Impact Strength and Failure Mechanisms of PBT/PC Blends

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ABSTRACT

Impact strength of a series of PBT/PC blends was tested at different strain rates. It was found that when fracture occurred under plane strain condition the impact fracture toughness of the PBT/PC blends with strong interface obeyed the rule of mixtures. But when fracture took place under non-plane strain condition, the toughness of the blends was much lower than that predicted by the rule of mixtures and negative blending effect was observed. Further study revealed that the PC domains of the blends are subjected to an additional plastic constraint imposed by the rigid neighboring PBT domains. Under this additional plastic constraint the PC domains have a tendency to undergo brittle fracture. Evidence from microscopic studies supports the failure mechanisms proposed.

1. INTRODUCTION

Development of polymer blends is aimed to achieve property combinations from the individual polymer components, which is not obtainable by any one of the polymer components alone [1-4]. To attain this goal, the microstructure of polymer blends has to be tailored carefully according to the properties of each polymer component. Therefore, an in-depth understanding of the mechanical properties of each polymer component is essential to the design of high strength and high toughness polymer blends. Moreover, this understanding should not be restricted to the knowledge obtained from tests conducted on bulk polymers, but more importantly, it should include information from each polymer component when it is in a blended state. The deformation behavior of a polymeric material in a blended state is generally expected to be different from that observed in bulk state even under identical testing conditions. This is because the size, shape and environment of the polymer are changed drastically after blending with other polymers. Certainly, the effects of testing temperature, strain rate and composition on the deformation behavior of the blend components would also be different to those of the bulk polymers. The important issue is to find out the relationship between the properties obtained from both states so that the deformation behavior of a polymeric material in a blended state can be predicted from the information obtained in its bulk state. The latter aspect has been studied for several decades and is reasonably well understood. Thus, once the correlation is established, tough polymer blends may be designed through proper selection of polymer components, optimum composition and well-controlled microstructure.

The purpose of this work was to investigate the effects of strain rate and stress state on impact fracture toughness of PBT/PC blends. Special attention was placed on the mechanisms involved in the deformation processes of the blends and especially, on the significance of each

component in the blended state. Possible correlation between the properties of PBT and PC in bulk and blended states were discussed with due consideration of the influence of stress state, strain rate and morphology of the blends.

2. EXPERIMENTAL WORK

Charpy impact tests on a series of PBT/PC blends with different compositions were conducted on a Zwick 5102 pendulum impact tester at an impact velocity of 2.93 m/s. The single edge notched (SEN) sample geometry was adopted. Two different sample thicknesses were employed to investigate the effect of stress state on impact toughness of the blends. The dimensions of the specimens were $6.4 \times 12.75 \times 64 \text{ mm}^3$ and $3.2 \times 12.75 \times 64 \text{ mm}^3$, respectively. All specimens were notched at the center of one side with different notch lengths in order to apply the specific essential work of fracture method [5-7]. The impact fracture energy was directly read from the scale on the impact tester during the tests. Transmission electron microscope (TEM) was used to study the failure mechanisms.

3. RESULTS AND DISCUSSION

Fig. 1 shows the variation of impact toughness with PBT percentage for the PBT/PC blends tested with 6.4 mm thick samples at 25°C and 3.2 mm thick samples at -40°C. The experimental results demonstrate that at 25°C the impact toughness of the bulk PBT and PC obtained with 6.4 mm samples are low (the unfilled squares). The fracture of both PBT and PC occurred elastically. Using the same sample thickness, the two PBT/PC blends having a strong interface, i.e. PBT/PC (40/60) and (50/50), obeys the rule of mixtures (RoM). The toughness values of the two blends lie on the additive line between the

toughnesses of the bulk PC and PBT (the broken line). No synergistic effect was found. For the two PBT-rich blends, i.e. PBT/PC (60/40) and (80/20), the toughness values are below the RoM line, i.e. a negative blending effect on toughening was found. The causes of the negative blending effect are not difficult to understand. As discovered by our previous work [4], the PBT-rich blends consist of dispersed PC particles in the continuous PBT matrix, and the interfacial bonding between the PBT and PC is poor. Hence, when a crack propagates in the blends, the dispersed PC particles would act as holes and provide the propagating crack with an easy path. They decrease not only the crack resistance of the blends severely but also result in a significantly smaller effective fracture surface area. Hence a toughness lower than that predicted by the rule of mixtures is not surprising.

When the fracture tests were conducted with 3.2 mm samples at -40°C (the solid diamonds in Fig. 1), it was found that the toughness of the bulk PC increased from 1.31 kJ/m^2 (6.4 mm) to 2.84 kJ/m^2 (3.2 mm). But the toughness of the bulk PBT remained essentially the same as that obtained with 6.4 mm samples at 25°C. The fracture was still elastic for both bulk PBT and PC without noticeable plastic deformation although the toughness of the bulk PC obtained using 3.2 mm thick specimens is higher. Once again, the toughness values of the two blends with a strong interface

Figure 1. Variation of impact toughness of the PBT/PC blends with PBT percentage obtained at two temperatures with two sample thicknesses.

follow the RoM line (dotted line in Fig.1) between the toughnesses of the bulk PC and PBT. As expected, the PBT/PC blend with a poor interface, i.e. PBT/PC (60/40), has an impact toughness lower than that predicted by the RoM line.

When the tests were carried out with same 3.2 mm thick samples at 25°C, the results of the tests, as shown in Fig. 2, display some interesting phenomena:- (a) the toughness of the bulk PC under this test condition is quite high (4.12 kJ/m²), indicating that the fracture occurred under non-plane strain condition; (b) the toughness of the bulk PBT remains unchanged as compared to the data obtained with 6.4 mm samples at 25°C and 3.2 mm samples at -40°C (solid diamond in Fig. 3), (c) the toughness of the blends with a strong interface does not follow the rule of mixture between the PBT and PC at 25°C (the chain line in Fig. 2), instead, it follows the rule of mixtures at -40°C (the broken line in Fig. 3). The impact toughness at -40°C and 25°C for these two PBT/PC blends is essentially the same. This coincidence implies that the PC domains inside the blends at 25°C have a ductility lower than that of the bulk PC at 25°C but close to that of the bulk PC at -40°C. Since the ductility of the bulk PC at 25°C is considerably higher than that at -40°C, it is reasonable to infer that the PC domains inside the blends were subjected to an additional plastic constraint not arising from sample geometry. It is this additional plastic constraint that suppressed the deformation of the PC domains and reduced their ductility.

To find out the reasons for the additional plastic constraint, a comprehensive discussion on the deformation behavior of the PC and PBT under different strain rates and stress states is needed. In Fig. 4, the variation of the static fracture toughness of the PBT/PC blends is plotted against the PBT percentage [4]. When Figs. 1-3 and 4 were studied together, the following strain/stress effects on the fracture behavior of the PBT and PC were revealed:

(1) The toughness of the bulk PC at the strain rate of $\sim 2.45 \times 10^{-3} \text{ s}^{-1}$ (5 mm/min., Fig. 4) is essentially the same as that at the strain rate of $\sim 1 \times 10^3 \text{ s}^{-1}$ (2.93 m/s, Fig. 1,2). This is true for both sample thicknesses although the thinner sample has a higher toughness value. Hence, the fracture toughness of PC is not sensitive to strain rate. The same conclusion can also be found in a more thorough study done by Yee [8].

Figure 2. Variation of impact toughness of the PBT/PC blends with PBT percentage obtained using two sample thickness at room temperature.

Figure 3. Variation of impact strength of the PBT/PC blends obtained using 3.2 mm thick sample at two temperatures.

(2) Contrary to the bulk PC, the fracture toughness of the bulk PBT varies significantly with strain rate. With 6.4 mm thick samples, the fracture toughness of the bulk PBT decreases from 10.40 kJ/m^2 to 1.85 kJ/m^2 when the strain rate changes from $\sim 2.45 \times 10^{-3} \text{ s}^{-1}$ (Fig. 4) to $\sim 1 \times 10^2 \text{ s}^{-1}$ (Fig. 1). A similar trend can also be found in the work done by Hobbs [9]. These results suggest that PBT is a strain rate sensitive material.

(3) Both impact and static fracture toughnesses of the bulk PC obtained with 3.2 mm thick samples are much higher than those obtained with 6.4 mm thick samples, indicating that sample thickness, or the stress state,

has a strong influence on the fracture behavior of PC. In other words, fracture of the PC is sensitive to stress state. The thickness sensitivity of PC was also reported by Fraser [10] and Brown [11].

(4) On the other hand, the impact toughness of the bulk PBT is not sensitive to sample thickness and testing temperature (Fig. 1-3), suggesting that the fracture behavior of PBT is not affected by the stress state because both thickness and temperature change the stress state inside the sample. In summary, PC is a stress state sensitive material but not sensitive to strain rate under the plane stress condition. PBT is a strain rate sensitive material but not sensitive to stress state under impact loading.

Based on the above analysis, possible reasons for the proposed additional plastic constraint on the PC domains may be given as follows. It was revealed previously [4] that the PBT/PC (40/60) and (50/50) blends have a bi-continuous structure. Each PC domain in the blends is surrounded by some adjacent PBT domains. If there was no strong bonding between PBT and PC, when the blends were subjected to high strain rate loading, the PC domains would elongate in the principal stress direction and shrink laterally because they are small in size (hence, in plane stress condition) and are not sensitive to strain rate. However, our experiments showed that there was a strong bond between the two phases. In addition, since the neighboring PBT domains are sensitive to high strain rate, their deformation was suppressed under an impact strain rate and the PBT domains became more rigid. As a result,

Figure 4. Variation of static fracture toughness of the PBT/PC blends with PBT percentage obtained with two sample thicknesses at room temperature.

Figure 5. TEM micrograph taken from an arrested crack tip of an post-impact loaded specimen. Crack tip is sharp and the PC domains (black) crossing the propagating crack were fractured without noticeable plastic deformation.

the PBT domains acted like rigid rods surrounding the PC domains and prevented the PC domains from lateral contraction. In other words, the PC domains are now subjected to an additional plastic constraint from the rigid neighboring PBT domains. This is somewhat similar to the situation of a thin adhesive layer sandwiched between two rigid adherents in which the toughness of the adhesive is reduced below that of bulk adhesive material [12].

If debonding and/or cavitation at the interface between the PBT and PC domains occurs then the high plastic constraint from the rigid PBT domains may be relieved. The lateral deformation of the PC domains may occur readily and toughening through matrix shear yielding and crack bridging of the PC domains would be possible [4]. But, because the formation of the debonding-cavitation consists of three processes, namely, initiation of a craze-like structure at the interface, growth and breakdown of the craze-like structure, it requires sufficiently long time for the processes to complete. As both PBT and PC are rigid polymers, the time needed to complete the processes is expected to be longer than the loading time of the impact process. Hence, the debonding-cavitation mechanism is unable to complete before the stress intensity factor reaches the critical level for brittle fracture to occur. Obviously, if there are no other events to relieve the plane-strain condition, such as rubber particle cavitation, the PC domains will undergo brittle fracture. Fracture energy absorption processes, such as matrix shear yielding and crack bridging of the PC domains, are not expected to happen under this circumstance.

The TEM study on the failure mechanisms of the blends supports the above conclusion. A TEM micrograph (Fig. 5) taken from an arrested crack tip shows that the growing crack tip was sharp and both PC and PBT domains were simply fractured in a brittle manner. The toughening events observed in the static fracture tests, namely, debonding-cavitation between the PBT and PC domains; significant shear yielding of both components and crack bridging of PC domains, are not found in the impact fracture tests, refer to Fig.6.

4. SUMMARY

Impact fracture toughness of the PBT/PC blends has been investigated. The tests were conducted at various strain rates, with different sample thickness. The experimental results and

Figure 6. TEM micrograph taken from an arrested crack tip of a statically loaded specimen. It is clearly seen that the PC domains (black) crossing the propagating crack were plastically deformed and bridging the two fracture surfaces and the growing crazes at the crack tip.

microscopic study reveals that:

(1) Impact toughness of the PBT/PC blends with poor interfacial bonding obtained under all test conditions is lower than that predicted by the rule of mixtures, i.e. a negative blending effect is observed. This is mainly caused by the poor bonding between the PBT and PC phases, which provides the propagating crack with an easy path and reduces the effective fracture surface area.

(2) Impact toughness of the PBT/PC blends with a strong interface is found to obey the rule of mixtures when the tests are carried out under plane strain condition, e.g. using thick samples or under low temperatures. Fracture occurs essentially in the elastic mode and the toughness values of the blends lie on the RoM line between the toughnesses of the bulk PC and PBT obtained under identical test conditions.

(3) However, the impact toughness of the PBT/PC blends with a strong interface does not follow the rule of mixtures when they are tested under non-plane strain condition, e.g. using thin samples or at high temperatures. The toughness values obtained fall below the RoM line between the toughnesses of the bulk PC and PBT. Failure to toughen under this test condition is tentatively attributed to the strain rate sensitivity of the PBT, which makes the PBT domains perform as rigid rods and imposes a high plastic constraint on the PC domains. Under this condition, PC tends to undergo brittle failure because of its high sensitivity to hydrostatic stress.

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