



# Mechanisms of ultrasonic joining of textile materials

Ultrasonic  
joining of textile  
materials

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**Keywords** Seams, Ultrasonic, Welding, Bonding, Woven fabrics, Fiber optics

**Abstract** Investigates the potential for building smart seams by incorporating optic fibers ultrasonically. The heating and bonding mechanisms of ultrasonic welding process in fabrics were studied. Battle dress uniform (BDU) (50/50 nylon/cotton), 100 percent cotton, 100 percent polyester and Nomex fabrics were used and were bonded ultrasonically with and without polyurethane adhesives. The effects of three important welding parameters, namely weld pressure, weld time and amplitude of vibration, on the joint strength and the temperature profile at the interface were examined. The temperature profiles for different fabrics were measured during ultrasonic welding process. The attenuation degree of signal transition properties of optic fibers incorporated was tested to determine if ultrasonic process provided a possible way of embedding optic fibers into seams and achieving sufficient joint strength while the signal transmission properties of optic fibers incorporated were not changed significantly.

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## Introduction

Apparel is changing in terms of its functions by integrating “smart” materials. In addition to current comfort and aesthetic attributes, the garment of the future will include inherent “circuitry” to transform the traditional garment into an intelligent and individually protective clothing system. Seams and patches of the garment are latent places to incorporate these functions. This paper looks at the potentials for building “smart seams” which incorporate sensors or actuators and data from these paths communicate with a wearable transmitter. Optic fibers and ultrasonic bonded seams offer one way to fabricate intelligent clothing systems. In this paper, the state of the art is reviewed and the research to optimize the fabricating methodology is presented.

## Joining techniques

Fabric, the most common form of textile materials for garments, can change shape by bending, shearing, stretching or contracting. Despite fabric’s capability to drape over simple 3D objects, complex 3D shapes of human bodies require that garments must be made by joining panels of various 2D shapes. Many joining methods are available to garment manufacturers, such as sewing, ultrasonic bonding, thermal bonding and laser enhanced bonding (LEB), etc., each with their own advantages and disadvantages.

Sewing, which joins individual panels together with another textile element (thread), provides adequate strength, elasticity and aesthetic properties. However, sewing produces discontinuous joints and perforated seams. To

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produce continuous and non-perforated seams, other joining methods are necessary. Thermal bonding (i.e. hot-tool and hot-gas welding), LEB and ultrasonic bonding involve melting and cooling of thermoplastics at the joining interface. These thermoplastic components may be present as hot-melt fibers, powders, films, or the sheath on bicomponent fibers. In the thermal bonding process, surfaces to be joined are melted individually by direct contact with heated elements and then brought together. The interfaces are allowed to cool and solidify under controlled pressure (Stokes, 1989). The main disadvantage of this technique is that excessive heat conducted through fibers can cause fiber degradation. Light Technologies Group and Union Special Corporation (Fraser and Whitwell, 1971) developed LEB as a high-speed, non-contact technique for welding thermoplastics. In this method, a laser (precisely controlled, highly localized infrared CO<sub>2</sub> gas) is used to drive polymers into fabrics to create a seam. The laser offers a source of concentrated energy which produces thermal effects without direct physical contact, and thermoplastic materials absorb sufficient energy at this wavelength so that bonding temperatures are readily achieved. Properly controlled LEB produces flexible, impermeable and high strength bonds (*Adhesive Age*, 1995; Black, 1995), but highly focused and excessively intense laser radiation may degrade some thermoplastics (Potente and Uebbing, 1997).

Ultrasonic bonding is an advanced technique for joining synthetic materials and blends to produce continuous and impermeable seams. Fabrics may be 100 percent synthetic (thermoplastic) or blends with up to 40 percent natural fiber content. It is very fast, clean and economic (no thread needed) for apparel fabricators. In ultrasonic bonding process, the material is fed between a vibrating ultrasonic horn and a stationary anvil (or a moving wheel). High-frequency mechanical vibrations (20-40kHz) are transmitted through thermoplastic parts to generate a frictional heat built up at an interface, and hence to achieve a sufficient temperature to melt and bond the materials. Because the heat necessary for bonding is produced at the interface (not from the outside of materials), ultrasonic welding process starts exactly at the interface (Kuttruff, 1991). For non-synthetic fabrics or blends with more than 40 percent natural fiber content, heat-activated materials are placed between two pieces of fabrics. Ultrasonic vibrations and pressure cause heat-activated materials to melt and penetrate into the inter-fiber spaces of fabrics (Technical Report from Branson Ultrasonic Corp., 1996).

#### *Weldability and compatibility of ultrasonic welding of thermoplastics*

Although thermoplastics can be welded by ultrasound, different thermoplastics have different weldability because of their differences in structure, melt point, modulus and other additives, such as flame retardation and colorants, etc. (Technical Report from Branson Ultrasonic Corp., 1996). Welding dissimilar materials has to meet two requirements (Technical Report from Branson Ultrasonic Corp., 1996):

- (1) A similar temperature between materials to be welded, which is a basic requirement for successful welding of rigid parts (a temperature difference of 22°C can be sufficient to hinder bonding even for materials with like structures). This is because the lower melt temperature material melts and flows first, leveling the micro-irregularities at the interface and thus preventing generation of sufficient heat to melt the higher melt temperature material (Mozgovoi *et al.*, 1968).
- (2) A like molecular structure (i.e. chemically compatible) with some components of the material, usually a blend.

#### *The bonding strength of ultrasonically welded bulky thermoplastics*

Despite wide-spread applications of ultrasonic bonding techniques in the textile industry, not much research work has been done on the bonding and heating mechanisms of woven fabrics. Most of previous work was focused on ultrasonic welding of bulky polymers (Mozgovoi *et al.*, 1968; Matsyuk and Bogdashevskii, 1960; Mordvintseva and Druzhinin, 1964; Alosio *et al.*, 1972; Chernyak *et al.*, 1973; Frankel and Wang, 1980; Tolunay *et al.*, 1983; Benatar *et al.*, 1989) and thermal bonding of non-wovens (Chu and Yan, 1994; Dantuluri *et al.*, 1987; Flood, 1992; 1994; Hassan and Rust, 1986; *Non-woven Report International*, 1982; Britton and Sampson, 1984; Warren and Partenio, 1994; Wei and Vigo, 1985; Lobomir, 1986; Lutzow, 1993).

Matsyuk and Bogdashevskii (1960) studied the ultrasonic welding of lap joints between polymer pieces. During a welding cycle, interfacial temperatures were measured for some types of polymers (poly(methyl methacrylate), polyethylene, and poly(vinyl chlorides)). It was found that the highest weld strength was attained at an intermediate value of weld force.

Mordvintseva and Druzhinin (1964) found that ultrasonic bonding strength of polyethylene increased within a range of welding time and welding force at first and then decreased beyond that range. The study on microstructures of ultrasonically welded polyethylene indicated that no new chemical group or bond was formed, and the only noticeable change was a slight increase in molecular weight (Mozgovoi *et al.*, 1968). The joint strength depends on the degree of fusion of the material at the interface. Frankel and Wang (1980) studied the ultrasonic welding of acrylonitrile-butadiene-styrene copolymer (ABS) and observed that, the highest joint strength was obtained in the case of longest weld time and lowest weld force from nine different welding conditions involving three levels of force and time. The rate of temperature rise increased with the increase of amplitude of vibrations.

#### *Current research*

In addition to factors affecting various resins (structure, glass transition temperature, melting point, specific heat capacity, melt index and modulus), ultrasonic welding of textile materials also depends on their thermoplastic content, fabricating types (woven or knit) and desired end results (Technical Report from Branson Ultrasonic Corp., 1996). The main objective of the present

study, therefore, was to correlate the resulting bond strength with welding conditions and examine the nature of heat evolution in fabrics during ultrasonic welding. In the experiment, temperature profiles during ultrasonic welding were measured and determined in relation to the properties of the fabrics being welded and welding conditions. The weld strength was tested by fabric grab and tension tests. The microstructure of ultrasonically welded fabrics was examined in terms of chemical and physical characteristics, which gives a direct picture of the joint development in ultrasonic welding of fabrics. Based on these findings, the ultrasonic process for embedding optic fibers into seams to fabricate “smart structures” was studied. The morphologies of optic fibers embedded were examined under varying welding conditions and the power loss of signal transition of incorporated optic fibers was tested to determine their attenuation degree of signal transition properties.

### Experimental techniques

Figure 1 shows the experimental configuration for ultrasonic welding and temperature detection, which includes a Branson 901 AES ultrasonic welding machine (actuator, power supply and weld profile controller), SC-2345 signal conditioning box (National Instruments Inc.), data acquisition board and a personal computer. The welding process was set under “time” mode. During welding, the microprocessor-controlled welder was used to record weld time, hold time, pressure, power, energy and down speed. The amplitude of vibrations can be adjusted by using different boosters. An anvil (James, 1997) (Figure 2) with a groove in the middle was developed to accommodate the placement of an optic fiber strand between the two fabrics during welding process. In our experiment, 0.008-inch-diameter thermocouples (type T) were placed at the interface of two fabric layers (Figure 3). During welding, the

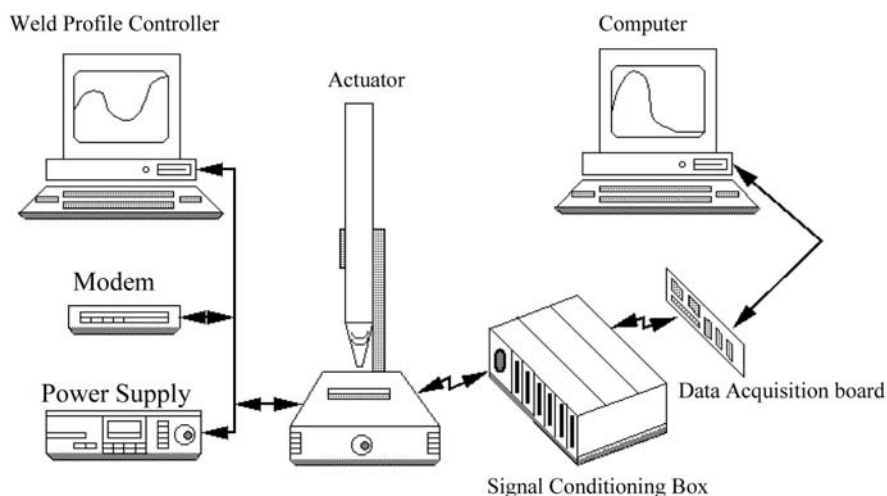
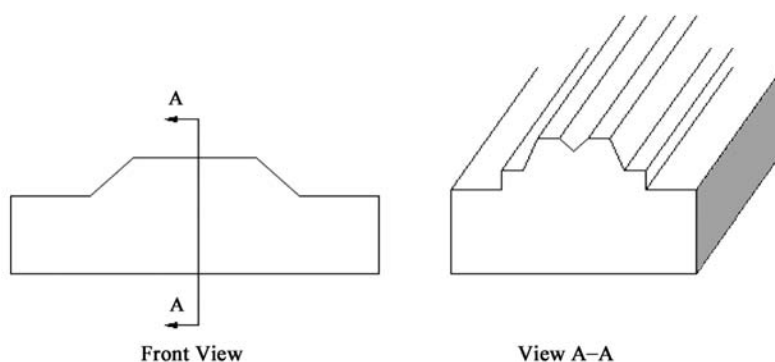


**Figure 1.**  
Experimental  
configuration for  
ultrasonic welding and  
temperature detection



Source: James 1997

**Figure 2.**  
Modified anvil for the  
placement of the optic  
fiber

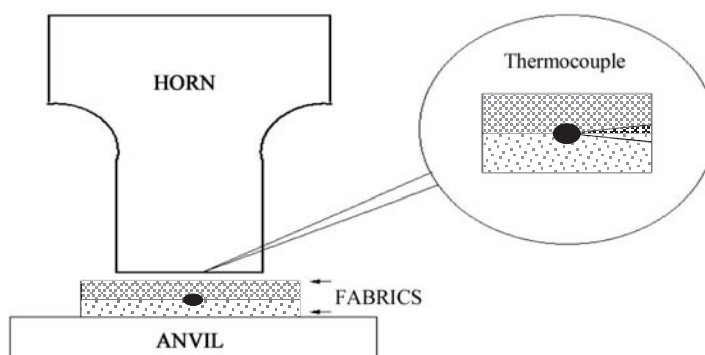


**Figure 3.**  
Thermocouple  
placement in  
temperature profile  
experiment

temperature change at the interface was detected by the thermocouple and modified by the signal conditioning box, then the data was sent to a data acquisition board and a temperature profile graph was recorded.

Ultrasonic welding was performed on five different sets of fabrics. The physical properties of materials used are listed in Table I. For the 50/50 nylon/cotton blend BDU fabrics, polyurethane adhesive films were used between two fabric pieces. The reason we choose polyurethane is that it has excellent bond strength when ultrasonically bonded (Technical Report from Branson Ultrasonic Corp., 1996) and its softening temperature is close to that of nylon fibers (about 110°C).

#### *Factorial experiment design*

Ultrasonic welding strength is determined by degree of fusion, which is mainly dependent upon the temperature at the interface (Frankel, 1976). Thus, welding strength is correlated with the thermal energy at the interface.

An ultrasonic weld is governed by process parameters, illustrated in Figure 4.

| Materials                      | Description                                                                                                                                                                                   | Density<br>(g/cm <sup>3</sup> ) | Thickness <sup>a</sup><br>(mm) |
|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|--------------------------------|
| 100 percent cotton fabrics     | Knit                                                                                                                                                                                          | 0.024                           | 0.67                           |
| 100 percent PET fabrics        | Ponte-de-Roma knit                                                                                                                                                                            | 0.021                           | 0.43                           |
| 50/50 nylon/cotton BDU         | Light-weight knit                                                                                                                                                                             | 0.021                           | 0.66                           |
| 50/50 nylon/cotton BDU         | Twill knit                                                                                                                                                                                    | 0.025                           | 0.86                           |
| Nomex fabrics                  | Degrading 310°C                                                                                                                                                                               | 0.015                           | 0.50                           |
| Polyurethane film <sup>b</sup> | Soften 115-135°C                                                                                                                                                                              | 1.18                            | 0.05                           |
| Optical fibers <sup>c</sup>    | Core/cladding/jacket<br>diameter: 100/140/250μm,<br>SiO <sub>2</sub> /SiO <sub>2</sub> /plastic<br>Core/cladding/jacket<br>diameter: 210/230/270μm,<br>SiO <sub>2</sub> /soft plastic/plastic |                                 |                                |

**Table I.**  
Properties of the  
materials used

**Notes:** <sup>a</sup> Measured at 0.5g force per cm<sup>2</sup>; <sup>b</sup> PUROX form Adhesive Films Inc.; <sup>c</sup> Fiber Optics and Photonics Manufacturing Centre, Material Engineering Department, Drexel University

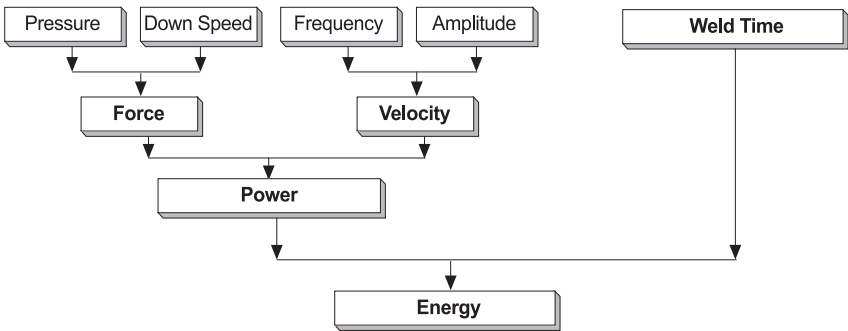


**Figure 4.**  
Governing parameters  
for ultrasonic weld

From Figure 4, it can be seen that welding time, amplitude of vibration and welding pressure affect the amount of energy that goes into the weld area. Based on this, a 2<sup>3</sup> factorial experiment (Figure 5) was carried out to study the effects of weld time, pressure and amplitude of vibration with weld strength. Two levels were chosen for each parameter according to some preliminary experiments. Down speed (2.1 inches/second) and hold time (0.5 seconds) were kept constant. The BDU light-weight fabrics with or without polyurethane films, and BDU twill fabrics with polyurethane films were tested.

Individual experiments were also carried out to investigate effects of weld pressure and weld time on the bonding strength. The weld pressures used were 20, 25, 30, 35 and 40psi. The weld times used were 1, 1.5, 2.0, 2.5 and 3.0 seconds. The amplitude (60μm), down speed (2.1 inches/second) and hold time (0.5 seconds) were kept constant.

The joint strength of various samples was tested in the direction perpendicular to the bond with a Sintech universal testing machine (UTM). The testing speed is 30mm/min. For each set of parameters, 20 welds were

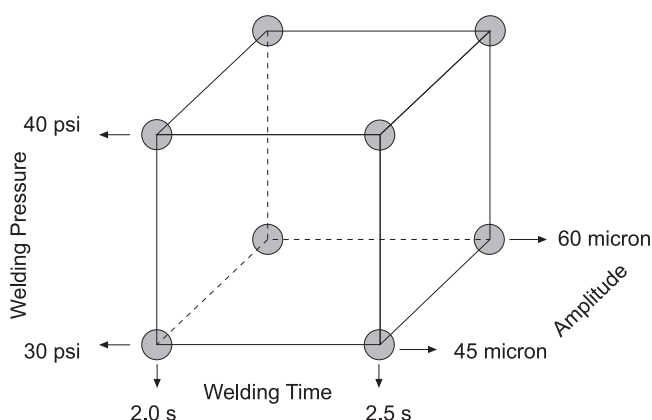


**Figure 5.**  
Graphical representation  
of  $2^3$  factorial design

performed and the strength was compared with the sewing strength. Strength tests were also carried out on laundered samples to test the durability of ultrasonically welded seams.

#### *Study on the microstructure of welded fabrics and optic fibers*

SEM analysis was carried out to examine the condition and morphology of fabrics and the incorporated optical fibers.

Fourier transmission infrared (FTIR) test was performed to study the possible chemical conversions in the weld zone under the influence of ultrasonic vibrations. BDU fabrics and polyurethane films were examined by using attenuated total reflectance (ATR) connector before and after ultrasonic welding and their spectra were compared. The tests were carried out on Nicolet 510P FTIR spectrometer at frequencies from  $400\text{--}4,000\text{cm}^{-1}$  with resolution of  $32\text{cm}^{-1}$ , scan = 128.

#### *Power loss of optic fibers incorporated in fabrics*

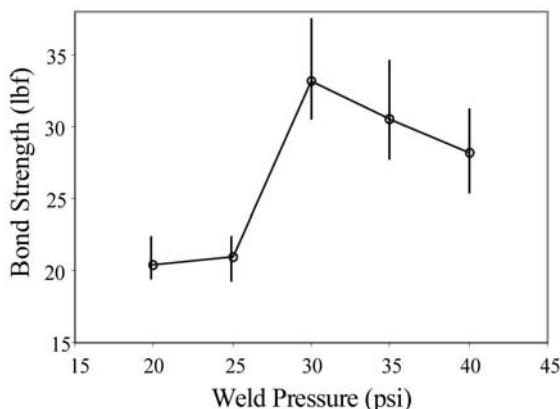
The samples embedded with optic fibers were tested in the Fiber Optics and Photonics Laboratory at Drexel University to see if the enclosed fiber was damaged by checking the continuation of the optic signals propagating within the fiber and the power loss.

## **Results and discussion**

### *$2^3$ factorial experiment*

Preliminary experiments showed that bonding strength increased with weld pressure up to 30psi and then decreased (as shown in Figure 6). It was also observed that a minimum pressure was required to produce satisfactory welds. As mentioned earlier, the purpose of weld pressure is to provide contact between horn and materials to transmit the vibrations and also to bond the heated surfaces. Low pressure provides poor contact and thus poor energy transmission. An increase in pressure will improve the weld strength initially, but higher pressures will orient polymer chains during ultrasonic welding and

**Figure 6.**  
Effects of weld pressure  
on bond strength (weld  
time 2.5s; amplitude  
60 $\mu$ m)



decrease the weld strength (Mozgovoi *et al.*, 1968; Benatar *et al.*, 1989). Too great a pressure can also damage fibers and reduce the strength of fabrics.

A similar trend was observed in the effect of weld time on bond strength (Figure 7). The reason is that energy dissipation increases with the increase of weld time and thus the strength increases until the maximum strength is achieved. If weld time is too long, this may damage cotton fibers (char or burn) and thus decrease the bond strength.

The average peak loads for seam strength of BDU light-weight fabrics with polyurethane films are listed in Table II. It can be seen that the seam strength increased up to 80 percent when the amplitude was increased from 42-60 $\mu$ m keeping other parameters constant. Compared with the amplitude, the effects of weld pressure and weld time on strength are smaller but important (up to 15 percent). Therefore, amplitude of vibrations seems to be the most important variable affecting weld strength. The maximum weld strength was obtained

**Figure 7.**  
Effects of weld time on  
bond strength (weld  
pressure 30psi;  
amplitude 60 $\mu$ m)

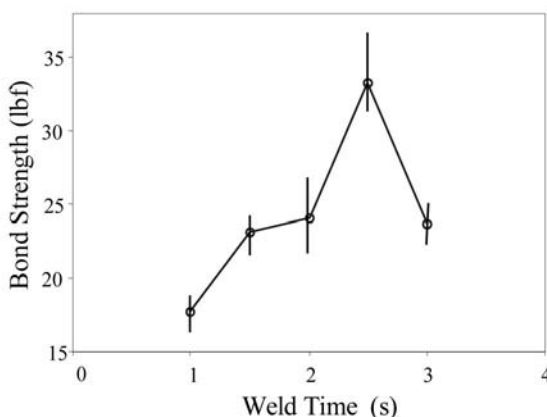


**Table II.**  
Experimental design  
and results for BDU  
light-weight fabrics  
with polyurethane  
films

| Exp.<br>no. | Welding conditions                |                |                | Actual setting  |                   | Pr<br>(psi) | Average peak<br>load (psi) | Energy<br>(joules) |
|-------------|-----------------------------------|----------------|----------------|-----------------|-------------------|-------------|----------------------------|--------------------|
|             | Coded variables<br>X <sub>1</sub> | X <sub>2</sub> | X <sub>3</sub> | WT<br>(seconds) | Amp<br>( $\mu$ m) |             |                            |                    |
| 1           | –                                 | –              | –              | 2.0             | 42                | 30          | 18.0 $\pm$ 1.3             | 652                |
| 2           | +                                 | –              | –              | 2.5             | 42                | 30          | 17.4 $\pm$ 2.1             | 800                |
| 3           | –                                 | +              | –              | 2.0             | 60                | 30          | 24.0 $\pm$ 2.8             | 788                |
| 4           | +                                 | +              | –              | 2.5             | 60                | 30          | 33.2 $\pm$ 4.4             | 958                |
| 5           | –                                 | –              | +              | 2.0             | 42                | 40          | 17.1 $\pm$ 2.4             | 827                |
| 6           | +                                 | –              | +              | 2.5             | 42                | 40          | 20.8 $\pm$ 2.5             | 891                |
| 7           | –                                 | +              | +              | 2.0             | 60                | 40          | 29.4 $\pm$ 4.5             | 835                |
| 8           | +                                 | +              | +              | 2.5             | 60                | 40          | 28.2 $\pm$ 3.8             | 1,031              |

**Notes:** –, lower level; +, higher level; WT, weld time; Amp, amplitude of vibrations;  
Pr, weld pressure

under conditions of the longer weld time (2.5 seconds), the lower weld pressure (30psi) and the higher amplitude of vibration (60 $\mu$ m), which had energy input of 957 Joules. The weld strength reached a saturation value at this energy input (957 Joules) and further increasing in energy input inversely affected the strength. This observation is supported by the fact that increasing the energy input from 958 Joules to 1,031 Joules decreased the strength 15 percent. Similar observation has been reported in another paper (Wei and Vigo, 1985).

The average peak load for seam strength of BDU light-weight fabrics without additional adhesives and BDU twill fabrics with polyurethane films are listed in Tables III and IV, respectively.

Compared with the data in Table II, the average peak loads for seam strengths in Table III are much lower than those in Table II under the same welding conditions. Although the average peak loads in Table IV are higher in most cases than those in Table II, all the bond failure occurred because of fabric

| Exp.<br>no. | Welding conditions                |                |                | Actual setting  |                   | Pr<br>(psi) | Average peak<br>load (psi) |
|-------------|-----------------------------------|----------------|----------------|-----------------|-------------------|-------------|----------------------------|
|             | Coded variables<br>X <sub>1</sub> | X <sub>2</sub> | X <sub>3</sub> | WT<br>(seconds) | Amp<br>( $\mu$ m) |             |                            |
| 1           | –                                 | –              | –              | 2.0             | 42                | 30          | 9.3 $\pm$ 1.7              |
| 2           | +                                 | –              | –              | 2.5             | 42                | 30          | 13.3 $\pm$ 1.7             |
| 3           | –                                 | +              | –              | 2.0             | 60                | 30          | 8.4 $\pm$ 2.0              |
| 4           | +                                 | +              | –              | 2.5             | 60                | 30          | 10.8 $\pm$ 1.6             |
| 5           | –                                 | –              | +              | 2.0             | 42                | 40          | 8.5 $\pm$ 1.3              |
| 6           | +                                 | –              | +              | 2.5             | 42                | 40          | 14.0 $\pm$ 1.7             |
| 7           | –                                 | +              | +              | 2.0             | 60                | 40          | 9.5 $\pm$ 1.6              |
| 8           | +                                 | +              | +              | 2.5             | 60                | 40          | 13.3 $\pm$ 2.0             |

**Notes:** –, lower level; +, higher level; WT, weld time; Amp, amplitude of vibrations;  
Pr, weld pressure

**Table III.**  
Experimental design  
and results for BDU  
light-weight fabrics  
without additional  
adhesives

**Table IV.**  
Experimental design  
and results for BDU  
twill fabrics with  
polyurethane

| Exp.<br>no. | Coded variables |                |                | Welding conditions |                                     | Pr<br>(psi) | Average peak<br>load (psi) |
|-------------|-----------------|----------------|----------------|--------------------|-------------------------------------|-------------|----------------------------|
|             | X <sub>1</sub>  | X <sub>2</sub> | X <sub>3</sub> | WT<br>(seconds)    | Actual setting<br>Amp<br>( $\mu$ m) |             |                            |
| 1           | –               | –              | –              | 2.0                | 42                                  | 30          | 27.7 $\pm$ 3.0             |
| 2           | +               | –              | –              | 2.5                | 42                                  | 30          | 30.6 $\pm$ 4.0             |
| 3           | –               | +              | –              | 2.0                | 60                                  | 30          | 25.4 $\pm$ 2.3             |
| 4           | +               | +              | –              | 2.5                | 60                                  | 30          | 28.5 $\pm$ 2.2             |
| 5           | –               | –              | +              | 2.0                | 42                                  | 40          | 26.1 $\pm$ 2.9             |
| 6           | +               | –              | +              | 2.5                | 42                                  | 40          | 29.5 $\pm$ 3.4             |
| 7           | –               | +              | +              | 2.0                | 60                                  | 40          | 24.2 $\pm$ 1.9             |
| 8           | +               | +              | +              | 2.5                | 60                                  | 40          | 34.2 $\pm$ 3.0             |

**Notes:** –, lower level; +, higher level; WT, weld time; Amp, amplitude of vibrations;  
Pr, weld pressure

failure. Therefore, the peak load obtained here is more indicative of the strength of fabrics. For the results in Table IV, the effect of amplitude of vibrations, weld time and pressure on the strength is not as apparent as observed earlier.

#### *Comparison of the strength of ultrasonic weld and sewing seams*

The optimum ultrasonic bonding strength in our experiment is equivalent to sewing strength (about 30lbf/inch). Strength tests were also carried out on samples after up to five laundry cycles (Figure 8). Machine-washing had no statistically significant effect on bonding strength.

#### *Failure modes of the ultrasonic bond*

Three kinds of failure modes for ultrasonically welded seams were found:

- (1) failure in bond without damaging fabrics;
- (2) damage in fabrics; and
- (3) a combination of (1) and (2).

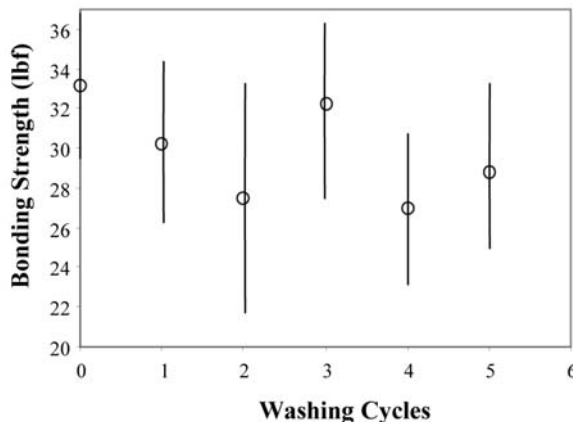


**Figure 8.**  
Effect of washing cycles  
on ultrasonic bonding  
strength of BDU  
light-weight fabrics with  
polyurethane films (weld  
time 2.5 seconds;  
amplitude 60 $\mu$ m;  
pressure 30psi)

The first mode of failure is desirable in that the seam is strong and ductile with yield points being observed in the stress-strain curves. The correlation between the weld parameters, the properties of materials and the failure modes need to be investigated further.

### *SEM analysis*

*Samples bonded with adhesive films.* Figure 9(a)-(f) show SEM micrographs for the cross section of original fabric and specimens obtained at weld time 0.2, 0.5, 1, 1.5 and 2.5 seconds, with weld pressure 30psi and amplitude of vibrations  $60\mu\text{m}$ .

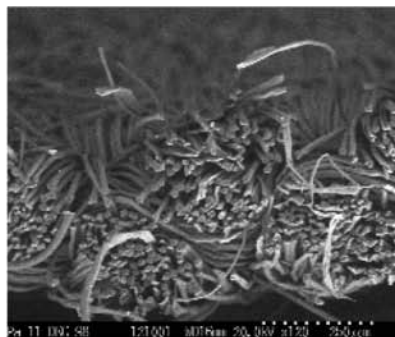
Figure 9(a) shows the cross section of BDU fabrics before welding, in which those with larger diameter are cotton fibers and those with smaller diameter are nylon fibers. At weld pressure 30psi and amplitude of vibration  $60\mu\text{m}$ , applying the vibration of 0.2 seconds produced the section which is mainly the original structure with the adhesive film softened and deformed (Figure 9(b)). Increasing the weld time to 0.5 seconds and 1 second results in melted or partially melted nylon fibers and polyurethane film (Figure 9(c) and (d)). At weld times of 1.5 up to 2.5 seconds, melting flow is visible and sufficient.

Also from Figure 9, the fibers at the interface have undergone more melting than those towards the outsides of the sample (individual fibers are obvious). The ultrasonic vibrations apply rapid impacts and cyclic tangential stress to the sample surfaces against each other. The considerable stress in micro-roughness peaks brings about their plastic deformation. The material which becomes plastic around micro-roughness peaks has increased sound absorption and continues to be preferably heated and hence the heating process at these points will be accelerated in an avalanche-like manner (Kuttruff, 1991; Abramov, 1994). At the beginning of a weld cycle, the asperities at the sample interface are pronounced, and they generate heat first, then dissipate heat to regions near the ultrasonic horn and anvil. The thermal energy causes the temperature rise at the interface and hence increases the mobility of polymer chains and promotes intense intermingling of polymer chains at the interface. When the vibration is removed and the interface is cooled down, the intermingling state of polymers is retained and results in a welded seam.

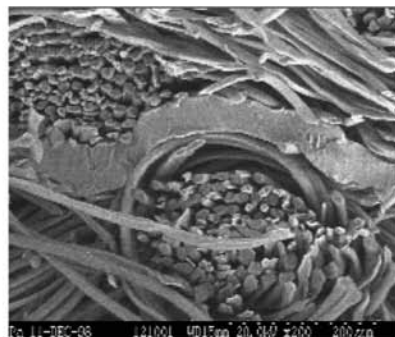
*Seams incorporating optic fibers.* Figure 10(a)-(d) illustrate the seams incorporating optic fibers, which were made at weld times of 0.2 seconds, 0.5 seconds, 1 second and 1.5 seconds, weld pressure 30psi and amplitude of vibration  $42\mu\text{m}$ . At a weld time 0.2 seconds, the two fabric layers were separated from each other and no obvious change occurred in the optic fiber (Figure 10(a)). With the increase of weld time, the interface of the two fabric layers began to fuse (Figure 10(b) and (c)). At a weld time 1.5 seconds, although a good weld resulted, the optic fiber was damaged and a crack can be seen clearly along the interface of the core and cladding (Figure 10(d)).

### *Temperature profiles for ultrasonic welding process*

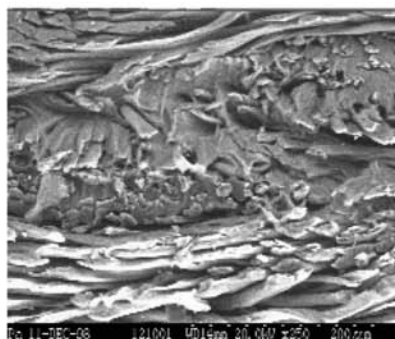
Figure 11 illustrates the temperature traces for four different fabrics, which were recorded by thermocouples placed at the weld interface. From these



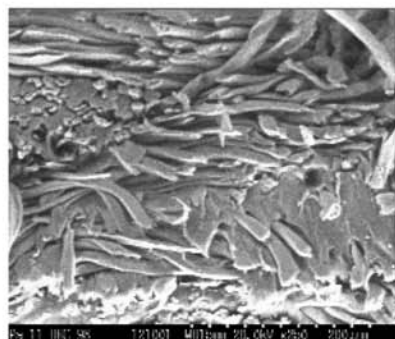
(a) Original



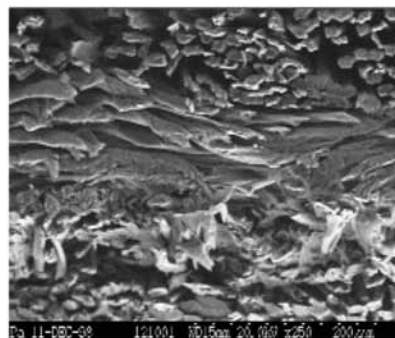
(b) WT=0.2 second



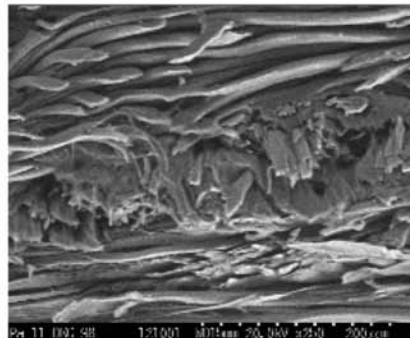
(c) WT=0.5 second



(d) WT=1 second

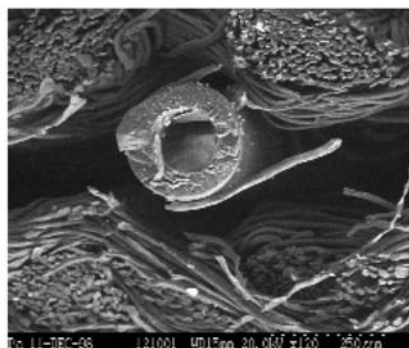


(e) WT=1.5 seconds

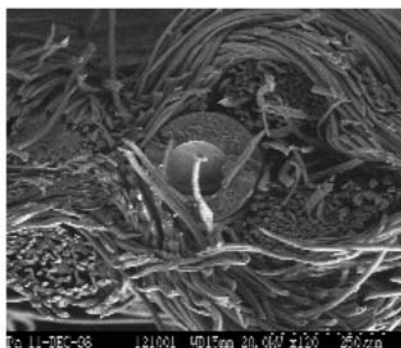


(f) WT=2.5 seconds

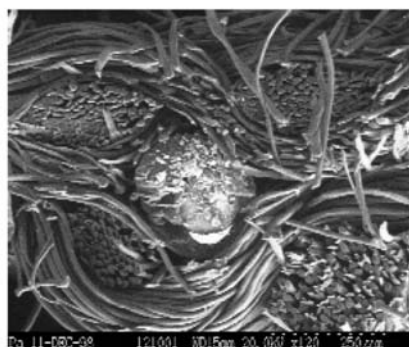
**Figure 9.**  
SEM micrographs of the  
melting condition at the  
interface of the BDU  
fabrics with  
polyurethane films: (a)  
before welding;  
(b)-(f) weld pressure  
30psi and amplitude  
60 $\mu$ m.  
WT = weld time



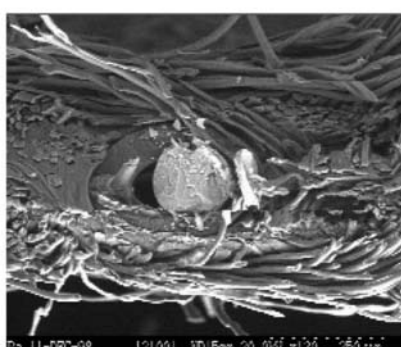
(a) WT=0.2 second



(b) WT=0.5 second



(c) WT=1 second



(d) WT=1.5 seconds

**Figure 10.**  
SEM micrographs for  
ultrasonic welding  
seams incorporated with  
optc fibers (weld  
pressure 30 psi;  
amplitude 42 $\mu$ m).  
WT = weld time

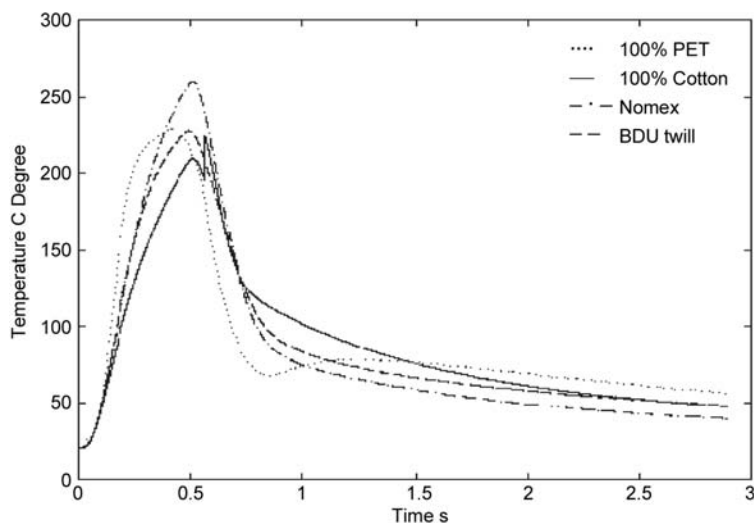


**Figure 11.**  
Temperature profiles in  
ultrasonic welding  
process for four kinds of  
fabrics (weld time 0.5  
seconds; pressure 30psi;  
amplitude 60 $\mu$ m)

graphs, some general trends in the thermal profiles recorded are apparent. At the beginning of a weld cycle, interfacial temperatures increased rapidly and reached peak temperatures within about 0.5 seconds, and then temperatures decreased rapidly after the ultrasonic vibration was removed.

However, for 100 percent PET fabrics, the temperature rose rapidly at the beginning of a weld cycle and the peak temperature (225°C) was reached in about 0.35 seconds (before end of weld time). The rest time of the weld cycle was characterized by cooling at the interface. Such observation has been reported (Wei and Vigo, 1985). For the other fabrics in Figure 11, the peak temperatures were reached in approximately 0.5 seconds and when ultrasonic vibrations was stopped at 0.5 seconds, the temperatures dropped dramatically. At 0.7 seconds, the interfacial temperature for 100 percent PET was about 60°C, and approximately 75°C for Nomex, 80°C for BDU twill, 100°C for 100 percent cotton. After 0.7 seconds, an unexpected increase in temperature was observed in 100 percent PET fabric.

Among the graphs in Figure 11, the rate of temperature change is the highest for 100 percent PET fabric and it is followed by Nomex, 50/50nylon/cotton BDU and 100 percent cotton fabrics. Thermal conductivity affects the absorption of ultrasonic wave in solids and hence the temperature variation (Bhatia, 1967; Ensminger, 1988). The thermal conductances for four different fabrics used are listed in Table V. It can be seen that the higher the thermal conductance of fabrics, the larger the changing rate of temperature. The difference in measured rates of temperature rise among the thermal graphs of Nomex, BDU twill and 100 percent cotton fabrics was not obvious in the initial period (until 0.2 seconds), which may be caused by the melting condition of weld areas and precision of thermocouples used.

Also from Figure 11, different peak temperatures were observed for different fabrics under the same welding condition. Among these fabrics, Nomex achieved the highest peak temperature during welding process and was followed by 100 percent PET and BDU and 100 percent cotton. This may be related with melt temperatures and morphology of fibers under weld and the attenuation of ultrasonic waves, which need to be investigated further. In the experiments, no weld was obtained for 100 percent cotton or Nomex fabrics because these fibers cannot melt and flow although they can be heated by absorbing ultrasonic vibrations. Nomex will degrade above 371°C and cotton will be “charred” above 250°C.

The function of weld pressure is to bring two surfaces into contact and ensure vibration energy transmitted. The effect of changing weld pressure is

| Fabrics                                 | PET   | Nomex | BDU   | Cotton |
|-----------------------------------------|-------|-------|-------|--------|
| Thermal conductance ( $Wm^{-2}C^{-1}$ ) | 91.60 | 80.00 | 82.00 | 78.00  |

**Table V.**  
Thermal conductances  
for fabrics used

**Notes:** Tested by Thermal and Protective Apparel Lab in North Carolina State University.  
Thermal conductance = thermal conductivity/thickness of fabrics at 6g force

shown in Figure 12. The peak temperature reached in curve 1 is higher than that in curve 2. The energy input increases with the increase of weld pressure. Increasing the weld pressure from 30psi to 40psi caused the energy input to increase from 957 Joules to 1,031 Joules and the peak temperature increased from about 250°C to 280°C.

As indicated before, amplitude of vibrations strongly affects the energy dissipation and thus determines the weld strength. The decrease of amplitude from 60 $\mu$ m to 42 $\mu$ m decreased temperature-rising rates and peak temperatures reached at the interface from 280°C to 190°C (Figures 13 and 14). Thus a decrease in the amplitude of vibrations requires longer weld time to attain the same level of weld strength.

During ultrasonic welding, the temperature at the interface of two welded pieces is different in different fabrics and welding parameters used. Thermal conductance is found to be a factor affecting rates of temperature change during welding process. The higher the thermal conductance of fabrics, the larger the rate of temperature change. For the same fabric, the increase in weld pressure or amplitude of vibrations increases the energy dissipated, and thus increases the rate of temperature change and the peak temperature attained. Temperature is critical to a successful joint. If the temperature is too high at the weld area, the materials to be welded will be over-welded or degraded. If the temperature is too low, the materials cannot melt and flow sufficiently and a poor weld strength will result.

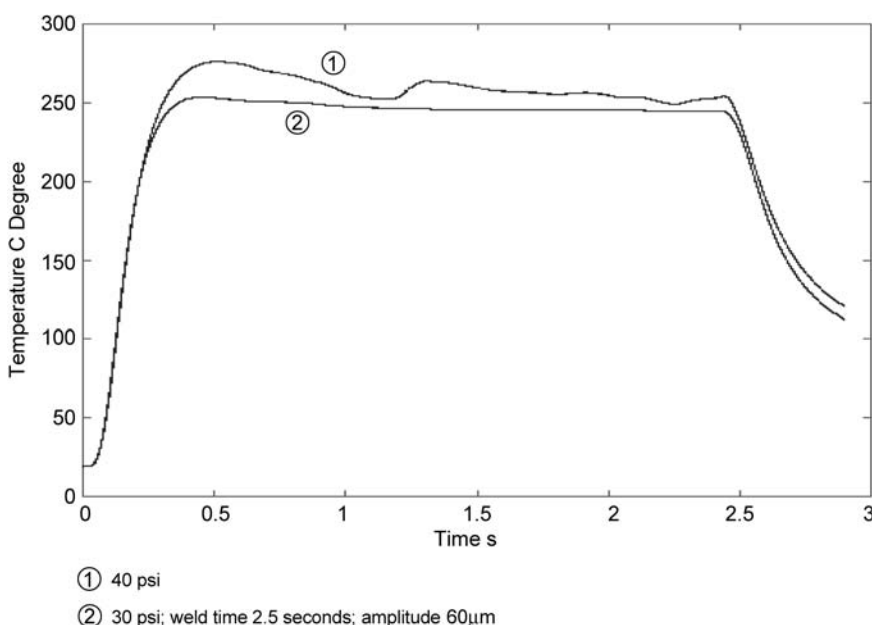


**Figure 12.**  
The effect of weld  
pressure on temperature  
profiles (fabric: BDU  
light-weight; weld  
pressure: curve 1, 40 psi;  
curve 2, 30 psi; weld  
time 2.5 seconds;  
amplitude 60 $\mu$ m)

**Figure 13.**  
The effect of amplitude  
on the welding strength  
(fabric: BDU twill; weld  
time 0.5 seconds;  
pressure 30psi)

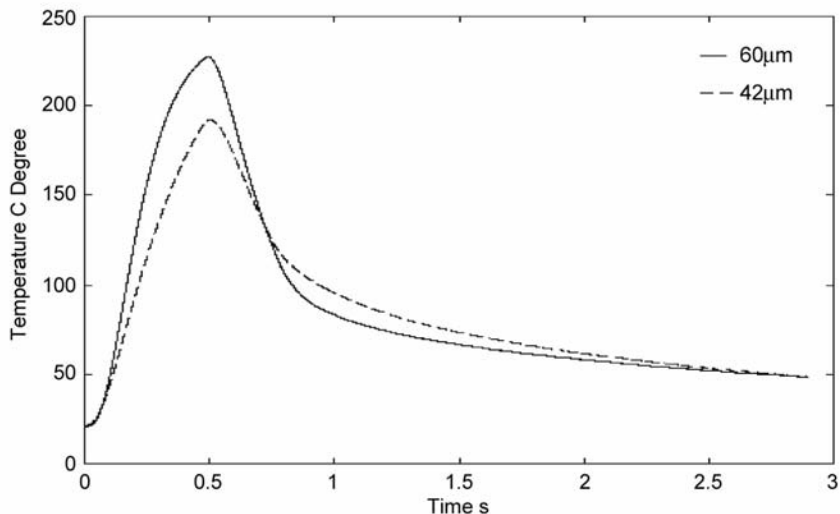
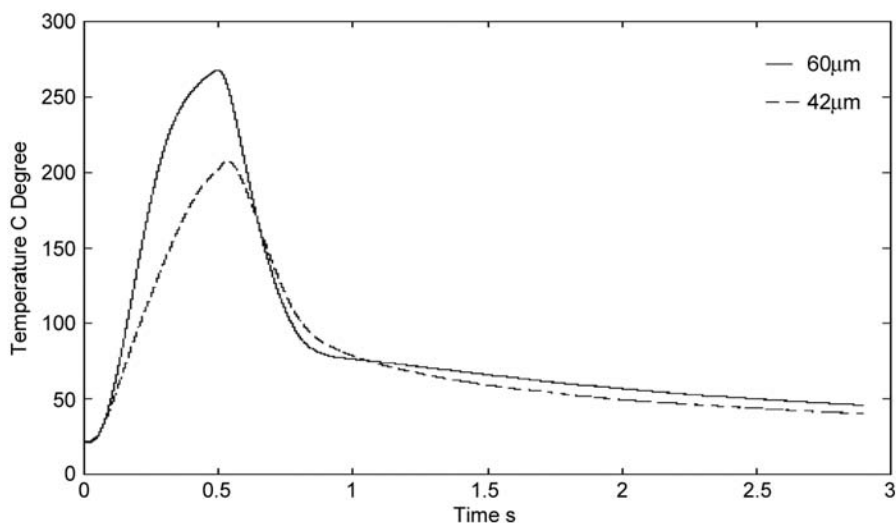


**Figure 14.**  
The effect of amplitude  
on the welding strength  
(fabrics: Nomex; weld  
time 0.5 seconds;  
pressure 30psi)



#### *FTIR-ATR spectra*

Figures 15 and 16 are FTIR-ATR spectra for BDU fabrics and polyurethane films before and after ultrasonic welding. The spectra show that no new chemical groups have been formed under these ultrasonic bonding conditions used. The ultrasonic bonding mechanism is a physical process, rather than a chemical process. It results from molecular diffusion and inter-fiber encapsulation at high temperature and when ultrasonic vibrations are turned off, such state is stiffened and a joint is attained.

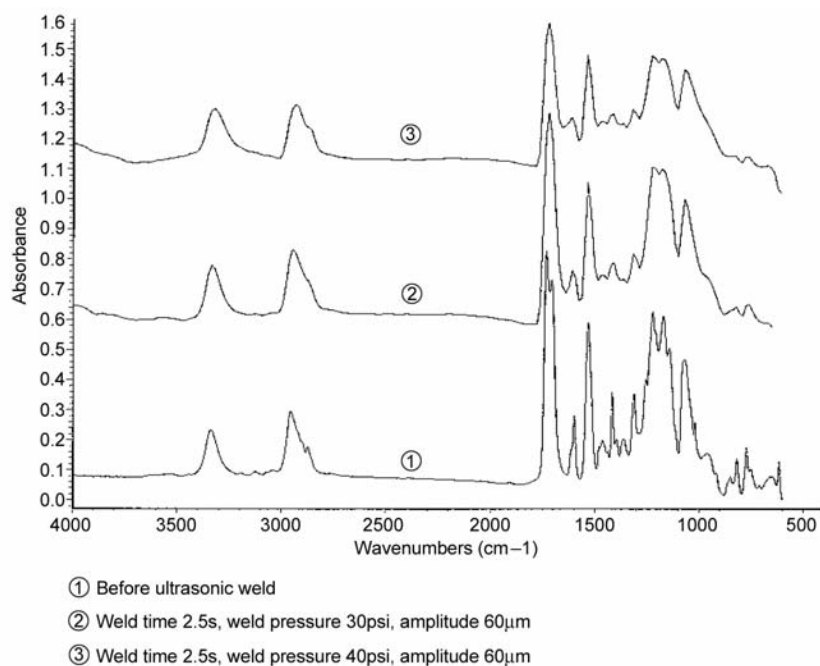


**Figure 15.**  
Comparison of  
FTIR-ATR spectra for  
polyurethane films  
before and after  
ultrasonic welding

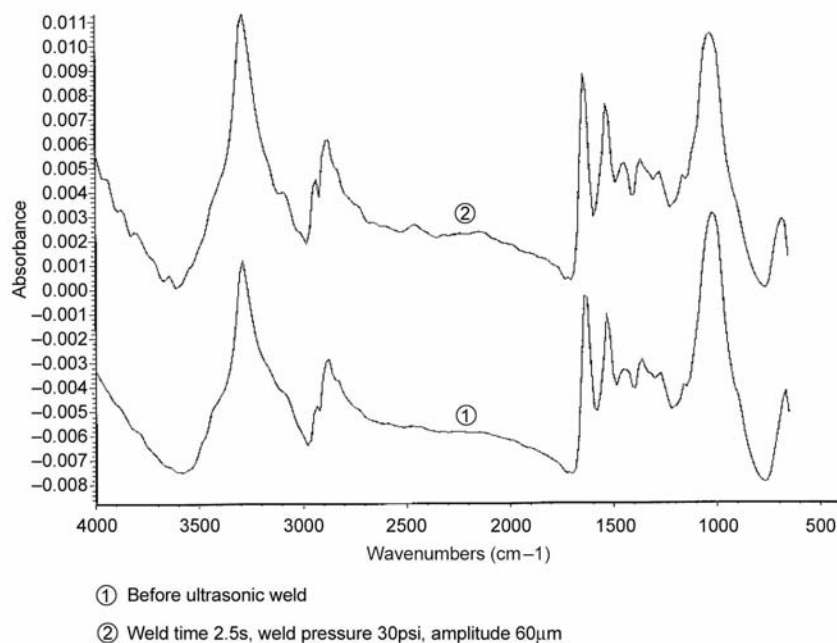


**Figure 16.**  
Comparison of  
FTIR-ATR spectra for  
BDU fabrics before and  
after ultrasonic welding

*Survival of optic fibers*

The test on the power loss of optic fibers embedded (El-sherif, 1998) indicated that, the signal transmission properties of the optic fibers were not significantly changed under certain welding condition. Therefore, optic fibers can be integrated into fabrics ultrasonically.

**Conclusions**

Ultrasonic welding experiments were performed on three kinds of fabrics as well as BDU fabric incorporating optic fibers as data channels. The effects of changing welding time, welding pressure and amplitude of vibrations were studied in terms of joint strength, thermal profiles at the interface during welding process, and the morphology of fibers at weld areas. Some conclusions can be drawn from the experiments:

- (1) Increasing the weld pressure (up to 30psi) increases the weld strength initially, but further increases in pressure cause a decrease in the strength. The same effect was observed in changing weld time, the critical value being 2.5 seconds.
- (2) The amplitude of vibrations strongly affects the bonding strength obtained. Increasing the amplitude of vibrations (from 42 to 60 $\mu$ m) enhances the energy dissipated and strength.
- (3) The strongest welds were obtained in BDU light-weight fabrics with polyurethane films at the condition: weld pressure 30psi; weld time 2.5 seconds; and amplitude of vibrations 60 $\mu$ m.
- (4) Under the same weld condition, the joint strength with polyurethane films was much higher than that without adhesives. No significant decrease in the strength was observed after up to five laundry cycles.
- (5) The specimens with polyurethane films failed in three modes:
  - fabric damage;
  - bond damage; and
  - a combination of fabric and bond damage.

The second mode is desirable because the seam is strong and flexible, and yield point was observed in this mode.

- (6) SEM analysis indicated that melting of polymeric fibers occurred first at the interface. This is because the asperities at the interface are generally more pronounced and the attenuation of vibration energy there is more severe.
- (7) The rate of temperature change and the maximum temperature developed in the weld area depend on the thermal properties of fabrics and welding parameters (i.e. pressure and amplitude of vibrations). A reduction in amplitude of vibrations results in a decrease in the temperature rising rate and the maximum temperature achieved at the

interface. An increase in pressure leads to an increase in the maximum temperature obtained. Under the same weld condition, the peak temperatures and temperature rising rates for different kinds of fabrics are different because of their different thermal conductances. It was found that higher thermal conductances usually resulted in higher rates of temperature change.

- (8) FTIR-ATR analysis indicated that, no considerable formation of new chemical groups or bonds was found.
- (9) A compromise is necessary between the joint strength and the survival of optic fibers, in that too long weld times can melt the cladding of optic fibers and damage their signal transition properties.

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