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Material properties

The influence of reactive compatibilization on uniaxial large strain deformation and fracture behavior of polyamide 6 and poly (ethylene-*co*-butyl acrylate) blends

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ABSTRACT

The role of reactive compatibilization on the uniaxial tensile deformation and fracture resistance behavior of polyamide 6 (PA6) and ethylene-*co*-butyl acrylate (EBA) was systematically studied by using the maleated derivative of EBA containing two different MAH graft percentages of 0.49 (EBA-g-MAH$^{0.49}$) and 0.96 (EBA-g-MAH$^{0.96}$) as reactive compatibilizers. In the uncompatibilized PA6/EBA blends, debonding at the polymer/elastomer interface was observed during tensile deformation. At lower EBA concentrations, the interface cavitation resistance is relatively good with higher work of yield in these samples. This interface cavitation has generated extensive matrix shear yielding in the samples during cold drawing after localized necking. At higher EBA concentrations, cavitation resistance was relatively poor, leading to macro-voiding around the elastomer domains, and the stress–strain behavior of the samples showed rubber like deformation. In the compatibilized blends, the high interfacial adhesion achieved by reactive compatibilization prevented interface cavitation and arrested cold drawing of the samples at higher compatibilizer concentration. The essential work of fracture (EWF) method revealed that the compatibilized PA6/EBA blends show much better fracture resistance than the uncompatibilized blends. High interfacial adhesion with finer dispersion of EBA domains induced extensive shear yielding with the formation of thin ligaments during EWF testing in compatibilized blends, which is assigned to be responsible for the higher crack resistance behavior of these blends.

1. Introduction

Toughness of a semi-crystalline polymer can be modified to a much greater extent by blending with an elastomer [1–5]. The macroscopic properties of these blends depend on several key parameters, especially blend composition, size, shape and distribution of the dispersed particles, interparticle distance and the interfacial adhesion between the dispersed phase and the matrix. Since the nature of the modifier and the interfacial adhesion greatly influence the final morphology and the deformation behavior of the material under external loading conditions, significant efforts were made to understand the mechanism responsible for the improvements in toughness [6]. Reactive compatibilization is a preferred route to strengthen the adhesion between the phases and to stabilize the phase morphology. Under external loading conditions, the elastomer domains act as stress concentrators to nucleate local plastic deformation by relieving the hydrostatic pressure by stretching, delamination or internal cavitation, leading to extensive plastic deformations such as multiple matrix crazing [6–8], shear yielding [2,9–11] and crazing with shear yielding [12–15]. The role of the dispersed phase is to induce an overall deformation mechanism rather than a localized one.

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Polyamides have been successfully toughened by incorporating thermoplastic elastomers such as ethylene–propylene rubber (EPR), ethylene–propylene–diene terpolymer rubber (EPDM), polyethylene–octene elastomer (POE) and ethylene vinyl acetate (EVA) by using their maleated derivatives as compatibilizers [3,16–18]. In our previous work, polyamide 6 was toughened by incorporating ethylene-*co*-butyl acrylate (EBA) by using its maleated derivative as a reactive compatibilizer [19]. The influence of the dispersed phase microstructure, particle size, matrix ligament thickness and reactive compatibilization in reducing the interfacial tension between the component polymers and the deformation behavior under impact loading conditions was thoroughly investigated [19].

In this work, we have reported the uniaxial large strain tensile deformation behavior and essential work of fracture (EWF) of the binary and the reactively compatibilized PA6/EBA blends. The deformation mechanisms induced under these loading conditions in the presence and absence of maleic anhydride grafted EBA (EBA-g-MAH) reactive compatibilizer were studied by analyzing their fracture morphology under scanning electron microscopy.

2. Experimental

2.1. Materials

Polyamide, PA6 (Gujlon M28RC, density 1.14 g/cc, melt flow index 28 g/10 min at 230 °C and 2.16 kg load), was obtained from Gujarat State Fertilizers and Chemicals Ltd., Vadodara, Gujarat, India. Ethylene butyl acrylate, EBA (Elvaloy 3427AC, density 0.926 g/cc, butyl acrylate content 27% and melt flow index of 4 g/10 min at 190 °C and 2.16 kg load) from DuPont Industrial Polymers, Wellington, USA, was used as the minor component. EBA-g-MAH containing grafted maleic anhydride content 0.49% and 0.96% (represented as EBA-g-MAH$^{0.49}$ and EBA-g-MAH$^{0.96}$, respectively) prepared by reactive extrusion in a twin screw extruder were used as compatibilizers [19].

2.2. Processing of blends

2.2.1. Compounding in twin screw extruder

PA6, EBA and EBA-g-MAH polymers were first vacuum dried at 80, 60 and 60 °C, respectively, for 6 h. Binary blends and ternary blends at various combinations as shown in Table 1 were prepared in a co-rotating intermeshing twin screw extruder, Model JSW J75E IV-P ($L/D = 36$, $D = 30$ mm), at a screw speed of 240 rpm and temperature profile ranging from 150 to 240 °C from the feed zone to the die zone. The extruded strands were granulated. In order to keep the thermal history similar to that of the blends, the component polymers were also extruded under identical processing conditions.

Table 1
Binary and ternary blend formulations

Binary blends (uncompatibilized)		Ternary blends (compatibilized)	
PA6/EBA (pbw)	Volume fraction of EBA (ϕ_d)	Volume fraction of dispersed phase, $\phi_d = 0.110$	
100/00	0	PA6/EBA-g-MAH$^{0.49}$/ EBA blends (pbw)	PA6/EBA-g-MAH$^{0.96}$/ EBA blends (pbw)
100/05	0.058		
100/10	0.110	100/1/9	100/1/9
100/20	0.198	100/2/8	100/2/8
100/35	0.301	100/3/7	100/3/7
100/50	0.381	100/4/6	100/4/6

2.2.2. Injection molding

The pellets were injection molded after drying for 12 h at 80 °C on an L&T Demag (Model-PFY 40 LNC 4P) machine at a temperature range of 170–260 °C from the feed zone to the nozzle and screw speed of 90 rpm, while keeping the mold temperature constant at 30 °C, to prepare dumbbell shaped tensile specimens.

2.2.3. Compression molding

The pellets were compression molded after drying for 12 h at 80 °C on a compression molding machine (Wabash, Carver Inc., Indiana, USA) at a temperature and load of 260 °C and 5 t respectively, to prepare rectangular specimens of dimensions 70 × 50 × 3 mm for the EWF test.

2.2.4. Tensile properties

Tensile testing was carried out in Zwick universal testing machine model Z010 according to ISO 527-1 test procedure at a cross-head speed of 50 mm/min at 35 °C. Stress–strain curves were recorded until fracture of the specimen.

2.2.5. Morphological characterization

The morphology of the tensile fractured blends was observed by using a Carl Zeiss EVO5O scanning electron microscope (SEM). The blend samples were examined parallel to the tensile direction to study the nature of deformation. The samples were dried and sputter coated with silver prior to SEM examination.

2.2.6. Essential work of fracture (EWF)

The EWF approach has been employed to study the crack propagation resistance of the blends. EWF tests were performed on double-edge-notched tension (DENT) specimens using a Zwick universal testing machine model Z010 at a speed of 1 mm/min. DENT specimens of length 70 mm, width 50 mm and thickness 3 mm with identical notches made on the either side of the specimen along the width exactly at the midpoint of the specimen length were used for the testing. The notching was done in two steps: first a saw cut was made, which was then sharpened by a fresh razor blade dipped in liquid nitrogen. A typical EWF sample used for EWF testing is shown in Fig. 1. Samples with six varying ligament lengths ($l = 10$–15 mm) were prepared in this manner. At least five samples were tested for each ligament length and the load–displacement curve was recorded until fracture of the specimen.

2.2.7. Essential work of fracture approach

The EWF approach has gained popularity recently because of its simplicity when compared to other methods, such as the *J*-integral method or crack tip opening displacement (CTOD) method, for characterizing the crack resistance and toughness of polymers and their blends. The EWF