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High-frequency welding of an industrial thermoplastic polyurethane elastomer-coated fabric

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The high frequency (27.12 MHz) weldability of a thermoplastic polyurethane elastomer coated fabric was investigated after determination of its dielectric properties. It was shown that at 27.12 MHz, maximum heating occurred at 50°C. Subsequent tests were thus carried out at this temperature. Temperature needs to be measured continuously during the welding operation as the integrity of the weld depends on the core temperature. Since conventional methods using probes or adhesive indicator strips are disrupted by high frequency (HF) radiation, the integrity of the weld obtained by HF was compared to that obtained by impulse welding at a given temperature under the same conditions of pressure with the same peeling performance and with the same temperature variation after welding, measured by the i.r. thermometer. The highest peeling forces were found when the welding temperature exceeded that of the melting point (180°C) of the hard segments in the polymer.

The interactions occurring during welding were found to depend on the temperature. At temperatures below 180°C, the peeling resistance only derived from entanglements of flexible segments at the interface between the two TPU-coated fabrics. At temperatures of 180°C and above, melting and mixing of hard segments produced total cohesion of the two coated fabrics resulting in an enhanced peeling force. © 1998 Elsevier Science Ltd. All rights reserved.

(Keywords: HF welding; thermoplastic polyurethane elastomer-coated fabric; impulse welding)

INTRODUCTION

Thermoplastic polyurethane elastomers (TPU) are high performance materials, TPU-coated fabrics being employed, for example, in inflatable structures, conveyor belts, protective coverings, etc.

They are derived from three basic compounds:

(1) a long-chain polyester diol or polyether,
(2) an aromatic or aliphatic diisocyanate,
(3) a short-chain diol as chain extender, which in most cases is butanediol.

TPU are characterized by a segmented structure consisting of flexible segments, the diol chains, and hard segments, the urethane groups (*Figure 1*). Their thermoplastic nature indicates that they should be weldable, possibly by high frequency (HF) techniques.

The principle of HF welding has been described by numerous authors[1,2] and the process is now in widespread use in industry[3,4]. The heat required for HF welding derives from dielectric losses in the materials to be joined. Among the allowed frequencies for industrial use, 27.12 MHz was selected for the present tests. In this process, the two parts to be joined serve as the dielectric between two mobile plates of a condenser connected to a powerful HF generator. The heat dissipated in the material must be sufficient to melt it or produce adequate molecular mixing at the interface between the two parts. The success of the process is a function of the degree of inter-diffusion of particles between the two parts to be joined. The mechanical integrity of the weld for a given material depends not only on the extent of entanglements of the macromolecules and on the residual stress[5] but also on the geometry of the weld, on the nature of any applied stress and on conditions of surfaces and tests. The main welding parameters are thus temperature at the joint of the two parts to be welded, pressure and weld time.

At a given frequency, materials differ considerably in dielectric properties, which are described by the complex permittivity $\underline{\varepsilon}^*$:

$$\underline{\varepsilon^* = \varepsilon' - j\varepsilon''}$$

where $\underline{\varepsilon}'$ is the permittivity of the material, representing the ability of the material to store electric charge, and $\underline{\varepsilon}''$ is the loss factor corresponding to the physical processes producing energy losses within the material. These losses are mainly heat. $\underline{\varepsilon}''$ has a peak value at a frequency of relaxation of the molecules submitted to an electric field: $\underline{f = 1/\tau}$, τ being the relaxation time. As various components are comprised of molecules with different relaxation times, the overall relaxation peak deviates somewhat from the symmetrical Debye shape[6]. Furthermore, $\underline{\varepsilon}''$ depends on temperature, the frequency of relaxation shifting towards higher frequencies with rise in temperature.

A number of authors have described the fundamental principles of the dielectric properties of polymers[7,8]. Although the dielectric properties of some TPU are known, values for the commercial fabrics studied here

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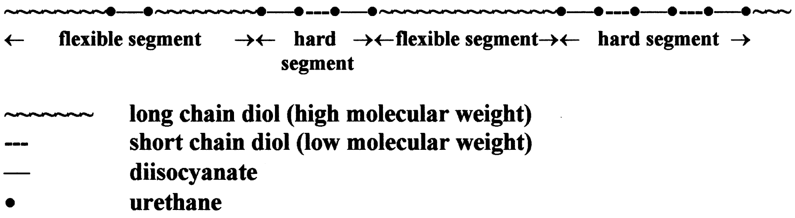

Figure 1 Structure of macromolecular chain of thermoplastic polyurethane elastomer

(coated on both sides) have yet to be reported[9]. Since dielectric properties depend on the exact formulation of the product[8], the dielectric properties of the material were determined at 27.12 MHz prior to optimization of the HF welding process.

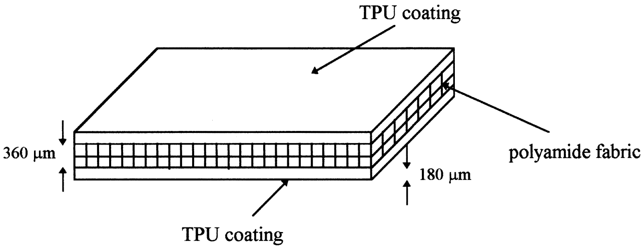

Figure 2 Sketch of the thermoplastic polyurethane elastomer-coated fabric

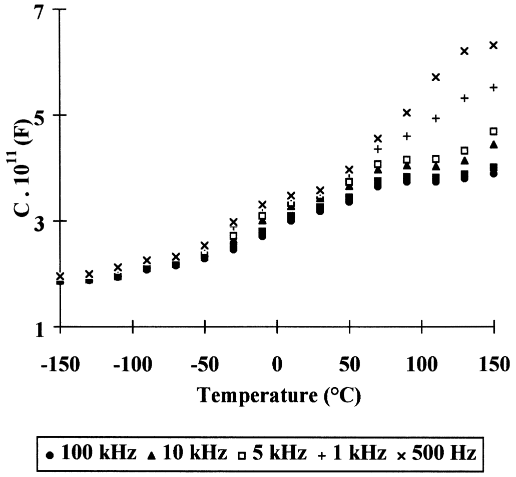

Figure 3 Plot of capacitance $\underline{C}$ (F) of the fabric against temperature T (°C) over a frequency range of 500 Hz to 100 kHz

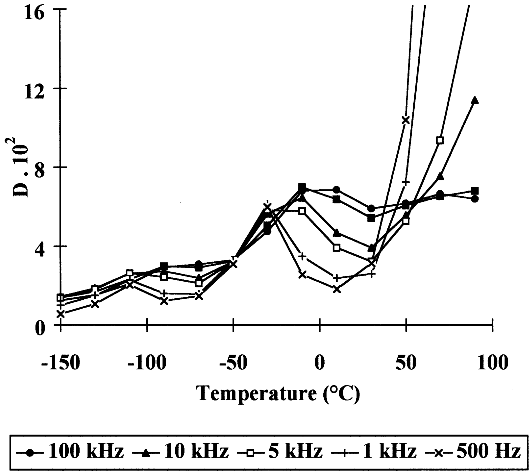

Figure 4 Plot of tangent of angle of dielectric losses $\underline{D}$ of the fabric as a function of temperature (°C) over a frequency range of 500 Hz to 100 kHz

DETERMINATION OF DIELECTRIC PROPERTIES

Material

The material studied was a black TPU coating based on a polyether diol, an aromatic diisocyanate and a polyamide fabric (nylon 6/6) (*Figure 2*). It was an industrial fabric coated on both sides and manufactured by the extrusion/calendering method. The coated fabric was stored in the form of rolls at room temperature and protected from light. The samples were cut directly from the rolls and the surface was not treated with solvents or additives. The samples had a maximum water content of 1%. The properties of the material were not thought to be affected by this level of water content as the variations in humidity during our tests probably lay well within the error in the measurements.

Experimental

The total capacitance of the material $\underline{C}$, ($\underline{C} = \varepsilon_0\varepsilon' S/d$, ε_0 and $\underline{\varepsilon}'$ being the permittivities of vacuum and of the material respectively, S the surface area of the material and d its thickness) and the tangent of the angle ($\underline{\delta}$) of the dielectric losses, $\underline{D}$, ($\underline{D = \tan\delta = \varepsilon''/\varepsilon'}$), of the TPU-coated fabric, were measured as follows: the samples in the shape of 5 cm × 5 cm squares were metallized in the middle on a surface of radius 1.25 cm and were then placed between the plates of a condenser of the same surface area. The samples thus prepared were placed in a temperature-controlled chamber; the temperature in the chamber could be varied from −150°C to +150°C. The frequency was swept from 100 Hz to 100 kHz for each temperature and the values of $\underline{C}$ and $\underline{D}$ read-off from an LCRmeter (Hewlett Packard 4284 A) and stored on computer disk. The results were then analyzed by computer.

Results

$\underline{C}$ is a function of temperature at various frequencies (*Figure 3*), and $\underline{D}$ is also a function of temperature: two relaxation peaks were observed for $\underline{D}$, one main peak (the strongest) and a secondary peak (*Figure 4*).

The results were in accord with the William–Landel–Ferry (WLF) law relating frequency to temperature for the relaxation peaks. This law is expressed as:

$$f = f_0 \exp(-W/k_b T)$$

where W is the activation energy, f_0 is a constant determined for $1/k_b T$ tending to zero and k_b is the Boltzman constant (8.62×10^{-5} eV/K).

The results for the relaxation peaks of the TPU-coated

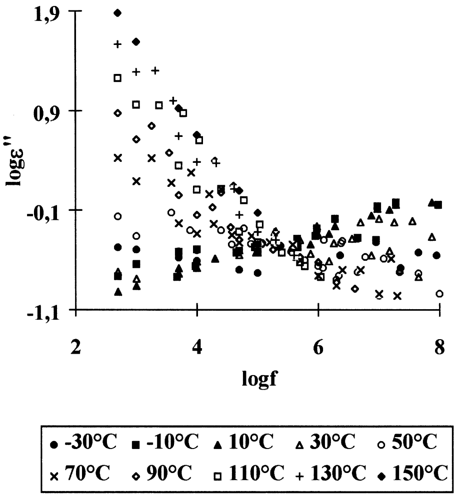

Figure 5 Plot of log of loss factor ε'' as a function of log of frequency f at several temperatures above 100 kHz using the WLF relationship

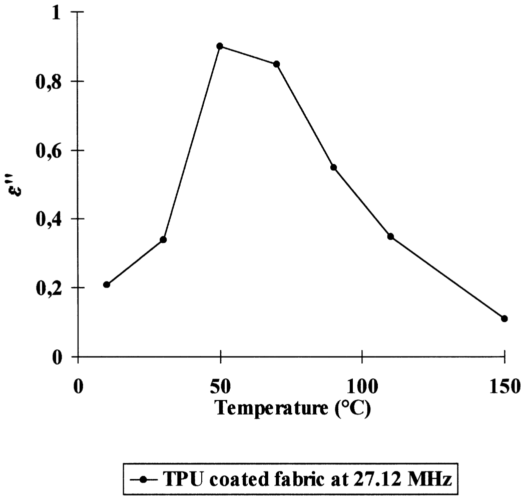

Figure 6 Plot of loss factor ε'' as a function of temperature (°C) at 27.12 MHz derived from curves shown in *Figure 4*

fabric were: $f = 2.71 \times 10^{20} \exp(-0.84/8.62T \times 10^{-5})$ for the main peak, with a coefficient of correlation, $r = 0.996$, and $f = 2.22 \times 10^{12} \exp(-0.29/8.62T \times 10^{-5})$ for the secondary peak, $r = 0.990$.

The temperatures for maximum dielectric loss at 27.12 MHz were thus: +50°C for the main peak, and +19°C for the secondary peak.

These results could be extrapolated to 27.12 MHz since we had ascertained that the WLF law was obeyed[6]. This enabled determination of the variation of ε'' as a function of temperature from the plots of log ε'' as a function of log f at various temperatures, f ranging from 500 Hz to 100 kHz (*Figure 4*) to lead to f ranging from 500 Hz to 100 MHz (*Figure 5*). The traces of the relaxation peak of the TPU-coated fabric at 27.12 MHz, presented in *Figure 6*, shows that the maximum dielectric loss occurred at 50°C.

Discussion

Since the material studied is composite, its overall behaviour is a function of the behaviour of the different constituents and their volume fractions. Therefore it was difficult to draw conclusions about any relationships between the different relaxation peaks and the components of the material. Consequently, the overall behaviour of the TPU-coated fabric was considered as a complete system.

WELDING TESTS

In order to weld two TPU-coated fabrics, the melting point of the hard segments must be attained. This melting point is 180°C[10–12]. This is the temperature at which the material is no longer an elastomer but a molten polymer. It is therefore important to measure temperature during the HF welding process. Conventional adhesive indicator strips and temperature probes were affected by the 27.12 MHz radiation. Thus the HF welding of the TPU-coated fabric was compared with that of impulse welding where temperature could be determined accurately. The welds were compared by the magnitude of the peeling force required to separate the two TPU-coated fabrics and from the i.r. measurement of temperature after welding.

Experimental

HF welding tests. For HF welding tests, the two samples of TPU-coated fabric to be joined were placed between a mobile electrode (15 cm × 4 cm) and a flat table. The apparatus produced a constant voltage of 8000 V. A pressure of 5 kg/cm^2 was applied for different durations and holding times. The holding time was the duration of pressure applied to the sample in the absence of HF radiation. The energy transferred from the main circuit to the sample was regulated by a variable condenser, the value *Cv* of which ranged from 0 to 100. Since the peak dielectric losses occurred at 50°C, the mobile electrodes and samples were maintained at this temperature in an oven. Welding tests were also carried out at room temperature. The samples were welded using various settings of the apparatus, and then subjected to peeling tests on strips measuring 10 cm × 3 cm.

Impulse welding tests. The impulse welding machine consisted of a heating electrode (10 cm × 2.5 cm) and a table on which the sample to be joined was placed (*Figure 7*). A pressure of 5 kg/cm^2 was applied after heating the electrode and sample to 50°C. The electrode was then heated to a temperature that could be adjusted over a range from 140°C to 190°C. The core temperature *To* in the sample was measured with a thermocouple placed between the two surfaces to be joined.

The peeling force per unit width was determined on strips of 10 cm × 2 cm. The tests were designed to determine the maximum peeling force required for the samples welded at various settings.

I.r. measurement of temperature. Since conventional methods using probes or adhesive indicator strips were inappropriate, an i.r. method by which the temperature of

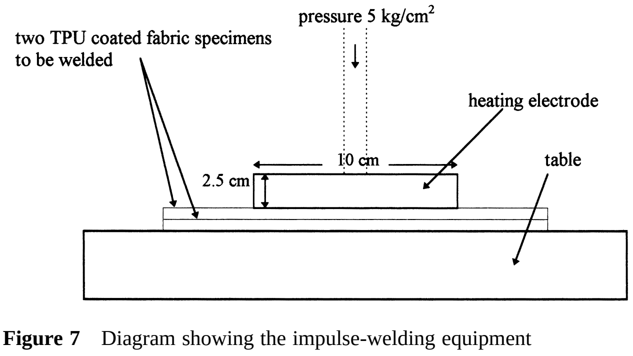

Figure 7 Diagram showing the impulse-welding equipment

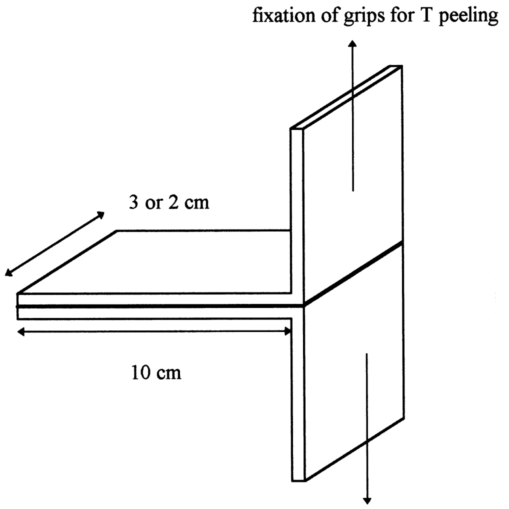

Figure 8 Sketch showing the specimen dimensions for the 'T' peel test

Figure 9 Photograph of surface of sample before welding and peeled surface of HF welded sample giving rise to peeling forces of 700–1000 N/m at 70°C, magnification ×15

a surface could be measured with an i.r. thermometer was employed. The thermometer was equipped with lenses to collect and concentrate energy on the i.r. detector producing a voltage directly proportional to the amount of energy received and thus to the target temperature.

Two samples were impulse welded at a known temperature *To* (measured with the thermocouple) over 6 seconds (s) without holding time and were peeled off the heating electrode. The side of the sample previously in contact with the electrode was then placed in front of the thermometer. The surface temperature of a 1.1 cm diameter area was measured by the previously calibrated thermometer from a distance of 20 cm. The thermometer was connected to an apparatus which recorded the temperature every second on one channel, and on another channel a signal from a switch started when the samples were removed from the electrode, corresponding to the time at which sample temperature was at *To*.

The same method was used for the HF welding tests.

Peeling forces. For measurement of peeling force, a Lloyd T5K model TC 520 traction apparatus was employed. The 'T' peeling test is shown schematically in *Figure 8*. The samples were strips 10 cm × 3 cm or 10 cm × 2 cm. After opening the sample close to the welded seam, the mean peeling force was recorded at a rate of 10 cm/min up to the maximum extension of the grips (10 cm). The peeling forces were recorded at both room temperature and 70°C. After checking that the peeling force was proportional to the width of the sample, forces were expressed per m width. The scatter in the peeling results was determined over 12 trials carried out at different times on different samples of the same fabric with the same welding parameters. Three separate values of peeling force were recorded for three series of 12 trials. It was observed that 10 out of 12 measurements lay within an interval of ±10% of the mean of the 12 measurements. The mean was thus considered to be close to the true value, and conversely, the true value was considered to be within ±10% of any single measurement.

Results

For HF welding tests, the results are listed *Table 1*. The maximum mean peeling forces were observed for a weld carried out at 50°C (Tw) with a welding duration (t_w) of 6 s, a holding time (t_h) of 9 s and a variable condenser value (*Cv*) of 38: 6500 N/m in the peeling tests carried out at room temperature, and 4000 N/m for the peeling tests carried out at 70°C.

Maximum peeling forces of 5000–6000 N/m at room temperature and 2300–2700 N/m at 70°C were observed for the samples welded using the following welding parameters: Tw = room temperature, $t_h = 5$ s, $t_h = 6$ s and $Cv = 35$. Minimum peeling forces of 1500–2000 N/m at room temperature and 700–1000 N/m at 70°C were observed for the samples welded using other groups of welding parameters among which: Tw = room temperature, $t_w = 4$ s, $t_h = 6$ s and $Cv = 40$. These samples were not satisfactorily welded at room temperature. The tear occurred within the joint of the two TPU-coated fabrics at room temperature and at 70°C and the peeled surface was the same as that of the samples before welding (*Figure 9*).

For the other peeling tests carried out at room temperature, the two parts were peeled by delamination

Table 1 peeling forces (*F*) per m width and characteristics of tear obtained at room temperature and at 70°C for samples of thermoplastic polyurethane elastomer-coated fabric HF-welded with different parameters[a]

HF welding parameters	*F* (N/m) at room temperature	Tear and peeled surface at room temperature	*F* (N/m) at 70°C	Tear and peeled surface at 70°C
Room temperature $t_w = 4$ s $t_h = 6$ s $Cv = 40$	1500–2000	Tear in the joint surface like before welding	700–1000	Tear in the joint surface like before welding
Room temperature$t_w = 5$ s $t_h = 6$ s $Cv = 35$	5000–6000	Delamination	2300–2700	Tear in the joint smooth peeled surface
50°C $t_w = 6$ s $t_h = 9$ s $Cv = 38$	6500	Delamination	4000	Tear in the joint pitted peeled surface

[a] (t_w = welding duration in seconds (s), t_h = holding time (s) and Cv = value of the variable condenser ranging from 0 to 100).

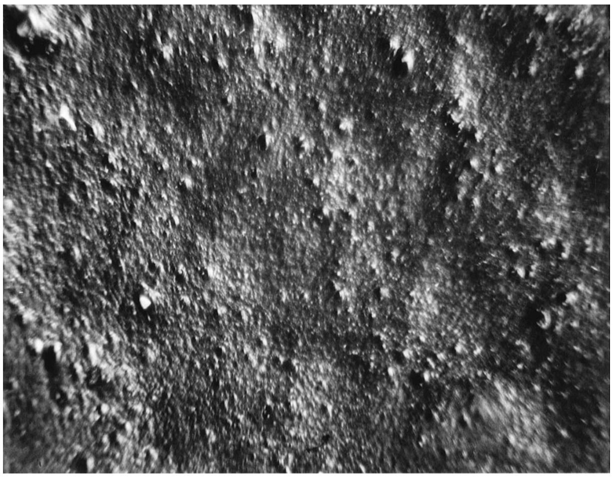

Figure 10 Photograph of peeled surface of HF-welded sample giving rise to peeling forces of 2300–2700 N/m at 70°C. Note smooth appearance, magnification ×15.

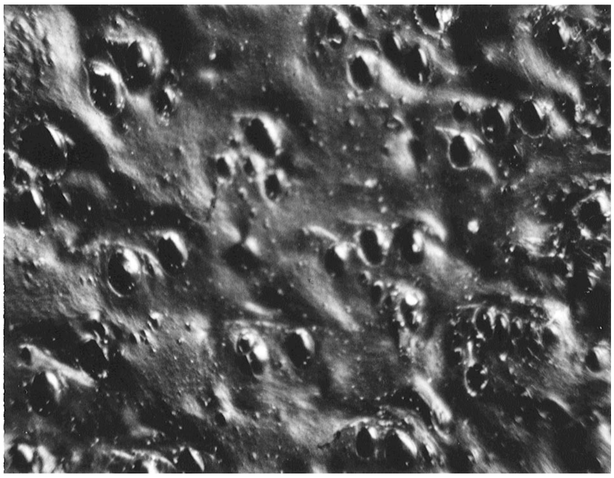

Figure 11 Photograph of peeled surface of HF-welded sample giving rise to peeling forces of 4000 N/m at 70°C. Note pitted appearance, magnification ×15.

i.e. breaking by adhesive failure between coating and fabric. For the peeling tests carried out at 70°C, the tear occurred within the joint of the two TPU-coated fabrics. The samples giving rise to peeling forces of 2300–2700 N/m at 70°C and delaminating at 5000–6000 N/m at room temperature appeared to be correctly welded. At 70°C, the tear occurred within the joint but the peeled surface appeared smooth (*Figure 10*), as if it had not been welded. The samples giving rise to peeling forces of 4000 N/m had pitted peeled surfaces (*Figure 11*).

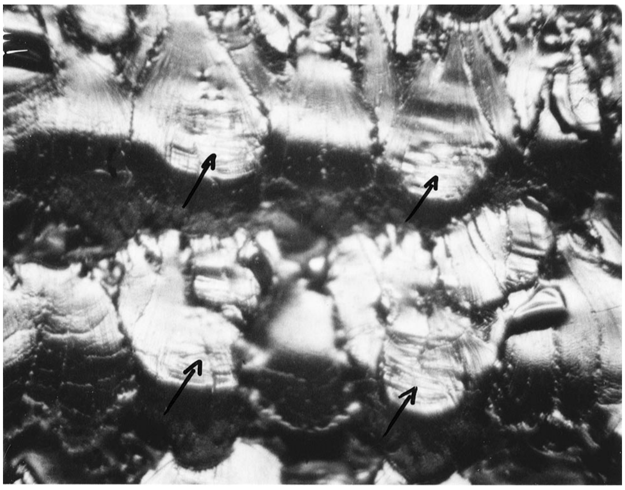

Figure 12 Photograph of peeled surface of impulse-welded sample. Note points of delamination, magnification ×15

For the impulse welding tests, the temperature T was held for 6 s, the electrode was cooled and the pressure was maintained on the sample for 9 s. The peeling forces expressed per m width are listed in *Table 2*. Samples heated to 130°C were not satisfactorily welded at room temperature. Their peeling forces were 1500–2000 N/m at room temperature and about 800–1000 N/m at 70°C. The tear occurred within the joint and the peeled surface was the same as that of the samples before welding. Samples heated to between 150°C and 160°C appeared to be welded satisfactorily. The peeling test produced an even delamination at a mean force of 6000 N/m at room temperature. For the tests carried out at 70°C, the results were comparable to those obtained by HF: a smooth peeled surface after a peeling force of 2300–2700 N/m. The samples heated to 180°C had a pitted peeled surface after application of similar peeling forces to those applied to samples welded by HF. The samples heated to 185–190°C gave rise to mean peeling forces of 5700 N/m at 70°C. At this peeling temperature, strain peaks were observed every 0.2 cm with areas of delamination over the peeled surface (*Figure 12*). Above this temperature, the sample was burned.

The results of i.r. measurements were: for impulse welding, temperature T as a function of time, t, was plotted for $To = 130$°C and 160°C (*Figure 13*). The error was ±3°C for a given time and temperature.

The temperature of samples zone-joining at the end of HF welding were the same as those of impulse welding with similar plots $T = f(t)$.

Table 2 Peeling forces (F) per m width and characteristics of tear obtained at room temperature and at 70°C for samples of thermoplastic polyurethane elastomer-coated fabric, impulse-welded at different temperatures

Impulse welding temperature (°C)	F (N/m) at room temperature	Tear and peeled surface at room temperature	F (N/m) at 70°C	Tear and peeled surface at 70°C
130	1500–2000	Tear in the joint surface like before welding	800–1000	Tear in the joint surface like before welding
150–160	6000	Delamination	2300–2700	Tear in the joint smooth peeled surface
180	6500	Delamination	4000	Tear in the joint pitted peeled surface
> 180	> 6500	Delamination	> 5700	Areas of delamination over the peeled surface

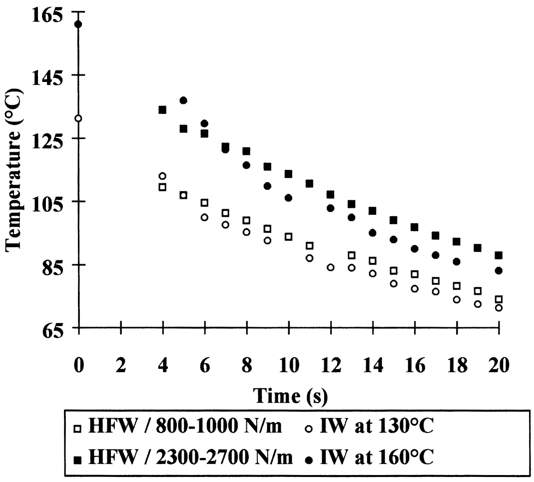

Figure 13 Plot of temperature *T* (°C) as a function of time (s) for HF welding (HFW) samples giving peeling forces of 700–1000 N/m and 2300–2700 N/m and for impulse welding (IW) tests at 130°C and 160°C giving peeling forces of 800–1000 N/m and 2300–2700 N/m, respectively

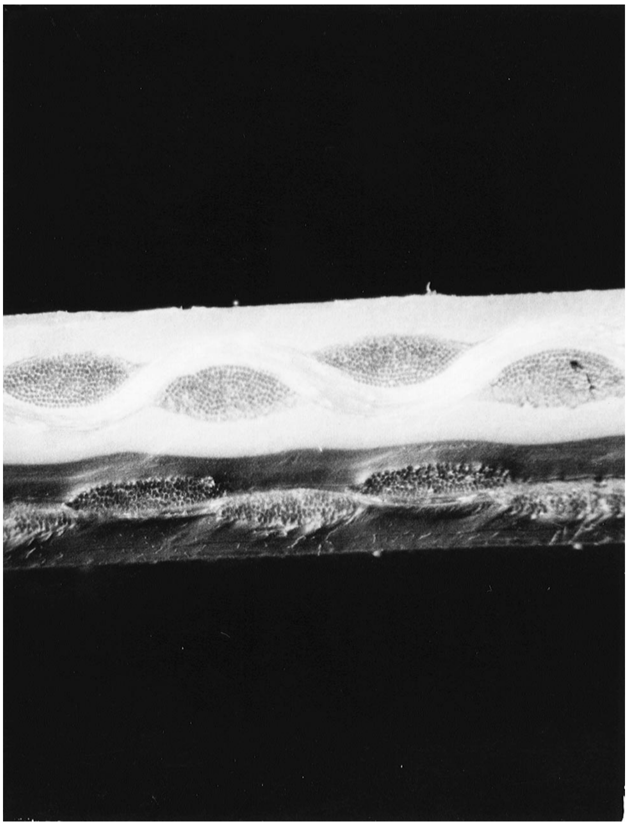

Figure 14 Photograph of cross section of HF-welded sample giving rise to peeling forces of 2300–2700 N/m at 70°C. Note no mixture of TPU coatings, magnification ×15

The temperature–time profile for HF welding giving rise to a peeling force of 800–1000 N/m corresponded to that of impulse welding at 130°C ± 3°C (*Figure 13*).

The temperature–time profile for HF welded tests giving rise to a peeling force of 2300–2700 N/m corresponded to that of impulse welded tests at 160°C ± 3°C (*Figure 13*).

Discussion

Measurement of temperature by the i.r. method showed that one could compare peeling forces obtained by HF and impulse welding. If the peeling force of the HF weld was equal to that of the impulse weld, these samples were assumed to have attained the same weld temperature at least up to the melting point. Differences could be thought to occur in this correlation for the two welding processes due to the molecular orientation from melt flow to cooling. But if the effect of hard segments melting is positive on the peeling force during the welding process, as is most likely, then in any case if the peeling force for HF welding is the same as that of impulse welding for the melting point, the temperature of HF welding necessarily exceeds the melting point. It can be seen from *Tables 1* and *2* that the maximum peeling force in HF welding tests corresponded to that of impulse welding at 180°C. Therefore HF welding produces a temperature of 180°C ± 3°C at the joint corresponding to the melting point of the hard segments in the TPU[10,12]. To confirm that melting did in fact occur, leading to deep interpenetration of macromolecules from both TPU coatings, two photographs are included representing HF welds between the same coated fabric but of different colours: black and orange. *Figure 14* represents the cross section of an HF weld giving rise to peeling forces of 2300–2700 N/m at 70°C. It can be seen that the TPU coatings of the two pieces are not mixed. *Figure 15* represents the cross section of a HF weld giving rise to peeling forces of 4000 N/m at 70°C. It can be seen that the TPU coatings of the two pieces are mixed. Only the coatings appeared to be involved in the weld. The thermal analysis of the polyamide fabric nylon 6/6 will thus not be discussed, especially in view of the fact that its melting point is around 250°C. The results as a function of temperature are interpreted solely in terms of the thermal behaviour of TPU.

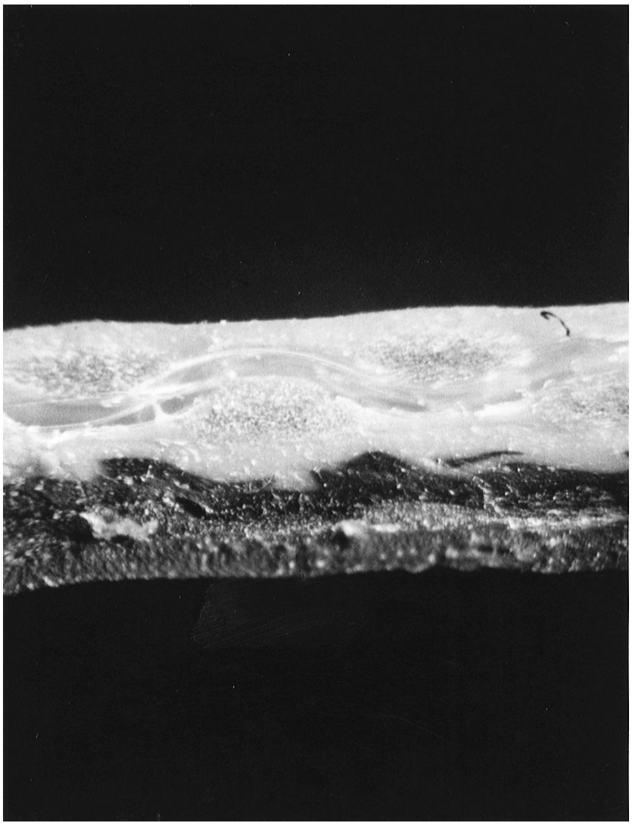

Figure 15 Photograph of cross section of HF-welded sample giving rise to peeling forces of 4000 N/m at 70°C. Note mixture of TPU coatings, magnification ×15

Below 180°C during the welding operation, there is the possibility of entanglement diffusion of the flexible macromolecular segments between the two surfaces to be joined resulting in a relatively low peeling force. At 70°C and under the relatively low strain of the peeling force, the flexible segments rearrange to a new equilibrium position corresponding to that of the initial state of the two surfaces. There is no mixing of crystalline nodes between the two surfaces, and they have a smooth appearance after the welded sample is peeled (*Figure 10*).

At a temperature of 180°C during the welding operation, the increase in the entanglements of flexible segments and the resulting mixture of some melted hard segments augment the number of interactions on a certain thickness and gives rise to an enhanced peeling force (*Figure 11*).

Temperatures ranging from 185°C to 190°C during the weld give rise to total melting of hard segments and mixing of macromolecules by diffusion to a certain thickness resulting in an even higher peeling force. The cohesion between the two welded parts almost attains that of the adhesion between the polymer and the fabric. On peeling, areas of delamination were observed on the peeled surfaces with adhesion peaks at points reflecting the weave of the fabric (*Figure 12*).

The peeling force was also measured at 130°C, a temperature at which there is still some cohesion of hard segments. Tests conducted on samples HF welded at various temperatures were classified into three groups (<180°C, 180°C and >180°C). At 130°C, the small residual peeling force was attributed to interactions involving crystallization. It ranged from 130 to 370 N/m. The differences in peeling forces could not be accounted for by interactions between hard segments, which on structural considerations would not be expected to be high in TPU. Differences in peeling force were attributed more to interactions between the flexible segments, which depend on temperature. Above the melting point of the hard segments (180°C), interactions between the flexible segments, the major species, were enhanced.

The HF welds giving rise to peeling forces of 2300–2700 N/m and 4000 N/m at 70°C were aged in an oven at 90°C and peeled at 70°C after ageing. The peeling force in all tests was above 30% of the original value after 1 aging day and remained constant after 130 aging days. This can be accounted for by molecular movement which is enhanced by increase in temperature. This will lead to an entanglement of flexible segments by diffusion, giving rise to a higher peeling force. Moreover, the extent of entanglements did not appear to depend on whether the hard segments were melted or not.

CONCLUSIONS

The weldability of an industrial TPU-coated fabric was investigated by HF welding at 27.12 MHz after determining the dielectric properties of the coated fabric between -150°C and $+150$°C over a 100 Hz to 100 kHz frequency range. It was shown that the relaxation peaks obeyed the William–Landel–Ferry law. This enabled graphical extrapolation of the dielectric properties to a frequency of 27.12 MHz. It was shown that at this frequency the maximum heating of the TPU-coated fabric occurred at 50°C and welding tests were thus carried out at this temperature. For the welding of two TPU-coated fabrics, the hard segments of the material must be melted, and the temperature thus needs to be monitored during the welding operation. The direct measurement of the joint temperature during HF welding is not possible. Therefore to show that HF welding was effective, the following three characteristics of welding have been measured in comparison with impulse welding done at a temperature higher or equal to 180°C and where melting of hard chain segments has occurred: (1) the peeling force at 70°C as a function of welding temperature, (2) the appearance of the peeled surfaces and (3) the appearance of welded cross sections of similar coated fabrics in different colours. The evaluation of the last two characteristics at the melting point suggested that HF welding was possible. It also appeared that welds made above the melting point of the hard chain segments produced a positive effect on the peeling force as expected.

These experiments showed that the melting point of hard-chain segments (180°C) must be exceeded to create an extensive layer of entanglements of flexible chains producing true cohesion between the TPU-coated fabrics being joined. If the temperature did not attain the melting point of hard segments, only the entanglements between the flexible segments of the two fabric surfaces in contact appeared to produce a weld at room temperature. However, these welds were readily peeled at higher temperatures, for example, at 70°C and under relatively modest applied mechanical loads.

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