Thermal Bonding of Polypropylene Films and Fibers

Raghavendra R. Hegde,[1] Gajanan S. Bhat,[1] R. A. Campbell[2]

[1]*Department of Materials Science and Engineering, The University of Tennessee, Knoxville, Tennessee 37996–2200*
[2]*Sunoco Polymers, Pittsburgh, Pennsylvania*

Received 29 July 2007; accepted 12 March 2008
DOI 10.1002/app.28901
Published online in 8 September 2008 Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: The thermal bonding behavior of different grades of polypropylene was studied in this research. Initial bonding studies were done with polypropylene films of different grades of polymer with varying morphology, and the studies were extended to polypropylene fibers. Polypropylene fibers manufactured with different cross-sections, deniers, polymer melt-flow rates, and different processing conditions were bonded under various conditions. The effect of film structure, properties, and bonding conditions on the bonding efficiency was studied by comparing the tensile strength of bonded films. Thermal bonding was carried for a range of temperatures covering poor, optimum, and over bonding. Changes taking place to the polymer in bond point and the original surface were analyzed using the SEM. Higher bond strength was observed in the vicinity of melting temperature and the strength reduced with a further increase in bonding temperature. The frequent failure point was observed at the bond edge crossover points where film undergoes maximum thickness transition. Lower pressure and shorter time were found to be appropriate for bonding. Films with lower orientation formed better bonds. The optimum bond strength and the optimum bonding temperature observed were different for different polymers. Fiber bond strength results were similar to the results observed in the case of films with respect to the bonding temperatures studied. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 110: 3047–3058, 2008

Key words: bond strength; poly(propylene) (PP); thermal bonding; thermal properties

INTRODUCTION

Thermal point bonding is one of the most eminent steps in the production of nonwovens and polymer composites where a thermoplastic film, fiber, or powder is made to hold the constituent elements of the web by the thermal energy.[1] Nonwoven production by the thermal bonding eliminates the requirement of chemical binders. Low energy consumption, a high production rate, environmentally benign, and superior properties of resultant fabrics are all the added advantages of thermal bonding.[2]

Polypropylene is a very versatile polymer available in a wide variety of forms such as staple, bicomponent staple, monofilament, multifilament, slit film yarns, slit-fibrillated film yarns, spunbond, melt blown nonwovens, synthetic pulps, and extruded nettings. A relatively lower melting point makes it ideal for thermal bonding and presently it is one of the major polymers for the production of nonwovens by spunbond and meltblown techniques. Metallocene catalyzed resins typically melt at temperatures that are 10–15°C below that of the Ziegler-Natta resins with similar melt flow rates. Metallocene catalyzed polypropylene resin has a narrower molecular weight distribution (MWD) and lower defect distribution compared with the Ziegler-Natta resins, and this results in higher tensile properties. They also crystallize more slowly and frequently develop lower crystallinity during processing than their Ziegler-Natta counterparts. These differences lead to substantial differences in the structure and properties of the fibers produced from these two types of polypropylene resins and will have significant effects on the properties of nonwovens produced through the thermal bonding process.[3]

Recent studies reveal the changes in morphology occurring during thermal bonding of polypropylene fibers.[4–7] It has been shown that requirements to make strong nonwoven fabrics substantially differ from the requirements to form strong fibers. The morphology of spun fibers and ultimate thermal bonded nonwoven web properties depends on the material variables and processing conditions. During thermal bonding, the individual fibers are joined together by the external force in-terms of pressure and the temperature of a calender roller with a pattern. Inter-fiber connection requires sufficient melting and diffusion of polymer chains. Formation of a bond involves the melting of ordered chains, diffusion, and the entanglements of chains in between the fibers.

It is believed that the bonding occurs only at the surface of two fibers in contact, only in a region as

Correspondence to: G. S. Bhat (gbhat@utk.edu).
Contract grant sponsor: NCRC.

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TABLE I
Properties of Films Supplied by Sunoco Chemicals

Film sample	Thickness (mm)	Crystallinity (%)	Xylene soluble (%)
S-A	0.085	38.93	4.7
S-B	0.059	38.81	4.8
S-C	0.03	30.59	3.6
S-D	0.051	33.83	2.3
S-E	0.05	39.25	2

thick as a single chain, ~ 5 nm. It was also observed that birefringence drops by ~ 50% within two fiber diameters of the bond edge indicating a substantial loss of strength at the bond edge. For a constituent fiber to regain strength at bond spot, these fibers have to regain or restructure new association within the chain segments. The structural integrity of fibers is lost during bond formation because in the commercial thermal bonding process, fibers remain in the bond spot just for a fraction of a second and there is no sufficient time for cooling or to regain the lost structure. Also, the compression of fibers under hot calendering roller damages fibers mechanically. The pressure of the calender roller generates stress concentration on fibers at bond spot. Fibers at the centerline of bond spot will be strained more compared to the fibers at the edge.[8] Fibers with lower orientation and crystallinity form stronger thermal point bonded nonwovens presumably because the fibers can deform more before rupturing at the bond edge by sharing the load better.[9] Melt gradient fibers and many of the bi-component fibers perform better in thermal bonding because of differences in surface and bulk properties. The molecular weight and MWD may be different at the surface than in the bulk fiber. Crystallinity, rate of melting, and crystallization are different at the surface than at the bulk.[10] In the earlier studies, effects of polymer variables on the morphology and properties of melt spun iPP fibers have been extensively studied.[11,12]

Primary material variables such as molecular weight distribution, stereoregularity, the presence of nucleating agents in the resin, composition, and distribution of comonomer influence on the properties such as melt flow rate (MFR), rheology, melting temperature, and crystallization kinetics were investigated.[13] Studies have also included the comparison of the morphology and properties of fibers and spunbond nonwovens produced from Ziegler-Natta catalyzed resins to those of fibers produced from metallocene-catalyzed resins with the same MFR. The metallocene catalyzed polypropylene formed better quality fiber and bonded fabric than the Ziegler-Natta catalyzed polypropylene.[14]

Polymer type, copolymer, polymer MFR, and MWD, all have an influence on the structure and properties of the spun fibers. Misra et al. studied the spinnability of polypropylene with different MFR and MWD.[15] It was found that a higher MW resulted in a higher orientation, crystallinity, and stronger fibers. Broader MWD resulted in a high density and low birefringence in the fibers.

Though extensive research has been done in earlier studies, the effect of important material variables like polymer grade, fiber structure, cross-section and its effect on thermal bonding is not clear. The objective of this research was to (1) understand the thermal bonding process with raw material variables like polymer MWD, MFR, and the structural variable like cross-section, denier, (2) to study the thermal bonding behavior of polypropylene films, (3) to analyze failure mechanism of bonded films, (4) to study bonding at different processing conditions: time, temperature, and pressure.

Bonding studies were carried out on metallocene and Ziegler-Natta catalyzed resins under similar bonding conditions. The minimum and optimum sealing time, pressure, and temperature range were determined using the initial bonding studies on polymer films. Studies were extrapolated at those predetermined conditions on polypropylene films and fibers of different processing conditions.

EXPERIMENTAL

Materials and processing

Three different grades of polypropylene resins were used in this study. A 35 MFR Ziegler Natta catalyzed PP (PPZ) and a nominal 35 MFR Metallocene catalyzed PP (PPM) were obtained from Exxon-Mobil Chemical Company. Lower MFR PP (PPH) was obtained from Hercules. Five different polypropylene cast films (S-A, S-B, S-C, S-D, and S-E) with different amounts of xylene soluble were supplied by Sunoco Chemicals Company. Properties of these films are shown in Table I.

Polypropylene fibers with different processing conditions, polymer properties, cross-sections (delta, round), MFRs (low melt flow rate (LMFR), high melt flow rate (HMFR)) and deniers (low denier per filament (LDPF), high denier per filament (HDPF)), were also received from Sunoco Chemicals Company. Properties of these fibers are shown in Table II.

TABLE II
Filament Sample Details

Sample	Peak force (kg)	Peak elongation (%)	Denier	MFR (dg/min)
Delta	1.533	80	5.8	18
Round	3.801	47	7.9	18
LMFR	4.041	47	7.2	4.2
HMFR	2.721	41.29	5.6	14
HDPF	5.987	45.06	16	18
LDPF	3.801	47	7.9	18

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TABLE III
Description of Fiber Samples

Sample	Type	MWD	Draw ratio	Spinning speed (m/min)	Denier
1	Impact copolymer	4.3	3.1	1430	2.4
2	Impact copolymer	4.5	3.1	1430	2.6
3	Homopolymer	2.5	1.45	1310	2.7
4	Homopolymer	3.3	1.45	1310	2.8
5	Homopolymer	3.6	1.45	1310	2.7
6	Homopolymer	3.4	1.45	1310	2.9

In addition, polypropylene fibers produced from different polymer composition and grades, under different conditions were also obtained from Sunoco Chemicals Company. Properties of these fibers are listed in Table III.

Preparation of films

PPM, PPZ, and PPH polymers were cast into thin films using a Randcastle microtruder with a screw diameter of 1.25 cm. Schematic diagram of extrusion set up is shown in Figure 1.[16] The extruder was customized with a slit die and chill roll for the production of films. The chill roll also had a winder to facilitate the rolling of films. The material output was regulated by the screw speed. Different temperatures were used in the three different zones of the extruder. For the three different polymers, screw speed, winder speed, and die to collector distance (DCD) were attuned to get polymer film samples of consistent width of around 1.25 cm.[17] The polymer melt coming out of the die in the form of film passes over the chill roller, cools itself and then is wound on to the winder. Cast film properties depend on distance between the die and the chill roll, take up speed of the winder, and also on extruder screw speed.[15] Stretching of the extruded film results in arrangement of molecules in the direction of the stretch. So with an increase in distance between the die and the chill roll, orientation and crystallinity increase in the resultant film. Higher the die to chill roll distance, the higher the orientation and crystallinity of the cast film will be. In this study, the orientation was tailored by selecting two different die to chill roller distances.[15,16]

Bonding of films

Polymer cast films were bonded using a Wabash hydraulic hot press. For efficient heat transfer, aluminum foil was placed in the actual bond area. A schematic of the bonding arrangement is shown in Figure 2. Film samples were bonded at different temperatures in the vicinity of the melting point of

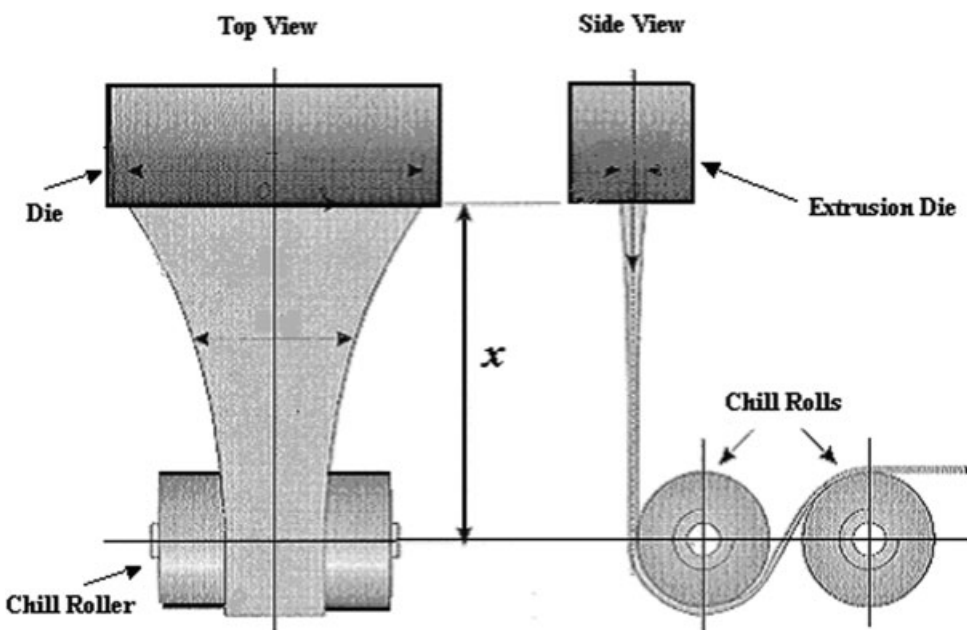

Figure 1 Schematic diagram of polymer film casting using Rand caster (Adapted, with permission, from Ref. 16, Copyright 2003 Wiley Periodicals, Inc.).

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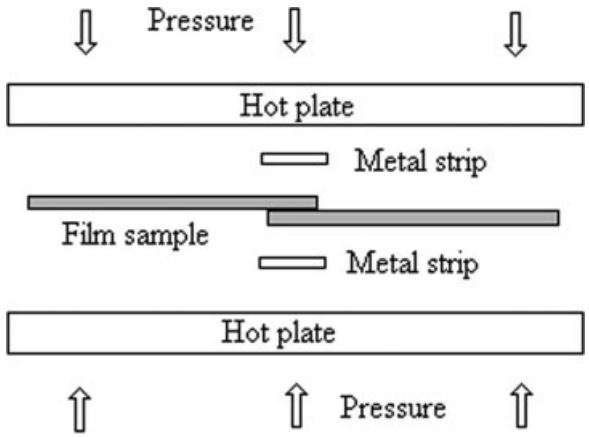

Figure 2 Schematic of cast film bonding on hot press.

the polymer. Before carrying out bonding studies at different temperatures, the optimum time and pressure for bonding were determined by bonding PPZ films at a constant temperature of 130°C at different times and pressures. Film bonding studies were carried out in the temperature range of 120–155°C in the interval of 5°C at a predetermined optimum bonding time of 2 s and a bonding pressure of 200 kPa.

Bonding of fibers

Fiber bonding studies were carried out using two different heat sealers; Dynisco HTH2 and American International Inc., Constant heat sealer. The HTH2 Hot Track heat sealer has capability of carrying out bonding at preset closure times and pressures of the hot plates. The instrument specifications for the HTH2 sealer are listed in Table IV. Since the contact time and sealing pressure were different for these sealers, results are not directly compared between the two of these sealers. HTH2 Hot Track heat sealer is shown in Figure 3. Combed fiber bundles were overlapped at a fixed distance, placed in between the two plates of the sealer using tweezers and bonded at the preset bonding conditions. The fibers were bonded at series of different bonding temperatures with a constant closure time of 25 ms and 1400 kPa. In each case, 10 fibers were combed, overlapped at 1 cm, and bonded using the heat sealer. Picture of the constant heat sealer is shown in Figure 4. Fiber bundles were overlapped about 1 cm and bonded for about 2 s. Strength variation with temperature was studied and bond points were analyzed using SEM photographs.

TABLE IV
Specifications of Dynisco Hot Sealer

Sealing temperature range	50–400°C
Closure time	25 ms to 20 s
Sealing Pressure	14 kilopascal to 4080 kilopascal

TABLE V
Thickness and Crystallinity of Produced Films

Film sample	Thickness (mm)	Crystallinity (%)
PPM-5	0.195	36.52
PPM-10	0.238	37.38
PPH-5	0.213	40.20
PPH-10	0.156	43.89
PPZ-5	0.240	41.65
PPZ-8	0.217	43.95

Testing and characterization

The film thickness was measured using the TMI Thickness tester (Model No 49-70). Ten measurements were taken at different places of the film and averages of those readings are reported. Thermal analysis of polymer film samples was carried out using the Mettler Toledo DSC 822. The samples were scanned at a heating rate of 10°C per min in the nitrogen atmosphere.

The peak strength of the bond was measured using the United Tensile tester. The bonded polymer film samples were tested using the 45.45 kg load cell, at a gauge length of 7.5 cm. The schematic of the film sample bonded for testing of bond strength is shown in Figure 5. The bonded fiber filaments

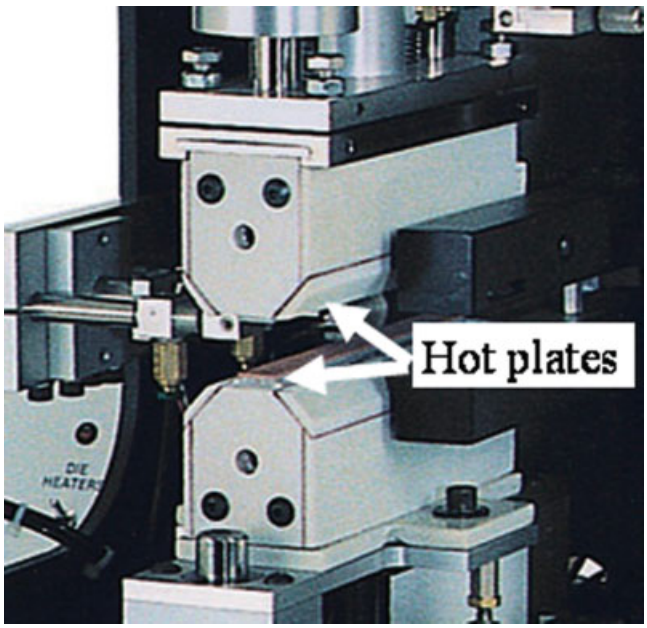

Figure 3 Dynisco hot tack heat sealer.[18] [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

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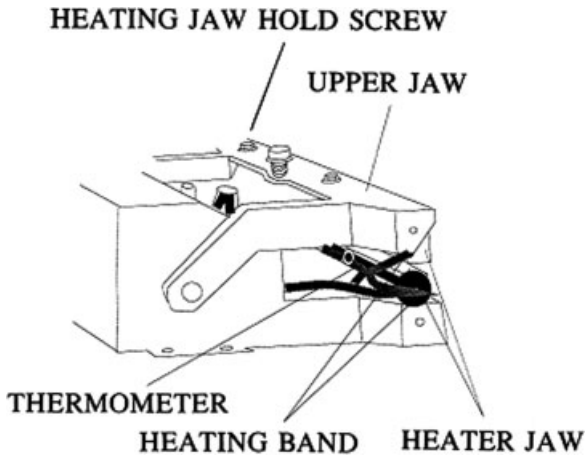

Figure 4 Constant heat sealer.

were tested using the 45.45 kg load cell, at a gauge length of 2.54 cm.

The SEM images of samples were obtained using the Leo 1525 Field emission Gun. To avoid charging problems in the SEM, the samples were gold coated for 10 s using the SPI sputter coater.

RESULTS AND DISCUSSION

The DSC scans of the films are shown in Figure 6. PPM shows lower melting point as expected. The thickness of the films and crystallinity values obtained from the DSC for the cast films are reported in Table V. The thickness varied from sample to sample, as it was hard to precisely control them. The higher DCD samples showed higher crystallinity values for all three PPs. Properties of the polypropylene film samples produced at Sunoco are shown in Table I. Thicknesses of the films were in a range of 0.03–0.08 mm. The crystallinity values of these films varied from 30 to 39% and film S-C had the lowest crystallinity. Each of these films had different amount of xylene solubles, ranging from 2 to 4.7%.

Thermal bonding of film samples

As mentioned before, bonding studies were carried out on polymer films using a hydraulic hot press. Since the film is also exposed in the unbonded region, it was of interest to see whether exposure to heat and pressure significantly affects the film properties. The effect of bonding conditions on the properties of the films was analyzed. From the results shown in Figure 7, it is evident that the effect of bonding conditions on film properties is negligible (only 0.8% reduction in tensile strength) under the bonding conditions studied. At very high temperatures, the rough surface topology is observed in the polymer film. Film surface topology changes due to bonding conditions as it is evident from the SEM images of control film and film subjected to elevated conditions as shown in Figure 8(a,b).

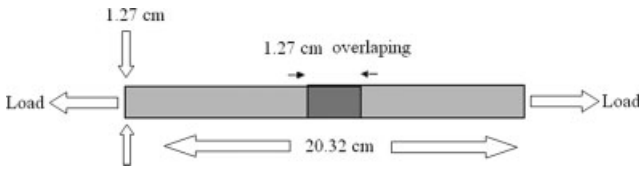

Figure 5 Schematic of bonded film for tensile testing.

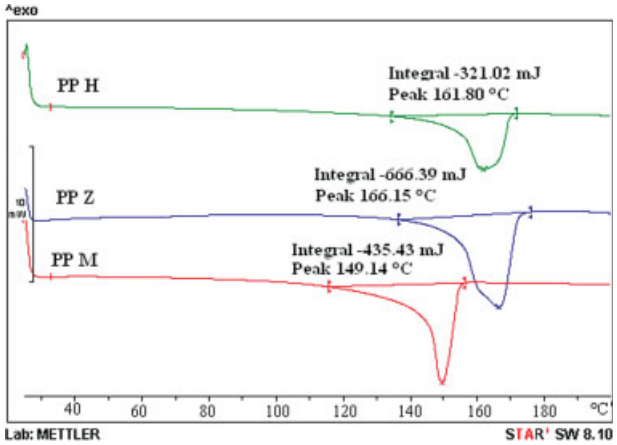

Figure 6 DSC scans of polymers. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Effect of bonding time on bond strength of cast films

Tensile properties of the same films samples that were bonded at one temperature and the pressures for different time intervals are shown in Figure 9. The bond strength increases with the bonding time due to a better heat transfer and melt flow. Increase in melt flow at interface of two films is indicated in Figure 10. In the shorter bonding time amount of polymer melt flowing in to bond point is less so applied force causes failure by slip at interface between the two films. With the increase in the

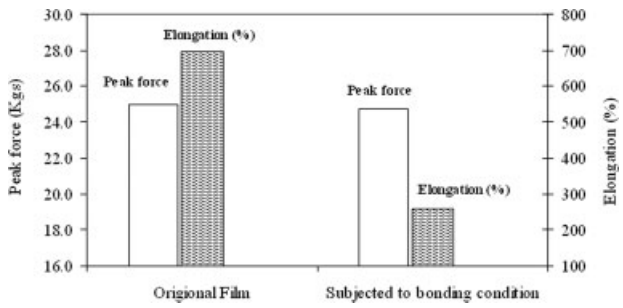

Figure 7 Effect of bonding conditions on film properties.

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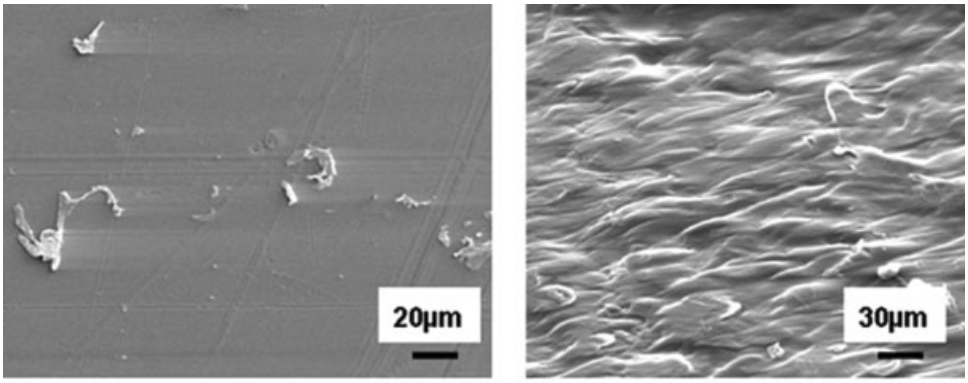

(a) (b)

Figure 8 SEM image of (a) Original film surface (b) Film surface at very high temperature.

bonding time, bond strength increases because increase in melt flow and bond area at interface.[19]

Beyond 15 s of sealing time the strength starts to decline. It appears that 15 s or less is the ideal time for bonding. Compared with the bonding time of 15 s, although actual strength values are lower with 2 s, the drop in strength is small. Also in commercial bonding, the contact time is in the order of milliseconds. According to Chidambaram et al., the commercial bonding time of fiber web in thermal bonding is only 8–20 ms.[20] On the basis of this, in all further studies a bond time of 2s was used.

Effect of pressure on bond strengths

In the thermal bonding process, pressure is required so as to achieve sufficient heat transfer through conduction to melt the interface of the polymer samples. Properties of same cast film bonded at the same temperature and time, but at different pressure shown in Figure 11 indicate that bond strength decreases with increasing bonding pressure. Results can be explained from thermodynamic principles yielding the Clapeyron effect. For pure material, melting temperature varies as function of applied pressure and the relationship that is commonly referred to as the Clapeyron effect. Clapeyron effect equation given by

$$\frac{\Delta T}{\Delta P} = \frac{T_m(v_e - v_s)}{h_f} \tag{1}$$

$$T_m = \left\{\frac{h_f}{v_e - v_s}\right\}\frac{\Delta T}{\Delta P} \tag{2}$$

where, ΔT is change in melting temperature, ΔP is change in pressure, v_s is the molar volumes of the liquid, v_s is the molar volumes of solid phases, and h_f is the molar latent heat of freezing.[21] An increase in pressure causes increased temperature at the nip by the Clapeyron effect. So the polymer sample in nip of calendar roller or heat sealer may encounter substantial increase in temperature with pressure based on time.

The increase in pressure can lead to an excessive increase in temperature at the nip causing an

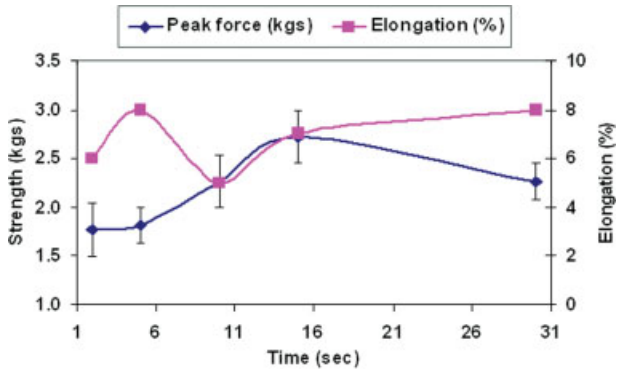

Figure 9 Effect of time on bond strength and elongation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

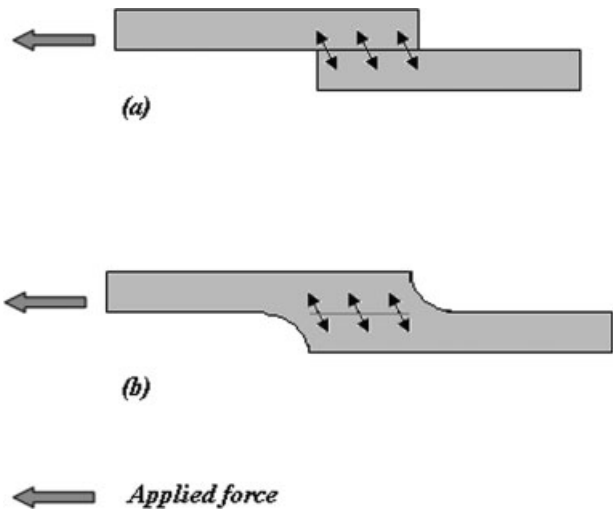

Figure 10 Film bonded at (a) short and (b) long bonding.

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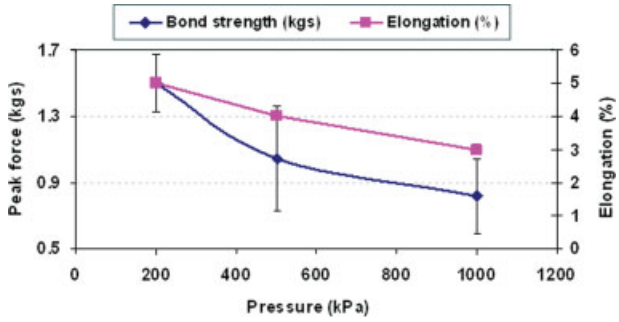

Figure 11 Effect of pressure on bond strength and elongation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

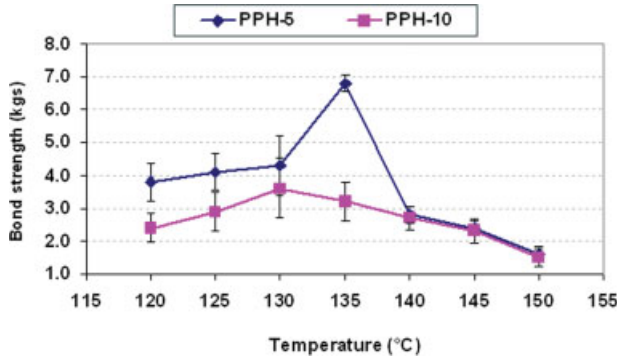

Figure 13 Effect of bonding temperature on strength for PPH films. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

excessive degradation of film morphology. Warner illustrates about 15°C increases in temperature by higher bonding pressure due to Clapeyron effect.[22] Also reported in earlier studies, bonding pressure have little or no effect on fabric performance beyond a certain minimum once the fiber-to-fiber contact is achieved at bond spot.[23] Discrepancies in reported results are due to differences in tested samples, processing variables like time, temperature, and pressure.

It is evident from the results observed in this study (Fig. 11), that more pressure than the required minimum pressure can cause increased thermal degradation and bonding pressure must be carefully selected. Since the 200 kPa pressures resulted in maximum strength, in further studies the 200 kPa pressures was used.

Effect of bonding temperature

Variation of the tensile strength of bonds for different grades of polymer films at a range of bonding temperatures is shown in Figures 12–14. In all the cases, bonding was done over a range of temperatures, to cover under, over, and optimum bonding conditions. They all show a pattern of increasing strength with bonding temperature, reaching a maximum value at an optimum temperature and then dropping off at higher temperatures. The optimum bonding temperature observed is slightly different for the three polymers. Earlier studies have shown that the fibers with lower orientation formed better bonds.[3] As mentioned before, films manufactured with higher DCD have slightly higher crystallinity. Both metallocene catalyzed and Ziegler-Natta catalyzed films manufactured with higher DCD attained their maximum strength at a higher temperature range compared to films manufactured with a lower DCD. Bond strength results of Sunoco films at different bonding temperatures are shown in Figure 15.

Crystallinity and xylene soluble percentage of each of these films were different. Temperature range in which film attained optimum bond strength was also different for these films. Here samples have to be interpreted carefully because of differences in xylene solubles, crystallinity and thickness. Overall, samples with the higher xylene soluble content optimum bonding temperature was lower, indicating increased ease of thermal bond formation. The

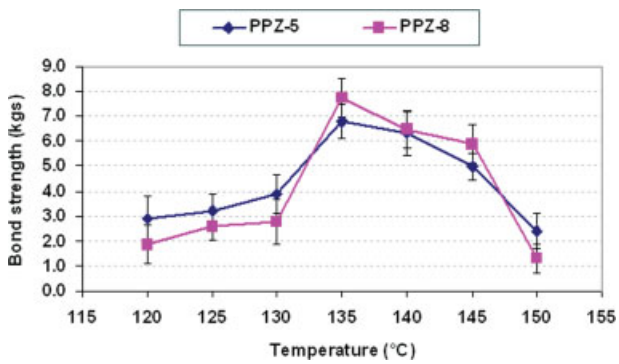

Figure 12 Effect of bonding temperature on strength for PPZ films. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

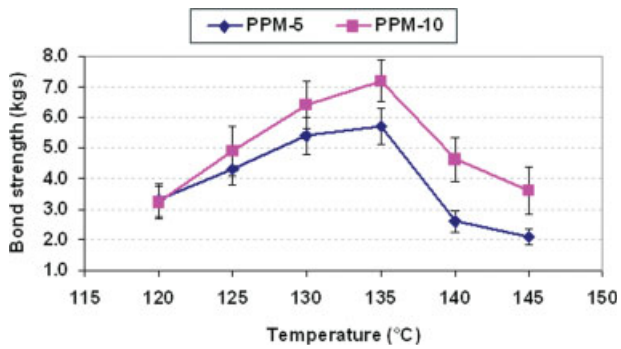

Figure 14 Effect of bonding temperature on strength for PPM films. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

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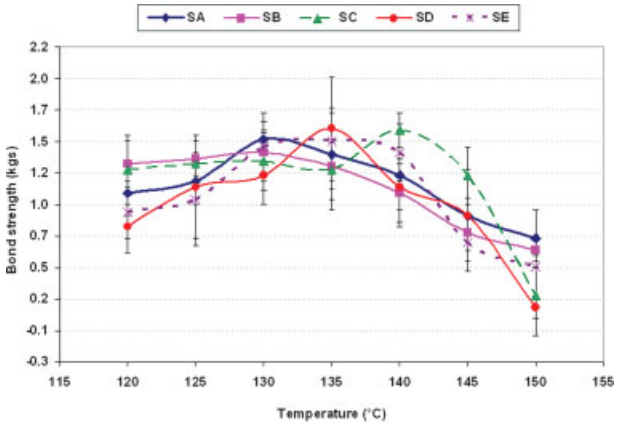

Figure 15 Effect of bonding temperature on strength for PP films supplied by Sunoco. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

maximum strength values obtained were almost in the same range for all the samples. Also, film samples with higher xylene extractables showed less sharper drop off in strength values with increase in bonding temperature, compared with samples with lower level of xylene solubles. For the range of bonding temperature studied, PPM forms better bond at lower temperature range than that of PPZ. These results are in agreement with the earlier observations.[14] Even at the optimum bonding temperature, tensile strength of bonded films is only 14–20% of original film tensile strength.

Just as the strength changes with a change in bonding temperature, there is also difference in failure mechanism for these different samples. The low temperature samples show slippage, indicating incomplete or under-bonding. In the case of films bonded at optimum temperature, failure occurred after sufficient strain of film segment at bond point edge and unbounded film. As the bonding temperature increases, the failure shifts to the bond edge.

TABLE VI
Fiber Cross-Section and Bond Strength

Fiber Id	Fiber cross-section	Bonding temperature (°C)	Peak force (kg)	Elongation (%)
DELTA	Delta	145	0.331	25
		147	0.408	27
		150	0.381	10
ROUND	Round	145	0.154	5
		147	0.327	8
		150	0.540	9

The optimum bond strength for films occurs in the vicinity of their melting point and strength decreases due to excessive change in morphology at higher bonding temperatures. Most of the tensile failures were observed at bond edge where the film undergoes higher deformation. An SEM image of frequent failure point is shown in Figure 16.

A similar failure mechanism is observed for thermally bonded nonwovens. Failure for under bonded sample with flexible bond point occurs by disintegration of bond point, peel off, and subsequent filament failure. Strain initiates from the bond point. Sample bonded at optimum and higher bonding temperature has a rigid bond point where the strain occurs mainly at unbounded fibers. Web rupture in case of such samples occurs at bond periphery where melt is squeezed out by the pattern of calender roller.[7,24]

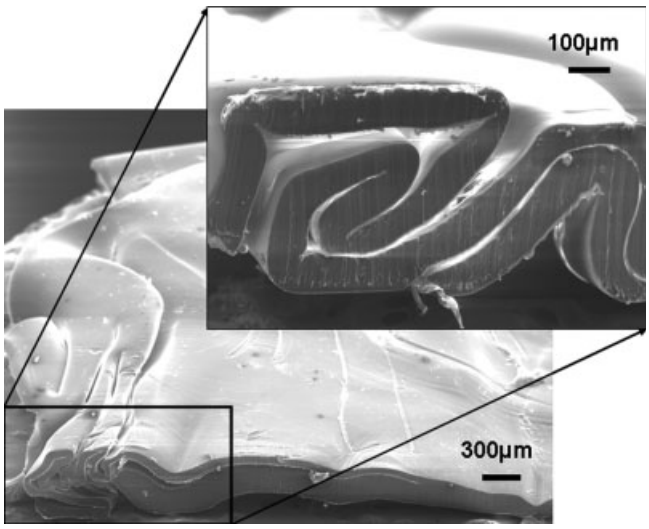

Figure 16 SEM micrograph showing failure at the bond edge.

Thermal bonding of polypropylene filaments

Polypropylene filaments each spun at different processing conditions with fixed number of fibers

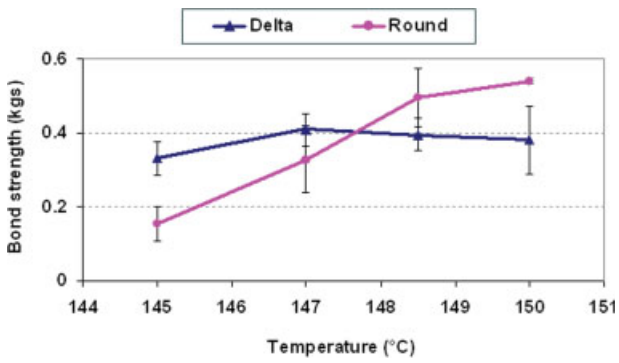

Figure 17 Effect of fiber cross section on bond. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

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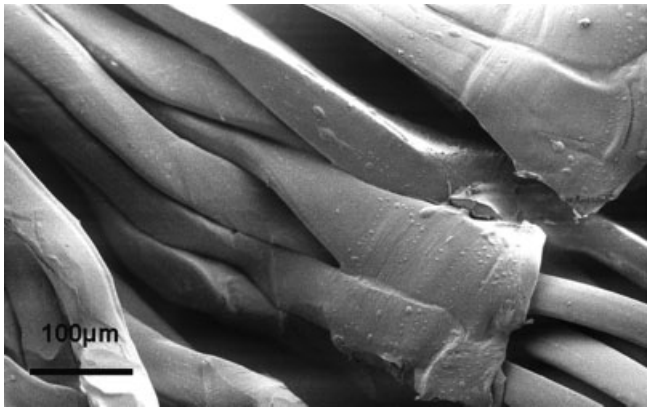

Figure 18 SEM micrograph of PP fibers with Delta cross-section bonded at 150°C.

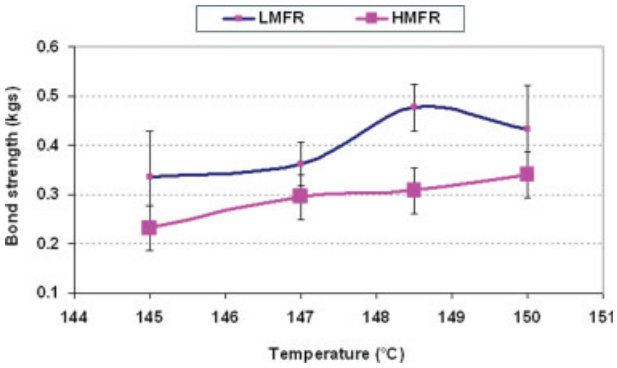

Figure 19 Effect of melt flow on bond strength. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

were used for fiber bonding studies. The effect of different variables: cross section, MFR, MWD, and denier on the thermal bonding were investigated.

Effect of fiber cross-section

Results for PP continuous fiber filaments with delta and round cross-section bonded at three different temperatures using a constant heat sealer are shown in Table VI and Figure 17. An SEM image of the bonded delta fiber bundles is shown in Figure 18. Delta fiber attained high strength at lower temperature range compared with that of the round fiber bundle. This may be due to easy melting of verge of delta cross-section and increased contact area/interface. These results are to be interpreted carefully because of the differences in the elongation of the two fibers. It has been shown in earlier studies that fibers with higher breaking elongation, due to differences in their morphology, are likely to show better bonding with improved bonded web structures.[25] Also, even small differences in denier are likely to contribute to the differences seen in bond strength.

TABLE VII
Bond Strength and Melt Flow of Fibers

Fiber Id	MFR	Bonding temperature (°C)	Peak force (kg)	Peak elongation (%)
LMFR (low melt flow rate)	4.2	145	0.336	13
		147	0.362	10
		150	0.431	16
HMFR (high melt flow rate)	14	145	0.231	7
		147	0.295	15
		150	0.340	13

Effect of MFR

Results for continuous filaments produced from different MFR PP, bonded at three different temperatures using a constant heat sealer is shown in Table VII and Figure 19. The strength values are slightly higher for fiber from low melt flow rate (LMFR).

High melt flow rate (HMFR) fibers are weaker and bond strength from these fibers are lower compared to low MFR fibers. These differences may be due to a difference in initial fiber denier, strength or may be due to the molecular weight effect. Under same bonding conditions, the loss of structural integrity is more in case of a fiber with a HMFR compared with LMFR fibers. One has to remember that these temperature differences are small.

Effect of denier

Normalized bond strength in case of both low and high denier is represented using tenacity (grams/denier) and the results are shown in Table VIII and Figure 20. It is clear that the overall strength of the low denier fiber bundle bond strength is higher than that of higher denier fibers. This might be due to increased contact area and packing of fibers forming a better bond. These results are in contrast to thermal bonding studies done by Larry Saidman who claims that the larger fibers forms stronger bonds due to the capability of larger fibers to hold more heat, better flow for given bond time the ability of large fibers to bridge the gap between substrates, and a better flow at the nip.[26] Studies have also shown that weaker fibers share higher load and form a stronger web. Highly oriented strong fibers form brittle bonds and weak fabrics due to lack of melt flow.[9,23] Again the conclusions have to be carefully interpreted since the method of bonding, raw

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TABLE VIII
Effect of Fiber Denier on Bond Strength

Fiber Id	DPF	Bonding temperature (°C)	Peak force (kg)	Tenacity (g/denier)	Peak elongation (%)
LDPF (low denier per filament)	7.9	145	0.204	0.25	5.4
		147	0.612	0.77	8.3
		150	0.594	0.75	8.5
HDPF (high denier per filament)	16	145	0.508	0.31	18.0
		147	0.676	0.42	17.8
		150	1.020	0.63	17.0

materials used, the bonding conditions, and the end products tested are different in these studies.

Effect of processing conditions

HTH2 and a constant heat sealer were used to bond PP fibers with different processing conditions: MWD, spinning speed, and dpf. Bond strength variation for two different sealers in the same temperature range is different because of the difference in the pattern on the sealing plates and the bonding conditions. Bond strength results are shown in Table IX. The variation of fiber bond strength for fibers with different MWDs is shown in Figure 21. For each of these three fibers, though the number of filaments, spinning speed and draw ratios were the same their bonding behavior is different.

So, if the polymer MWD is different then their respective optimal bonding temperature and respective bond strength will also be different. Higher MWD samples showed the maximum strength at a lower bonding temperature, may be due to low molecular weight fractions helping to form bonds at lower temperature range. Although a low MWD sample had low strength at the initial low temperature range, trend indicated that they reach their maximum at a higher temperature but the values are almost same.

Results for the fiber with different denier per filament are shown in Figure 22. The results bond strength results match with the constant heat sealer results, reconfirming the trend of increased bond strength for finer fibers. An increase in crystallinity, birefringence, tensile strength, and modulus of the spunbond fiber with a decrease in diameter is reported in earlier studies.[27] SEM images of fiber bundles bonded at different temperatures using the HTH2 sealer are shown in Figures 23. The fiber bundle bonded using the constant heat sealer is shown in Figure 24. There is very little melting at lower bonding temperatures. Melting of fiber surface increases with the bonding temperature. At higher bonding temperatures the fiber completely loses its morphology and the polymer melt takes the configuration in concurrence to pressure and space. Mukhopadhyay et al. also have observed similar results.[28] On the basis of the strength and SEM studies they observed that the polypropylene fibers well bonded between the interfaces without affecting the bulk gave better bond strength than the other polypropylene fiber with change all through the structure. At higher temperatures there is severe change in the fiber structure both in the bond area and in the vi-

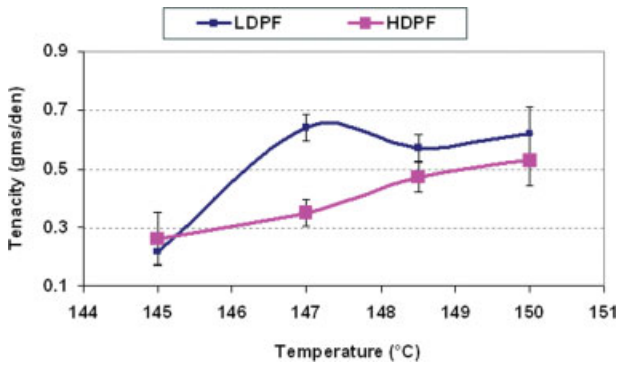

Figure 20 Effect of fiber denier on bond strength. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE IX
Bond Strength of Fibers at Different Temperatures

	Bond strength to Kgs					
H2H2 sealer						
Sample	1	2	3	4	5	6
Control	0.694	0.689	1.360	1.569	1.537	1.437
140°C	0.099	0.102	0.485	0.179	0.517	0.263
145°C	0.204	0.133	0.542	0.217	0.884	0.326
150°C	0.190	0.222	0.789	0.857	0.562	0.653
Constant sealer						
Control	0.694	0.689	1.360	1.569	1.537	1.437
140°C	0.108	0.290	0.408	0.412	0.426	0.294
145°C	0.145	0.131	0.485	0.639	0.589	0.517
150°C						

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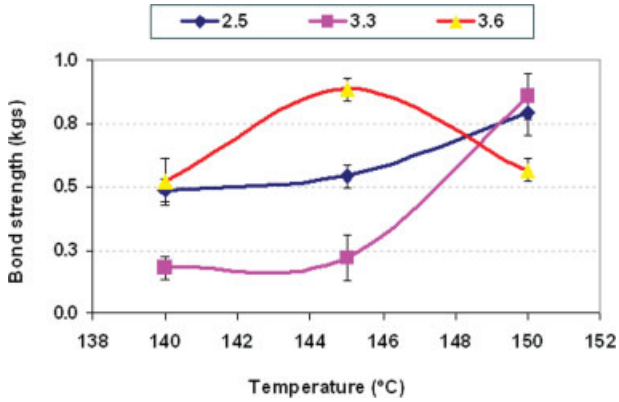

Figure 21 Thermal bond strength variation of fiber with different MWD. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

cinity of the bond leading to decreases in bond strength. For the range of bonding temperature studied, even at optimum bonding temperature the tensile strength of the bonded fiber bundle is only 8–12% of the original unbounded fiber bundle.

CONCLUSIONS

The effect of temperature on bond strength clearly indicated the pattern as seen with PP fibers in earlier studies, showing an increase in strength with an increase in temperature till it reaches an optimum, and decreasing at higher temperatures due to an excessive change in morphology. Bond strength results for cast films and fibers were similar under comparable conditions. Lower pressure and shorter sealing time in the vicinity of the melting point of the polymer were appropriate for the bonding of films. Temperatures at which maximum strength is observed are different for different grades of the polymer, indicating the differences in bonding behavior. For the temperature range studied, it is clear that the thermal bonding behavior of fibers can be predicted from film bonding studies. Since it is easier to prepare films from a small sample of the polymer, this can be a good scanning technique. Also, it is possible to get a preliminary estimate of bonding performance for fiber webs, without going through

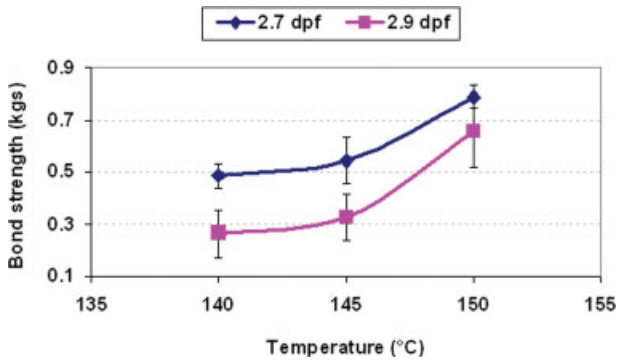

Figure 22 Effect of fiber denier on the bond strength's observed from the HTH2 heat sealer. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

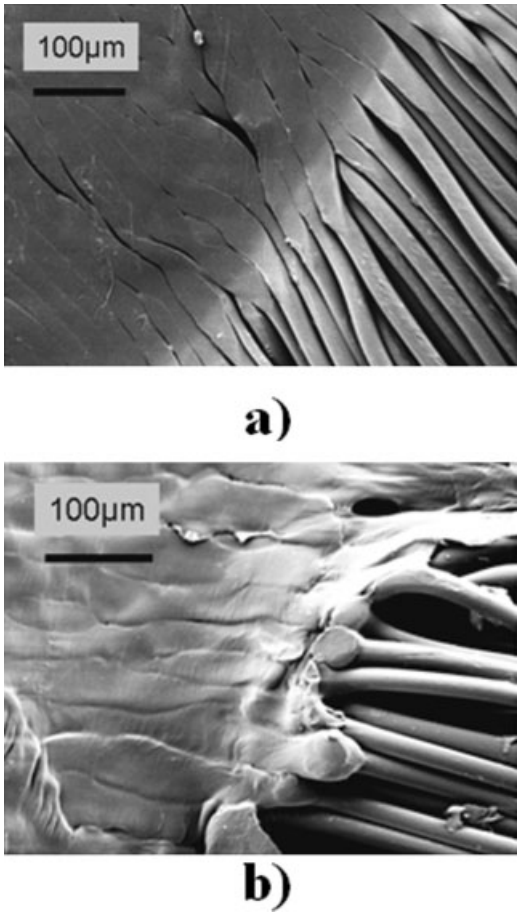

Figure 23 SEM micrograph of PP fiber bundle bonded using HTH2 (a) 145°C (b) 150°C.

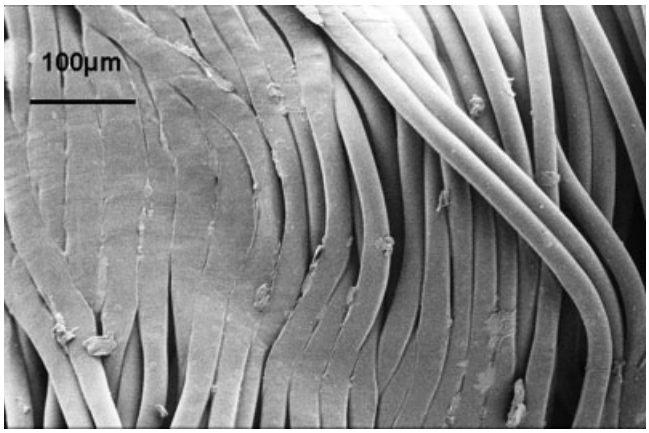

Figure 24 SEM micrograph of PP fiber web bonded at 145°C using constant heat sealer.

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tedious processes requiring relatively expensive equipments.

Authors acknowledge Sunoco chemicals, Exxon-Mobil Chemical Co, and Hercules Corporation for providing polymer/fiber samples.

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