Available online at www.sciencedirect.com
SCIENCE DIRECT
Polymer 47 (2006) 3505–3519
polymer
www.elsevier.com/locate/polymer

Comparison of fracture behavior of nylon 6 versus an amorphous polyamide toughened with maleated poly(ethylene-1-octene) elastomers

J.J. Huang, D.R. Paul *

Department of Chemical Engineering and Texas Materials Institute, The University of Texas at Austin, Austin, TX 78712, USA

Received 25 January 2006; received in revised form 10 March 2006; accepted 14 March 2006
Available online 3 April 2006

Abstract

The fracture behavior of an amorphous polyamide (Zytel 330 from DuPont), a-PA, and nylon 6 toughened by maleated poly(ethylene-1-octene) elastomers are reported. The deformation mechanisms during fracture were verified by examining an arrested crack tip and the surrounding regions using transmission electron microscopy analysis. a-PA blends show higher levels of impact strength and lower ductile–brittle transition temperatures than nylon 6 blends. Fracture toughness, characterized by both linear elastic fracture mechanics techniques in terms of the critical strain energy release rate, G_{IC}, and the essential work of fracture methodology, i.e. the limiting specific fracture energy, u_o, and the dissipative energy density, u_d, using thick (6.35 mm) samples with sharp notches, depends on ligament length, rubber content, rubber particle size and test temperature. In general, a-PA blends show larger values of u_d than do nylon 6 blends while the opposite is seen for u_o. The amorphous polyamide shows a similar critical upper limit on rubber particle size, or interparticle distance, for toughening as the semi-crystalline nylon 6; thus, it is clear that the crystal morphology around the rubber particles must not be the dominant cause of this critical size scale. The deformation mechanisms involved include cavitation of rubber particles followed by some crazing and then massive shear yielding of the matrix.

Keywords: Amorphous polyamide; Fracture behavior; Essential work of fracture

1. Introduction

We have recently explored toughening of an amorphous polyamide (Zytel 330 from DuPont) using maleated elastomers [1–3]; in part, the motivation for this work was to compare its responses with those of semi-crystalline polyamides like nylon 6 and 66 to gain insights about the role of matrix crystallinity in toughening. These studies have demonstrated that the amorphous polyamide and nylon 6 exhibit similar relationships for room temperature Izod impact strength and the ductile–brittle transition temperature (T_{db}) as rubber particle size is varied over a wide range; however; the amorphous polyamide blends have somewhat higher impact strength and lower T_{db}. The previous results were based on standard notched Izod impact testing of thin specimens (3.18 mm thick) with the standard ligament length and notch radius. It would be useful to compare the fracture behavior of blends based on the two types of polyamides under more severe plane-strain conditions, i.e. thicker (6.35 mm thick) samples with a sharp notch, and varying ligament lengths for different rubber contents and test temperatures. In addition, the deformation mechanisms of toughened blends of this amorphous polyamide are largely unexplored [4]; considerably more literature is available on how the rubber toughened semi-crystalline polyamides (e.g. nylon 6 and nylon 66) deform during fracture [5–17]. The purpose of this paper is to make these comparisons between blends based on the amorphous polyamide and nylon 6. The fracture behavior is examined as a function of rubber particle size, rubber content, ligament length and temperature via instrumented Dynatup impact tests using single-edge notched three-point bend (SEN3PB) specimens. The deformation mechanisms involved are examined in the vicinity of arrested cracks using transmission electron microscopy.

2. Background

Fracture mechanics techniques, traditionally designed for testing metallic alloys, have been employed extensively to characterize fracture behavior and to understand the deformation processes in rubber-toughened plastics [18–27]. Linear elastic fracture mechanics (LEFM) methodologies have been applied to brittle polymeric materials to measure the critical

* Corresponding author. Tel.: +1 512 471 5392; fax: +1 512 471 0542.
E-mail address: drp@che.utexas.edu (D.R. Paul).

0032-3861/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.polymer.2006.03.038

strain energy release rate (G_{IC}) or the critical stress intensity factor (K_{IC}). According to this model, the total fracture energy, U, is related to G_{IC} via the following equation [28,29]

$$U = U_k + G_{IC} t W \phi \quad (1)$$

where U_k is the kinetic energy of the tested specimen after fracture, G_{IC} is the critical strain energy release rate which ideally is a material parameter independent of specimen geometry, t and W are the specimen thickness and width, respectively, and the term ϕ is a function of a/w where a is the ligament length or notch depth given in the literature [29]. Plane-strain conditions are necessary for this model to apply and are ensured only if the ratio of the notch depth to the width, a/W, is less than or equal to 0.6.

While LEFM is effective for describing fracture of brittle polymers, it fails to describe fracture of ductile polymers, such as rubber-toughened blends, because these materials generally do not meet the assumptions of linear elasticity due to extensive plastic deformation surrounding the crack during fracture. Furthermore, the specimen thickness required for ensuring plain-strain conditions exceeds what can be conveniently molded. The J-integral approach [23,30], on the other hand, does not require the assumptions of linear elasticity and is regarded as more appropriate for ductile polymers. However, this methodology involves quasi-static loading and some sophisticated and labor intensive techniques for accurate crack growth measurement. Moreover, the specimen thickness required may still be greater than what can be conveniently made by injection molding.

Mai and coworkers [31–36] have developed a methodology based on Broberg's unified theory [37,38] of fracture to characterize fracture behavior of polymeric materials that is simple to implement, yet offers more detailed characterization than standard notched Izod impact tests. According to this essential work of fracture model (EWF), the total work of fracture during crack growth, W_f, can be partitioned into two components: the essential work of fracture (W_e), associated with the inner fracture process zone and the non-EWF in the outer plastic zone (W_p):

$$W_f = W_e + W_p \quad (2)$$

This model further assumes the EWF is proportional to fracture area and the non-EWF is proportional to the volume of the plastic zone:

$$w_f = w_e + \beta \ell w_p \quad (3)$$

where, w_f is the specific fracture energy, w_e is the specific essential work of fracture, β is a shape factor, ℓ is the ligament length, and w_p is the specific non-essential plastic work. The model assumes that the ligament must be fully yielded prior to crack initiation and, thus, has certain limitations on the ligament length.

Since the yielding and ligament length size criteria of the EWF method proposed by Mai and coworkers may not always be satisfied in the high speed bending configuration used in this study, a different nomenclature is employed here and in previous papers [39–42]

$$\frac{U}{A} = u_o + u_d \ell \quad (4)$$

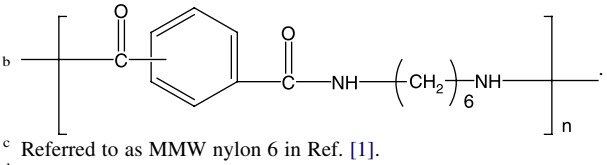
The linear terms in the right hand side are defined as follows: u_o is the limiting specific fracture energy and u_d is the dissipative energy density. Under appropriate conditions, $u_o = w_e$ and $u_d = \beta w_p$.

The EWF approach has been used to analyze both ductile and brittle fractures. However, this approach is found to be more suitable for ductile fractures than brittle ones. The LEFM model which gives the critical strain energy release rate, on the other hand, is used to characterize only the samples failing in a brittle manner. By applying both models, the entire range of fracture behavior is quantified.

Table 1
Materials used

Designation used here	Materials (commercial designation)	Composition	Brabender torque (N m)[a]	Supplier
a-PA	Zytel 330[b]		10.7	DuPont
Nylon 6[c]	B73WP[d]		6.37[e]	Honeywell
EOR	Exact 8201	28 wt% Octene	9.5	ExxonMobil
EOR-*g*-MA-0.35%	Exxelor VA 1840	28 wt% Octene, 0.35 wt% MA	9.2	ExxonMobil
EOR-*g*-MA-1.6%	Exxelor MDEX 101-2	28 wt% Octene, 1.6 wt% MA	6.9	ExxonMobil
EOR-*g*-MA-2.5%	Exxelor MDEX 101-3	28 wt% Octene, 2.5 wt% MA	6.3	ExxonMobil

[a] Measured after 10 min at 240 °C and 60 rpm.

[b] 

[c] Referred to as MMW nylon 6 in Ref. [1].

[d] Formerly Capron 8207F.

[e] Data from Oshinski AJ, PhD Dissertation, The University of Texas at Austin, TX, USA; 1995.