Impact-induced fracture mechanisms of immiscible PC/ABS (50/50) blends

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Abstract. This paper presents a study on fracture mechanisms of polycarbonate (PC)/acrylonitrile-butadiene-styrene (ABS) (50/50) blends with different ABS types under a drop weight impact test (DWIT) using a circular sheet specimen. Formation of secondary crack indicated by a stress-whitening layer on the mid-plane of scattered specimens and secondary surface of fracture perpendicular to primary fracture surface were captured under scanning electron microscope (SEM). Although the both blends finally failed in brittle modes, SEM observation showed that their secondary fracture mechanisms were completely different. Observation through the thickness of the etched PC/ABS specimen samples using SEM also clearly showed that PC and ABS were immiscible. The immiscibility between PC and ABS was indicated by presence of their layer structures through the thickness of the blends. It was revealed that layer of ABS structure was influenced by size of rubber particle and this latter parameter then affected microstructure and fracture mechanisms of the blends. Impact-induced fracture mechanisms of the blends due to such microstructures are discussed in this paper. It was also pointed out that the secondary cracking was likely caused by interface delamination between PC and ABS layers in the core due to transverse shear stress generated during the impact test.

1. Introduction
PC/ABS blends have been the subject of many studies and their behaviours have been reported in a numerous published scientific works due to widely application of the blends [1-3]. They have revealed that properties of such ternary blends strongly depend on the structure properties of the components while morphology of the blends depends on blending and injection moulding conditions [4,5]. At an ABS volume fraction of about 50%, for instance, microstructure of the blend shows a co-continuous morphology [4]. Whilst, a moulded material produced from an injection moulding process may

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experience the effect of significant normal stresses, especially at the flow front. Because of such
effect, the obtained moulding has a structure gradient through the thickness, varying also along the
respective flow path [5-11]. Furthermore, characteristics exhibited in the final polymer blend products
depend on the properties of the individual components as well as on the microstructure formed mainly
in the process [12].

Many research works have reported that fracture mechanisms of PC/ABS blends were influenced
by the ABS types [13-15]. In an investigation of correlation between morphology formation and
fracture mechanism of injection-moulded PC/ABS (60/40) blends under Izod impact test, Bärwinkel et
al. [15], for instance, revealed that with dependent on molecular weight of SAN, there was a
correlation between interphase adhesion among PC and ABS layers and fracture mode of the blends.
However, study on influence of the microstructure gradient through the thickness produced after
moulding due to ABS type on fracture mechanisms of the PC/ABS blends under impact has been very
rare.

In a preliminary study using a drop weight impact test, it was pointed out that similarity of failure
mode exhibited by the PC/ABS (50/50) blends at a certain speed eliminated the role of ABS type in
the blends and performance of the blends under such impact has therefore not clearly been understood.
Since microstructure can provide a useful basis for understanding the fracture of materials, this paper
is therefore presented to gain an understanding of the influence of ABS type on the microstructure
gradient through the thickness of PC/ABS (50/50) blends as well as on their impact-induced fracture
mechanisms. The latter type of PC/ABS blends was selected since they have become frequently used
engineering materials combining several advantageous properties of both components.

2. Materials and Experiments

2.1. Materials
Two grade specimens of PC/ABS (50/50) blends containing butadiene rubber of about 10 wt% with
large (≥270 nm) and smaller rubber (≥150 nm) particle size in ABS system, further respectively
called as PA-01 and PA-02, were used. Both of the PC/ABS (50/50) blends used in this study were
supplied by Japan Synthetic Rubber Co. Ltd.

2.2. Experiments
2.2.1. Impact test. Most recent reported experimental studies have been carried out using Izod and
Charpy impact tests on notched specimens [16]. Due to use of such specimens, they only measure
crack propagation energy, not crack initiation energy, and thus, they do not give a ‘true’ indicating
impact resistance of the materials. In this study, impact resistance characteristics of PC/ABS (50/50)
bends were hence carried out on sheet specimen by use of a drop weight impact testing (DWIT)
apparatus outfitted with instruments. The instrumented DWIT apparatus which was used then to study
the fracture mechanism of the materials is similar to that of used by Machmud et al. [17]. Samples of
circular sheet specimen with a diameter of 99.3 mm and initial thickness of 2 mm were used. The
specimen was simply-supported on its bottom surface at 8.5 mm inside around the outer edge of the
sheet. A mass was dropped from a certain height and the striker struck perpendicularly the centre
of the circular sheet specimen. Body of the mass attached to guiding rods brought a total weight of 2.4
kg. Response of the materials was then induced by a hemispherical tip-ended cylindrical striker made
of stainless steel (SS55) with diameter of 20 mm. Three samples for each material were tested at room
temperature (25±2°C) under a rate of 4 m/sec.

2.2.2. Microstructure test. As microstructure plays an important role on characteristics of materials
under impact, it is necessary to characterize their through-thickness microstructures using scanning
electron microscope (SEM). Before performing this work, the sample of the PC/ABS blends was
prepared by cutting the sheet specimen into small pieces (25 mm × 25 mm) with 2 mm thickness using
diamond-tip cutter. After polishing, they were etched then in Potassium Hydroxide (KOH) solution
with a certain concentration for ten days to remove the PC phase. After coating the etched samples with a thin layer of gold of approximately 2 nm in thickness, observation was then carried out using SEM (JEOL JSM-5300T) at accelerating voltage of 15 kV.

2.2.3. SEM observation on fracture. Secondary surface of fracture perpendicular to primary fracture surface and secondary crack formation captured on the mid-plane were found in the both scattered PA-01 and PA-02 samples. For as an example, Figure 1(a) and Figure 1(b), respectively, show the secondary fracture and the secondary formation of crack on PA-01 captured under SEM with low magnification. The secondary fracture mechanisms exhibited by PA-01 and PA-02, however, were completely different. Since there is a correlation between microstructure and fracture exhibited by both blends, it is therefore necessary to characterize such fracture using SEM. After cutting these latter samples into pieces (25 mm × 25 mm) with thickness of approximately 2 mm using diamond-tip cutter and then coating samples with a thin layer of gold of approximately 2 nm in thickness, investigation on the fracture was also carried out using SEM (JEOL JSM-5300T) at accelerating voltage of 15 kV. In situ observation of the primary and the secondary fractures using SEM on the piece of fractured PC/ABS blend samples is illustrated in Figure 2.

![Figure 1. SEM micrograph of: (a) secondary fracture and (b) secondary crack captured on the mid-plane of a PC/ABS blend specimen.](image1)

![Figure 2. In situ observation of primary and secondary fractures using SEM. The shaded part is the observed sample.](image2)

3. Results and discussions

3.1. Through thickness microstructure of PC/ABS (50/50) blends
Through thickness skin-core-skin microstructures of PA-01 and PA-02 are respectively showed in Figure 3(a) and Figure 3(b). Observation of through thickness microstructure of the specimen using SEM captured immiscibility between PC and ABS. Skin of the specimen made of the blends was mostly occupied by ABS. The immiscible PC and ABS could be identified from the combination of PC and ABS layers, especially in the core of the specimen. One also can see co-continuous structure as well as continuous structure formed, respectively, in the skin and the core of both PA-01 and PA-02. Seemingly, such structures in both skin and core did not depend on the size of rubber particles distributed in the ABS systems.

On the core of specimen, structures of PC and ABS layers were also easily distinguished. Although structures on the core formed in the both blends were PC and ABS, composition of PC and ABS represented by both thickness and number of their layers in each blend was not similar. It was therefore revealed that the size of rubber particle influenced the thickness of ABS layer structure formed in the core of the blends. As shown in Figure 3(a), large size of rubber particle led to increase thickness of the ABS layers and hence reduced number of the ABS layers in the core of PA-01. As shown in Figure 3(b), due to its smaller size of rubber particles, PA-02 had a much more number of the ABS layers in the core rather than PA-01. There was thus a contradiction on the composition described by Hamada et al. [7] who indicated that composition of PC was highly distributed in the core.
Figure 3. From the top to the bottom, SEM micrograph views of through-thickness skin-core-skin structures for: (a) PA-01 and (b) PA-02.

3.2. Fracture mechanisms analysis
3.2.1. Primary fracture. Both PA-01 and PA-02 finally failed in brittle modes under the impact test. Primary fracture surface of PA-01 and PA-02 obtained under SEM observation in low magnification is shown in Figure 4 and Figure 5, respectively. Formation of the secondary crack exhibited by each of the blends was also captured on the surface as seen in the both figures. Since formation of the secondary crack was transverse to the structure gradient through the thickness, such crack was likely caused due to interface delamination between PC and ABS layers in the core induced by transverse shear stresses generated during the impact test.

Figure 4. From the left to the right, respectively: secondary crack formation and failure mode with the location of secondary fracture surfaces of the scattered PA-01 as indicated by arrows.

Figure 5. From the left to the right, respectively: secondary crack formation and failure mode with the location of secondary fracture surfaces of the scattered PA-02 as indicated by arrows.

Fracture surface of PA-01 and PA-02 obtained under SEM observation in higher magnification are shown in Figure 6(a) and Figure 6(b), respectively. These latter fracture surfaces were taken from the three locations in the primary fracture surface of the blends as indicated by (1), (2) and (3) in Figure 4 and Figure 5. SEM observation on the primary fracture surface of PA-01 showed that PA-01 actually
failed in mixed modes fracture (semi ductile to brittle modes). As shown in Figure 6(a), the skin of PA-01 exhibited a number of pores (usually voids formed due to rubber cavitation) and failed in semi ductile modes while its core failed in brittle mode. It was indicated that large size of rubber particles played a role in generating such formation of pores in the skin of PA-01. With significant concentration of stresses associated with the pores, increase in load induced crack to initiate in the skin of the blend. Further increase in load led then the crack to propagate fast through the core. As exposed earlier in subsection 3.1, blending ABS with large size of rubber particles into PC led to reduce composition of the ABS in the core of PA-01 (Figure 3(a)). Since composition of ABS determines ductility of the core of PA-01, reducing composition of ABS led the core to fail in brittle mode and finally led the PA-01 to fail in brittle mode too. At this point, it could be pointed out that blending ABS with large size of rubber particles into PC improved ductility of the skin but reduced the ductility of the core of the blends.
Figure 6. SEM micrographs with higher magnification of primary fracture surface for: (a) PA-01 and (b) PA-02.

SEM observation on the primary fracture surface of PA-02 showed that PA-02 actually failed in mixed modes fracture (brittle to ductile modes). As shown in Figure 6(b), the skin of PA-02 with a bit number of pores exhibited brittle modes of fracture while the core with the pores-induced cracking formations failed in ductile mode. With a bit number of pores in the skin of PA-02, it was indicated that increase in load did not significantly deform the smaller size of rubber particles in the skin. Without significant deformation of the rubber, crack initiated fast in the skin and it definitely led the skin to fail in brittle mode. Further increase in load led then the crack to propagate through the core. With a much more number of the ABS layers in the core rather than PA-01 (Figure 3(b)), the core of PA-02 failed in ductile mode as indicated by formation of the shear bands. Presence of pore-induced cracking formation in the core of PA-02 also indicated that the rubber was ever partly deformed. At this point, it could be pointed out that blending ABS with smaller size of rubber particles into PC improved ductility of the core but reduced ductility of the skin of the blends. Such different fracture mechanisms on the skin-core structure of the blends subsequently generated high stresses to take place along the interface of PC and ABS that would finally lead the blends to fail earlier.

3.2.2. Secondary fracture. Figures 7(a) and Figure 7(b), respectively, show the SEM micrographs of the secondary surface of fracture found in the scattered specimen for each of PA-01 and PA-02. Secondary surface of fracture exhibited by the both blends was perpendicular to the primary fracture surface. Such fracture was hence induced by shear stress working at the interface between PC and ABS layers in each blend. Their fracture mechanisms were completely different, however. In the figures, one can distinguish that fracture exhibited by PA-01 was collateral to propagation of crack. In vice versa, fracture exhibited by PA-02 was perpendicular to propagation of crack. Such mechanisms indicated that PA-02 showed a little bit more resistance to the crack propagation rather than PA-01.

Figure 7. SEM micrograph of secondary fracture mechanism for: (a) PA-01 and (b) PA-02. White arrow in each of the micrographs shows direction of the crack propagation.

3.2.3. Energy-based approach. Energy-based approach for identify initiation and propagation of fracture in polypropylene/polyethylene blends as expressed by Tai et al. [16] and Saifullah et al. [18] could be used to explain the difference of fracture mechanisms exhibited by the PC/ABS (50/50) blends. In such approach, an impact force-displacement curve derived from an impact force-time history of tested material obtained under a certain rate of impact was divided into two distinct regions, a region of crack initiation and a region of crack propagation. The absorbed energy in these latter
regions was then characterized by area under the impact force-displacement curve, before and after the maximum value of the impact force, respectively.

The impact force-time history of a PA-01 and a PA-02 tested under 4 m/sec is presented in Figure 8 and Figure 9, respectively. After deriving their impact force-time histories into their impact force-displacement relationships, energy absorbed for both initiation and propagation of crack in PA-01 and PA-02 is then presented in Figure 10. The presented results were the average of three measurements performed on each blend. As shown in Figure 10, crack initiation energy absorbed by PA-01 was 3.86 J, slightly higher than that of absorbed by PA-02 (3.61 J). Whilst, crack propagation energy absorbed by PA-01 was 2.95 J, was slightly lower than that of absorbed by PA-02 (3.07 J). It was therefore indicated that initiation of crack in PA-02 was slightly faster than that of in PA-01 and propagation of crack in PA-01 was slightly faster than that of PA-02. Such results were in correlation with both primary and secondary fracture mechanisms exhibited by both PA-01 and PA-02.

![Figure 8. Impact force-time history of a PA-01 under 4 m/sec.](image)

![Figure 9. Impact force-time history of a PA-02 under 4 m/sec.](image)

![Figure 10. Crack initiation energy ($E_{Init}$) and crack propagation energy ($E_{Prop}$) absorbed by PA-01 and PA-02 under impact.](image)

There was a correlation between size of rubber particles in ABS and composition of the ABS layers in the core of the blends. Both of the latter parameters significantly then contributed to determine
fracture mechanisms and failure modes of the skin-core structures under the impact. However, with such energy absorbed by PA-01 and PA-02, it could be pointed out that at rubber content in ABS of about 10wt%, macroscopically, size of rubber particles in ABS did not significantly affect the toughening in the blends. In overall, PA-01 and PA-02 exhibited a similar mode of failure at their fracture and showed slightly different in toughness since they absorbed 35.5% and 34.8% of the impact energy, respectively, before failure. Such results indicated that fracture energy of both PA-01 and PA-02 did not significantly differ. That is why both PA-01 and PA-02 failed in the similar brittle modes.

4. Conclusions
Fracture mechanisms of immiscible PC/ABS (50/50) blends with different ABS types under a drop weight impact test (DWIT) using a circular sheet specimen have been studied. Observation on through thickness structure of the blends using SEM clearly captured that PC and ABS were immiscible. The immiscibility between PC and ABS could be identified from presence of the PC and the ABS layer structures in skin and core of the specimen. SEM observation also revealed that size of rubber particles in ABS influenced thickness and number of ABS layer structures formed in the core of the blends. Large size of rubber particle led to increase of thickness of the ABS layer and hence reduced number of ABS layer in the core of the blends. In vice versa, smaller size of rubber particle led to reduce of thickness of ABS layers and therefore increase of number of ABS layers in the core of the blends. The number of PC and ABS layers, respectively, represents the composition of PC and ABS in PC/ABS blends. At rubber content of 10wt%, ABS exhibited co-continuous structures in the skin as well as continuous structures in the core of the blends. Such structures formed in both skin and core of the blends did not depend on size of rubber particles in ABS.

Microscopically, there was a correlation between size of rubber particles in ABS and failure mode exhibited by both skin and core of the PC/ABS (50/50) blends. Skin and core of the blends occupied by ABS with large size of rubber particles failed in semi-ductile and brittle modes, respectively. Whilst, skin and core of the blends occupied by ABS with smaller size of rubber particles failed in brittle and ductile modes, respectively. It could be therefore pointed out that blending ABS with large size of rubber particles into PC improved ductility of the skin but reduced ductility of the core of the blends while blending ABS with smaller size of rubber particles into PC reduced ductility of the skin and improved ductility of the core. Such different fracture mechanisms, exhibited by both skin and core of the blends, subsequently generated high stresses to take place along the interface of PC and ABS that would lead the blends to fail earlier. Such early failure of the blends was macroscopically indicated by their brittle fracture under the impact. Size of rubber particle in ABS, therefore, did not significantly play a role in determining failure modes of the blends under impact. At a certain content of rubber, blending ABS with smaller size of rubber particle into PC, even, did not properly work to significantly improve toughness of the blends. In such case, such size of rubber particles in ABS only contributed to influence thickness and number of the ABS layers in the skin-core structures of the PC/ABS (50/50) blends. Composition of ABS represented by both thickness and number of its layers, further, significantly influenced fracture mechanisms of the skin and the core of the blends under impact.

It was revealed that the secondary fracture mechanisms exhibited by the blends were strongly influenced by the type of ABS. Due to different type of ABS, shear stress working at the interface between PC and ABS layers in each blend led the secondary fracture mechanisms of the blends under impact were completely different. Fracture mechanisms of the blend with smaller size of rubber particle showed a little bit more resistance to the propagation of crack rather than that of the blend with large size of rubber particle.

With energy-based approach, it was also revealed that the similar mode of failure at fracture exhibited by both of the blends under impact was due to their similarity in fracture energy.
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