Ultrasonic Sealing of Polyester and Spectra Fabrics Using Thermo Plastic Properties

Subhas Ghosh, Renuka Reddy

Eastern Michigan University, School of Technology Studies, Ypsilanti, Michigan 48197

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ABSTRACT: A study of polyethylene terephthalate (PET) and spectra fabric's ultrasonic sealing (welding) potential was conducted using both continuous and discontinuous ultrasonic welding machines. The effects of two important welding parameters such as weld pressure and weld time were investigated on the fabric's bond strength. Depending on the thermal property of the polymer, a certain level of temperature rise during sealing is required to soften the fibers, to facilitate the development of rows of welding points between the fabric layers. This happens under the compaction due to weld pressure. The gaps between the points are so narrow that the rows appear to be a complete sealing of the layers. Excessive melting under weld pressure, to create melt bonding caused polymer degradation and poor bond strength. Scanning Electron Microcopy images and the temperature measurements at the fabric's interface were used to examine the bond locations of the fabric. Differential Scanning Calorimetry analyses of PET and spectra fabrics have been used to examine the thermal behavior of the ultrasonic sealed material. Adequate seam strength was achieved under certain conditions of sealing for both the fabrics using both continuous and discontinuous methods of operation. © 2009 Wiley Periodicals, Inc. J Appl Polym Sci 113: 1082–1089, 2009

Key words: ultrasonic; seam efficiency; thermoplastic; bond strength

INTRODUCTION

Sewing remains the most popular method of joining fabrics despite such disadvantages as discontinuous joints producing perforated seams, sewing thread deteriorating with time and sewing speed limitation. Most textile products consist of more than one component joined by means of sewing, thermal bonding, laser enhanced bonding, adhesive bonding, or ultrasonic seaming. This article describes a study on the various parameters used in the ultrasonic sealing of polyester (polyethylene terephthalate, PET) and spectra (gel spun polyethylene) fabrics in both continuous and discontinuous modes.

As an alternative for joining together fabrics made from thermoplastic polymer or fabrics that contain a significant amount of thermoplastic fibers, ultrasonic sealing offers many advantages. This technique requires no needles, solvents, adhesives, mechanical fasteners, or other consumables; thus reducing cost. Second, as Flood[1] noted, fiber degradation is minimized because heat energy is generated within the fibers using ultrasonic energy at the point of the joint site, unlike thermal bonding where heat energy is conducted through the fibers to melt them. The additional advantages of ultrasonic bonding are the conservation of energy, the possibility of precise automated assembly using computer-aided-manufacturing technology, and that it is relatively easy to recycle the product as foreign yarns are not used to make a seam. Another advantage is achieving an impermeable seam for technical textile application such as unmanned air craft and clothing for a contaminated environment.

ULTRASONIC WELDING

The generation of ultrasonic energy begins when a power supply converts 115 V, 60 Hz of electrical energy into 15–40 kHz of electrical energy, depending on the end application. An electromechanical converter, or a transducer, converts the high frequency electrical energy from the power supply to mechanical vibrations of 15–40 kHz. Ultrasonic energy and pressure are applied directly onto the fabric panels to be bonded.

The vibrations travel through the material, and the mechanical energy is converted to thermal energy due to intermolecular and surface friction. When sufficient heat is generated the thermoplastic materials melt and bond with each other at the interface, followed by cooling and recrystallization. A schematic diagram of the ultrasonic bonding apparatus is illustrated in Figure 1.

Correspondence to: S. Ghosh (sghosh@emich.edu).

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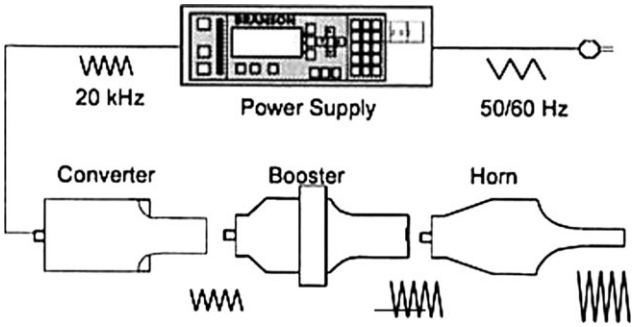

Figure 1 Ultrasonic conversion sequence.

The mechanical vibrations are conducted through a booster, which is mounted between the converter and the horn. Boosters are used to either increase or decrease the amplitude at the horn face, to transmit the required energy to the joint interface. The mechanical vibratory energy is transferred from the booster to the work piece by the horn. Another function of the horn is to maintain the pneumatic pressure necessary to form a weld once joint surfaces melt.[2]

The integrity of a bond is dependent on the correct amount of energy provided, which is governed by following equation.

$$E = P \times T,$$

where E = energy, P = power, and T = time.

Power can be further broken down as follows.

$$P = F \times V,$$

where F = force and V = velocity, frequency, and amplitude.

The above equations relate the energy applied for bonding with weld pressure, amplitude of vibration and weld time. This article describes a study on the effects of ultrasonic weld time and weld pressure on the sealing of PET and spectra fabrics. This article also investigates how ultrasonic sealing is affected by the thermal properties of the fibers to form the bond between the fabric layers. The investigation was conducted using both discontinuous and continuous modes of sealing apparatus, using Branson's ultrasonic assembly system, model 2000d/aed and ultrasonic fabric seaming machine, model F-90.

PREVIOUS STUDIES

Several studies have been conducted with different polymeric fabrics to understand the bond formation mechanism in ultrasonic seaming. Shi and Little[3] investigated seam formation using ultrasonic energy with 50/50 nylon/cotton fabric and polyurethane films. The investigators used the Fourier Transform Infrared-Ahenuated Total Reflectance (FTIR-ATR) analysis technique to study the possibility of the chemical conversion of polymer at the weld zone, as affected by ultrasonic vibration. Shi and Little[3] did not find any chemical bond formation within the normal range of operation, although at extreme conditions polymer degradation may occur. Mozgovoi et al.[4] also found no new chemical groups or bonds while studying the microstructure of ultrasonically welded polyethylene; hence, it seems that the ultrasonic bonding mechanism is essentially a physical process and not a chemical process. The ultrasonic bonding phenomenon has been described by Benatar and Godowsky[5] in five steps; the mechanics and vibration of the parts, the viscoelastic heating of the thermoplastics, heat transfer, flow and wetting, and intermolecular diffusion. Ultrasonic vibrations create sinusoidal strain in thermoplastic materials, which generates heat as a consequence of intermolecular friction. The amount of heat generated is dependent on the material's properties, particularly its complex modulus. Goswami and Mao[6] have numerically calculated the heat generated during the ultrasonic bonding process of nonwoven using the storage and the loss moduli of the material. They found that the heat generation is highly concentrated in the middle bonding positions and that the rate of temperature rise was highest in the middle bonding positions. Tolunay et al.[7] observed that the welding force has an appreciable effect on the heating rate, both at the interface and within the interior of the parts, and bond strength increases with weld time up to a point. Our study concentrates on the nature of bonding of two different thermoplastic fibers at the different level of compactions and ultrasonic energy transmission.

MATERIALS AND METHODS

Weld pressure applied during ultrasonic seaming is determined by a pneumatic pressure system on the machine. In the continuous mode, pressure was adjusted between 40 and 60 psi during this investigation to create a range of pressure values. Weld time determines the length of time a fabric is subjected to ultrasonic vibration. Time is a function of the throughput speed in the continuous mode of operation that was set at 22.5, 30, and 37.5 ft m^{-1} for PET fabrics and 15, 22.5, and 30 ft m^{-1} for spectra fabrics. In discontinuous plunge mode, specimens were exposed to ultrasonic vibration for 1.5, 2.0, and 3.0 s at 30 to 60 psi weld pressure. Amplitude of ultrasonic vibration was maintained at 69.5 μm for continuous mode and at 59.5 μm for plunge mode. Minor adjustments of the parameters for the two

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Figure 2 Seam designs: Knurl pattern.

apparatus were necessary because of their design differences. A 1/4" knurl pattern was used for sealing in this study, which results in a continuous weld due to the design as depicted in Figure 2. Often a heat activated material is placed between the fabric layers that are difficult to bond. In this study, a 4-mm wide thermoplastic polyurethane (TPU) adhesive tape was used during the sealing of spectra to improve joint strength as suggested by Branson Ultrasonic Corporation. This tape had a softening point at 110°C which was somewhat lower than that of spectra used in this investigation. Having lower softening temperature than spectra the TPU melts and flow under compaction, leveling the microirregularities at the fabric interface and hence preventing generation of sufficient heat to melt and degrade the spectra.

The polyester (PET) fabric used in this study was a 3 × 2 twill weave having air jet textured filaments in both warp and weft directions. The construction was 76 × 68 ends and picks per inch. The fabric weight was 7.9 oz.yd^{-2} and the thickness was measured at 0.0157 in. The spectra fabric was of a plain weave construction having 34 × 34 ends and picks per inch. The fabric weight was 6 oz.yd^{-2} and the thickness was 0.0173 in. The breaking strengths of the fabrics were measured using an ASTM D 5034 test method and a Standard Test Method for failure in the seam of woven apparel fabrics; ASTM D 1682 was used to determine seam strength. All tests were conducted on a MTS Tensile Tester. The breaking force required to rupture a seam or fabric specimen was read directly from the Material Testing Systems (MTS) Tensile Tester.

The maximum seam strength of an individual specimen was calculated using the following equation.

$$S_s = kS_b/W_s,$$

where S_s = sewn seam strength (lbf), k = a constant equal to 1 for inch-pound units, S_b = observed seam breaking force (lbf), and W_s = width of specimen in jaws (inch).

Seam efficiency is calculated using the equation given below.

$$E = 100S_s/F_b,$$

where E = seam efficiency %, S_s = sewn seam strength (lbf), and F_b = fabric breaking force (lbf).

An additional conventional seam with thread was used in comparison with the ultrasonic sealing. The rise in fabric temperature at the interface between the two layers was measured by placing thermocouples (Type T) between the fabrics while they were under the horn. Scanning Electron Microcopy (SEM) images of the ultrasonic seams were taken at a distance of 20 mm and 20 kV to examine the physical characteristics of the interface; however, the imaging parameters were altered in some instances to improve the illustration of the specimen characteristics. No quantitative measurements were made based on these images. Differential Scanning Calorimetry (DSC) was used to study the melting behavior of the thermoplastics when ultrasonic energy was applied, using a Perkins Elmer DSC 9 series instrument, the heating rate for all tests was 10°Cm^{-1}.

RESULTS AND DISCUSSION

Effects of sealing time on PET fabric

In continuous mode, speed is taken as weld (sealing) time because the exposure length to the ultrasonic vibration is constant at any given time. As the speed increased, or the exposure time decreased in the continuous mode, the sealing strength of the polyester fabric decreased as seen in Table I. When ultrasonic energy is applied to the thermoplastic PET the fabric temperature increases, causing the polymer to melt or partially melt at that location. Consequently, intermolecular diffusion occurs between the two layers of the fabric followed by recrystallization and new bond formation. In this study, the PET fabric temperature at the sealing point increased from 79.1 to 202°C when sealing speed was reduced from 37.5 to 22.5 ft m^{-1}. As a result of this increased amount of energy transmission to the fabric softening of the PET fibers occurs, and thus allows the fibers between the two fabric layers to bond with each other.

In the Plunge mode of sealing, there was also an increase in sealing strength in general when weld time increased from 1.5 to 3 s along with the increase in fabric temperature from 181.4 to 236.8°C as seen in Table II. This rise in fabric temperature at

TABLE I
Polyester Fabrics' Seam (Seal) Strength at Different Sealing Time and Weld Pressure in Continuous Mode

Fabric sealing strength, lbf			
	Weld pressure, psi		
Sealing speed, ft m^{-1}	40	45	60
22.5	11	23.6	23.6
30		11.2	14.8
37.5			5.1

Empty entries indicate no seam was formed.

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TABLE II
PET Fabrics' Seam (Seal) Strength at Different Sealing Time and Weld Pressure in Plunge Mode

Fabric seam strength, lbf			
	Weld pressure, psi		
Sealing speed, ft m^{-1}	40	50	40
1.5	18.6	25.3	23.7
2.0	22.6	26.1	20.9
3.0	23.3	12.8	8.3

longer sealing time allowed stronger bonds to form between the fabric layers. These trends, however, were not always maintained due to the compaction effects onto the fabric as seen in both Tables I and II.

Effects of weld pressure on the PET fabrics

This increase in strength due to higher weld times in both modes of seal formation was greatly influenced by the weld pressure. A pressure was applied onto the fabric during sealing to ensure energy transmission and bonding between the fabric surfaces. This pressure creates a hot compaction on the synthetic fibers that affects the bonding between the fabric layers whereas ultrasonic energy generates heat into the thermoplastic fabric. Ibar[8] has found that polymer viscosity increases at the higher pressure of the horn, which is attributed to the reduction of free volume due to packing. Hence, the hot compaction of the fabric causes fibers to deform and interlock with each other after localized welding. It has been found[9] that most of the original fiber properties can be retained during hot compaction of the fabric under optimum conditions. Moreover, it was observed during the seam strength testing that interfacial bonding developed due to ultrasonic welding through surface melting of the fibers, so that failure occurs in the original fibers rather than at the interface between the fibers and the crystallized matrix. Under sufficient pressure, fibers are restrained from shrinking and loosing orientation consequently, retaining the fiber strength and promoting strong bonding.[9] The PET fabrics' bond strength generally increased at higher weld pressure in the continuous mode as illustrated in Table I. It is noted that even at higher speed (lower weld time) fabric seams began to form at higher weld pressure as evident in Table I.

In the Plunge mode, however, the high weld pressure exhibited a deteriorating effect on the seam strength at higher sealing time, particularly at 3 s weld time as seen in Table II. The application of excessive ultrasonic energy at a very high weld pressure causes the complete melting of the fibers in that location resulting in the lower strength of the recrystallized matrix that provides weak bonding. Figure 3

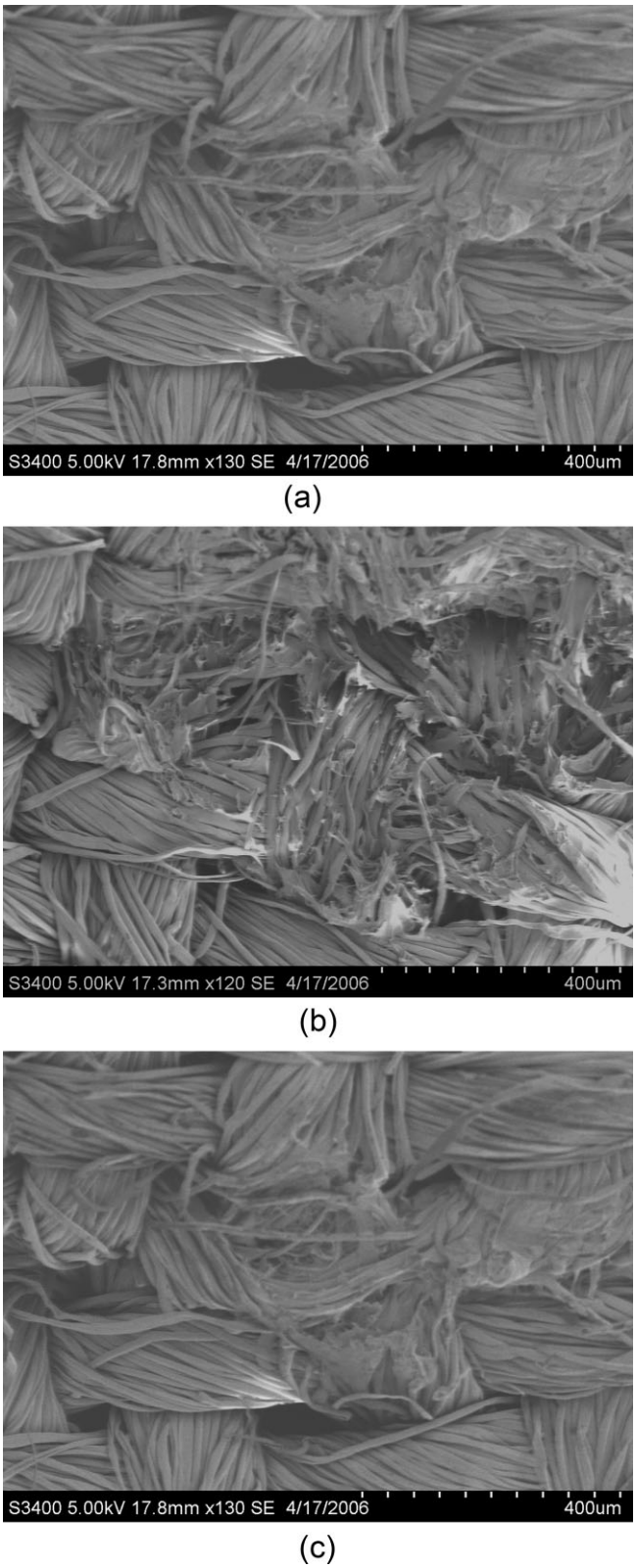

Figure 3 The SEM micrographs of three PET fabric interfaces under different conditions of bonding: (a) weld time 3 s and weld pressure 30 psi (17.8 mm, 5 kV), (b) weld time 3 s and weld pressure 35 psi (17.3 mm, 5 kV), and (c) weld time 3 s and weld pressure 40 psi (16.4 mm, 15 kV).

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TABLE III
Spectra Fabrics' Seam (Seal) Strength at Time and Weld Pressure in Continuous Mode

Fabric seam strength, lbf		
	Weld pressure, psi	
Sealing speed, ft m^{-1}	40	50
15.0	17.4	13.8
22.5	6.6	12.3
30.0		

Empty entries indicate no seam was formed.

shows the SEM micrographs of the three fabric interfaces under different conditions of bonding where Figure 3(c) exhibits the excessive melting of fibers at the interface which leads to a weaker and stiffer bond. Pressure is applied during welding to provide a good contact between the horn and the fabric to effectively transmit vibration and facilitate bonding between the layers when fabric temperature is raised. At low pressure poor transmission of energy takes place, and consequently, fabric temperature does not rise to the required level and the fiber orientation is also not maintained due to lack of constraint. Different morphological events take place within the fibers depending on the amount of energy transmitted and the level of weld pressure. We generally found seam strength increased with increasing weld pressure; however, strength tends to decrease at a very high pressure and weld energy.

Effects of sealing time on spectra fabrics

The effects of ultrasonic welding on the spectra fabrics have been found, as expected, to be considerably different because of the thermal property and the morphological differences between PET and spectra fibers. As the weld speed increased from 15 to 30 ft m^{-1} in the continuous mode the sealing strength of the spectra fabrics' seam strength decreased considerably and no seam was formed at 30 ft m^{-1} even at the higher weld pressure as illustrated in Table III. At 15 ft m^{-1} sewing speed fabric temperature was raised 143°C, forming the seam; however, at a very high speed (30 ft m^{-1}) rather low ultrasonic energy was transmitted to the fabric, which could not raise the polymer temperature to near melting or softening to join the two layers. At 30 ft m^{-1} maximum temperature was raised to 110°C only.

TABLE IV
Spectra Fabrics' Seam (Seal) Strength at Different Sealing Time and Weld Pressure in Plunge Mode

Fabric seam strength, lbf						
	Samples with tape			Samples without tape		
	Weld pressure, psi			Weld pressure, psi		
Time, s	30	35	40	30	35	40
1.0	11.6	12.8	12.4	2.6	5.0	5.5
2.0	14.1	14.4	11.1	7.5	10.0	9.5
3.0	9.8	7.9	6.4	9.0	7.5	7.5

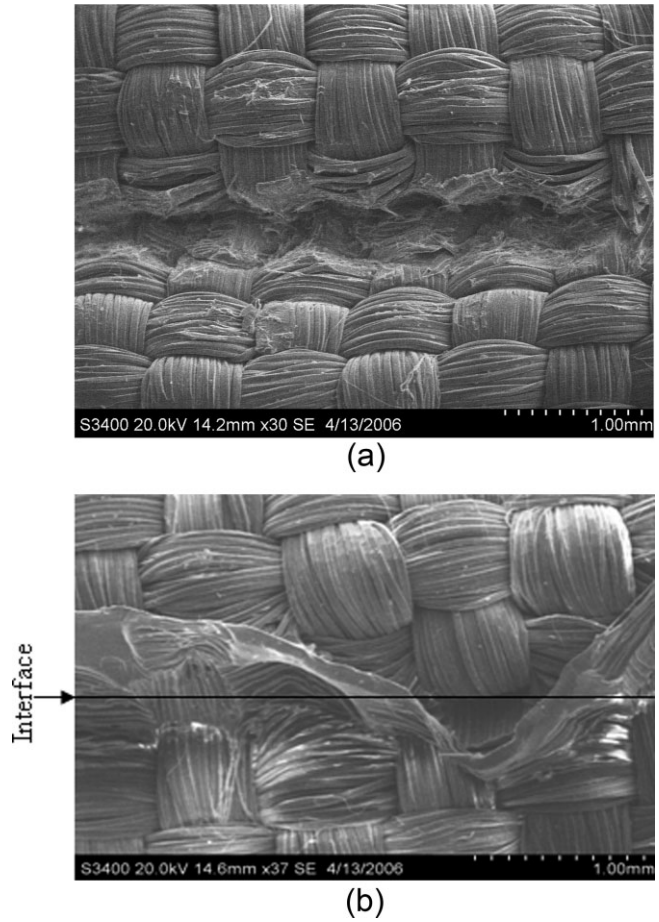

Figure 4 SEM images of spectra fabric interface (a) without (14.2 mm, 20 kV) and (b) with adhesive urethane tape (14.6 mm, 20 kV).

In the plunge mode, increasing weld time from 1 s to 2 s the sealing strength of spectra fabrics increased, but a further increase in weld time to 3 s seam strength deteriorated with or without the use of TPU tape, as illustrated in Table IV. In most conditions there are some increases in sealing strength as a result of using TPU tape between the fabric interfaces. The addition of polyurethane tape at the Spectra fabric interface was found to have enhanced bonding and strength. SEM images of the fabric interface with and without polyurethane tape is illustrated in Figure 4, which shows less melting of individual filaments when polyurethane was added.

Effects of sealing pressure on spectra fabrics' bond strength

Spectra fabric sealing strength did not change significantly by increasing bonding pressure from 30 to

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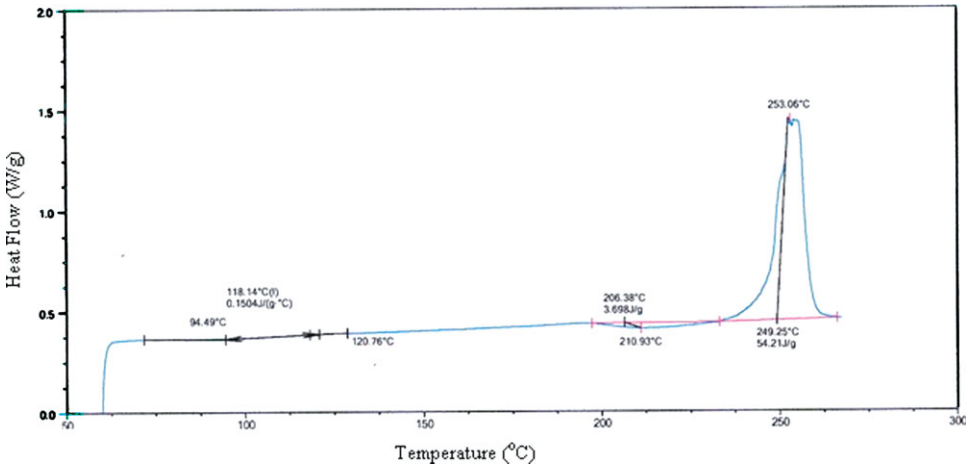

Figure 5 DSC thermogram of untreated polyester fabric. [Color figure can be viewed in the online issue which is available at www.interscience.wiley.com.]

40 psi. As mentioned earlier the overall sealing strength of spectra fabrics were low, which improved somewhat using TPU tapes. This low bonding strength can be attributed to the melting behavior of spectra that makes it difficult to optimize bonding parameters. The meting behavior of both the PET and the spectra fabrics were compared using Differential Scanning Calorimetric (DSC) Analysis.

Melting behavior of PET fabrics

DSC thermogram of both untreated and ultrasonic treated PET fabrics is shown in Figures 5 and 6. On set of glass transition zone in the untreated spectra, Figure 4 was observed between 94 and 120°C with a midpoint at 118°C, which is normally found for a fully drawn and annealed PET fiber. The glass transition; however, shifted to a lower temperature between 82 and 102°C having a midpoint at 95°C when the fabric was subjected to ultrasonic energy, Figure 5, which may be attributed to the breakages of some of the weak bonds in the noncrystalline mesophase zones and allowing the chains to start moving in the amorphous regions at a lower temperature. The crystal melts on set was at 206°C and reached a peak at 253°C for untreated PET while the ultrasonic energy treated sample exhibited a crystal melt on set at 198°C that peaked at 254°C. There is a difference in the shape of the melt peak where treated sample shows less broader and sharper crystal melt peak. This phenomenon may be attributed to higher crystallinity and more molecular order of the polymer microstructure. When the ultrasonic energy was applied to the PET fabric that raises the temperature near melting causing the intermolecular bonds having the most energy to melt and

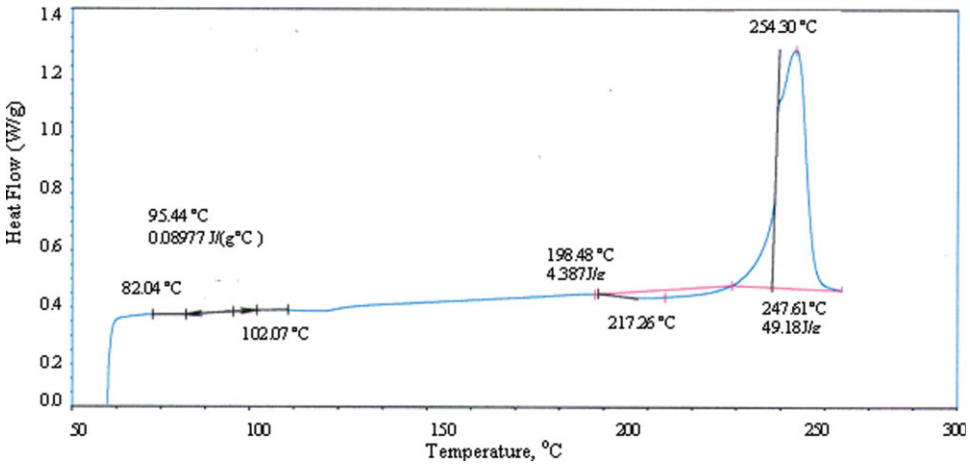

Figure 6 DSC thermogram of the PET treated with ultrasonic energy. [Color figure can be viewed in the online issue which is available at www.interscience.wiley.com.]

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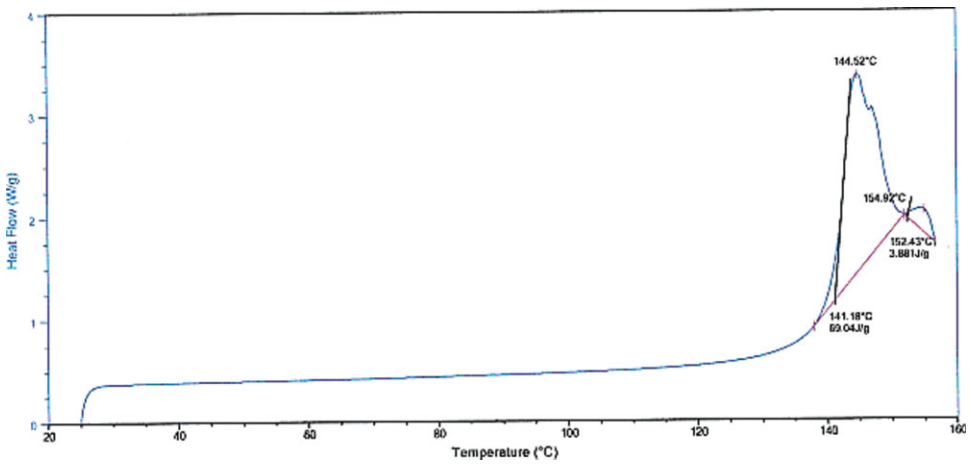

Figure 7 DSC thermogram of untreated spectra fabric. [Color figure can be viewed in the online issue which is available at www.interscience.wiley.com.]

consequently short length molecules move to form more stable intermolecular bonds resulting in better perfection and crystal growth.

Melting behavior of spectra fabrics

The amount of ultrasonic energy and the conditions of application to the spectra fabric is more complex to form an acceptable seam. The DSC thermogram of untreated and treated spectra is shown in Figures 7 and 8. The DSC thermogram of spectra fabric before being exposed to the ultrasonic energy, Figure 6, shows a double melting peak. This phenomenon is normally expected for a highly crystalline gel spun polyethylene fiber[10] owing to the formation of a hexagonal crystalline phase during melting. The development of this phase has been shown by X-ray diffraction studies on constrained ultra drawn polyethylene fibers.[11,12] The melt on set to complete crystal melt region for spectra, 141–154.9°C seemed to be considerably narrower than the PET crystal melt region, 206 to 253°C. Yan et al.[9] have also reported that the temperature range over which significant melting of spectra fiber takes place is very narrow. At the narrow melting range, it is difficult to make a strong seam within this temperature window.

The DSC thermogram of spectra treated with ultrasonic energy is seen in Figure 7, which exhibited significant changes in the melting behavior. The peak at the higher temperature near 154°C in the untreated spectra (Fig. 6), cannot be seen in Figure 7, instead a lower temperature crystal melt peak can be seen at 134°C indicating the formation of a new species by melting and recrystallizing during the

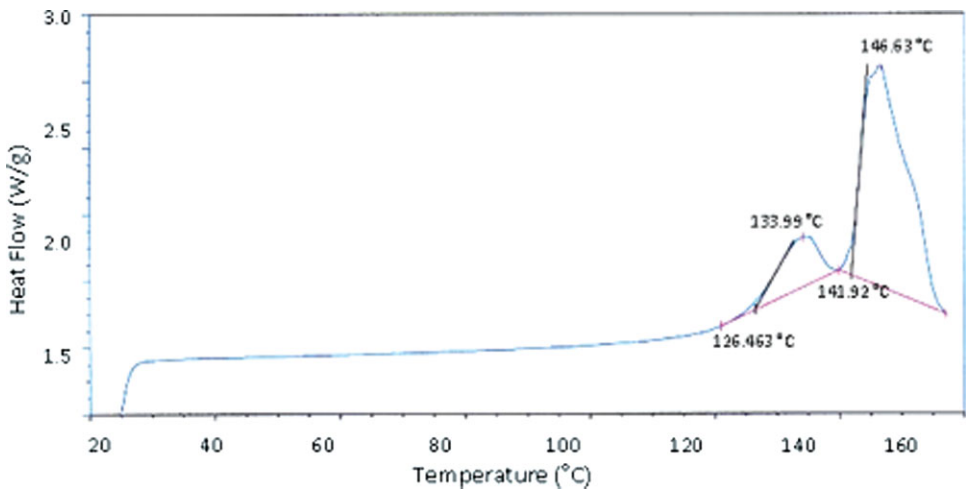

Figure 8 DSC thermogram of spectra fabric treated with ultrasonic vibration. [Color figure can be viewed in the online issue which is available at www.interscience.wiley.com.]

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TABLE V
Comparative Seam Efficiencies of the Ultrasonic Bonded Fabric and Traditionally Sewn Seam Strength

Fabric breaking load, lbf	Ultrasonic seam breaking load, lbf	Traditional seam breaking load, lbf	Seam efficiency (%)	
			Ultrasonic	Traditional
PET fabrics				
112.6	26.1	31.5	23.2	28.0
Spectra fabrics				
450.0	22.1	22.1	4.09	4.09

application of ultrasonic vibration under pressure. This suggests that in the ultrasonic energy treated fabric, under low pressure and a low weld time, the energy transmission and the constraint on the individual fibers may not be high enough to raise the temperature sufficiently to form a hexagonal crystalline phase during sealing. At a lower temperature only a small portion of the fiber softened and recrystallized during welding under hot compaction.

In the plunge mode, however, fabric temperature was raised in the range of 154–206°C. Yan et al.[9] have shown that drastic morphological changes occur in spectra at 155°C and fibers begin to soften as well as melt, creating fiber to fiber weld points and recrystallizing to form the continuous fiber crystals into a new form of lamellar crystals, during the welding process. This explains the reason for increase in seam strength when welding speed was reduced from 22.5 to 15 ft m^{-1} or weld time was increased from 1 to 2 s causing the fabric temperature to rise from 149 to 160°C. When the fabric temperature was raised near 206°C, fibers melted completely in the fabric and also degraded to some extent, producing weak or no bonds between the layers.

Traditional sewn seam versus ultrasonic bonded seam

Ultrasonic energy bonded and traditionally sewn fabrics' seam efficiency is reported in Table V. The ultrasonic seam values are relatively lower than the traditionally sewn seam's strength, which was constructed with thread used for upholstery. These ultrasonic seam values are acceptable in many applications, including apparel use.

CONCLUSIONS

Ultrasonic seaming investigations on PET and spectra fabrics were conducted using both continuous and discontinuous welding machines to form seams at different weld times and pressures. PET fabrics showed higher seam efficiency than that of Spectra. Both machines produced fabric bonds with adequate strength at certain combinations of parameters. The effect of weld time and pressure on the bond morphology has been discussed. When a certain amount of ultrasonic energy is applied under pressure fabric temperature is raised to soften the fibers, which creates sufficient mobility for the molecular chains to slide within the crystalline regions and to form the rows of weld points between the fabrics layers, causing spot welding rather than surface melting and melt bonding. Ultrasonic bonding parameters need to be carefully controlled to avoid excessive melting and polymer degradation.

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