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Polycarbonate and co-continuous polycarbonate/ABS blends: influence of notch radius

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Abstract

The influence of notch tip radius in the range of 1–0.002 mm was studied on polycarbonate (PC) and co-continuous PC/acrylonitrile–butadiene–styrene (ABS). Co-continuous PC/ABS blend was obtained by mixing PC and ABS containing 15% polybutadiene (PB) in a twin screw extruder. PC and PC/ABS specimens were injection moulded into test bars. A notch was milled-in, with notch tip radius of 1, 0.5, 0.25 and 0.1 mm. Very sharp notches with a radius of 0.015–0.002 mm were obtained with an Excimer LAZER. The specimens were tested by single edge notch tensile tests at 1 m/s (apparent strain rate 28.5 s^{-1}) and at different temperatures (−60 to 130 °C). Initiation and propagation phases of the fracture process were monitored and the brittle–ductile transition temperature (T_{bd}) determined. It appeared that the amount of deformation in the initiation phase of fracture was extremely sensitive to notch tip radius. Temperature measurements of the deformation zone showed that the size of the deformation zone decreased with decreasing notch radius. The T_{bd} of PC increased rapidly with decreasing notch radius, until the glass transition temperature was approached. Remarkably, for PC the notch sensitivity was strongest around the standard notch tip radius of 0.25 mm. This means that a small deviation of this standard notch leads to large deviations in the results. The PC/ABS blend was much less sensitive to notch tip radius and the T_{bd} was almost constant. Thus the sensitivity of PC to sharp defects can be neutralised by adding ABS.

Keywords: Polycarbonate; Co-continuous blends; Notch radius

1. Introduction

Polycarbonate (PC) is an engineering plastic; a transparent material with excellent mechanical properties, such as impact properties, dimensional stability and high T_g. This material, however, has one major drawback that is the notch sensitivity [1–4]. Transition from ductile to brittle fracture in PC can be induced by (among other variables) increasing section thickness [5], by increasing test speed [6], by decreasing temperature [5,6] or by introduction of sharp flaws, for example as a result of ageing. The transition from ductile to brittle behaviour has been explained by a competition between shear yielding and crazing mechanism [2,4] and appears to involve a mixed-mode transition [3,7,8].

The notch sensitivity can be described by the influence of radius of curvature on the stresses around an elliptical hole in a material [9]

$$\sigma_{yy} = \sigma\left(1 + 2\sqrt{\frac{A}{\rho}}\right) \quad (1)$$

with σ_{yy} the stress in the y-direction at $x = A$, radius of curvature $\rho = B^2/A$ at the tip of the elliptical hole, and remote stress σ. This equation can be used to estimate the stress concentration for notches that can be approximated by an ellipse. For a circular hole, $\rho = A$ and $\sigma_{yy} = 3\sigma$. For a crack, $B = 0$, and this model results in infinite stress at the crack-tip.

Using the fracture toughness parameter G, it was deduced that a linear relationship exists between the blunt-notch strain energy release rate G_B and the notch tip radius [9,10]

$$\frac{G_B}{G_C} = \frac{1}{2} + \frac{\rho}{8l_0} \quad (2)$$

with G_C the value for a sharp notch, l_0 distance ahead of the notch tip at which the stress reaches a critical level and fracture occurs, and $\rho \gg l_0$. This linear relationship was confirmed for PVC [9]. The method for determination of G_B is only effective when crack initiation is followed by unstable brittle fracture with no further energy absorption, thus for rather brittle materials. When blunting occurs at the crack-tip, the constraint ahead of the tip is reduced and this influences the measured toughness. The effect of notch radius on K_{Ic} was described by Kinloch et al. [11,12] and

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Table 1
Material properties

Material	Provided 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 g/cm^3, MFR = 21 g/10 min
PB: GRC 310	DOW Benelux	ABS: SAN grafted PB powder, PB content 50%, particle size 0.1 μm

Chang and Chu [3]. They found also that an increase in notch radius resulted in higher fracture stress and thus a higher toughness.

The effect of notch radius on the fracture of PC has been studied on several occasions [1–3,13,14]. Many practical impact tests are carried out on specimens with notches of finite tip radius because these notches are more easily reproduced. Standard ASTM specimens have a notch tip radius of 0.25 mm. Sharp notches are usually obtained by pushing a razor blade in the material and, with this method, tip radii on the order of 10 μm or less can be obtained [10]. On materials with a sharp notch and fracturing in a brittle manner LEFM is applicable. The razor-procedure, however, results in plastic deformation in the material around the crack-tip zone prior to actual testing and this can influence the test results. The reproducibility of the notches by a razor blade is often also a problem.

Polato [15] studied PBT containing a standard notch in the Charpy test and found that strain rate at the notch root was 2300 s^{-1}, which is very high. In notched Izod, strain rate at notch tip has been estimated to be in the order of 5000 s^{-1} [16]. This indicates the extent that a notch concentrates stress and strain at the notch tip. Bauwens-Crowet studied the dependence of the yield stress on strain rate for PC [17], and found the yield stress to increase with strain rate. A smaller notch radius will therefore cause an increase in yield stress [3] and thus eventually lead to a transition from ductile to brittle behaviour. Also, the stress state ahead of a sharp notch is more plane strain and this can also lead to more brittle behaviour.

The addition of rubber can by cavitation of the rubber change the stress state ahead of a notch. This raises the stress at which crazing takes place and hence results in lower brittle-to-ductile transition temperature. It was found that rubber modification reduced the sensitivity of PC to sharp notching [3]. This was explained by constraint relief due to cavitation of the rubber particles [18]. Cavitation or void nucleation is closely related to the macroscopic hydrostatic tension. Notch geometry affects the hydrostatic stress ahead of the tip and therefore directly affects the toughness behaviour of the material. Pearson and Yee [19,20] observed rubber particle cavitation in the crack-tip region before noticeable plastic deformation occurred in epoxy matrix material.

Pitman and Ward [2] used different notch tip radii in their study on impact behaviour of PC, as did Fraser and Ward [1]. PC specimens were fractured in a brittle manner for small radii, and ductile for very blunt-notches. In between these two extremes a region was found where three types of fracture were observed: brittle, brittle with small yielded zones, and completely ductile. This was associated with the transition from plane strain (sharp notch) to plane stress (blunt-notch). Similar behaviour was found by Havriliak et al. [13], who also stated that changing the notch tip radius directly affected the strain rate at the tip.

Notch radii used in the earlier mentioned surveys, however, are usually quite large when compared to the radius of a hairline crack due to ageing, a craze or a running crack in the material. In such cases the notch tip radius is in the order of 1 μm [21]. Also, the influence of rubber addition to PC in this context has been rarely studied [3].

We studied the influence of notch radius in a very wide radius range (1–0.002 mm) on PC and a co-continuous PC/ABS blends. The deformation was with single edge notch tensile (SENT) test. The effect of notch radius on fracture stress, fracture displacements and fracture energies as a function of temperature were studied. The changing fracture behaviour could well be typified by the change of brittle-to-ductile transition temperature. The temperature development in the samples was followed by an infrared thermographic system.

2. Experimental

2.1. Materials

Commercially available PC, SAN and SAN/PB were kindly supplied by DOW Benelux and GE Plastics. The material specifications are listed in Table 1.

2.2. 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 required amounts of GRC rubber, producing ABS with 15 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 of 74 × 10 × 4 mm^3 using an Arburg Allrounder 221-55-250 injection moulding machine. The barrel temperature was 230 °C, mould temperature 80 °C and injection pressure 55 bar at 100 rpm screw speed.

A single-edge 45° V-shaped notch of 2 mm depth was milled in the specimens, notch radii of 1, 0.5, 0.25 or 0.1 mm were possible by using different saws. Using an Excimer LAZER, 0.1 mm notch radius specimens were

Table 2
Technical data for the infrared camera, equipped with close-up lens (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

then modified by adding a small extra notch at the tip. This resulted in very small notch radii of 0.002 and 0.005 mm for the PC/ABS blends and 0.004 and 0.013 mm for PC. These radii are not as well defined as the larger milled-in notches and the values for notch radius represent an average value.

2.3. SEM photography

Scanning electron microscopy was used to look at the notch radii. A section containing the notch was cut across the complete thickness of the specimen. After coating it with gold, the sample was examined using a Hitachi S-800 field emission scanning electron microscope.

2.4. SENT tests

The notched specimens were fractured at different temperatures and at 1 m/s clamp speed in SENT tests to investigate the influence of notch radius on energy and displacement results, and the brittle-to-ductile transition. With a specimen length of 35 mm between the clamps, the macroscopic strain rate was 28.5 s^{-1}. A Schenck VHS servohydraulic tensile test machine was used. All measurements were performed in five-fold. The stress–strain results of the notched tensile test can be divided in an initiation part which is the displacement up to the maximum stress, a maximum stress at which moment fracture is also initiated and a propagation displacement. If a sample fractures in a brittle manner the propagation displacement is minimal. Also the fracture energies can be calculated. The fracture energies are based on the cross-sectional area behind the notch.

2.5. Infrared thermography

The temperature rise during fracture of specimens containing notches of radius 1–0.002 mm was monitored using an infrared camera. Specifications are listed in Table 2. With the infrared camera, only temperatures at the surface of the specimen can be determined. Temperatures inside the specimen are expected to be higher than at the surface. 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 at the fracture surface, which is expected to be highest, therefore cannot be determined. The maximum temperature that will be determined

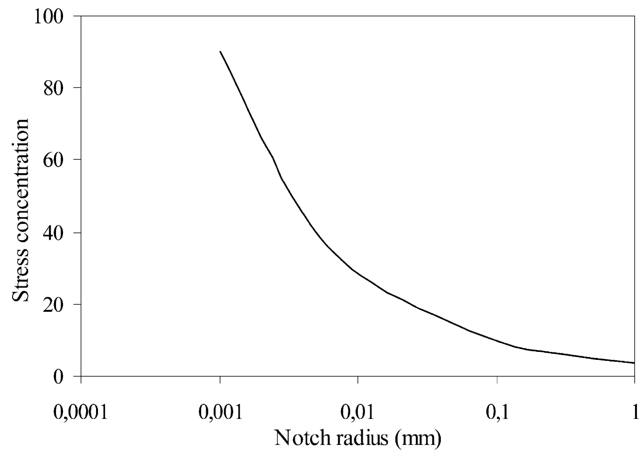

Fig. 1. Influence of notch tip radius on stress concentration σ_{yy}/σ, on log scale, calculation based on Eq. (1).

from the infrared images is thus not the maximum surface temperature.

3. Results and discussion

PC and PC/ABS 50/50 blend with ABS containing 15% polybutadiene was tested by SENT tests. The SENT tests were done at a test speed of 1 m/s and over a wide temperature range. The strain rates in 1 m/s SENT test compare well to a notched IZOD test, but with this instrumented tensile method more data could be gathered. The ABS was made by blending a core–shell rubber in SAN. Notch tip radius was varied between 1 and 0.002 mm, with a notch length of 0.2 mm. Results for PC and PC/ABS are discussed separately. Based on Eq. (1), the stress concentrations ahead of notches in a plain strain situation with different radii can be calculated (Fig. 1). The stress concentration is a function of $\rho^{-1/2}$, whereby ρ is the notch radius. The stress concentration increases strongly with decreasing notch radius and thus fracture properties are expected to be sensitive to the notch radius.

Notch radii: In both, PC and PC/ABS, co-continues blend notch were made with a wide range in radii. By machining, radii 1–0.015 mm were made and with an Excimer LAZER of radii 0.015–0.002 mm were obtained. The machined notches were rather clean (Fig. 2(a)). The LAZER notches were made on specimens containing already a 0.1 mm notch and this resulted in an additional sharp notch at the original notch tip (Fig. 2(b)). The tip of the LAZER notched specimen having a radius of 0.002 mm is shown in Fig. 2(c).

3.1. Polycarbonate

PC is known to be a very notch sensitive material and the influence of the notch radius on the fracture behaviour was studied with a SENT test. The SENT tests were done at a test speed of 1 m/s and over a temperature range of −70 to 140 °C. The notch in the specimens had radii of machined

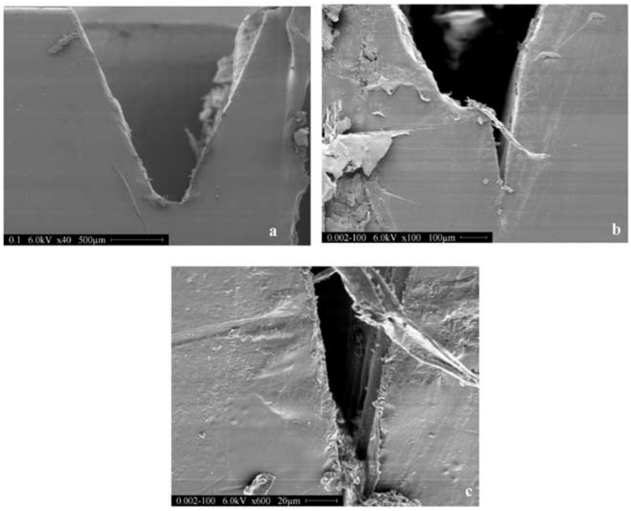

Fig. 2. SEM micrographs of notch tips: (a) 0.1 mm machined radius; (b) 0.002 mm laser notch radius in PC/ABS, ×100; (c) enlargement of (b).

notches 1, 0.5, 0.25, 0.1 mm and of LAZER notches 0.013 and 0.004 mm.

3.1.1. Fracture surfaces

The notch radii had a strong influence on the fracture behaviour of PC which can be typified by the fracture surface of the tested samples. The appearance of the fracture surfaces is discussed.

1, 0.5 and 0.25 mm: At low temperatures, the surface showed brittle fracture, and crack branching was clearly visible. At higher temperatures, the material yielded and fractured in a tough manner. No mixed-mode surfaces were observed; fracture was either completely brittle or completely ductile.

0.1 mm: At low temperatures, brittle fracture was obvious and crack branching occurred. At higher temperature, a smooth mirror-like surface with brittle features appeared. The outer layer of the specimen is in plane stress situation, resulting in the formation of very thin shear lips on the surface. At temperatures close to T_g of PC, the material softened and this resulted in ductile behaviour with massive yielding.

0.013 mm: At 20 °C, a smooth brittle surface was observed, with crack branching at the far end of the fracture surface, indicating acceleration of the crack during propagation. At higher temperatures, fracture resulted in a mirror-like brittle surface, with very small shear lips at the wall at higher temperatures. At 130 °C and higher, extreme deformation took place, and fracture occurred at a random location in the specimen. This was considered ductile fracture.

0.004 mm: The fracture surfaces observed were very much the same as those described for the 0.013 mm notch radius. At 20 °C, a smooth brittle surface with some crack branching at the far end of the surface appeared. At higher temperatures this changed into a smooth mirror-like surface, with very small shear lips at the sidewalls at higher temperatures. At 135 °C and higher, massive yielding was observed. This was considered ductile behaviour.

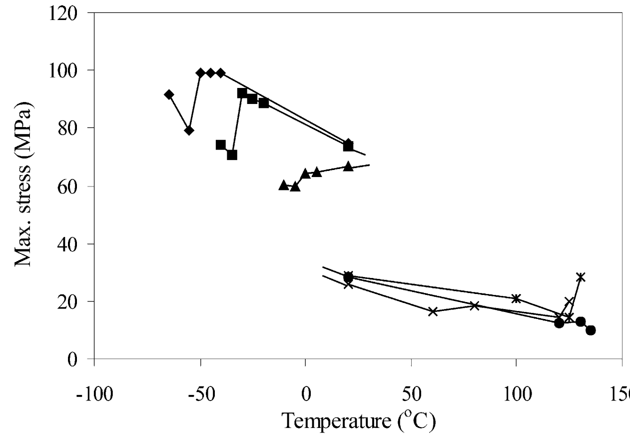

Fig. 3. SENT maximum stress for PC containing a notch with different radii: ◆, 1 mm; ■, 0.5 mm; ▲, 0.25 mm; ×, 0.1 mm; ∗, 0.013 mm; ●, 0.004 mm.

3.1.2. Single edge notch tensile test

Force and clamp displacement are recorded during the SENT test, and fracture energy can be determined, as explained in Section 2. SENT tests were performed with PC specimens containing a notch with notch tip radius varying from 1 to 0.004 mm.

The maximum stress (fracture stress), which is the stress at which a crack is initiated, is a function of temperature and determines whether the fracture is brittle or ductile [7]. In the brittle region, the maximum stress increased with temperature and in the ductile region it decreased with temperature (Fig. 3). The increase in the brittle region, like in the 0.5 mm notched sample between −45 and −30 °C, is due to the increasing plastic deformation in the notch with temperature and hence results in blunting and higher maximum stress. The decrease of the maximum stress in the ductile region, like in the 0.5 mm notched sample above −30 °C, is due to a lowering of the yield stress. Yield stress of PC has been reported to decrease by a factor of about 2.5 when the temperature is increased from 20 to 100 °C [17].

Based on the influence of notch radius on the stress concentration (Fig. 1), it is to be expected that the maximum stress will decrease with decreasing notch radius. As can be seen from the values at 20 °C, the fracture stress strongly decreases with decreasing notch radius. This effect is particularly strong between 0.25 and 0.1 mm. Samples with large radii fracture showed ductile fracture at 20 °C, while those with small radii showed brittle fracture.

The fracture process has been divided into an initiation part and a propagation part.

Initiation displacement is the displacement up to the maximum stress, at which point fracture is initiated and which is a combination of an elastic displacement in the whole sample and a plastic deformation just ahead of the

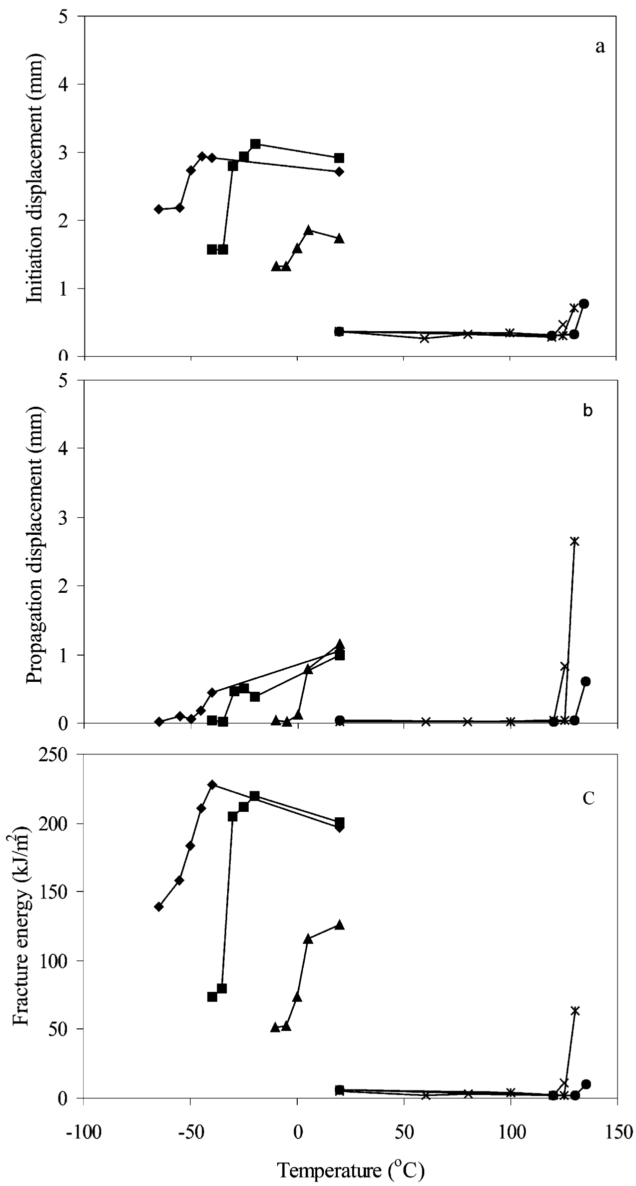

Fig. 4. SENT displacements and fracture energies for PC containing a notch with different radii: ◆, 1 mm; ■, 0.5 mm; ▲, 0.25 mm; ×, 0.1 mm; ∗, 0.013 mm; ●, 0.004 mm.

notch. The initiation displacement is expected to increase from brittle-to-ductile [7]. The initiation displacement decreased dramatically with decreasing radius, as can be seen at 20 °C (Fig. 4(a)). The decrease is even stronger than for the maximum stress (Fig. 3). With a sharp notch, the maximum stress is low and so also the crack initiation displacement, this results in higher stress concentration and severe constraint ahead of a sharp notch. It is surprising to see that in the ductile region, for the 0.25, 0.5 and 1 mm notched samples at room temperature, the initiation displacements still decrease with notch radius, although the maximum stresses are similar. One expects the blunting of the notch to be independent of notch radius as can be concluded from the maximum stresses. However, the

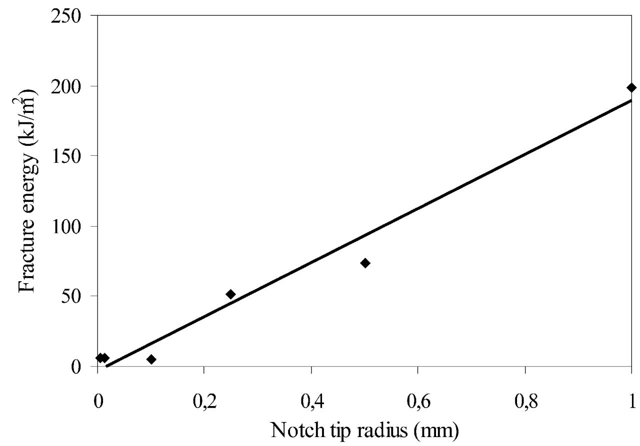

Fig. 5. Influence of notch tip radius on fracture energy of PC at 20 °C.

amount of the deformation (in the notch) is strongly dependent on the notch radius. The initiation deformation decreases the notch radius and this is same in the case of ductile fracture also.

Propagation displacement is minimal in the brittle region, like 0.5 mm radius at <0 °C, and increases in the ductile region, like 0.5 mm radius above 0 °C (Fig. 4(b)). The propagation displacements in the ductile region, like the 0.25, 0.5 and 1 mm notched samples at room temperature, were little dependent on the notch radius. A running crack is expected to have about the same tip radius, which is not influenced by the radius of the initial notch tip. Once the crack is initiated, the displacement needed to propagate the crack will be the same. At low temperatures the minimal propagation displacements indicated brittle fracture. At higher temperatures fracture was ductile and propagation displacements were higher. The onset of ductility, the brittle-to-ductile transition temperature, increased with decreasing radii. Propagation displacements were low compared to initiation displacements, especially for large radii and thus are only a small part of the total fracture displacement.

Fracture energies are a product of the maximum stress and the displacements. The conclusions for the fracture energy initiation and propagation are similar as for the displacement results discussed earlier. Therefore only the total fracture energy results are given (Fig. 4(c)). The fracture energies in the ductile region are appreciably higher than in the brittle region. The fracture energies depend strongly on the notch radius, both the maximum stresses and the initiation displacements decrease strongly with decreasing radius and the fracture type changes from brittle-to-ductile, shown also in Fig. 5. PC with large radii is highly ductile and with small notch radii is very brittle.

Very characteristic for the changing deformation behaviour is the shift in the brittle–ductile transition temperature. The brittle–ductile transition temperatures T_{bd} were determined based on fracture surfaces and propagation results (Fig. 4(b)) and are given in Fig. 6. PC has at large

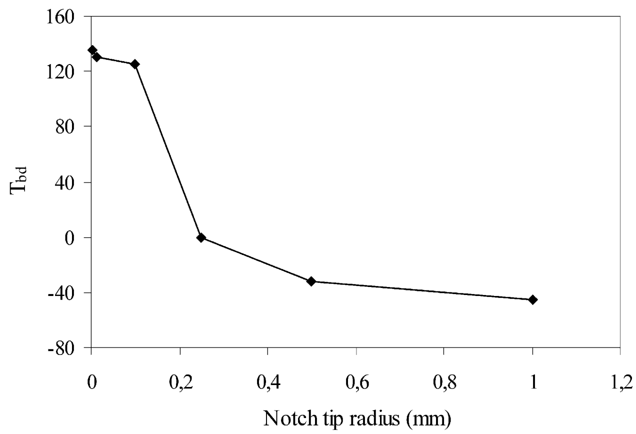

Fig. 6. Influence of notch tip radius on brittle-to-ductile transition temperatures for PC tested at 1 m/s.

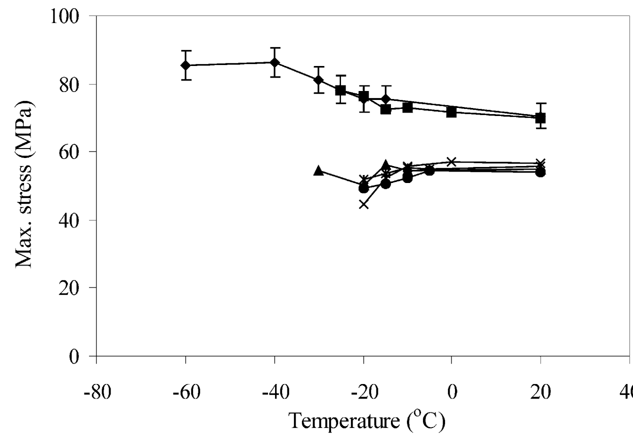

Fig. 7. SENT maximum stress for PC/ABS with different notch radii: ◆, 1 mm; ■, 0.5 mm; ▲, 0.25 mm; ×, 0.1 mm; *, 0.005 mm; ●, 0.002 mm.

radii a T_{bd} at −40 °C and at small radii at 135 °C, with a rapid change around 0.1–0.25 mm radius. This region of rapid change is just at the size of a standard notch in the notched Izod and Charpy tests, which means that in PC small variations in the standard notch can have a large effect on the impact value. PC is very sensitive to the notch radius in both fracture energy and brittle-to-ductile transition temperature.

3.2. Polycarbonate/ABS

SENT tests were done on co-continues PC/ABS 50/50 blends, ABS containing 15% polybutadiene. The main reason for adding ABS is to lower the notch sensitivity of the PC. This is particularly important for the sensitivity of the fracture behaviour to aging, as due to ageing sharp flaws may form on the surface of the polymer. The notch in the specimens had a tip radius in a range of 1–0.002 mm.

3.2.1. Fracture surface

For all notch tip radii, the fracture surface appearance developed in a similar manner from low temperature, brittle, to high temperature, ductile surface. At low temperature, the brittle surface was smooth without whitened zone. With increasing temperature, a whitened, ductile zone appeared just ahead of the notch and along the specimen surface (shear lips). This zone increased in size with increasing temperature, until the complete surface was whitened and showed massive material yielding. The thickness of the whitened zone below the ductile fracture surface decreased slightly with decreasing notch tip radius, roughly from about 3 mm maximum at 1 mm notch and 20 °C, to about 2 mm at 0.002 mm notch and 20 °C. Thus the size of the process zone decreased with notch radius.

During brittle fracture of the 1 and 0.5 mm notched specimens, a large wedge-shaped part of the specimen separated from the rest of the specimen, indicating two propagating cracks from the notch tip. This was not observed for the specimens containing notches with smaller radii.

3.2.2. Single edge notch tensile test

SENT tests were done on samples containing a notch, with notch tip radii varying between 1 and 0.002 mm. The maximum stress for the 0.5 and 1 mm radii samples decreased somewhat in the temperature region of −60 to 20 °C (Fig. 7). The maximum stresses for the smaller radii were lower and independent of temperature. Although at 20 °C the fracture was ductile in all cases, the maximum stress decreased with radius. This effect is for the PC/ABS blend stronger than for PC ductile at 20 °C (Fig. 3). This effect in the ductile region of decreasing maximum stress with decreasing notch radius is as yet unexplained. It seems that the extent of blunting in the notch in the ductile region is a function of the initial radius of the notch. A strong notch tip blunting is only possible if a large amount of material ahead of the notch is plastically deformed. Starting from a sharp notch the deformation is much more localised and blunting to a very shallow notch is more difficult. This notch blunting is thus a self-reinforcing process.

The initiation displacements of the blends increased steadily for all radii. As function of temperature no transition at T_{bd} (at about −20 °C) can be seen (Fig. 8(a)). Over the whole studied temperature region, the initiation results for the sharper notches were again lower than the other series and thus the size of the plastic zone smaller. With a sharper notch both the maximum stress and the initiation deformation is lowered.

The shape of the propagation displacements for large and small notch radii was remarkably the same (Fig. 8(b)). A running crack is expected to have a specific radius, and therefore the initial notch radius will not affect the propagation results. Also the transition from brittle-to-ductile fracture was not changed much despite the strong difference between the materials in maximal stress and initiation displacement. The propagation displacements were not as high as the initiation displacements. Thus in SENT the total fracture displacement is dominated by the initiation displacement. The total displacement increased with increasing radius. Temperature measurements of the deformation zone

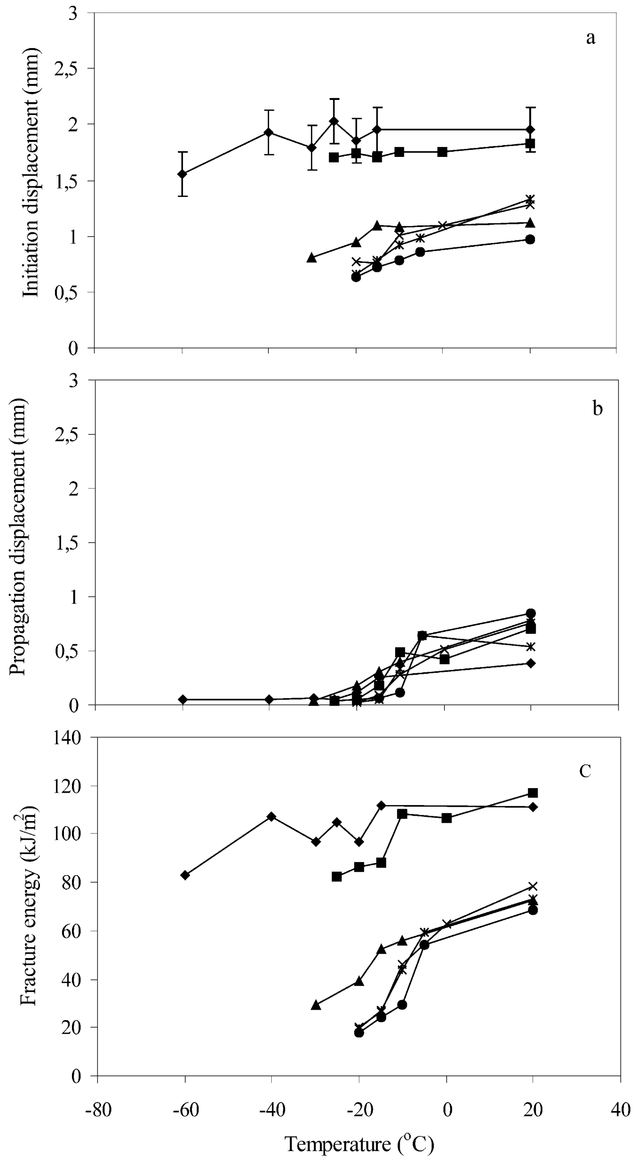

Fig. 8. SENT displacements and fracture energies for PC/ABS 50/50 15% with different notch radii: ◆, 1 mm; ■, 0.5 mm; ▲, 0.25 mm; ×, 0.1 mm; ∗, 0.005 mm; ●, 0.002 mm.

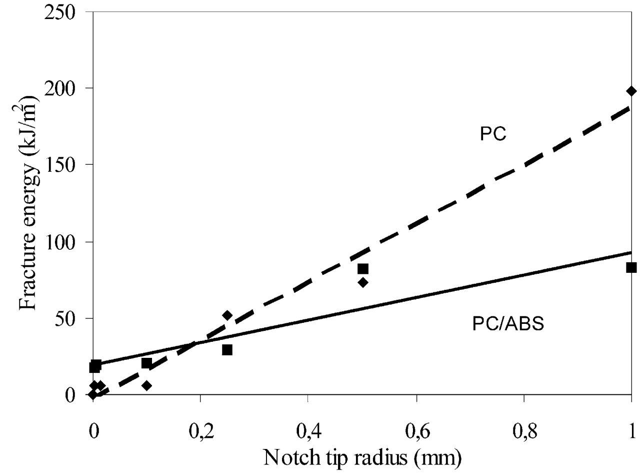

Fig. 9. Influence of notch tip radius on fracture energy of PC/ABS 50/50 and PC at 20 °C.

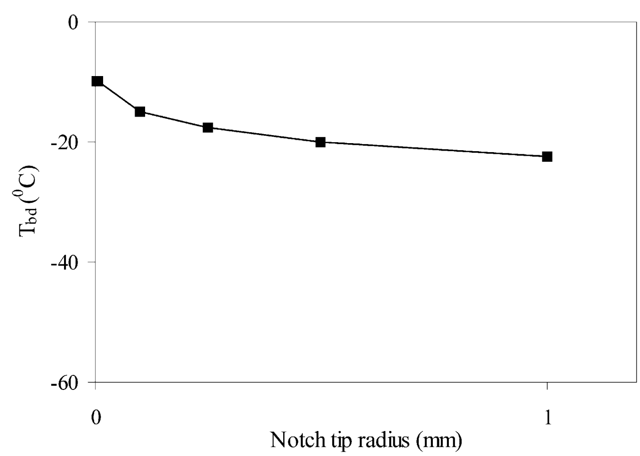

Fig. 10. Influence of notch tip radius on brittle–ductile transition temperature of PC/ABS 50/50 blend, ABS containing 15% PB.

showed that the size (thickness) of the plastic zone and the radius of the notch at crack initiation increased with increasing notch radius (see Section 3.1).

Fracture energy initiation and propagation results gave the same conclusions as the displacement results (Fig. 8(a) and (b)) so only the total fracture energy results are given (Fig. 8(c)). Fracture energy levels show a gradual increase with temperature and the low radii had over the whole studied temperature region lower fracture energy. The fracture surfaces had all the same appearance. This corresponds to the similar propagation results of all the radii. The fracture energies at room temperature decreased with decreasing notch radius although all samples are fractured ductile at 20 °C (Fig. 9). This effect seems mainly due to the larger fracture initiation at higher radii. Compared to PC fracturing ductile (Fig. 4(c)) we see that the fracture energies of the PC/ABS are lower. For small low radii the PC/ABS values are higher than the PC values, since now the PC/ABS fracture ductile while PC was brittle. When the fracture energies of brittle PC/ABS (Fig. 8(c)) are compared to brittle PC (Fig. 3(c)) for the small radii the fracture energies of the PC/ABS are still larger. Thus, the fracture energies are higher even under conditions where PC/ABS fractures brittle.

The brittle-to-ductile transition temperature of the PC/ABS blend did not change much with notch radius; only a slight increase was measured with decrease in radius (Fig. 10). There was certainly not a strong correlation between the fracture energy at the T_{bd} and the brittle-to-ductile transition temperature as sometimes suggested in the literature [4]. The modification of PC with ABS has a positive effect on the fracture energy and the brittle-to-ductile transition temperature if a sharp notch or crack is present.

3.2.3. Infrared temperature measurements

Temperature at the surface of the specimen was monitored

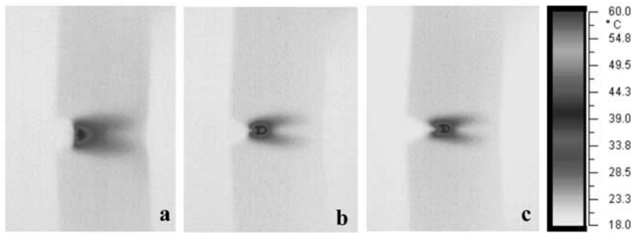

Fig. 11. Infrared thermographic images of PC/ABS tested at 10^{-3} m/s and room temperature in SENT with different initial notch radii: (a) 1 mm; (b) 0.1 mm; (c) 0.002 mm.

during fracture of SENT samples, using an infrared (IR) camera, producing 30 frames/s. During deformation of the material, yielding and softening will take place and most mechanical energy is transformed to heat so that the deformation zone is warmed up. Deformation at 1 m/s is so fast that the process is adiabatic, meaning that little heat is conducted to the surrounding material. The plastic deformation will lead to a rise in temperature in the deformation zone, and result in additional local softening of the material. This temperature effect is shown for PC/ABS specimens during SENT tests at 10^{-3} m/s, for different notch radii (Fig. 11). The frames for 1 m/s tests are not shown here, since at 1 m/s the fracture is so fast that the developing deformation zone is not visible and only undeformed or already broken specimens can be seen. It appeared that the specimens outside the notch zone showed an overall temperature rise of few degrees. This indicates that in the specimen far away from the notch homogeneous plastic deformation is taking place. A zone with increased temperature was visible ahead of the notch, where large plastic deformation takes place. This zone size decreased with decreasing notch radius. In the sample with the 1 mm notch extreme blunting took place (Fig. 11(a)). The PC/ABS samples with the sharper radii did not blunt as much and their zone size was smaller (Fig. 11(b) and (c)). The deformation zone was divided into two lobes, located symmetrically above and below the fracture plane. The highest temperature was recorded ahead of the notch. This was also observed for pure PC [6].

The recorded maximum surface temperature during 1 m/s SENT tests were determined for PC/ABS and ductile fracturing PC (Fig. 12(a)). The measured maximum temperature decreased somewhat with decreasing notch tip radius for both PC and PB/ABS blend. Although the initiation deformation and the fracture energies decrease with sharper notch radii the observed temperatures are still high and thus the deformations just ahead of the notch are still high.

The thickness of the warmed zone (more than 5 °C) was also measured for both PC and PC/ABS blend (Fig. 12(b)). The zone size decreases with decreasing radii both for PC/ABS and PC. This decrease in zone size indicated that less material could take part in the deformation process when a sharper notch is present in the specimen. The decrease corresponds to the influence of notch radius on initiation

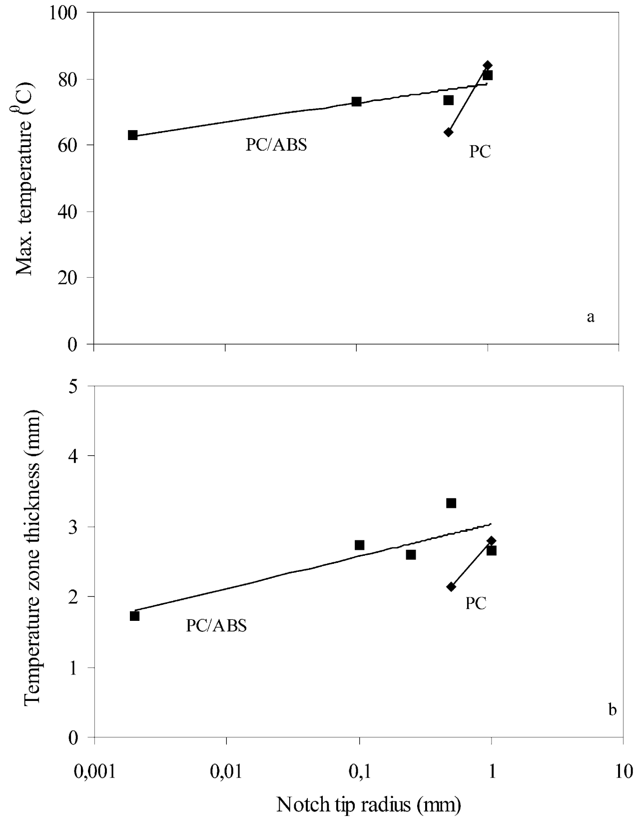

Fig. 12. Influence of notch radius for PC and co-continuous PC/AB tested at 1 m/s and room temperature in SENT: (a) maximum measured temperature; (b) thickness of the plastic deformation zone with at least 5 °C temperature increase.

displacement (Fig. 8(a)), which also showed a decrease with decreasing notch radius. The thickness of the plastic zone for the PC/ABS blend was higher than for pure PC. The presence of ABS in PC apparently leads to delocalisation of deformation. Especially for sharp notches, the deformation zone of the ABS material remains thick.

The presence of ABS in PC results in a reduced sensitivity to notch radius in fracture energy and brittle-to-ductile transition temperature. Maximum temperature and temperature zone size are higher for PC/ABS than for PC, and less dependent on notch radius. The size of the deformation zone and the extend of notch blunting decreased with decreasing notch radii.

4. Conclusions

A concise overview of the influence of notch radius on several factors is given in Table 3. In these semi-ductile materials the notch is blunted before a crack is initiated. The extent of blunting seems to depend on the initial notch radius. The sharper the initial notch tip radius was, the smaller the deformation before crack initiation and smaller the fracture energies were, for both PC and PC/ABS (Fig. 9). In PC the notch tip radius showed a strong

Table 3
Influence of decreasing notch radius on deformation behaviour for PC and PC/ABS 50/50, ABS containing 15% PB. − −: strong decrease, −: decrease, 0 no significant effect, + increase, + + strong increase

	PC	PC/ABS 50/50
Maximum stress	−	−
Initiation displacement	−/+	−
Propagation displacement	−	0
Fracture energy	−/+	−
Brittle–ductile transition temperature	−/+	0
Maximum temperature (IR)	−/+	−
Plastic zone size (IR)	−/+	−

effect on the brittle-to-ductile transition temperature too (Fig. 13). T_{bd} increased with decreasing notch tip radius, especially in the range of 0.5–0.1 mm notch tip radius. A small deviation in notch tip radius or flaw in the notch tip can lead to a much more brittle behaviour. The standard notch tip of 0.25 mm for the Charpy and Izod test is for PC right in the middle of this range and therefore scattered data are often obtained. A deviation from standard notch radius of only 0.01 mm can already lead to a shift in T_{bd} of around 10 °C. This explains the temperature range in which the brittle-to-ductile transition for PC usually takes place.

The addition of ABS to PC greatly reduced the notch sensitivity of PC (Fig. 13). The presence of ABS, or more specific the rubber, relieves the constraint ahead of the notch tip and this results in a brittle-to-ductile transition temperature that is hardly dependent on notch tip radius. The T_{bd} of the blend were only slightly affected by notch tip radius but the fracture toughness decreased significantly with decreasing notch radius. When large notch radii were present, surprisingly, the blend behaved in a more brittle manner than PC.

As was observed with the temperature development in the deformation zone, the size of the zone of PC/ABS decreased with decreasing notch radius (Fig. 9). Although the fracture energy decreased considerably with decreasing notch radius the T_{bd} showed little change. The T_{bd} does not seem to be directly related to the amount of plastic deformation taking place at the T_{bd}.

The extreme sensitivity of PC to sharp defects, like hairline cracks due to ageing, is effectively neutralised by the presence of ABS in PC.

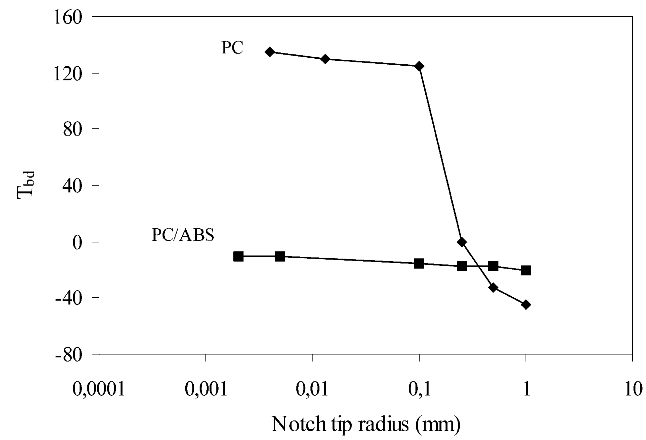

Fig. 13. Influence of notch tip radius on SENT brittle–ductile transition temperature for PC and PC/ABS 50/50, ABS containing 15% PB.

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