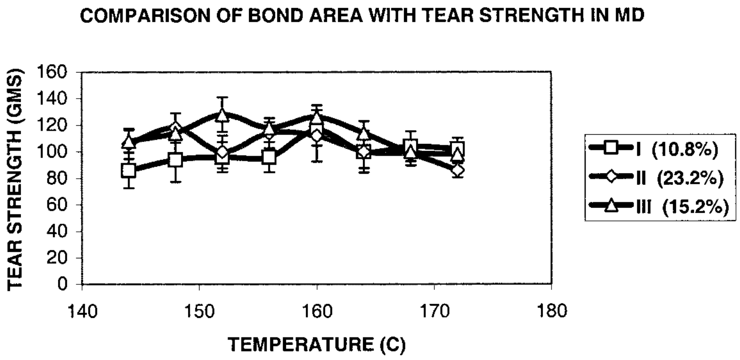


Figure 7 Comparison of bond area with tear strength for staple fiber webs.

bond size in the same range. For this, Set I (10.8%), Set III (15.2%), and Set II (23.2%) were chosen, so that one can clearly see the effect of differences in bond area. The peak load values from single bond-strip test in MD for the three sets of samples are shown in Figure 5. It is observed that the samples in Set II (23.2%) show higher strength along the range of bonding temperature investigated, when compared with the other two sets of samples, which had lower bond areas compared to Set II. This shows that the strength values are higher with an increase in bond area. There is a simultaneous decrease in elongation and an increase in modulus as well. These differences may also be attributable to differences in the failure mechanism. As a result of more efficient bonding with increase in bond temperature, the web becomes stiffer. Figure 6 shows the observed bending length values, which clearly show the trend with temperature for all the samples. The bending length differences seen in all the samples across the range of the bonding temperatures are very small. The tear-strength values of the three sets of samples are compared in Figure 7. It is observed that the webs with higher bond areas (Set II and Set III) show higher tear-strength values along the low-to-optimum range of bonding temperature when compared to web of Set I (10.8%). This unusual observation is due to the fact that at low bonding temperatures, effective bonding is very poor for low-bond area samples. However, at higher bonding temperatures, lower bond-area webs perform better against tear, as overbonding in higher bond-area samples produces easily tearable fabrics. The differences in the tear-strength values for all the three sets of samples are minimal.

Effect of bond size

For comparing the effect of bond size, three sample series selected are Set III (0.51 × 0.99 mm), Set IV (0.63 × 1.34 mm), and Set V (0.0.76 × 1.45 mm). These samples are selected in such a way that the bond areas are in the same range, and bond-area differences do not interfere with the bond-size differences. Figure 8. shows the values of the peak load of the three samples along the range of bonding temperature from the single bond-strip test. It is observed that the webs having higher bond sizes show higher load values compared to samples with lower bond sizes. Also, there is a slight increase in the peak load values with an increase in the bonding temperature for all three sets of samples. The differences observed for tear-strength values for the three sets of samples were very minimal. It is obvious from the data in Figure 9 that only small differences in bending length values are observed.

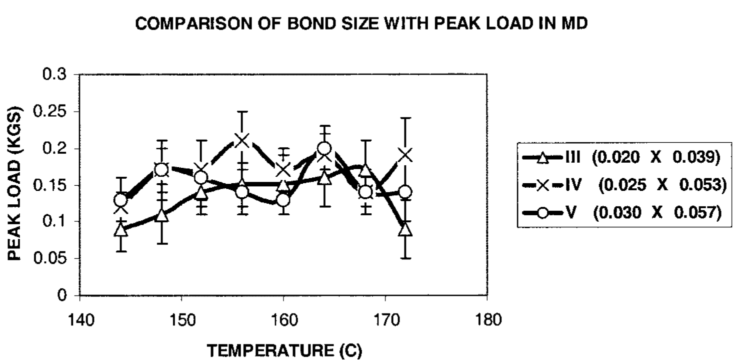


Figure 8 Comparison of bond size with peak load (MD) for staple fiber webs.

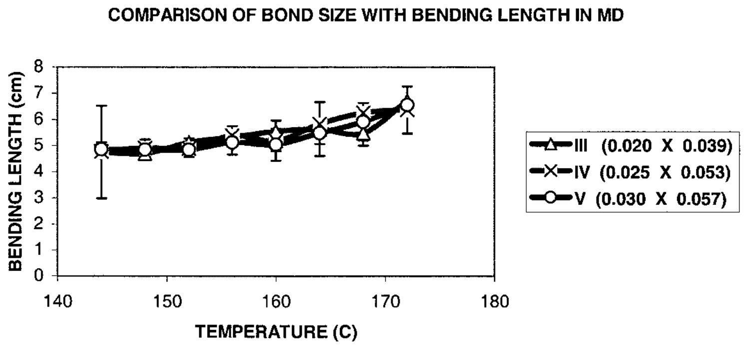


Figure 9 Comparison of bond size with bending length for staple fiber webs.

Despite minimal differences in bending length values, all three sets of samples show an increase in stiffness values along the range of bonding temperature. This is true as the webs become stiffer with the increase in the calender temperature.

Failure mechanism

SEM pictures were taken for samples produced at lower, medium (optimum), and higher bonding temperature at intermediate (65–80% of the breaking load) and failure stages. Samples, stretched to intermediate stages, were examined to see how the bond deforms during single bond-tensile testing. At a lower bonding temperature of 148°C, we can see that the bond starts disintegrating (i.e., fibers start pulling out one by one from the bond point) (Fig. 10). The first picture shows the neighboring bond point, where the bond stays intact. It is obvious that at the neighboring bond point (either above or below the bond at the notch), the fibers start pulling out from the bond and the bond disintegrates. This is the main reason the bond strength is less at lower bonding temperatures.

As observed from Figure 11, webs bonded at medium bonding temperature (160°C); at the intermediate stage, the fibers stretch out from the bond point, and at the neighboring bond, reorientation of fibers takes place making the bond point weak. Later on, fiber reorientation takes place and slight disintegration of the bond can be seen. That is why, at bonding temperatures around 160°C, the web strength and elongation were higher. At higher bonding temperature of 172°C (Fig. 12), it was observed that the filaments break at the bond perimeter and the bond is still intact. In this case, the breaking load and elongation were lower, but the modulus was higher.

The same phenomena of fracture mechanism that was observed from the tensile strips to see the effect of bonding temperature was also observed for the effect of bond area and bond size (i.e., at lower bonding temperatures, bond starts disintegrating, at medium bonding temperatures, reorientation of the fibers and slight disintegration takes place, making the bond weak, and at high bonding temperatures, the filaments break at the bond perimeter at both intermediate and failure stages). There was no distinct differ-

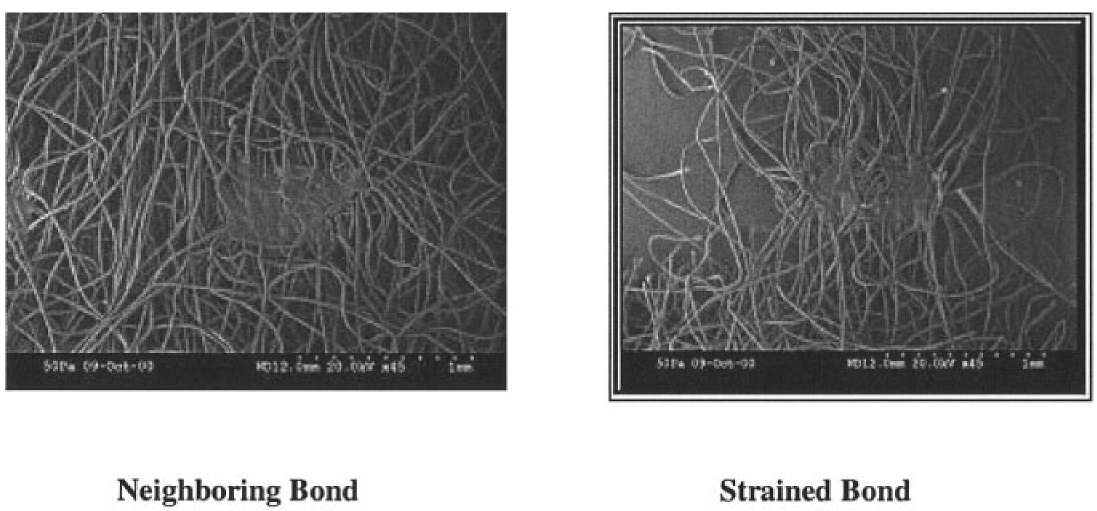


Figure 10 SEM image showing disintegration of bond at 148°C.

Neighboring Bond Strained Bond

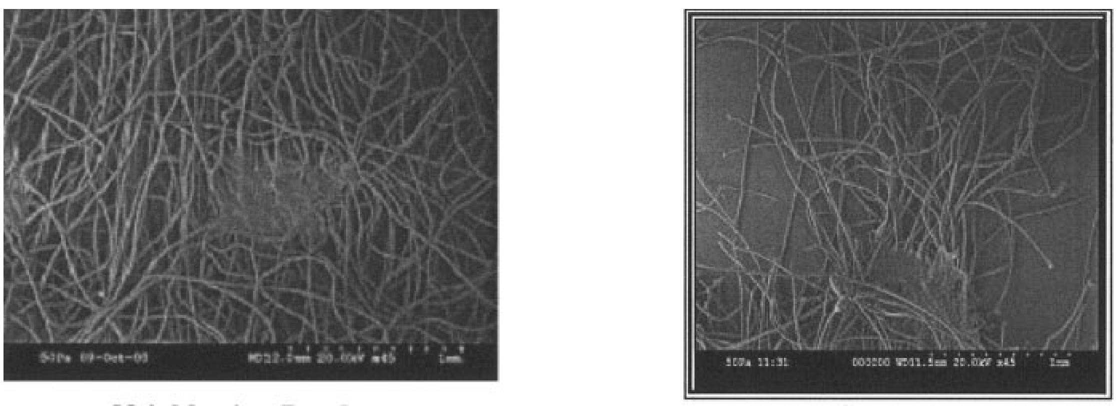
Figure 11 SEM image showing disintegration of bond at 160°C.

ence in failure mechanism with different bond-area and bond-size samples.

Spunbond studies

For spunbond samples, in addition to the single bond-strip test, a strip tensile test was also carried out, as the stress–strain response is determined, to a significant extent, by the changes taking place in the unbonded region, as well as by the load transfer between the bonds. Peak load values (from single bond-strip test) of all the sample series are shown in Figure 13. The strength values show the expected trend with the increase in bond temperature for all the series. In the case of the strip tensile test, it is observed that the web strengths follow similar trends as seen with single bond tensile test, except that the values of the fabric strip test are much higher than the single bond test values as shown in Figure 14. The web tensile strength increases up to an optimum bonding temperature and then decreases with the increase in bond temperature. The peak-elongation values (Fig. 15) show a smaller increase with increase in bond temperature. As a result of more efficient bonding with increase in bond temperature, the web becomes stiffer and all the samples show a slight increase (Fig. 16) in bending length values with an increase in bond temperature.

Although only the properties in the machine direction are reported here, testing was carried out in CD as well. It was observed that there is a large difference between the values in the two directions. The difference between the loads was small at lower temperatures. With an increase in bonding temperature, the difference increases, largely due to the increase in the strength values in the MD. These observations are consistent with the trends observed with staple fiber webs. This change in values with bonding temperature is attributable to a change in the failure mechanism. The optimum temperature for these samples was observed to be about 150°C, which results in the combination of maximum strength and elongation value from the tensile strip test results. The tear-



Neighboring Bond Strained Bond

Figure 12 SEM image showing filaments breaking the bond edge at 172°C.

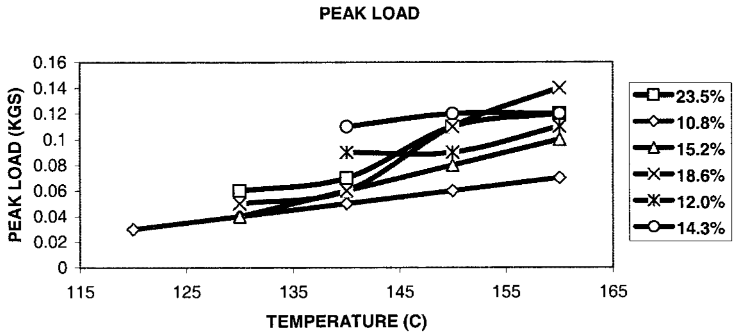


Figure 13 Peak load from single bond strip results in MD versus bonding temperature for all spunbond samples.

strength values for this sample in both MD and CD are shown in Figure 17. The tear-strength values in the MD are higher than in the CD at lower bonding temperatures. This difference between MD and CD reduces with an increase in bonding temperature and tear-strength values reduce in both directions with an increase in bonding temperature. However, the actual tear-strength values are much higher for spunbond fabrics compared to the values obtained with staple fiber webs of similar mass per unit area.

The effect of bond area was studied by using three sets of samples, with different bond areas, but bond size in the same range, so that the differences occurring due to bond size were minimal and the effect of bond area on fiber morphology and strength of the fabric could be analyzed. For this analysis, the three samples compared have bond areas of 10.8, 15.2, and 23.5%, respectively. From the single bond-strip test data, it was observed that the sample having high-bond area 23.5% had higher strength across the range of the bonding temperature when compared to the other two sets of samples. At low temperatures, all three webs showed low strength and with an increase in temperature, the peak load values increased for all three bond areas, making the webs much stiffer. For the strip tensile test values, it is observed that the peak load values for the samples with higher bond areas reach a maximum and then fall off, and these values are higher than those samples having lower bond area with an increase in bonding temperature. The tear-strength results correlate with the strip tensile results (i.e., it is tougher to tear the webs bonded at low bonding temperatures than those bonded at higher temperatures). It can be clearly seen from Figure 17 that webs having higher bond areas show higher tear-strength values at low-bonding temperatures and then decrease as the bonding temperature increases. This is true for the remaining webs as well. It is also observed that the differences in values of bending length (Fig. 16) are not as large as seen for strength values. However, the sample with higher bond area (23.5%) shows higher bending length compared to the sample having bond area of 10.8% with increase in bond temperature. These differences reflect bond-area differences.

When data for different bond sizes are compared, it is observed that the webs having higher bond sizes show higher peak load values, as obtained from the single bond-strip test. At lower bonding temperatures, webs with different bond sizes show lower strengths, and as the temperature increases, the strength also increases with webs having higher bond sizes showing higher strength values compared to the webs of smaller bond size. These differences can be attributed to the differences in the failure mechanism, as explained in the previous section. From the tensile strip test results, it is observed that the webs with different bond sizes increase in strength with an increase in the

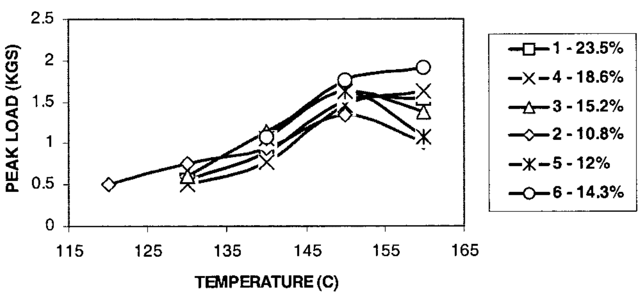


Figure 14 Peak load from tensile strip results in MD versus bonding temperature for all spunbond samples.

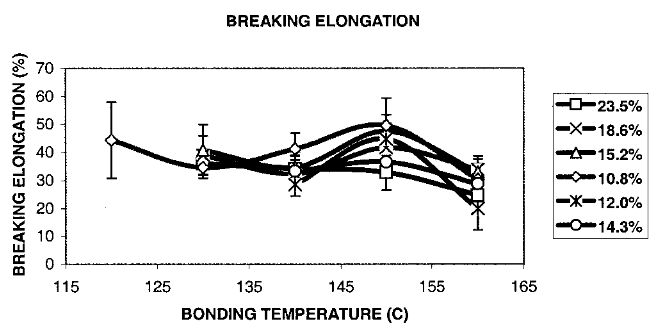


Figure 15 Breaking elongation values (MD) from tensile strip test for spunbond samples.

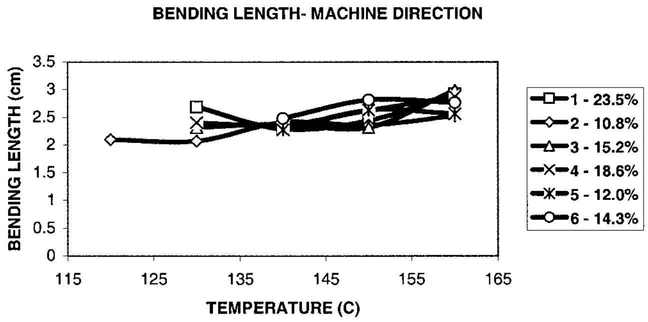


Figure 16 Bending length values (MD) for spunbond samples.

bonding temperature, just as observed from the single bond-test results. The webs having larger bond size have higher tear strength at lower bonding temperature and then the tear strength decreases as the temperature increases. This is true for the remaining set of samples (i.e., as the bonding temperature increases, the tear-strength values decrease). The bending length values show almost the same pattern for all the samples. At higher temperature (160°C), the values are almost the same for all three sets of samples. It appears that the effect of bond size on the stiffness values is minimal, which is consistent with the observations in the staple fiber studies as well.

From the data in Table III, we can see that the values of fiber birefringence and fiber diameter in the unbonded regions is in the same range for the sample at low- and high-bonding temperatures, indicating that the changes taking place during calendering, with short intervals of calendering, are very low. However, the crystal size values in the unbonded regions remain in the same range and the crystal size values of bonded regions are higher than that of the unbonded regions.

CONCLUSION

The series of samples produced under various bonding conditions, using both staple fibers and spunbond

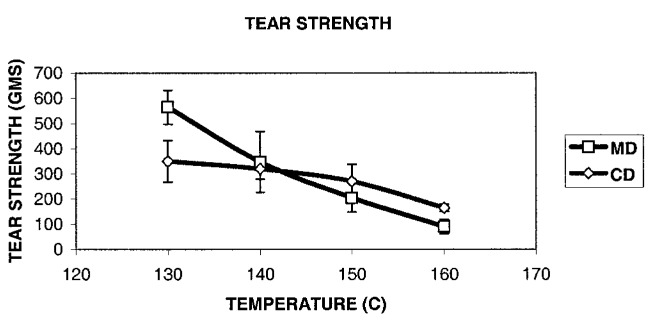


Figure 17 Tear-strength values for 23.5% area bonded spunbond webs.

TABLE III
Effect of Bond Area on the Morphological Parameters of Spunbond Fabrics

Bond area	Fiber diameter (μm)	Birefringence	Crystal size (A°) (unbonded)	Crystal size (A°) (bonded)
10.8%	20.2	0.021	107	162
15.2%	20.1	0.020	112	162
23.5%	19.9	0.019	118	162

fibers, were thoroughly characterized. Based on this study, the following conclusions can be drawn as far as the effect of bond temperature, bond area, and bond size are concerned: Bond strength increases up to a maximum and then decreases with increase in bonding temperature for both staple fiber and spunbond webs. The optimum bonding temperature for spunbond studies was shown to be 150°C. Bond strength increases with increase in bond area for both staple and spunbond samples. Bond strength increases with increase in bond size for staple and spunbond webs. Effect of bonding temperature, bond area, and bond size on fiber morphology in the unbonded region is negligible for both staple and spunbond webs. In all cases, crystal sizes were different in the unbonded and bonded regions, values being higher in the bonded regions. This is due to the effect of heat in the bonded region. However, in the unbonded regions, the effect is negligible at these processing conditions, for fibers investigated, which may be due to fairly well-developed structure of the fibers.

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