

# Structure-Property Relationships of Thermally Bonded Polypropylene Nonwovens

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## Synopsis

The effect of fiber structure and morphology on the resultant mechanical and low load deformation properties of thermally bonded nonwoven polypropylene fabrics has been studied. Commercially available staple polypropylene fibers varying in linear density and draw ratio (Herculon and Marvess staple fibers) were used in this study. The orientation of these fibers was characterized by birefringence measurements. Differential scanning calorimetry measurements were made to determine the heat of fusion and melting point of fibers. Experiments confirm that tensile strength and stiffness of the fabrics correlate with this fiber structure. Under the same bonding conditions fabrics made from fibers with low draw ratios show higher tensile strength and stiffness than do fibers with high draw ratios. The mechanical properties of fabrics were found to be greatly affected by the thermal bonding temperature. The tenacity and flexural rigidity of fabrics made from poorly oriented fibers show higher values than those made from highly oriented fibers. The shrinkage of the fabrics was observed to increase with increasing bonding temperature in both machine and cross machine directions. The changes in fabric thickness due to the thermal bonding are considerably lower for poorly oriented fibers.

## INTRODUCTION

Thermal bonding of nonwoven fabrics can be achieved by using heat in a variety of ways. The method of thermal bonding, the fiber type, and the carding technique ultimately influence the mechanical and esthetic properties of the resultant nonwovens. Harris<sup>1</sup> observed that the strength of nonwoven batting containing polyester binder fibers was dependent on the bonding temperature and the binder fiber concentration. Soszynski<sup>2</sup> described a laser technique for production of spot-bonded acrylic and polyester fiber nonwovens, whose fabric properties (such as tenacity, hand, and heat resistance) were found to be significantly better than those produced by conventional thermal bonding techniques.

Webs consisting of fibers with low melting points, such as polypropylene, can be thermally bonded by direct heating *via* a hot calendar or by heating the webs in a forced-draft oven. A recently published comprehensive review<sup>3</sup> indicated that most of the literature on thermally bonded polypropylene nonwovens pertains to its development and end uses. Only a limited amount of work on the structure-property relationships of thermally bonded staple polypropylene has been published. For polyester and polypropylene fibers, Shimalla and Whitewell<sup>4</sup> observed that during processing the crystallinity, elongation at break, and initial modulus of fibers influenced the resultant

TABLE I  
Properties and Bonding Conditions for Staple Polypropylene Fibers

Fiber type	Bonding temperature (°C)	Bonding pressure (kg/cm <sup>2</sup> )	Linear density (d/tex)	Length (cm)	Draw <sup>c</sup> ratio (X)
Herculon T-151-3D <sup>a</sup>	140-145	2.1-2.8	3.33	4.76	1.5
Herculon T-151-1.5D	140-145	2.1-2.8	1.66	4.81	1.5
Herculon T-123-3D	150-155	2.1-2.8	3.33	4.76	3.0
Herculon T-123-1.5D	150-155	2.1-2.8	1.66	3.81	3.0
Marvess <sup>b</sup>	162	7.1	3.33	5.08	3.0

<sup>a</sup> T-151 and T-123 fibers are made by Hercules, Inc.

<sup>b</sup> Trademark of Phillips Fibers.

<sup>c</sup> Nominal values from fiber manufacturers.

tenacity of the bonded web. This study reports the effect of fiber structure and morphology on the mechanical and esthetic properties of thermally bonded polypropylene nonwoven fabrics. Rebenfeld et al.<sup>5</sup> reported that the rate of cooling (annealing/quenching), which influences the rate of crystallization, can have a marked effect on the strength and other tensile properties of thermally bonded materials. The objective of this study was to investigate the effect of fiber structure and morphology on the mechanical and the low load deformation properties of thermally bonded nonwoven polypropylene fabrics.

## EXPERIMENTAL

**Materials.** Commercially available staple polypropylene fibers varying in linear density and draw ratio (Herculon and Marvess staple fibers) were used in this study. Fiber linear density, length, recommended pressures and temperatures for thermal bonding, and nominal draw ratios are given in Table I.

Parallel-laid webs were formed on conventional carding machines. The areal densities of webs were varied between 9 and 10 mg/cm<sup>2</sup>. The webs were fused by direct heating in a Wabash hot press at various temperatures varying between 135°C and 173°C and a bonding pressure of 11.7 kg/cm<sup>2</sup> for 1 min. The molecular orientation of fibers was determined by measuring their birefringence with a Leitz Ortholux polarizing microscope and Wetzlar 30-order compensator. Melting behavior was determined with a Perkin-Elmer DSC-2B Differential Scanning Calorimeter, as was the specific heat of the fibers ( $C_p$ ) in the temperature range of -30°C to 210°C. Typical in-

TABLE II  
Birefringence of Polypropylene Staple Fibers

Fiber type	Birefringence ( $\Delta n$ )
Herculon T-151-3D	0.027
Herculon T-151-1.5D	0.027
Herculon T-123-3D	0.031
Herculon T-123-1.5D	0.033
Marvess	0.030

strument settings were: heating rate of 20°C/min; a DSC range of 5 mcal/s; a recorder range of 10 MV; and a positive pressure of dry nitrogen of 137.9 kPA through the sample holder block and auto cool mode. The tensile properties of the bonded nonwoven fabrics were measured on an Instron Tensile Tester. (Fabrics were characterized in the machine direction only). Flexural rigidity of the fabrics was determined by the cantilever bending method. In this method the bending length of fabric strip (2.54 cm wide  $\times$  15 cm long) was allowed to bend to a predetermined angle ( $\sim 41.5^\circ$ ) under its own weight. The rigidity ( $G$ ) is then given by  $G = w^3 \times (l/2)^2$  (g  $\cdot$  cm), where  $w$  is the areal density and  $l$  is the bending length in proper units.

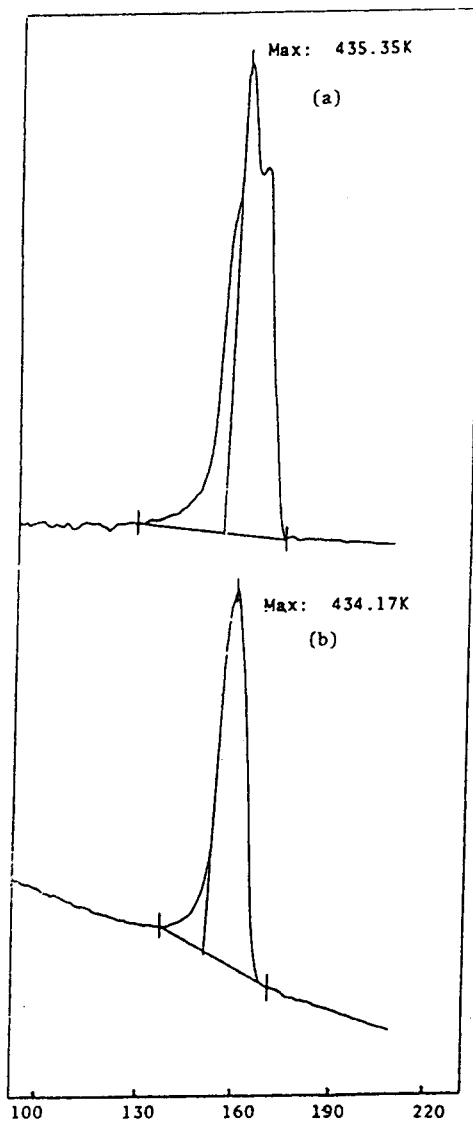


Fig. 1. DSC melting endotherms of thermally bonded fibers (°C): (a) Marvess; (b) T-151, 3D.

TABLE III  
Mechanical Properties of Polypropylene Single Fibers at 21°C and 124°C

Fiber type	Tenacity (breaking length) (km $\times 10^{-2}$ )		Breaking elongation (%)		Energy to break (kJ/kg)	
	21°C	124°C	21°C	124°C	21°C	124°C
T-151-3D	24.8	13.3	292	387	27.7	13.3
T-123-3D	50.5	23.3	111	200	14.8	11.1
Marvess	45.7	28.6	60	208	10.7	15.0

## RESULTS AND DISCUSSION

### Morphological Analysis of Polypropylene Staple Fibers

**Birefringence Measurement.** Birefringence data of fibers in this study are shown in Table II. The orientation as indicated by birefringence proved to be a sensitive and reliable fingerprint of the structure which formed originally during the drawing and heat setting process. The birefringence data indicate that T-151 fibers were presumably processed in a low-draw region, below a draw ratio of 2.0–2.25X. On the other hand, T-123 fibers and Marvess fibers were probably processed in the high-draw region, above a draw ratio of 2.0–2.25X. Higher birefringence (i.e., higher orientation) values of T-123 type fibers indicate that subtle changes in fiber morphology, such as the degree of perfection of crystalline regions and number and type of tie molecules, may be enhanced with increasing draw ratios and spinning stress. These morphological changes have been suggested for polyethylene melt-spun filaments.<sup>6</sup>

### DSC Analysis

Figure 1 shows typical DSC endotherms of T-151 fibers and Marvess fibers. The observed melting peaks indicate that the three fiber types have somewhat higher amorphous orientation compared to the latter, e.g., T-151 is in agreement with the published literature.<sup>7</sup>

### Mechanical Properties of Fibers

The mechanical properties of single fibers at standard conditions (21°C; RH = 65  $\pm$  2%) and at a higher temperature (124°C) are shown in Table III. In this table, T-151 shows low tenacity and high breaking elongation at both temperatures. This may be compared with the T-123 fiber and Marvess fiber, which have higher orientation than the T-151 fiber and consequently show substantially higher breaking strength but lower elongation. These mechanical properties are manifested in the properties of the bonded nonwovens described in the ensuing sections. These initial orientation effects on the tensile properties of single fibers for both types at room and elevated temperatures are apparent from the results given in Table III. The results of mechanical properties of single fibers are reflected in the ultimate mechanical properties of the bonded fabrics.

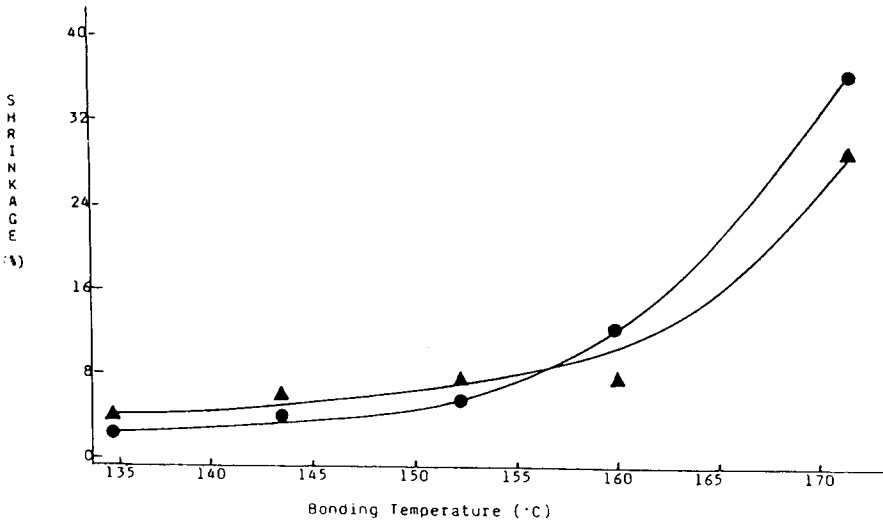


Fig. 2(a). Effect of bonding temperature on fabric shrinkage (machine direction of nonwoven fabrics): (▲) T-151, 1.5D; (●) T-123, 1.5D.

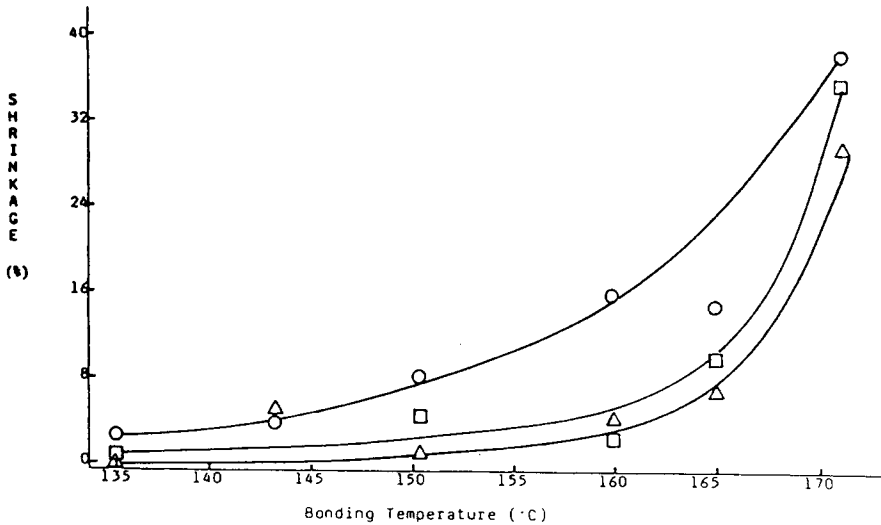


Fig. 2(b). Effect of bonding temperature on fabric shrinkage (machine direction of nonwoven fabrics): (△) T-151, 3D; (○) T-123, 3D; (□) Marvess.

**Effect of bonding temperature on fabric dimensions.** Figures 2(a) and (b) show the effects of bonding temperature on fabric shrinkage in the machine direction. In general, in the case of thermally bonded fabrics, shrinkage begins at a temperature below 150°C, probably because of molecular chain relaxation of amorphous regions; however, at higher temperatures (greater than 150°C), shrinkage occurs abruptly and very steeply for fibers coinciding with the melting of small and imperfect crystals. In Figures 2(a) and (b) T-151 fibers did not show as much shrinkage as the T-123 in the whole range of bonding temperatures, which suggests that T-151 fibers have relatively low amorphous orientation in the fiber axis direction. The

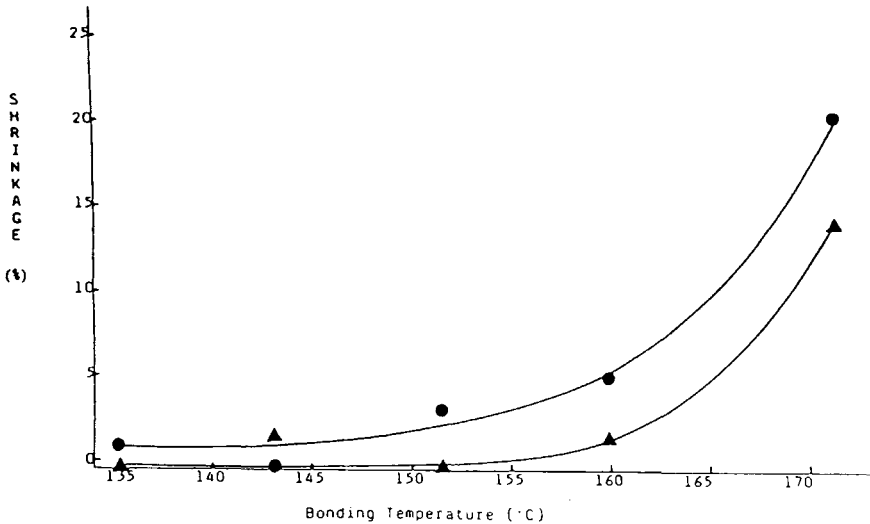


Fig. 3(a). Effect of bonding temperature on fabric shrinkage (cross direction) of nonwoven fabrics: (▲) T-151, 1.5D; (●) T-123, 1.50.

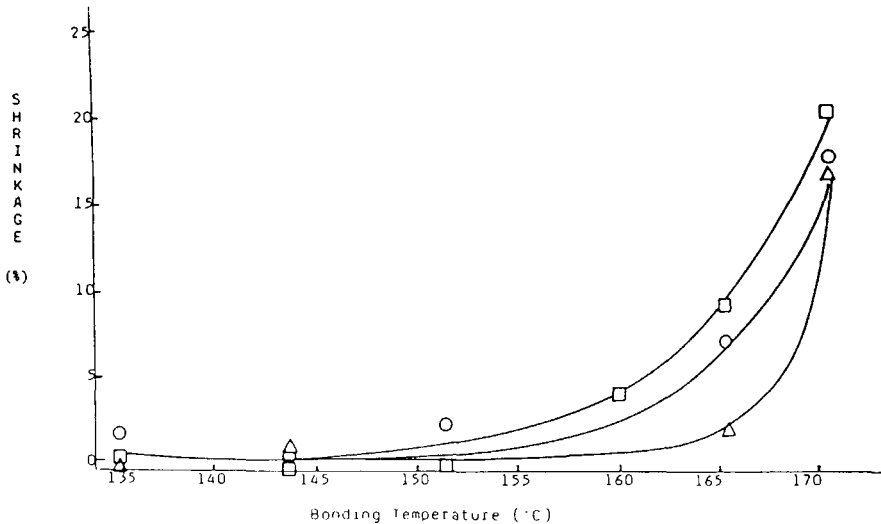


Fig. 3(b). Effect of bonding temperature on fabric shrinkage (cross direction) on nonwoven fabrics: (△) T-151, 3D; (○) T-123, 3D; (□) Marvess.

amount of disorientation of the amorphous chains will depend on the bonding temperature. The higher the bonding temperature, the higher would be the expected disorientation and, hence, the higher would be the shrinkage as expected. Figures 3(a) and (b) show the effects of bonding temperature on fabric shrinkage in the cross machine direction. It can be seen that the type 151 fibers have lower shrinkage than type 123 fibers for the whole range of bonding temperatures, which suggests that shrinkage mechanisms in the machine and cross machine directions are the same. Compared with the shrinkage in the machine direction, the low shrinkage in the cross

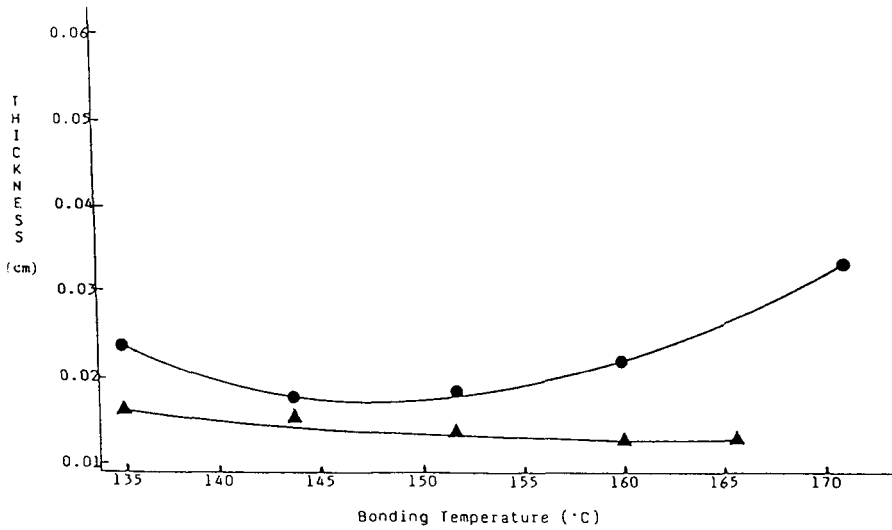


Fig. 4(a). Effect of bonding temperature on fabric thickness: (▲) T-151, 1.5D; (●) T-123, 1.5D.

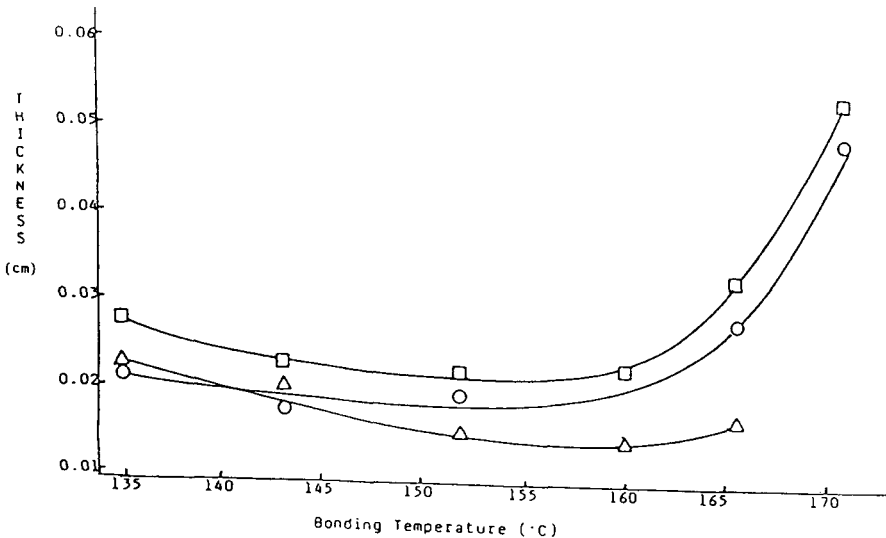


Fig. 4(b). Effect of bonding temperature on fabric thickness: (△) T-151, 3D; (○) T-123, 3D; (□) Marvess, 3D.

machine direction is solely a consequence of low fiber orientation in the web in this direction, an inherent factor in carded webs.

Figures 4(a) and (b) show the effects of bonding temperature on fabric (T-151, T-123, and Marvess fibers) thickness. In these figures, it can be observed that the type 151 fabrics did not show as much change in thickness as the type 123 and Marvess fibers during the thermal bonding process. This is explained by the low orientation in the amorphous regions of type 151 fibers. Higher fiber shrinkage tends to consolidate the web thickness, thereby reducing such thickness. One interesting feature that can be observed from

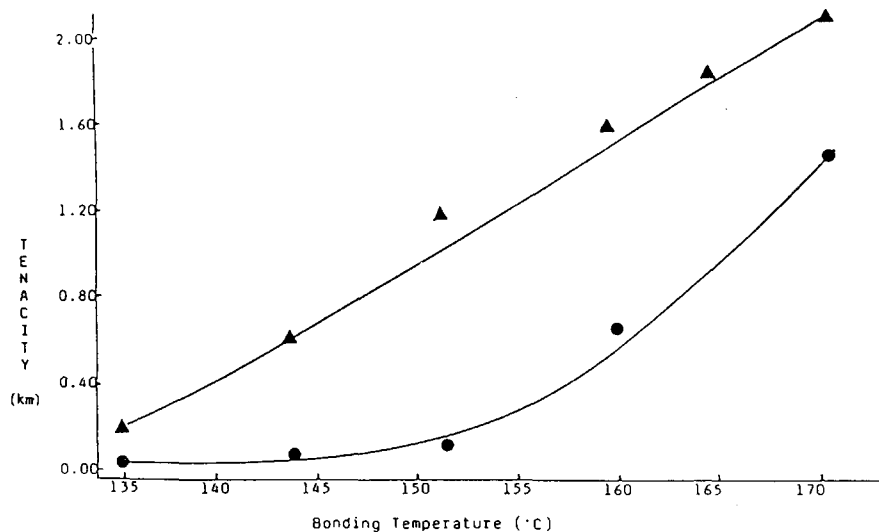


Fig. 5(a). Relation between tenacity and thermal bonding temperature in nonwoven fabrics: (▲) T-151, 1.5D; (●) T-123, 1.5D.

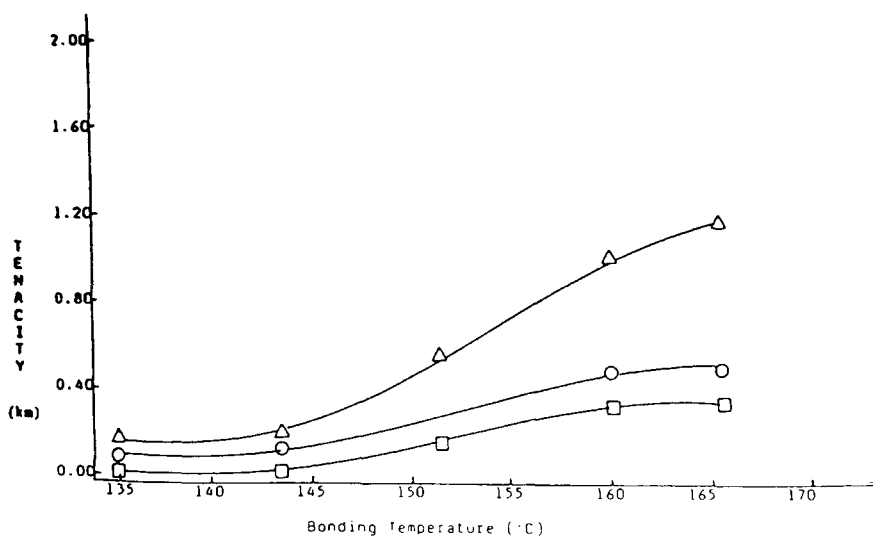


Fig. 5(b). Relation between tenacity and thermal bonding temperature in nonwoven fabrics: (△) T-151, 3D; (○) T-123, 3D; (□) Marvess, 3D.

these results is that the thickness of fabrics made from type 151 fibers (low orientation) tends to equilibrate over a large temperature range. However, the highly oriented fibers (type 123 and Marvess) exhibit pronounced increases in thickness for bonding temperatures above 160°C.

**Effect of thermal bonding temperatures on fabric mechanical properties.** The tenacity, breaking elongation, and energy to rupture of thermally bonded fabrics are plotted as a function of bonding temperature in Figures 5, 6, and 7. Each point is an average of five measurements and the fabrics were deformed at a strain rate of 50%/min.

During the thermal bonding process, significant morphological changes



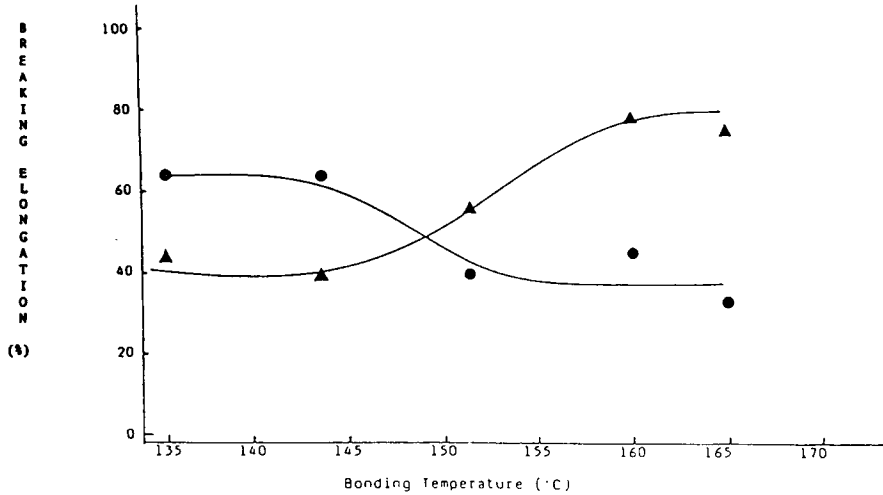


Fig. 6(a). Relation between breaking strain and thermal bonding temperature in nonwoven fabrics: (▲) T-151, 1.5D; (●) T-123, 1.5D.

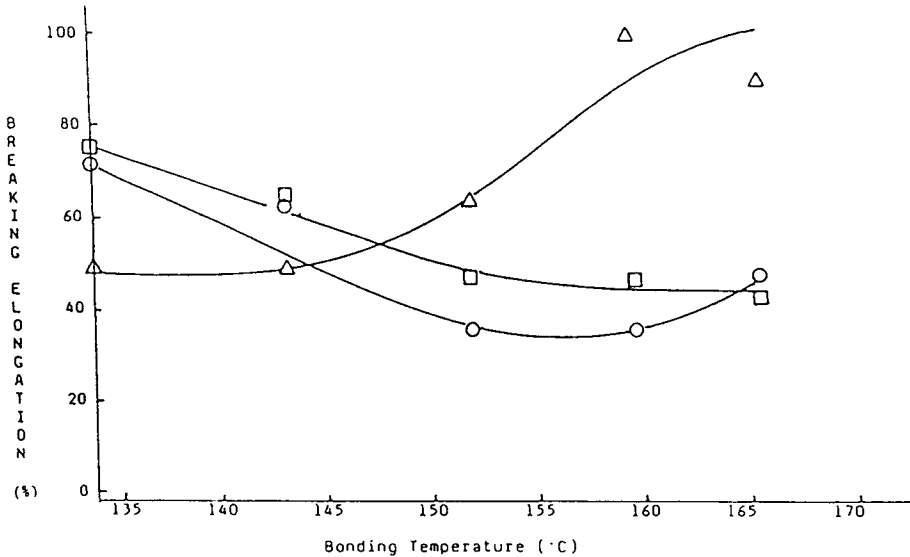


Fig. 6(b). Relation between breaking strain and thermal bonding temperature in nonwoven fabrics: (Δ) T-151, 3D; (○) T-123, 3D; (□) Marvess, 3D.

can be expected to occur in the bonding regions. The physical properties of thermally bonded fabrics are a manifestation of the characteristics (nature and quality) of bonding regions. As expected, the fabric tenacity, breaking elongation and the energy to rupture are strongly affected by the bonding temperature. It is clear from Figures 5, 6, and 7 that, below a temperature of 152°C, the tensile strength, breaking elongation, and energy to rupture of type 123 fibers and Marvess fibers show no significant change. As the temperature is raised from 150°C to 170°C, tensile strength and energy to rupture change rapidly. The tensile strength and energy to rupture of type 151 increases at a faster rate than that of the type 123 fibers. It appears

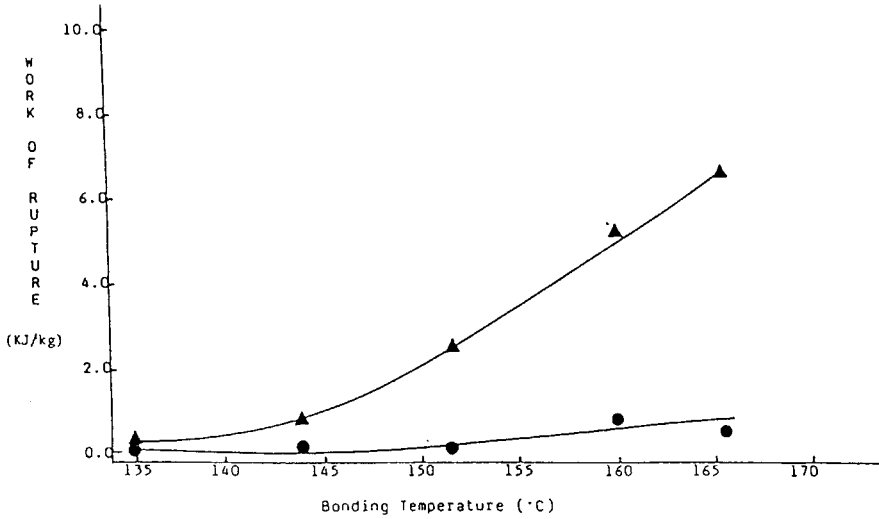


Fig. 7(a). Relation between work of rupture and thermal bonding temperature in nonwoven fabrics: (▲) T-151, 1.5D; (●) T-123, 1.5D.

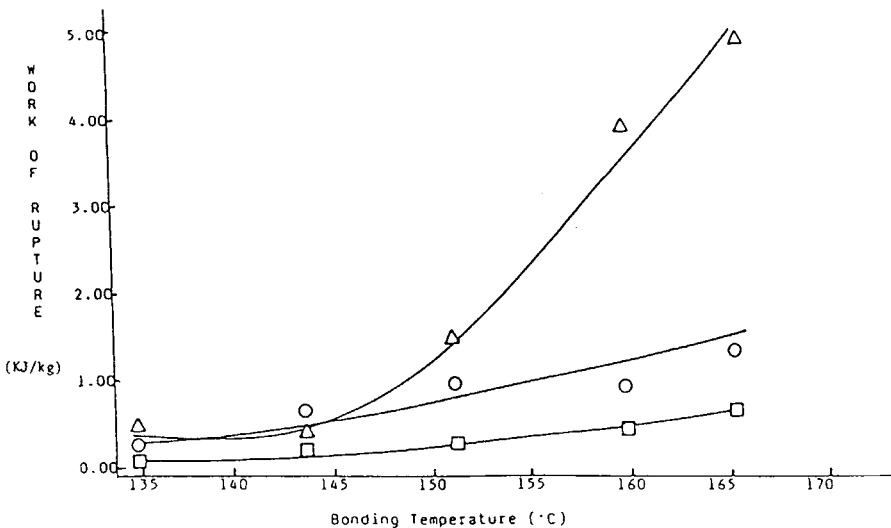


Fig. 7(b). Relation between work of rupture and thermal bonding temperature in nonwoven fabrics: (△) T-151, 3D; (○) T-123, 3D; (□) Marvess, 3D.

that type 151 fibers form stronger bonds than those formed by type 123 during the thermal bonding process. The less oriented amorphous regions and lamellar crystal structure promote the fusion in T-151 fibers during the thermal bonding process. On the other hand, microfibrillar structure in T-123 and fibers inhibit the fusion between fiber and fiber in thermal bonding processes. Figures 8(a) and (b) show the effect of bonding temperature on the flexural rigidity of bonded fabrics.

Flexural rigidity of fabrics, made from all three fiber types, increases with increasing bonding temperature as would be expected. At higher

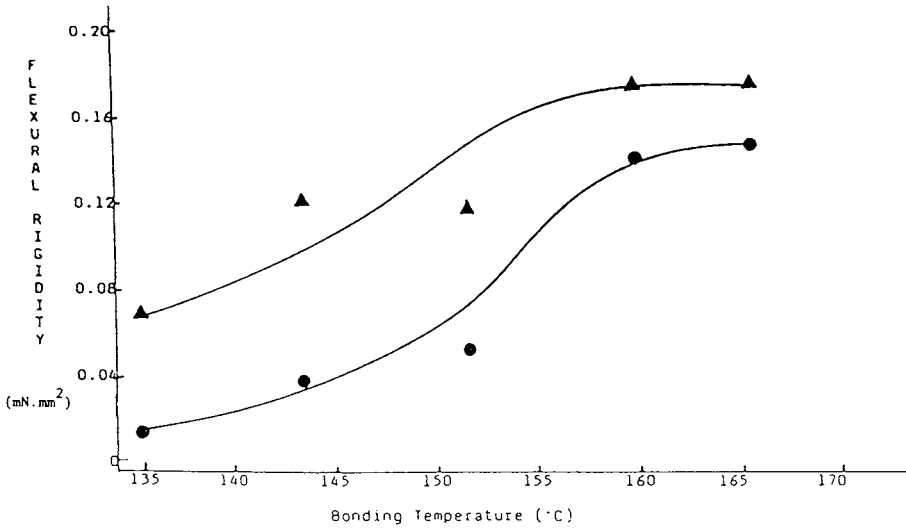


Fig. 8(a). Relation between flexural rigidity and thermal bonding temperature in nonwoven fabrics: (▲) T-151, 1.5D; (●) T-123, 1.5D.

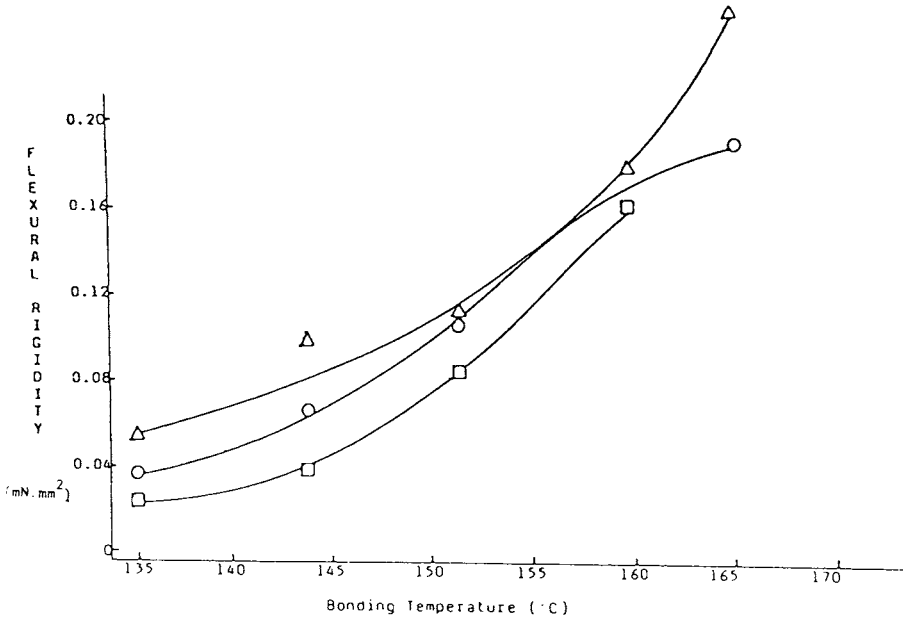


Fig. 8(b). Relation between flexural rigidity and thermal bonding temperature in nonwoven fabrics: (Δ) T-151, (○) T-123, 3D; (□) Marvess, 3D.

temperatures (beyond the recommended bonding temperature), a large part of the fiber melts, thus creating conditions that are conducive for the formation of polymer films and covering larger portions of fibers. This would result in increasing bond area and consequently decrease the length of the fibers between bonds; hence, the flexibility. Generally, T-151 type fibers yield fabrics with higher rigidity values as compared to those made from T-123 and Marvess fibers at all bonding temperatures.

### SUMMARY

The effect of bonding temperature on the esthetic and textile properties of thermally bonded polypropylene nonwoven fabrics has been studied. The mechanical properties (tenacity and flexural rigidity) of fabrics were found to be greatly affected by the thermal bonding temperature. The tenacity and flexural rigidity of fabrics made from lower birefringence (less oriented) fibers (type 151) show higher values than those made from type 123 (highly oriented) and Marvess fibers. The shrinkage of the fabrics was also observed to increase with increasing temperature in both machine and cross machine directions. It seems that, in the case of thermally bonded polypropylene fabrics, shrinkage begins at a temperature below 150°C. The tensile strength and stiffness of the fabrics can be correlated with fiber structures. Under the experimental bonding conditions, fibers with lower birefringence show higher tensile strength and stiffness than do fibers with higher birefringence. This could perhaps be attributed to partial melting of the ordered regions in the amorphous domains; however, at a higher temperature, shrinkage that coincides with the melting of small and imperfect crystals occurs abruptly and very steeply for both fibers. The changes in fabric thickness are considerably lower for fibers with lower birefringence, in other words those of lower orientation.

Finally, it needs to be emphasized that nonwoven fabric properties are primarily determined by the bonding regions, and to a lesser extent by the constituent fiber properties. During thermal bonding processes, significant morphological changes occur in the bonding regions. The physical properties of thermally bonded fabrics are a manifestation of the nature and quality of the bonding regions. Thus, low orientation fibers yield fabrics that are generally stronger and exhibit lower shrinkage.

### References

1. F. O. Harris, *Nonwovens Ind.*, **13**(8), 8; **13**(9), 10 (1982).
2. R. Soszynski, *Przegląd Włók*, **34**, 461 (1980).
3. A. T. Purdy, *Development in Nonwoven Fabrics*, Textile Progress, **12**(4) Stott Brothers, London, 1983.
4. C. J. Shimalla and J. C. Whitwell, *Textile Res. J.*, **46**(6), 405; **46**(7), 513 (1976).
5. L. Rebenfeld, C. K. Deakyne, and J. C. Whitwell, "The Strength of Interfiber Bonds", in *Proceedings of the 1976 INDA Technical Symposium*, 1976, p. 265.
6. G. M. Sze, J. E. Spruiell, and J. L. White, *J. Appl. Polym. Sci.*, **20**, 1823 (1976).
7. R. J. Samuels, *J. Polym. Sci., Polym. Phys. Ed.*, **13**, 1417 (1975).

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