Influence of Filming Process on Macromolecular Structure and Organization of a Medical Segmented Polyurethane

C. GUIGNOT,[1,2] N. BETZ,[1] B. LEGENDRE,[2] A. LE MOEL,[1] N. YAGOUBI[2]

[1] CEA/Saclay, DSM/DRECAM/LSI, Laboratoire des Polymères Irradiés, Bat. 466, 91191 Gif-sur-Yvette Cedex, France

[2] Groupe Matériaux et Santé, Faculté de Pharmacie, 92290 Chatenay-Malabry, France

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ABSTRACT: A medical segmented polyurethane, Tecoflex®, based on methylene bis(*p*-cyclohexyl isocyanate) and 1,4-butanediol as hard segments (HS), and poly(tetramethylene glycol) as soft segments (SS), was studied to evaluate the influence of different filming procedures on macromolecular structure and organization. Size-exclusion chromatography (SEC) and Fourier transform infrared (FTIR) spectroscopy were used to highlight differences between solvent-cast and hot compression-molded films (160 to 200°C). For compression-molded films, FTIR spectra showed weakened vibration bands attributed to HS and SS groups; SEC results indicated a decrease of M_n and M_w molecular weights that was dependent on processing time and temperature. These modifications were the result of both thermooxidation of soft segments and thermal dissociation of urethane linkages. Concerning solvent-cast films, no chemical or molecular modifications were observed. Moreover, we have highlighted that this procedure enhanced macromolecular organization: the carbonyl stretching region presented several bands assigned to free carbonyls and H-bonded carbonyls with different environments. Particularly, we observed a band at 1660 cm^{-1} reported in only one publication; we demonstrated that it originated from a bonded carbonyl in a well-ordered structure. We have concluded that solvent casting has to be preferred because it enhances macromolecular ordering without chain degradation. © 2002 Wiley Periodicals, Inc. J Appl Polym Sci 85: 1970–1979, 2002

Key words: polyurethane; FTIR; sampling; thermal properties; hydrogen bonding

INTRODUCTION

Polyurethanes (PUs) are copolymers that have found wide applications in the medical field[1] as pacemaker leads, heart valves, catheters, vascular grafts, and dialysis membranes as well as in other domains (automotive, adhesives, paints, coatings, etc.). These numerous applications are based on a wide panel of mechanical and physicochemical properties in parallel with an excellent biocompatibility and biostability.[1–3] For biomedical applications, PUs are generally synthesized through a two-step method, leading to a segmented structure: a prepolymer is synthesized by reacting an excess of diisocyanate with a polyol (i.e., polyester or polyether). In a second step, the addition of a chain extender, diamine or diol, which reacts with the isocyanate end groups of the prepolymer gives the final macromolecular chains. This segmented structure leads to a segregated material, given that soft segments (SS) (i.e., polyols) and hard segments (HS) (i.e., chain extenders and diisocyanates) are partially immiscible. Considering the relative proportion of each

Correspondence to: N. Betz (betz@drecam.cea.fr).

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type of segments, the macromolecular structure of segmented polyurethanes (SPUs) can be schematized as partially organized HS domains dispersed in an SS matrix.[4] At room temperature, SS are in a rubbery state, whereas HS are still in a glassy state (or crystallites), thus maintaining the mechanical properties of the material.

The intermolecular organization that takes place in SPUs is helped by hydrogen bonding, which is responsible for a significant number of their properties. In SPUs, only one type of hydrogen donor exists (i.e., NH of urethanes), whereas several acceptors localized in HS (i.e., C═O or C—O—C of urethanes) or SS (e.g., C—O—C of polyethers, C═O of polyesters, etc.) can compete to form the H-bonds. The quantitative evaluation of HS–HS and SS–HS hydrogen bonding and hydrogen-free urethane proportions gives an appreciation of the macromolecular organization in the material.[4–8] Given that chains are partially mobile through SS, an evolution of the internal phase mixing and phase segregation can occur to minimize entropy. These movements happen in a relatively long-range order of time.

The extensive use of SPUs has led to a considerable literature on structure–properties relationships,[5,7,9–15] biocompatibility, and biostability[16–20] where experiments are performed on processed samples, frequently in the form of films. Because some sampling procedures encountered in literature use partially stressing or degrading techniques, it is very important to evaluate their impact on the properties of SPUs. In particular, the internal organization described above can be altered by various factors, such as temperature,[4–6,13] adsorption of liquids,[21] or mechanical strains, thus leading to a modification of the material properties. This explains the peculiar attention that must be paid to processing procedures used to prepare samples: they must lead to an internal organization that does not significantly change during storage, to obtain reproducible samples. In other words, it is important to develop sampling procedures that allow optimal organization to be formed. Obviously, degrading treatments must be avoided, if possible.

Filming can be obtained by solvent casting in various solvents, or by compressed molding, film extrusion, and so forth. On a laboratory scale, the main techniques used and encountered in literature are solvent casting and compression molding. Casting can lead to several problems if parameters such as the solvent nature, the desorption rate, the temperature, or the atmosphere are not precisely defined[22]; films of significant thickness can contain traces of residual solvent even after a significant period of aeration/desorption. Moreover, problems of additives might be of concern, given that they might be eliminated, consumed, or heterogeneously dispersed in final films or localized on their surface.

Compression molding is a temperature-based technique and, consequently, problems that might occur from this procedure are those of thermal processing, that is, thermal degradation, oxidation, or additives consumption. As a function of cooling rate, strains can be trapped in the material; chains are not allowed to return to a stationary state, and intermolecular forces are minimized or avoided. Thermal degradation of PUs is well known[23–25] and is divided between a thermal dissociation of urethane linkages, partially or completely reversible, that occurs around 180°C and the thermal decomposition of chains that occurs around 250°C, and that is dependent on the nature of monomers. However, literature reports a significant number of publications dealing with processing temperatures higher than 180°C.[11,15,26,27]

In both cases, the demolding event also plays a significant role because stretching might imply deformation of the material as well as forced chain reorientation.[28] Microcracks and fractures can be generated and lead to a loss of biocompatibility.

This report summarizes our preliminary studies concerning sampling procedures of Tecoflex®. This commercially available SPU is used in biomedical applications such as, for example, pacemaker leads, artificial heart, and wound dressings. A model compound of this material, poly(tetramethylene glycol), has also been studied to highlight observed alterations of the polymer during processing.

Solvent casting and compression molding have been compared: parameters used for each procedure were based on those frequently encountered in literature. Our aim was to evaluate their influence on chemical structure and macromolecular conformation using size-exclusion chromatography (SEC) and Fourier transform infrared (FTIR) spectroscopy.

EXPERIMENTAL

Polymer

Tecoflex® 85A is a cycloaliphatic poly(etherurethane) provided by Thermedics (Woburn, MA),

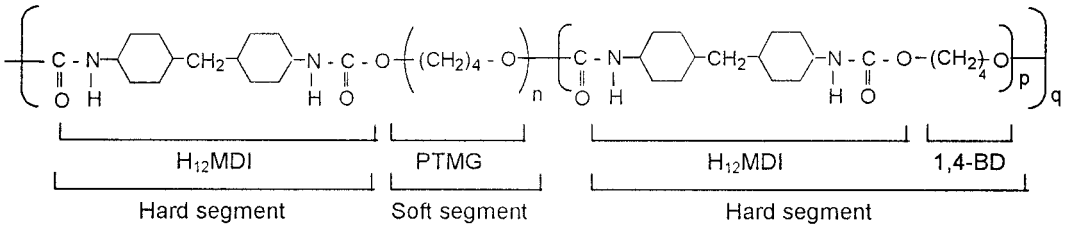

Figure 1 Chemical structure of Tecoflex® segmented polyurethane.

the SS of which are composed of poly(tetramethylene glycol) [molecular weight (MW) = 2000 (PTMG 2000)] and whose HS are formed by H_{12}MDI [methylene bis(*p*-cyclohexyl isocyanate) or hydrogenated MDI, extended with 1,4-butanediol]. The chemical structure of Tecoflex is shown in Figure 1.

PTMG of MW 2000 (PTMG 2000) from Aldrich (Milwaukee, WI), used as model compounds, was studied as received.

Film Preparation

For solvent-cast films, a solution was prepared at room temperature by dissolving Tecoflex pellets (10 mg/mL chloroform) under moderate stirring and inert atmosphere (nitrogen bubbling). Solution samples were deposited on Teflon® (PTFE) plates and, after maximal evaporation, plates were placed in a vacuum oven at 30°C to remove residual traces of solvent. Thickness of films was 10 ± 2 μm. The use of Teflon was made to avoid as much as possible problems resulting from demolding stretches.

Concerning compression molding, Tecoflex pellets were placed between two thin films of ethylene tetrafluoroethylene copolymer (ETFE) and pressed at about 50 bar. Temperatures studied were included between 160 and 200°C, and exposure times ranged from 2 to 10 min. Slowly cooled samples (2°C/min) and quenched samples (from processing to room temperature) were evaluated. Films obtained were 10–15 μm thick. For the study of the model compound, PTMG 2000 was placed in the same device, heated for 2 to 30 min without applying pressure, then rapidly cooled.

SEC Analysis

Aliquots of sample solutions (100 μL) were eluted with 1 mL/min THF and detection was performed using an LC-30 refractive index detector (Perkin Elmer Cetus Instruments, Norwalk, CT). Columns were chosen as a function of the analyzed sample: for lower molecular weight compounds (solutions ~ 3 mg/mL THF), a column with small exclusion limits was used (Jordi DVB 100 Å, 250 × 10 mm). For solutions of SPU (~ 1 mg/mL THF), this column was coupled with another one of higher exclusion limits (Ultrastyragel HR5, 300 × 7.8 mm, effective MW range: 5×10^4–4×10^6). Molecular weights M_n and M_w were calculated by averaging data obtained from three different samples.

FTIR Analysis

Transmission spectra were collected on a Nicolet Magna IR-750 spectrometer (Nicolet Instruments, Madison, WI) equipped with a DTGS detector, by averaging 32 scans at 2 cm^{-1} of resolution.

For FTIR analysis of liquid samples, a liquid transmission cell was used with a spacer of 0.5 mm.

For FTIR temperature scans, films were put on a KBr window that was placed in a variable-temperature cell (Graseby Specac); the internal cell was purged with nitrogen. The temperature was held constant using a temperature controller; the heating rate was 2°C/min and isotherm was maintained for 5 min each 10°. Spectra were normalized using the CH_2 area (3000–2800 cm^{-1}) to correct thermal evolution of the thickness.

RESULTS AND DISCUSSION

Impact on the Chemical and Molecular Structure

SEC experiments were used to evaluate the influence of sampling procedures on the chain distribution; results obtained from compressed and cast films were compared to molecular weight values obtained directly from the pellets. SEC results detailed below are related to rapidly cooled samples; indeed, a significant standard deviation characterizes SEC results obtained for

Table I Molecular Weight (M_n, M_w) Changes of Tecoflex After Thermal-Compression Molding

Temperature		0 min	2 min	4 min	10 min
160°C	M_n	104,850	99,380	91,010	78,680
	M_w	164,470	151,330	141,110	122,340
170°C	M_n	104,850	84,390	76,320	69,590
	M_w	164,470	130,770	118,370	109,310
180°C	M_n	104,850	79,260	69,850	63,090
	M_w	164,470	124,380	110,700	100,290
190°C	M_n	104,850	62,650	54,590	46,430
	M_w	167,470	99,510	91,400	77,140
200°C	M_n	104,850	55,390	36,560	10,370
	M_w	164,470	92,410	61,840	38,770

slowly cooled ones, as explained at the end of this section. SEC values showed that molecular weights were modified by compression molding, whereas no modification occurred from the casting procedure; indeed, chromatograms of thermally processed samples exhibited a peak shift to high elution volume, resulting in a decrease of number-average (M_n) and weight-average (M_w) molecular weights (Table I), whatever the heating time and temperature. For a given temperature, the degradation increases with increasing heating time. As shown in Figure 2, increasing the molding temperature accelerates degradation. This is particularly true for the highest processing temperature, where molecular weights are reduced by almost half after 2 min. Thus, the thermal degradation of such SPUs is time dependent and is accelerated when temperature increases.

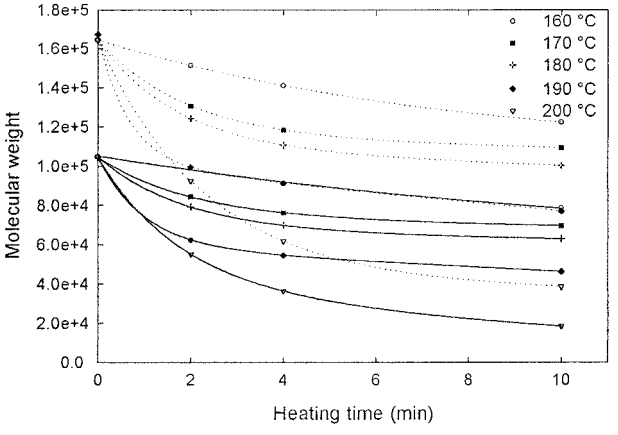

Figure 2 M_n (—) and M_w (· · ·) evolution for different temperatures of compression molding as a function of heating time.

FTIR study of films can bring precise information on the degradation observed by SEC. For a quantitative comparison, spectra normalization has been carried out, based on the vibration bands of the 1500–1300 cm^{-1} region corresponding to CH_2 bending modes. Figure 3 compares the IR spectra of a molded film and a solvent-cast film. Assignments of main absorbance peaks are reported in Table II.

Vibration bands attributed to methylene (3000–2800 cm^{-1}), HS urethane groups (1529, 1228 cm^{-1}), and SS ether group (1111 cm^{-1}) appear to be weakened by the processing temperature; a slight decrease of the amide I region area was also observed. This indicates that the degradation induced by temperature takes place in both hard and soft segments.

Modifications of HS can be highlighted by the presence of a new band at 2266 cm^{-1}, as shown in the insert of Figure 3. Indeed, this band is localized in the IR region, which is specific for cumulated double bonds. It is assigned to the $\nu_{N=C=O}$ stretching vibration of isocyanates, in accordance with literature.[24,25,29] Its appearance indicates that the temperature used to process Tecoflex is higher than the dissociation temperature of urethane linkages. When heated, urethane groups are dissociated to give the former isocyanates. This reaction, known as retrourethanization, can be reversible (transurethanization). Although literature reports onset dissociation temperatures around 160–180°C,[24,25,29] FTIR spectra of Tecoflex films from room temperature to 200°C show that isocyanate groups appear around 130–140°C (Fig. 4), which is well below the temperature range in which Tecoflex can be processed (160°C). Nevertheless, the cooling procedure of

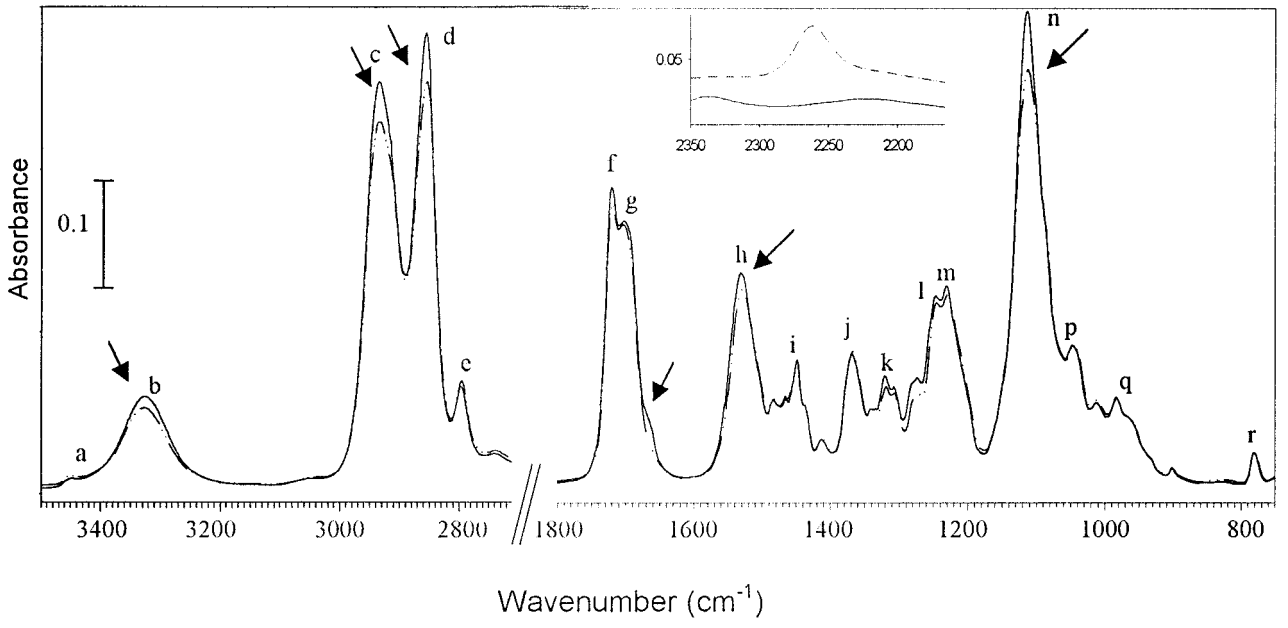

Figure 3 FTIR spectra of compression-molded film (– – –) and solvent-cast film (—).

molded films does not lead to a complete transurethanization, given that a significant number of isocyanate groups remain trapped in films once cooled. Even a slow cooling rate (2°C/min) leads to a substantial residue. This unstable species might induce secondary reactions that are responsible for chemical evolution during storage. This is confirmed by the significant variability of

Table II Assignment of the Major FTIR Absorption Bands of Tecoflex®

Reference[a]	ν (cm^{-1})	Assignment
a	3445	Free NH stretching
b	3323	H-bonded NH stretching
c	2933	Asymmetric β CH_2 stretching (polyether) + asymmetric CH_2 stretching (cyclohexane)
d	2854	Asymmetric α CH_2 stretching (polyether) + symmetric β CH_2 stretching (polyether) + symmetric CH_2 stretching (cyclohexane)
e	2796	Symmetric α CH_2 stretching (polyether)
f	1719	Free C═O stretching (amide I region)
g	1701	H-bonded C═O stretching (amide I region)
h	1529	C—N stretching + N—H bending (amide II band)
i	1447	CH_2 bending
j	1367	CH_2 wagging
k	1320	C—C stretching (cyclohexane)
	1271	CH_2 bending + wagging
l	1245	CH_2 wagging
m	1228	C—N stretching (amide III band)
n	1111	Asymmetric C—O—C stretching (polyether)
p	1044	Asymmetric C—O—C stretching (urethane)
q	900	Asymmetric ring stretching (cyclohexane)
r	779	Cyclohexane ring breathing

[a] Letter refer to the corresponding absorption bands annotated in Figure 3.

molecular weight values observed using SEC for slowly cooled films: reaction of isocyanate groups is dependent on both temperature and time, and the residual amount of such chemical groups might be more reproducible when samples are subject to a more drastic cooling rate.

To understand the mechanism involved in SS degradation, analysis of the homopolymer PTMG 2000 after thermal treatment (see Experimental section) has been performed. Figure 5 shows significant modifications of recorded spectra for PTMG 2000 subjected to 200°C for 30 min. A substantial decline of asymmetric (2859 cm^{-1}) and symmetric (2796 cm^{-1}) stretching vibrations related to methylene in α-position of the ether group is observed. A decrease of the 1112 cm^{-1} band indicates a loss of ether groups. In parallel, a new band appears at 1175 cm^{-1}. The growth of new bands in the carbonyl region at 1719 and 1730 cm^{-1} is also observed.

These modifications can be related to a thermooxidative degradation. Our results can be compared to the study of Gauvin et al.[30] related to the photooxidation of polymerized PTMG. The ether linkage is decomposed according to the reactional mechanism reported in Figure 6. According to their results, we assigned the bands at 1175 and 1719 cm^{-1} to formates, whereas esters explain the band at 1730 cm^{-1}. Hemiacetals and hydroperoxides mentioned by the authors are revealed to be absent in our experimental conditions. This was expected, given that they are extremely unstable species above 60°C.

The chain degradation is confirmed by the broadened molecular distribution observed by SEC experiments (Fig. 7). This degradation becomes prominent when PTMG 2000 is heated for more than 5 min at 200°C.

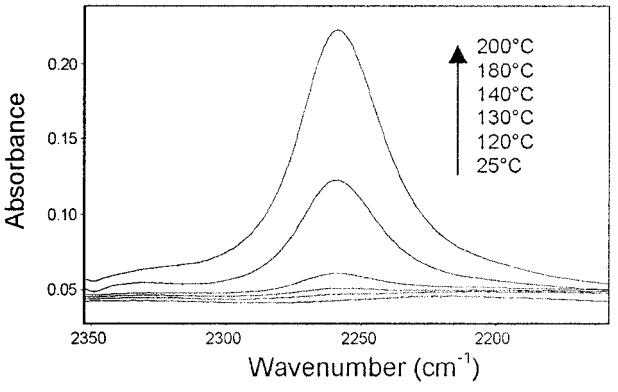

Figure 4 Evolution of solvent-cast SPU film in the N═C═O stretching region as a function of increasing temperature.

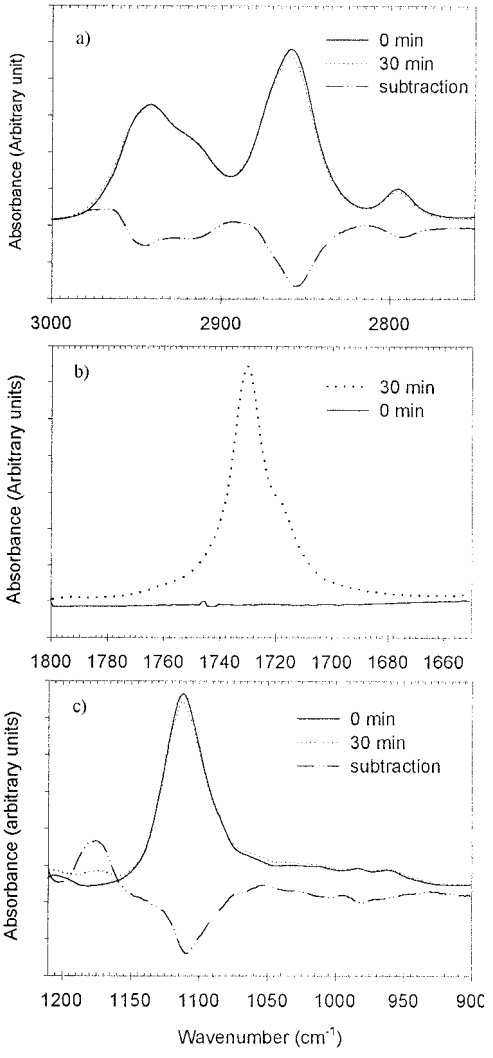

Figure 5 FTIR spectrum of PTMG 2000 before and after heating (30 min, 200°C): (a) CH_2 stretching vibration region, (b) carbonyl stretching region, and (c) ether stretching region. The subtraction spectrum (after − before) is added on a and c.

Thermal treatments degrade both HS and SS. If the scission of the latter gives rise to oxidation products, whereas the former induces the formation of isocyanate groups, it is clear that both can be involved in the production of chemical defects able to induce secondary reactions.

Impact on Macromolecular Organization

The functional groups involved in hydrogen bonding of SPUs, that is, N—H, C═O, and –O–, give rise to infrared vibration bands that can be re-

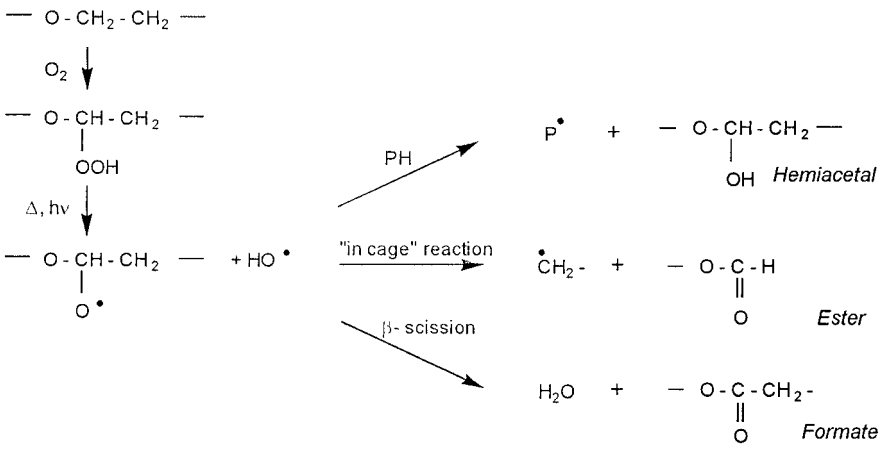

Figure 6 Reactional mechanisms proposed to explain PTMG 2000 thermal oxidation, according to photooxidation experiments of Gauvin and Lemaire.[30]

lated to chain conformation. In particular, bands related to the N—H and C═O groups are very sensitive to the chemical environment and, consequently, to the nature and the strength of hydrogen bonds. Indeed, the electronic distribution of such chemical bonds can be disturbed by the formation of intermolecular forces that induce a frequency shift of bands ascribed to the free form of the functional groups. Thus, the C═O and N—H stretching vibration regions can give a first appreciation of the organization in the material after various sampling procedures.

The N—H region is characterized by a free NH stretching vibration band at about 3450 cm^{-1}. When hydrogen bonded, the wavenumber shifts to 3350–3300 cm^{-1}. Quantitative interpretations based on this IR region are assumed to be generally misleading for two main reasons: because it is the only hydrogen donor in PU, almost all NH are bonded, the nature of the acceptor playing an insignificant role. Moreover, the extinction coefficient of the free N—H band is very weak compared to that of the bonded N—H band; authors report values of $\epsilon_F = 3.44 \times 10^3$ L mol^{-1} cm^{-2} for free NH and $\epsilon_B = 1.19 \times 10^4$ L mol^{-1} cm^{-2} for bonded NH.[13] A further complexity is brought about by the variation of ϵ_B with the strength of the intermolecular force.

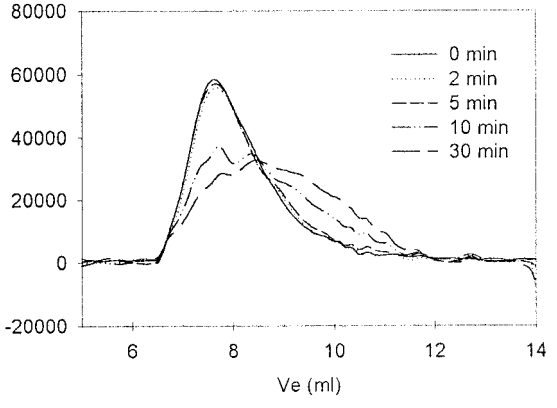

Figure 7 SEC chromatograms of PTMG 2000 as a function of heating time (T = 200°C).

The $\nu_{C=O}$ region or amide I region, localized around 1700 cm^{-1}, does not present such problems and is consequently more informative. A shift of frequency of the free form band from about 1730 to 1700 cm^{-1} is induced by H-bonding, but the extinction coefficient remains almost unchanged: the ratio between bonded and free $\epsilon_{C=O}$ is reported to be between 1.0 and 1.3.[13] Moreover, a large proportion of C═O groups remains in a free form, given the competition between acceptors.

Figure 2 shows the NH region and the amide I region of the compression-molded film versus the solvent-cast film. For the former film, two bands at 1719 and 1701 cm^{-1} are attributed to free and bonded C═O stretching vibrations. An additional band is observed at 1660 cm^{-1} for the solvent-cast films. The C═O stretching is very sensitive to the environment, like the supramolecular organization or the H-bonds of its adjacent NH. This has been described for polyamide,[6] poly(etherurethane)s, or poly(ether–urethane urea)s[31]; these authors have detailed up to four different bands in the amide I region originating from the carbonyl groups in various environments.[32] We have assigned the bands at 1660 and 1701 cm^{-1} to

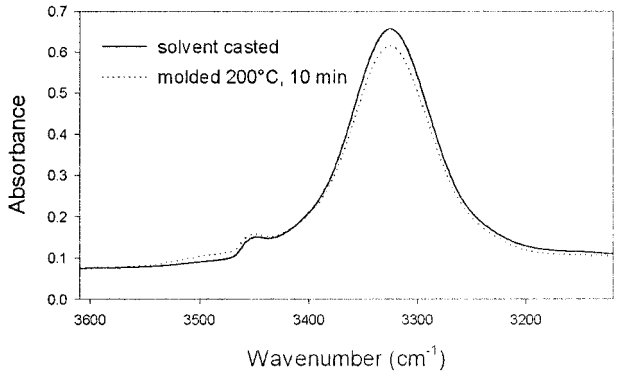

Figure 8 NH region of compression-molded films compared to solvent-cast film.

bonded C═O with different environments. Our experiments and arguments confirming this hypothesis are presented in the Appendix and clearly evidence the noncovalent nature of the chemical modification responsible for this absorption. Thus, this assignment indicates that casting allows intermolecular forces to develop and to form organized regions; during compression molding, chains are not allowed to reorganize completely and are trapped in a hindered conformation once cooled. Amide I, however, is a very complex region of several associated bands. An acceptable fit of our FTIR spectra was achieved with four peaks. One must keep in mind that it is not only linked to stretching vibrations but that C—N stretching and N—H bending also contribute to the absorption in a significant proportion.[33]

The NH region must be considered with much more suspicion, as disclosed previously; however, a broad band can be observed "under" the NH stretching vibration band in the case of compressed-molded film (Fig. 8). Two types of functional groups could be involved: the first one would be the stretching vibration band of appearing OH groups that are attributed to SS thermooxidation, in accordance with the thermal behavior of PTMG 2000. The second one would be the stretching vibration band of primary amines ($-NH_2$) that could be created by reaction of thermally formed isocyanates with water traces. In both cases, this underlying band is indicative of an undesirable chemical modification of the material.

CONCLUSIONS

This study stresses the attention that should be paid to the optimization of sampling procedures. Thermal treatments have to be avoided in the case of Tecoflex samples and this precaution can be generalized to all polyurethanes. Dissociation and degradation events lead to a material that does not retain the properties it has been chosen for. Moreover, evolution of residual isocyanates might involve secondary reactions leading to evolution of films over time.

Various solvents can be used to cast films, such as tetrahydrofurane (THF), 1,1,1,3,3,3-hexafluoroisopropanol (HFIP), and dimethylacetamide (DMA). We have compared their FTIR spectra to evaluate any influence of the solvent nature on the macromolecular organization; spectra were the same for all films, whatever the solvent used. Thus, the choice of the solvent for casting must be made as a function of the PU solubility, and special attention must be given to its boiling point to use a vacuum-oven temperature as low as possible when eliminating residual traces. A relatively elevated temperature might induce mobility of macromolecular chains and change the segregated structure. Moreover, additives might become volatile and could thus be desorbed from the film by this procedure.

Though not studied in this work, one should be aware that the nature of the casting substrate is also of importance. In these experiments, we used Teflon because its nonadhesive properties avoid demolding problems and stretching consequences. However, it is of common knowledge that a polymeric or metallic device significantly influences surface chemistry.

Thus, a global approach must be made to evaluate sampling parameters that might be critical for reproducible and reliable sampling.

APPENDIX: ASSIGNMENT OF THE 1660 cm^{-1} BAND

When starting our experiments, we were surprised by the presence of a band at 1660 cm^{-1} that was described, to our knowledge, in only one article: Elabd et al.[21] have studied an experimental PU based on the same monomers as those of Tecoflex® (H_{12}MDI/PTMG/BD), and have attributed this band to urea linkages. We were not convinced by their hypothesis, given that this band was not systematically observed on the spectrum of processed films.

To evidence its nature, we have performed additional experiments:

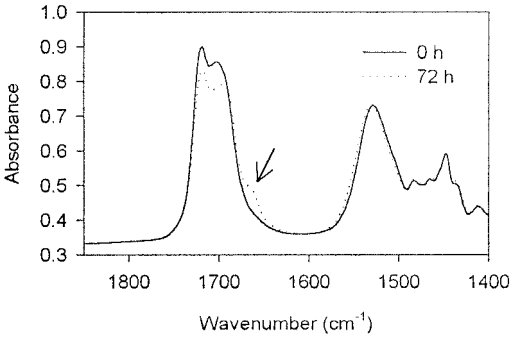

Figure 9 FTIR spectrum of films at 0 and 72 h after compression molding.

- We have observed the evolution of the spectra of FTIR films as a function of time after their compression molding: the 1660 cm^{-1} band appears slowly, whereas the 1719 and 1701 cm^{-1} bands decrease (Fig. 9). This evolution happens with a simultaneous conservation of the amide I area, which leads us to assume that the appearance of the 1660 cm^{-1} band is linked only to a reorganization of chains.
- Sample heating was performed on solvent-cast films from room temperature to 200°C and the evolution of FTIR spectra was observed (Fig. 10). It is noticed that the 1660 cm^{-1} absorbance decreased continuously; this behavior, also observed for the bonded C═O group at 1701 cm^{-1}, could be explained by the weakening of H-bonds attributed to the temperature increase.
- Tecoflex® films exhibiting the 1660 cm^{-1} band in solid FTIR were dissolved in THF and analyzed using liquid FTIR analysis. Comparison of both spectra (Fig. 11) highlights that no absorption peak is observed at 1660 cm^{-1}; the carbonyl region is characterized by a unique band at 1721 cm^{-1}. If the 1660 cm^{-1} absorbance was attributable to covalent bonds, it should be detected in the liquid state. The unique carbonyl stretching vibration band is consequently attributed to the carbonyl in a free form. This last experiment clearly points to the noncovalent behavior of the new band at 1660 cm^{-1}.

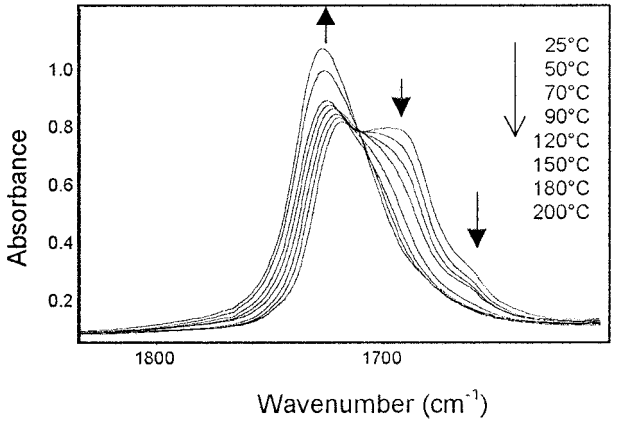

Figure 10 Evolution of the IR amide I region during heating of solvent-cast films.

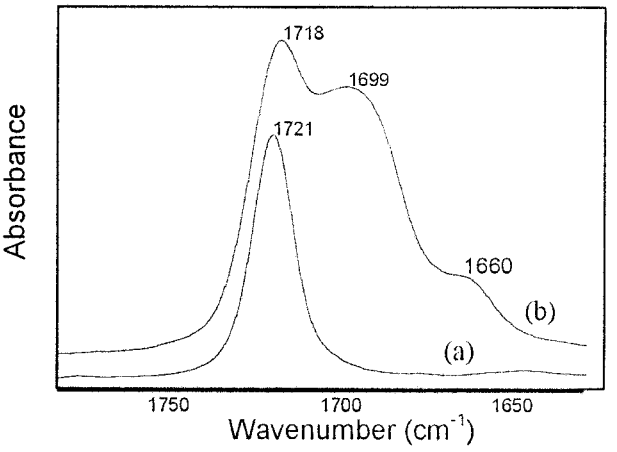

Figure 11 Comparison of FTIR spectra of a film in solid state (b) with its corresponding spectra in liquid state (a). THF was used to avoid electronic perturbation in the carbonyl region. No scale was indicated, given that liquid and solid FTIR spectra are based on very different extinction coefficients.

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