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Polycarbonate and co-continuous polycarbonate/ABS blends: influence of specimen thickness

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Abstract

The influence of specimen thickness on the fracture behaviour of polycarbonate (PC) and co-continuous PC/ABS (50/50) blends was studied in single edge notch tensile tests at 1 m/s and different temperatures (−80 to 130 °C). Specimen thickness ranged from 0.1 to 8 mm. In the co-continuous PC/ABS blends the rubber concentration in the ABS was 0, 15 and 30 wt%. The change in fracture toughness was typified by the change in brittle-to-ductile transition temperature (T_{bd}).

T_{bd} of pure PC depended strongly on specimen thickness, leading to very low transition temperatures for thin PC specimens. PC/ABS 0%, a 50/50 blend of PC and SAN (i.e. ABS without polybutadiene (PB)), was a brittle blend and showed a very high T_{bd} close to the T_g of SAN. T_{bd} did not seem to be influenced by specimen thickness. PC/ABS blends with 15 and 30% PB in ABS showed improved T_{bd} compared to PC/SAN and PC, indicating effective rubber toughening. T_{bd} decreased with decreasing thickness for PC/ABS specimens thicker than 1.5 mm. However, T_{bd} increased with decreasing thickness for specimens below 1.5 mm thickness. In thin specimens, the rubber-filled blend is less effective rubber toughening. The plane strain stress condition needed for rubber cavitation is apparently not present in thin specimens.

Keywords: Polycarbonate; ABS; Thickness

1. Introduction

Injection moulded polymer products often have small wall thickness. Thickness influences the stress state within the material and is therefore an important parameter in the study of fracture behaviour. It is well known that crazing is easier in a thick notched plate, because of the more severe plane strain stress state ahead of the notch in the material. In a thinner plate the stress state is less severe and can become plane stress. Deformation of the material is easier and less localised when under plane stress conditions and thus more energy can be absorbed by the material. Transition from plane stress to plane strain can be obtained by changing the specimen geometry or changing the test temperature [1].

In a sufficiently thick single edge notch specimen, the centre region is in plane strain while the surface region is in plane stress. The size of the plane stress region is of the same order as the plastic zone radius r_p. In order to have a plane strain region in the centre of the specimen, the thickness must be over $2r_p$ [2], with:

$$r_p = \frac{1}{2\pi}\left(\frac{K_I}{\sigma_y}\right)^2 [4(1 - \nu + \nu^2)] \quad (1)$$

with stress intensity factor K_I, yield stress σ_y and Poisson's ratio ν.

This results in fracture with plane stress edges and plane strain centre. In metals, clear shear lips are formed, but these are usually much smaller for polymers [3]. A model for this mixed mode state was proposed by Parvin and Williams [2,3]. The model uses two values for K_{Ic}; a plane strain value K_{c1} and a plane stress value K_{c2}, resulting in:

$$K_{Ic} = K_{c1} + \frac{2r_p}{B}(K_{c2} - K_{c1}) \quad (2)$$

reflecting the effect of specimen thickness B on K_{Ic}.

Brittle polymers show little effect of thickness, since the plastic zone is very small. Tough polymers, however, do show this effect. For PC this resulted in $K_{c1} \approx 2$ MN/m$^{3/2}$ and $K_{c2} \approx 5$ MN/m$^{3/2}$ [3].

The thickness B at which transition from plane stress to plane strain stress state takes place can be calculated for a

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Table 1
Material properties

Material	Produced by	Description
PC: Lexan HF1110R	GE Plastics	Bisphenol A polycarbonate, density 1.20 g/cm^3 MFR = 25 g/10 min
SAN: Tyril 790	DOW Benelux	Styrene acrylonitrile, 29% AN density 1.08 MFR = 21 g/10 min
Polybutadiene rubber (PB): GRC 310	DOW Benelux	Core-shell particles ABS: SAN grafted PB powder PB content 50%, particle size 0.1 μm

material using the empirical equation [ASTM E399-90]:

$$B = 2.5(K_{\mathrm{Ic}}/\sigma_{\mathrm{y}})^2 \quad (3)$$

For a polycarbonate specimen with a sharp notch and typical values for $K_{\mathrm{Ic}} = 2.24$ and $\sigma_{\mathrm{y}} = 64$ MPa [3,4], the calculation for the necessary specimen dimensions indicates that a polycarbonate (PC) specimen with thickness >3.1 mm would fracture under plane strain conditions. Smith [5] measured a transition in notched Izod tests at a thickness of 4.6 mm for PC. A transition at a thickness of 1/8 in. (3.2 mm), was reported by Paul et al. [6]. It was observed that this value can be shifted to higher values with the addition of small amounts of soft polymers.

Kim et al. [7] studied the effect of thickness and addition of core-shell rubber particles on the J_{Ic} values for PC at three different temperatures using multiple compact tension specimens, which had been fatigue precracked. Fracture toughness J_{Ic} values decreased with thickness increase over the range 3.18–6.35 mm, but differences between 6.35 and 9.53 mm were small. Based on the calculation of transition thickness from Eq. (2), these specimen sizes all lead to a plane strain stress state. Research results on PC/ABS [8] showed also a decreasing fracture toughness J_{Ic} with increasing thickness up to 8 mm, then a fairly constant level was reached. Wildes et al. [9] also studied PC/ABS blends with specimens of thickness 3.2 and 6.4 mm and with different ligament lengths behind the notch. They concluded that for these specific materials and testing conditions, the fracture energy is more a function of length behind the notch than area behind the notch (which equals ligament length × specimen thickness). This is supported by other research results [10,11].

Very thin samples have little been studied. Yee [12] studied PC in specimens of 1/8 and 1/4 in. (3.2 and 6.4 mm) and looked briefly at skin-core effect, but judged the effect not important for his results.

Skin-core effects are present in blends. In injection moulded samples of 6 mm PP/EPDM, the rubber concentration decreased near the skin [13]. The results indicate that a skin-core structure can lead to a more brittle behaviour. A morphology gradient through the thickness of an injection moulded specimen exists also for PC/ABS [14]. At the surface, the ABS phase is more elongated in the injection direction than in the core of the specimen. This can possibly lead to a more brittle behaviour of the skin.

No extensive study of the influence of specimen thickness on the fracture behaviour of PC and its blends with SAN and ABS could be found in open literature, certainly not for co-continuous materials. Co-continuous PC/ABS blends are important industrial materials having good ductility even after ageing. These blends are often applied in injection moulding products having a thin wall thickness. In rubber modified polymers the toughening process is in two steps first, a cavitation of the rubber particles and then shear deformation of the matrix material with cavities. For rubber particle cavitation a plane strain stress state is needed, exists in thick specimens. This would mean that PC/ABS which cannot cavitate should behave like the blend without rubber PC/SAN. Thus in thin samples PC/ABS might behave like PB/SAN.

One of the strongest effects of the toughening of polymers is the change in brittle–ductile transition. The brittle–ductile transition on notched samples can for best be studied with the notched tensile test and this is particularly so for thin samples.

The aim of this research therefore is to look at PC and its blends with SAN and ABS, and to study the influence of specimen thickness in notched tensile tests at different temperatures.

2. Experimental

Materials. Commercially available PC, SAN and SAN/PB were kindly supplied by DOW Benelux and GE Plastics. Material specifications are listed in Table 1. ABS was made by compounding SAN with a core-shell rubber. Co-continuous PC/ABS blends (50/50) were made by compounding PC with ABS.

Specimen preparation. Compounding of the materials was done in two steps using a Berstorff (ZE 25 × 33D) twin screw extruder. In the first extrusion step at barrel temperatures of 185/190/190/190/200/200/200 °C and screw speed 200 rpm, SAN was mixed with the necessary amounts of GRC rubber, producing ABS with 15 and 30 wt% PB. In the second extrusion step at barrel temperatures of 215/220/220/220/230/230/230 °C and 200 rpm, the ABS was blended into PC, producing a co-continuous 50/50 PC/ABS blend.

After compounding, the blends were injection moulded into rectangular bars (74 × 10 × thickness) using an Arburg Allrounder 221-55-250 injection moulding machine. Moulds of 8, 4, 3, 2, 1.5 and 1 mm depth were used. The barrel temperature was 230 °C, mould temperature 80 °C and injection pressure 55 bar at 100 rpm screw speed.

A single-edge V-shaped notch of 2 mm depth and tip radius 0.25 mm was milled in the moulded specimens.

A Wickert WLP 1600/5*4/3 press was used to press 0.1 and 0.2 mm thick sheets of PC, PC/ABS and PC/SAN at 200 bar and 210 °C. Rectangular strips of 10 × 74 mm were cut from the sheets with a scalpel with a fresh blade for each specimen. A notch was milled in the strips after clamping them between two thick specimens.

SEM photography. SEM pictures were taken to study the effect of thickness on the final morphology of the materials. Samples were taken from the core of the injection moulded bars and from a random spot in the compression moulded films. SEM specimens were prepared by cutting with a CryoNova microtome at −110 °C using a diamond knife (−100 °C) and cutting speed of 0.2 mm/s. The cut surfaces were then sputter-coated with a thin gold layer and studied with Hitachi S-800 field emission SEM.

SENT tests. Notched specimens were fractured in single edge notch tensile (SENT) tests. A Schenck VHS servo-hydraulic tensile test machine was used with clamps speed of 1 m/s corresponding to an apparent strain rate of 28.5 s^{-1} [15]. All measurements were performed in five-fold. In the SENT test results on the thin, compression moulded films (0.1 and 0.2 mm) the stress strain data could not be recoded. The thin film samples could not bear the weight of the clamp and were therefore clamped in together with a 1 mm thick sample. In this way only the brittle-to-ductile transition temperature could be determined by looking at the fracture surface. It was assumed that the presence of the 1 mm specimen did not influence the fracture processes in the thin film.

It was not possible to do notched Izod impact tests on the thin specimens, because these thin specimens cannot be clamped properly and twist during testing. SENT tests at 1 m/s correspond well to notched Izod impact testing [15] and these tests are therefore used over the complete thickness range.

Infrared thermography. The temperature rise during fracture of specimens of thickness 1–4 mm was monitored using an infrared camera. Test specifications are listed in Table 2. With the infrared camera, only temperatures at the surface of the specimen can be determined. The spot size of about 100 μm is relatively large. The temperature indicated in one spot is an average temperature over the entire spot size. The temperature can therefore not be determined directly at the fracture surface, which is expected to be highest.

In high speed tests only the temperature of an already broken specimen can be determined. This also can lead to less accurate temperature measurements.

Table 2
Technical data for the infrared camera, equipped with close-up lens. Data from data sheet

TVS 600 AVIO Nippon Avionics Co., Ltd	
Temperature range	−20 to 300 °C
Temperature resolution	0.15 °C
Spectral range	8–14 μm
Image rate	30 frames/s
Spatial resolution	0.1 mm spot size

3. Results and discussion

First, the results for PC will be discussed, then the results of the 50/50 blends for PC/SAN and PC/ABS and finally the materials will be compared. In the discussion below of PC/ABS, the material designation x% stands for the weight content polybutadiene (PB) in the ABS. ABS without PB present (i.e. SAN) is designated with $x = 0$.

3.1. Polycarbonate

Polycarbonate is a tough material but shows brittle behaviour in thick-walled applications. It is also notch sensitive, as it fractures brittle when a notch is present. Small flaws in the test specimens, like deviations from the standard notch tip radius of 0.25 mm, can lead to large scatter in test results [16]. This means that test results for PC are very sensitive to test conditions.

The SENT tests were carried out at 1 m/s, and the results showed unusually large scatter. Careful examination of the specimens and the test results was necessary. Brittle fracture occurred in the ductile region on several occasions and these results were discarded. This indicates that test results are strongly influenced by the presence of inhomogeneities or irregularities in the notch.

Maximum stress is defined as the maximum force measured during the SENT test divided by the cross-sectional area behind the notch. Maximum stress is measured as a function of test temperature at different specimen thicknesses (Fig. 1). The general trend is that maximum stress decreased with increasing temperature. This was found also in earlier research [17]. This lowering in maximum stress is due to a decrease in yield stress at higher temperatures. Maximum stress also decreased with increasing thickness. Maximum stress at 20 °C decreased from about 90 MPa at 1 mm thickness (ductile) to about 40 MPa at 8 mm thickness (brittle). Possibly a more developed plane strain stress state exists in thick specimens, leading to crack initiation at lower macroscopic stress level. In thinner specimens, a plane stress situation prevails, and the specimen can be loaded to higher stresses before craze formation takes place.

Displacements were measured during SENT testing. Fracture displacement is defined as the total clamp displacement needed to fracture the specimen. At low temperatures, brittle fracture occurred and fracture displacement was low for all specimen sizes (Fig. 2(a)). At high temperatures, in the ductile region, fracture displacements were higher. The brittle and ductile fracture displacements were almost the

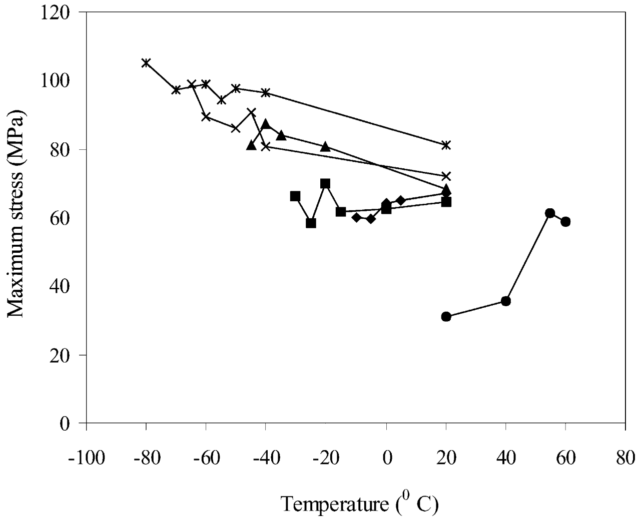

Fig. 1. PC, SENT test maximum stress results as function of temperature for different thicknesses: ∗, 1 mm; ×, 1.5 mm; ▲, 2 mm; ■, 3 mm, ◆, 4 mm, ●: 8 mm.

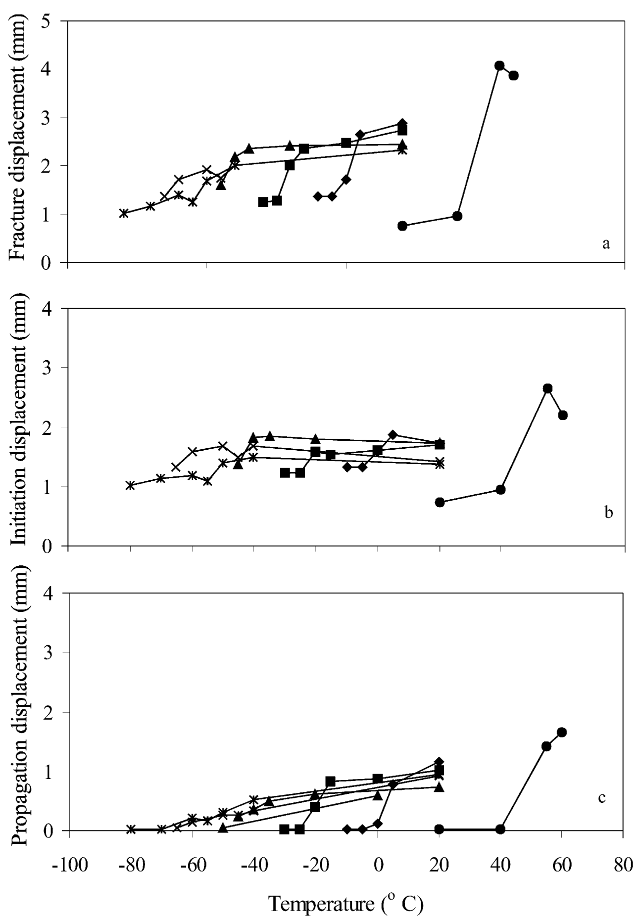

Fig. 2. PC, SENT displacements as function of temperature for different specimen thicknesses: ∗,1 mm; ×, 1.5 mm; ▲, 2 mm; ■, 3 mm; ◆, 4 mm, ●: 8 mm.

same for all specimen thicknesses, except for the 8 mm specimens. For the 8 mm specimens fracture displacement was low in the brittle low temperature region and high in the high temperature, ductile region.

Initiation displacement, defined as clamp displacement up to maximum force, was determined (Fig. 2(b)). The results show that initiation displacement was almost independent of temperature. The initiation displacement was about the same for all specimens sizes, except for 8 mm specimens. These thick specimens gave low initiation displacement at low temperatures and a high displacement at high temperatures.

At low temperatures, propagation displacements (the difference between the fracture displacements and the initiation displacements) were low (Fig. 2(c)). In this region, fracture was brittle. For high temperatures, propagation displacements were much higher. From these results the brittle-to-ductile transition temperatures can be determined. T_{bd} is the temperature below which brittle fracture occurs with low propagation displacement, and above which fracture is ductile with high propagation displacement (see Section 2).

It appeared that fracture, initiation and propagation displacements in either brittle and ductile region increased somewhat with specimen thickness. This unexpected effect is opposite to the effect found for maximum stress. Possibly in thick specimens relatively less elastic energy is stored in the system, so that less energy is available during crack propagation. Thus higher displacements are needed to propagate the crack. In the brittle region (at low temperatures) the propagation strain is minimal and the initiation displacement is the fracture displacement. To the displacement in the ductile region both the initiation and propagation displacement contribute.

For the energy results similar results were obtained as for the displacement data, with the exception that the temperature influence in the brittle and ductile region is now minimal (Fig. 3). With increasing temperature the

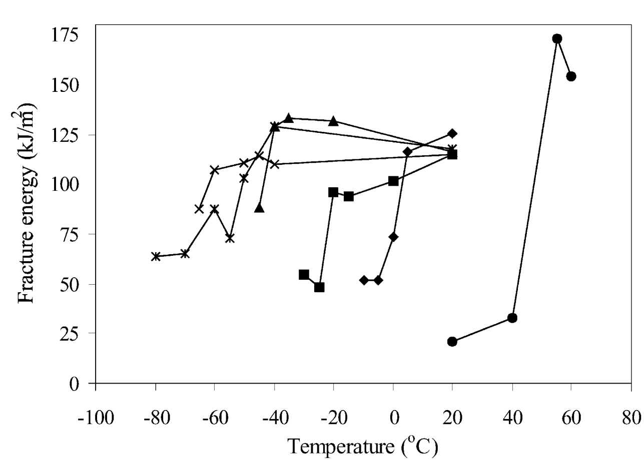

Fig. 3. PC, SENT fracture energy as function of temperature for different specimen thicknesses: ∗, 1 mm; ×, 1.5 mm; ▲, 2 mm; ■, 3 mm; ◆, 4 mm, ●: 8 mm.

Table 3
PC, transition from brittle-to-ductile fracture at different thicknesses ($T_{\text{all brittle}}$: temperature at which all specimens fractured brittle, $T_{\text{all ductile}}$: temperature at which all specimens fractured ductile)

Specimen thickness (mm)	$T_{\text{all brittle}}$ (°C)	$T_{\text{all ductile}}$ (°C)	Temperature range (°C)
0.1	−65	−40	25
0.2	−75	−55	20
1	−50	−80	30
1.5	−65	−40	25
2	−50	−35	15
3	−25	0	25
4	−5	5	10
8	50	60	10

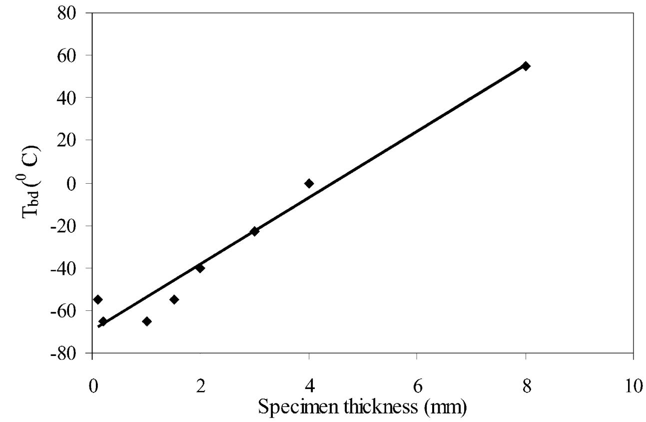

Fig. 4. PC, influence of specimen thickness on T_{bd}.

displacements increase and the maximum stress decreases and these two effects seem to level each other out. At low temperatures, thick PC specimens showed very low fracture energy levels, confirming the brittle behaviour of PC in thick applications. Crack initiation accounts for the majority of the total fracture energy at low temperatures. The propagation energy makes a more significant contribution in the high temperature region.

As mentioned before, PC is very notch sensitive, and a small flaw or variation in the notch tip radius can lead to large deviations. For each fractured specimen it is clear whether fracture was brittle or ductile. Detection of a sharp brittle-to-ductile transition can therefore be expected. However, even one batch of samples showed a broad temperature range where both brittle and ductile fracture was observed. The brittle-to-ductile transition in PC is thus very sensitive to minute difference in sample-to-sample variations and thus the brittle–ductile transition takes place over a temperature range rather than at a specific temperature. The determination of 'the' brittle-to-ductile transition temperature T_{bd} therefore involved not only the appearance of the fracture surfaces and the propagation displacement results, as is usually the case. Now also the temperature range in which the transition occurred had to be taken into account (Table 3).

The temperature range analysis can help to determine T_{bd} for PC. The transition was taken to occur in the middle of the transition temperature range. The temperature range from all samples brittle to all samples ductile was about 20 °C.

The T_{bd} was determined in the thickness range of 0.1–8 mm (Table 3, Fig. 4). On the thin film specimens the forces and displacements could not be measured and the T_{bd} was determined on fracture surface analysis alone. This was quite difficult since the fractured surface of the films was very narrow. The T_{bd} values for the thin specimens are therefore somewhat less accurate.

PC showed a strong decrease of T_{bd} with decreasing thickness (Fig. 4). T_{bd} decreased by about 130 °C with change from 8 to 1 mm thickness. Skin-core effects may give a more brittle behaviour for thin specimens, although this effect has been judged non-important in other research [12].

3.2. Polycarbonate/ABS blends

The influence of thickness was also studied for co-continuous PC/ABS (50/50) blends, using ABS with 0, 15 and 30 wt% PB. The 0% PB blend is a PC/SAN blend of course.

3.2.1. PC/SAN

First PC/SAN results will be discussed. PC/SAN was blended in a 50/50 weight ratio without rubber, to obtain a co-continuous PC/ABS 0% blend. The sample thickness ranged from 0.1 to 4 mm.

Maximum stress levels were hardly influenced by temperature (Fig. 5). With increasing thickness, the maximum stress decreased. This was also observed for PC, although the decrease for PC/SAN is less regular than it is for PC. The stress levels were low for all thicknesses (Fig. 5) and only half those of neat PC (Fig. 1).

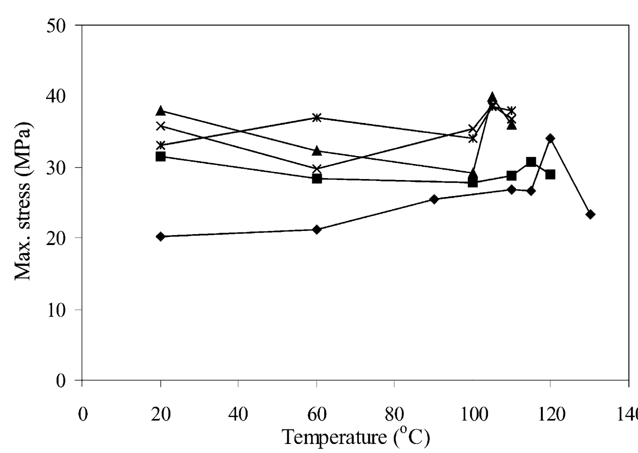

Fig. 5. PC/SAN, SENT maximum stress as function of temperature for different specimen thickness: at different temperatures for PC/ABS blend with 0% PB at different thicknesses: ∗, 1 mm; ×, 1.5 mm; ▲, 2 mm; ■, 3 mm; ◆, 4 mm.

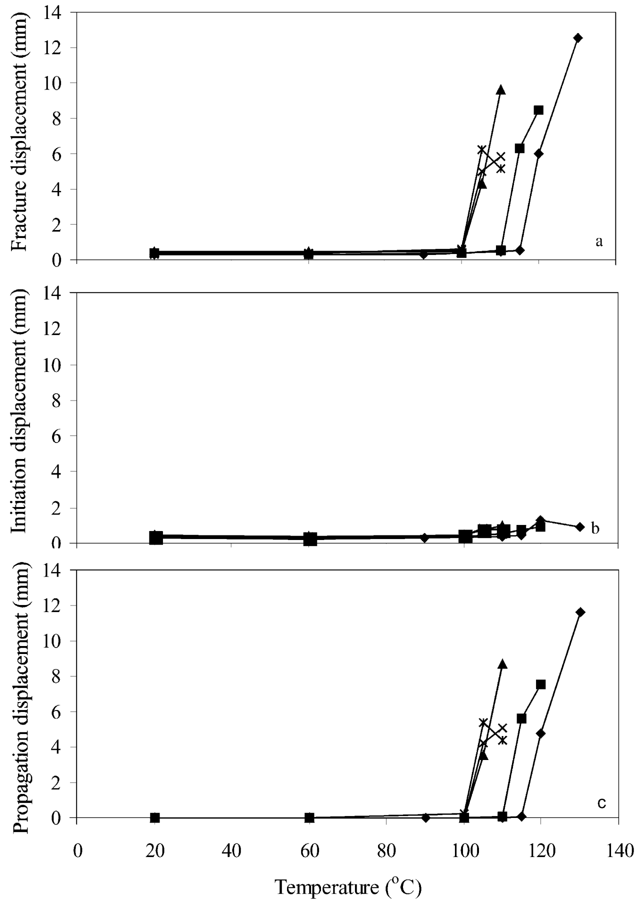

Fig. 6. PC/SAN, SENT displacement results as function of temperature for different specimen thicknesses: ∗, 1 mm; ×, 1.5 mm; ▲, 2 mm; ■, 3 mm; ◆, 4 mm.

At low temperatures, fracture displacements were very small (Fig. 6(a)). The materials all behaved in a very brittle manner, for all specimen thicknesses. PC/SAN (50/50) is apparently due to the presence of the co-continuous SAN phase a very brittle blend. For high temperatures, above about 100 °C, the fracture displacement values were much higher, even higher than the displacements measured for PC (Fig. 2(a)). As the T_g of the SAN phase is about 110 °C, the SAN-phase is probably already soft above about 100 °C, leading to high fracture displacements.

Initiation displacements were extremely low over the complete temperature range, although in the high temperature region the values become slightly higher. Apparently, the SAN-phase crazes at low stress and displacement, and this leads to early brittle fracture.

At low temperatures, the propagation displacements are also very low. At high temperatures, the material fractured in a ductile manner and the propagation displacements were much higher, even higher than for pure PC (Fig. 2(c)). The transition between brittle and tough fracture was very sharp for these blends.

It appears that PC/SAN is very brittle at temperatures below the SAN-T_g. Crack initiation takes place at low displacement, and no additional displacement (and energy) is necessary to propagate this crack, resulting in very brittle fracture. At temperatures close to the SAN-T_g, initiation only takes slightly more effort. But now the SAN-phase is more soft and rubbery and, because the SAN phase is continuous as is the PC-phase, very high propagation displacements can be realised. The SAN-phase probably can in this case possibly even act as a toughening phase.

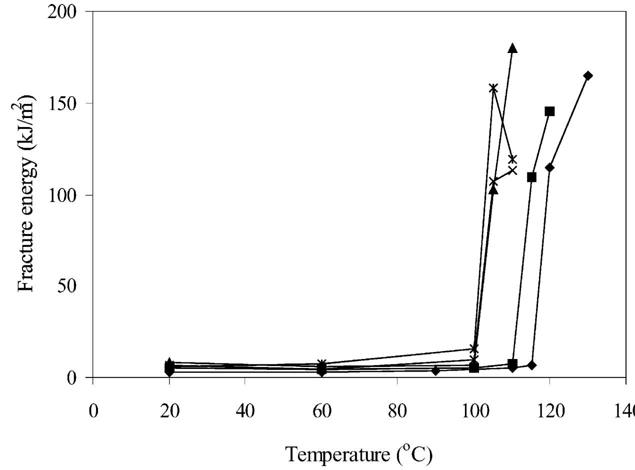

Fig. 7. PC/SAN, SENT fracture energy results as function of temperature for different specimen thicknesses: ∗, 1 mm; ×, 1.5 m; ▲, 2 mm; ■, 3 mm; ◆, 4 mm.

Since the SENT energy results give the same conclusions, only the fracture energy graph will be discussed briefly (Fig. 7). At low temperatures, in the brittle region, energy levels were extremely low, much lower than for brittle PC (Fig. 3). At high temperatures above 100 °C, in the ductile region, the energy values were very high, comparable to the ductile PC values.

The brittle-to-ductile transition temperatures could be determined from the propagation results and the examination of fractured specimens (Fig. 8). For the PC/SAN 0.1 and 0.2 mm films, no displacement and energy results could be measured and the T_{bd} was determined based on fracture

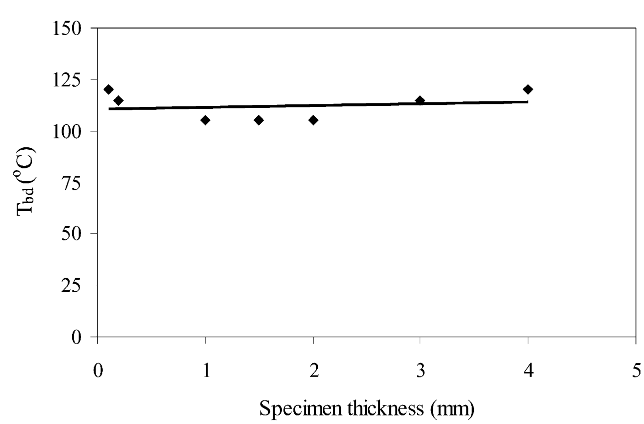

Fig. 8. PC/SAN, influence of specimen thickness on brittle–ductile transition temperature.

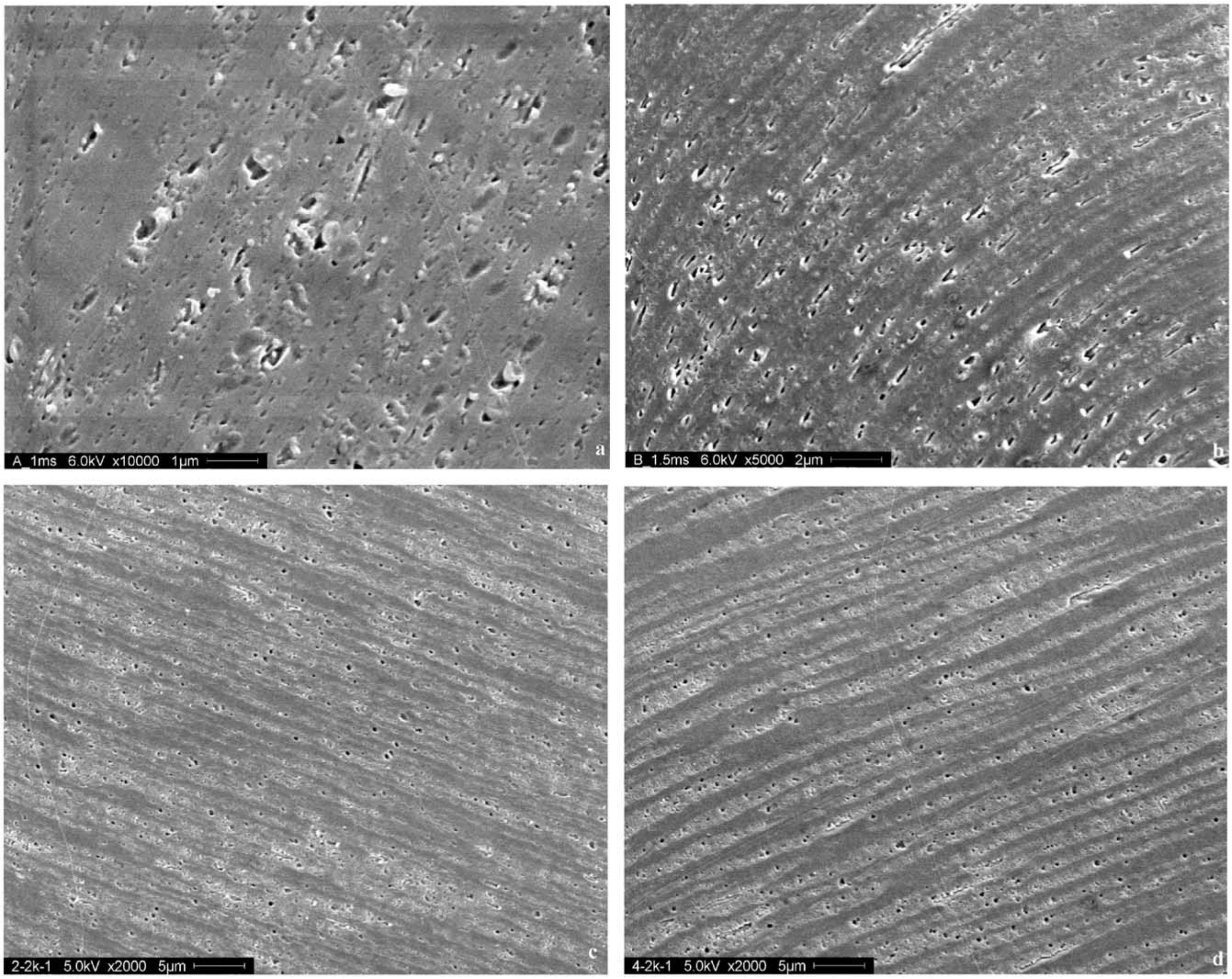

Fig. 9. PC/ABS (50/50) with 15% rubber in the ABS, SEM pictures of injection moulded specimen of different specimen thicknesses: (a), 1 mm (×10,000); (b), 1.5 mm (×5000); (c), 2 mm (×2000); (d), 4 mm (×2000).

surfaces. This was quite difficult, since the fracture surface was very small.

The brittle-to-ductile transition temperature was very high for the PC/SAN blend, between 105 and 120 °C. It remained high over the complete specimen thickness range. T_g for SAN used in these experiments was about 110 °C and thus the thickness did not seem to influence T_{bd}. Apparently the PC/SAN blend becomes ductile then the SAN-phase is softened.

3.2.2. PC/ABS with 15 wt% PB

Co-continuous PC/ABS blend (50/50) with ABS containing 15 wt% PB was studied over the thickness range 0.1–4 mm. SEM pictures were taken to see whether the co-continuous morphology changes because of different specimen thickness. Furthermore, the different processing method for the thin films can lead to a quite different morphology compared to that of the injection moulded material.

The SEM pictures taken of injection moulded specimens clearly showed a layered co-continuous morphology (Fig. 9). The layers appear to be thinner for thinner specimens. The 1 and 1.5 mm specimens (a and b) do not show the layered structure as clearly at low magnification, since here the layers became very thin due to the high shear forces during injection moulding. High injection speed and pressure is needed to injection mould the thin specimens. The SEM picture of a compression moulded specimen (Fig. 10) also showed a layered co-continuous morphology, indicating that test results for the two types of specimens can be compared.

The PC/ABS materials were tested in SENT tests at 1 m/s and different temperatures. For the 1, 1.5 and 2 mm thick specimens, fracture in the brittle, low temperature region showed that in many cases a wedge-shaped part of the specimen had separated from the specimen, indicating that two cracks propagated from the notch tip. In the ductile, high temperature region this was not observed.

Maximum stress was measured in SENT as function of

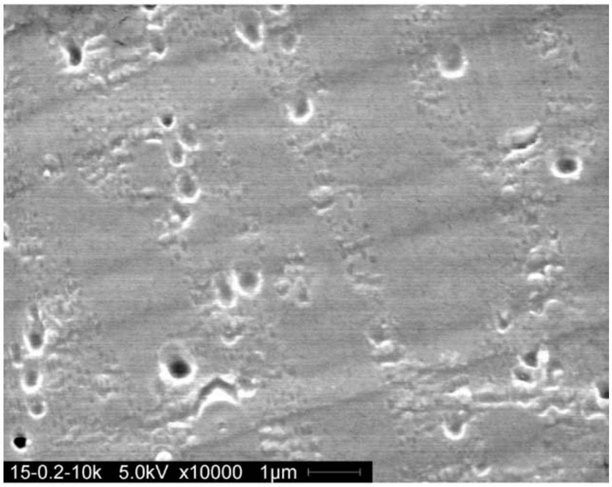

Fig. 10. PC/ABS (50/50) with 15% rubber in the ABS, SEM picture of compression moulded film, 0.2 mm thickness.

temperature for all injection moulded thicknesses (Fig. 11). Maximum stress did not change much over the temperature range, as was also found for the PC/SAN 50/50 blend. The stresses are higher than found for the PC/SAN blend, but lower than for pure PC. The influence of thickness is not strong.

Fracture displacement increased steadily with increasing temperature for all specimen thicknesses (Fig. 12(a)). Thickness did not seem to have major influence on displacement values for the 4, 3, 2 and 1.5 mm series. The 1 mm results however, showed surprisingly lower displacement values than the other series and lower than the 1 mm PC values (Fig. 2), indicating that fracture of these specimens is more brittle. Apparently, rubber toughening is not as effective for these specimens as it is for the thicker ones. It is likely that the plane strain situation, necessary for rubber cavitation and thus for the rubber toughening, cannot develop in the thin specimens and, as a result, the fracture in the specimens of 1 mm is less ductile and behaved more like PC/SAN.

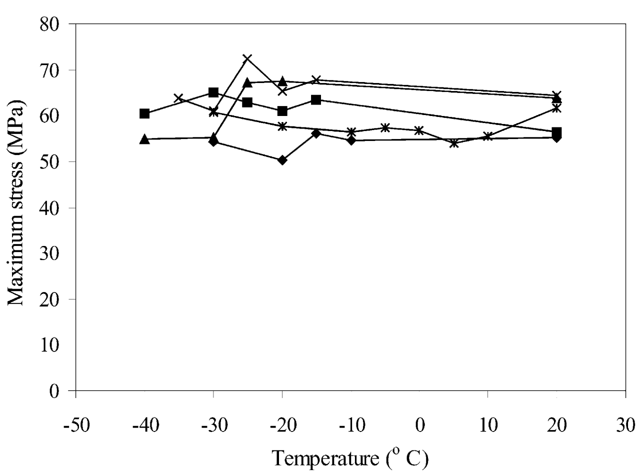

Fig. 11. PC/ABS (50/50) with 15% rubber in the ABS, maximum stress as function of temperature at different specimen thicknesses: ∗, 1 mm; ×, 1.5 mm; ▲, 2 mm; ■, 3 mm; ◆, 4 mm.

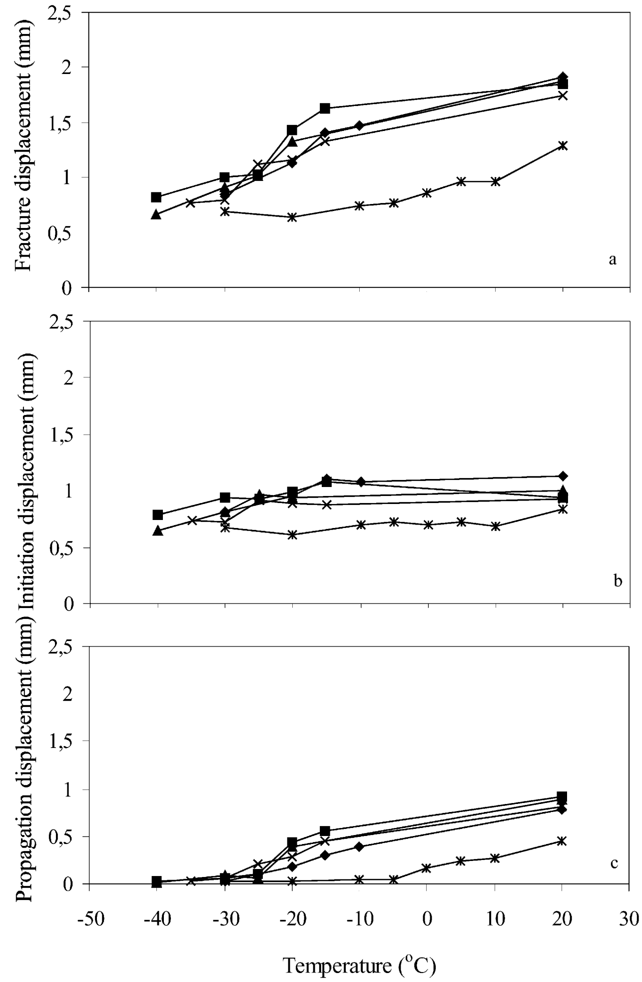

Fig. 12. PC/ABS (50/50) with 15% rubber in the ABS, displacement results as function of temperature at different specimen thicknesses: ∗, 1 mm; ×, 1.5 mm; ▲, 2 mm; ■, 3 mm; ◆, 4 mm.

Initiation and propagation displacement results (Fig. 12(b) and (c)) did not show unexpected results. For thin specimens, the propagation results showed a very gradual transition from brittle-to-ductile fracture. The transition was sharper for thick specimens.

SENT energy results gave the same conclusions and only the fracture energy results are therefore shown (Fig. 13). The thin 1 mm specimens showed much lower fracture energies, this is due to the recorded low fracture displacements and not due to the maximum stress.

Brittle–ductile transition temperatures (T_{bd}) were determined from the propagation results (Fig. 14) and the fracture surfaces. For the very thin specimens, it was difficult to see well whether fracture was brittle or ductile, as the surface is very small. The T_{bd} for the co-continuous PC/ABS blend with 15% PB is for the 4 mm sample about −20 °C, which is much lower than that of PC/SAN and PC. For specimens with a thickness larger than 1.5 mm, the T_{bd}

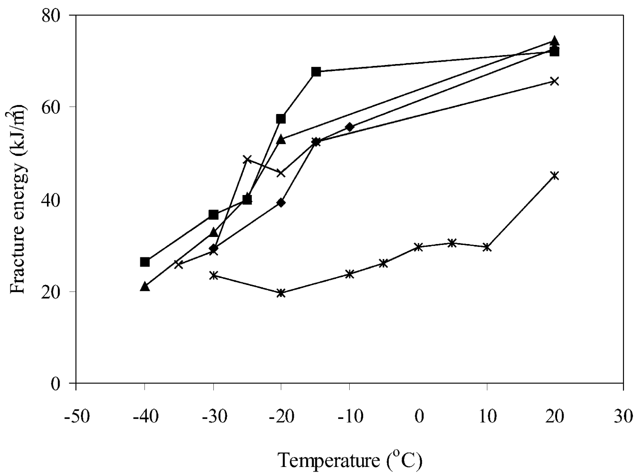

Fig. 13. PC/ABS (50/50) with 15% rubber in the ABS, fracture energy results as function of temperature at different specimen thicknesses: ∗, 1 mm; ×, 1.5 mm; ▲, 2 mm; ■, 3 mm; ◆, 4 mm.

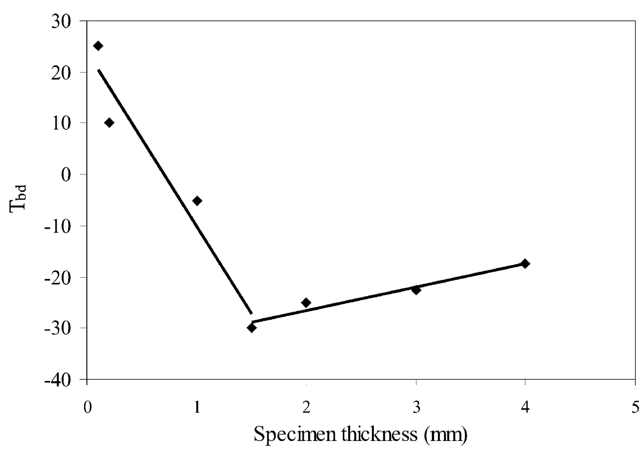

Fig. 14. PC/ABS (50/50) with 15% rubber in the ABS, influence of specimen thickness on brittle-to-ductile transition temperature.

increased slightly with thickness. For specimens thinner than 1.5 mm, T_{bd} increased strongly with decreasing thickness. This increase in T_{bd} with decreasing sample thickness is unusual and not seen in either PC or PC/SAN or any other polymer system in the literature. Apparently the toughening effect of the rubber, present in the SAN, disappeared when specimens were thinner than 1.5 mm. The toughening effect of the rubber modified polymers is based on the cavitation of the rubber particles well before the craze strain is reached. Cavitation and crazing are both volumetric process and for these a plane strain situation is needed. A plain strain situation is available in thick specimens. However, in thin sections, this situation is either not fully developed or even completely absent and in thin specimens cavitation of rubber particles is expected not to take place. If cavitation in PC/ABS is not taking place than the material is expected to behave like PC/SAN. In these thin samples PC/ABS is still less brittle than PC/SAN.

3.2.3. Infrared temperature measurements

The wall temperatures of specimen were monitored during fracture, using an infrared (IR) camera, producing 30 frames/s. During deformation of the material, yielding and softening will take place. Heat is developed with plastic deformation. Deformation at 1 m/s will be adiabatic, meaning that heat has no time to be conducted to the surrounding material. This will lead to a rise in temperature in the deformation zone, and result in local softening of the material. The temperature of the deformation temperature zone during SENT tests at 10^{-3} m/s is studied on samples with different specimen thicknesses during fracture. With this method, both the shape of the deformation zone as well at the maximum temperature can be studied. Concerning the recorded maximum temperatures one should bear in mind that the IR camera has a spot size of 100 μm and thus in the thin layer next to the fracture surface where the deformation is largest, the temperature cannot be measured. In Fig. 15 some IR pictures are given for both PC and PC/ABS on 1 and 3 mm specimen at moments when the crack propagation has started.

Far away from the fracture surface the specimens are warmed up few degrees. This indicates that outside the fracture zone homogeneous plastic deformation occurred and this little dependant on specimen thickness.

A zone with increased temperature was visible around and ahead of the running crack and the highest temperature

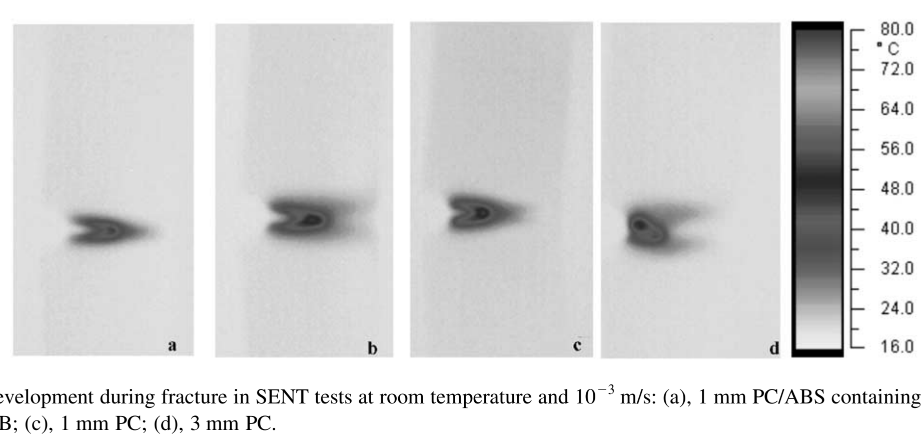

Fig. 15. Temperature development during fracture in SENT tests at room temperature and 10^{-3} m/s: (a), 1 mm PC/ABS containing 15% PB; (b), 3 mm PC/ABS containing 15% PB; (c), 1 mm PC; (d), 3 mm PC.

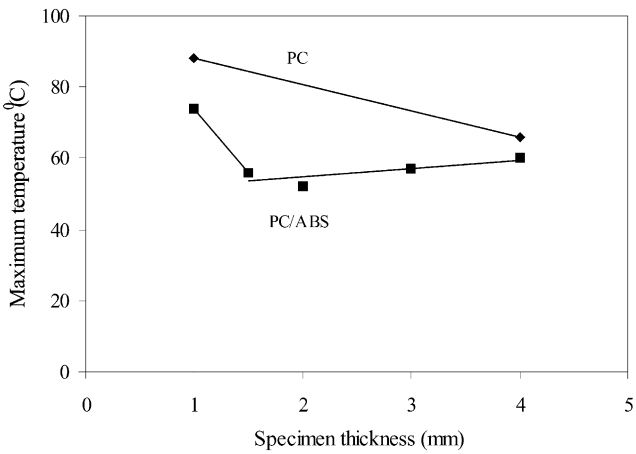

Fig. 16. Influence specimen thickness on maximum measured temperature SENT at 1 m/s and room temperature: ◆, PC; ■, co-continuous PC/ABS, ABS containing 15% PB.

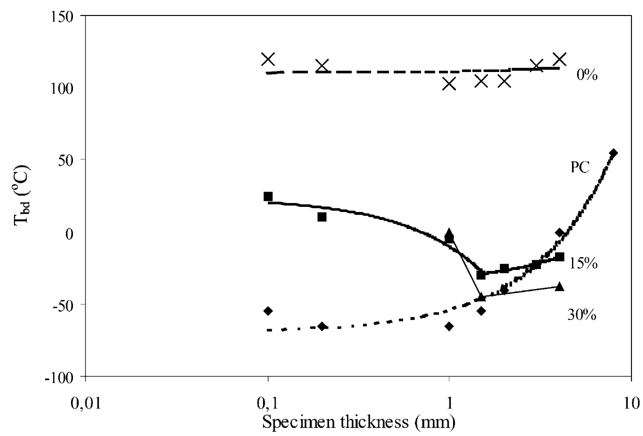

Fig. 17. Influence of specimen thickness (log scale) on brittle-to-ductile transition temperature: ◆, PC; ×, PC/ABS 0% (PC/SAN); ■, PC/ABS 15%; ▲, PC/ABS 30%.

was located at some distance ahead of the tip of the running crack. Remarkable is that in the specimen the deformation zone was divided into two lobes, located symmetrically above and below the fracture plane. This effect is stronger on PC than on PC/ABS samples.

The radius of the running crack is particularly blunt in the case of the 3 mm PC specimen. This blunted notch results in a broader deformation zone and this zone appears to be larger in PC than in the PC/ABS blend.

Maximum temperatures in the deformation zones during SENT testing at 1 m/s were determined (Fig. 16). In PC, the maximum temperature of the 1 mm sample was about 20 °C higher than that of the 4 mm sample, this although the fracture energy did not increase (Fig. 3). The temperatures in the PC/ABS specimens showed a higher value for the 1 mm samples than for the 1.5–4 mm samples. The higher temperature for the 1 mm PC/ABS sample is unexpected as the fracture energy of this sample at room temperature is lower than the other samples (Fig. 13). Thus the measured temperature effects do not seem to correlate well with the fracture energies.

3.3. Comparison of PC with PC/ABS

The changing fracture behaviour as function of sample thickness can well be characterised by the changing T_{bd}. The influence of specimen thickness on the brittle-to-ductile transition temperature T_{bd} for the PC, PC/SAN and PC/ABS are compared (Fig. 17). The sample thickness was varied nearly over two decades and therefore the results were presented as function of the logarithmic of the sample thickness. One would expect for all polymers that the T_{bd} is high at large thickness and low at very thin samples and that the change take place over a certain thickness interval. Where this interval lies depends on the type of polymer, for a ductile polymer at large thickness and a brittle polymer at small thickness.

For PC the T_{bd} changes strongly in the 1–10 mm range, from 60 °C of the 8 mm samples to about −70 °C for the thin samples (>1.5 mm).

PC/SAN has over the whole thickness range a high T_{bd} (near 120 °C), which lies just above the glass transition temperature of the SAN-phase. This material might have a low T_{bd} at extremely low thickness.

The T_{bd} of PC/ABS with 15% PB has a complex relationship. Specimens with a thickness of 1.5–8 mm had a low T_{bd}, but for thinner specimen (0.1–1 mm) this was remarkably higher. Apparently, rubber toughening worked well in thick specimens, but gradually less in thinner specimen. Also studied was a co-continuous PS/ABS blend with 30% PB. The T_{bd} of this blend is in the thickness range 1–4 mm very low (about −50 °C) and higher for the 1 mm sample. Thus in thin specimens PC is tougher than the PC/ABS blends and rubber toughening only works well if wall thickness is high enough.

4. Conclusions

Specimen thickness in PC had a strong effect on the deformation during fracture, fracture energy and the brittle-to-ductile transition temperature. The T_{bd} decreased 130 °C with decreasing thickness of 8–1.5 mm. The co-continuous PC/SAN blend (50/50) was extremely brittle and had a very high T_{bd} over the complete specimen thickness range. The co-continuous PC/ABS blends (50/50) having 15 and 30 wt% rubber in the ABS were reasonably ductile and showed much lower T_{bd} compared to the PC/SAN blend (0% rubber). For thick specimens, T_{bd} decreased with specimen thickness, and rubber toughening was effective in this range. However, for thin specimens below 1.5 mm thickness T_{bd} increased again. This increase was unexpected and indicated a less effective rubber toughening in the material at these small thicknesses. Rubber cavitation, essential for effective toughening, could not take place in these thin specimens, because the necessary triaxial stress state in the material was absent.

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