DYNAMIC CONSTITUTIVE FRACTURE BEHAVIOR OF NANOCOMPOSITES

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Summary

Polyester/TiO_2 nanocomposites have been fabricated and an investigation has been conducted to characterize their dynamic fracture constitutive behavior. A relationship between dynamic stress intensity factor, K_I, and crack tip velocity, $\dot{a}$ has been established. As well, the behavior of the nanocomposites has been compared with that of the virgin polyester matrix. Fractographic analysis was conducted to correlate fracture surface characteristics to experimental values. Dynamic photoelasticity coupled with high-speed photography is used to characterize the stress fields near the crack tip and to obtain crack tip velocities. Due to the opaqueness of the nanocomposite materials, the crack tip stress fields are obtained using birefringent coatings. Crack propagation velocities in nanocomposites were found to be 50% greater than those in polyester. Crack arrest toughness in the nanocomposites was 60% greater than in polyester.

Introduction

Dynamic fracture studies often tend to center attention on the characterization of crack initiation and/or propagation, with somewhat less attention paid to run-arrest or crack branching behavior. An understanding of the principles governing these two regimes is nonetheless of great importance, as it lends insight into how the catastrophic failure of materials can be stopped or at the very least subdued. The method of photoelasticity has been employed for many years to conduct dynamic fracture studies in polymers and metals [1-3]. In the case of metals and other opaque materials, successful employment of the photoelastic method has only been possible with the use of birefringent coatings.

Several theories have been advanced to suggest a direct relationship between $\dot{a}$ and K_I. Some of these theories attribute the relationship to strain rate sensitivity, the interaction of inertia and crack tip plasticity, and local heating at the crack tip. In linear elastic brittle solids under small scale yielding, the stress field near the moving crack tip can be represented by a single parameter, the

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stress intensity factor. This fact leads to another theory that suggests a possible dependence of crack velocity on the stress intensity factor [4]. To date, to the best of the authors' knowledge, the dynamic fracture constitutive behavior of nanocomposites via an $\dot{a}$ - K_I relation has never been done.

A multi-parameter series representation of the dynamic stress field surrounding the crack tip, coupled with a least squares method, is used in the analysis of the isochromatic data [5].

Materials

An unsaturated polyester resin and spherical TiO_2 (titania) nanoparticles with an average diameter of 36nm were used as the matrix and filler material, respectively, in the fabrication of the nanocomposites [6]. Polyester specimens were fabricated using a procedure developed by Shukla and Khanna [7].

Specimen Geometry

Modified compact tension (MCT) and single edge notch tension (SENT) geometries were used in this study in order to capture the broad range of velocities encompassing crack arrest to crack branching. The former was used to capture velocities approaching crack arrest values, and the latter higher propagating velocities. Figure 1 shows typical MCT and SENT nanocomposite specimens containing birefrigent coatings. As can be seen from Fig. 1(b), the MCT specimen was made by bonding a Plexiglas sheet to a polyester/TiO_2 nanocomposite sheet. The two-part specimen had to do with the limitation on the amount of nanocomposite material that could be fabricated while still maintaining a good dispersion of particles within the matrix. Crack detection strain gages were bonded near the starter notch to detect the initiation of fracture.

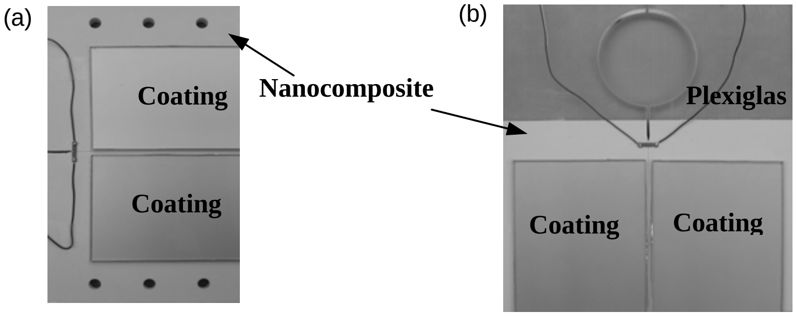


Figure 1. Polyester/ TiO_2 nanocomposite specimens: (a) SENT; (b) MCT.

Birefringent Coatings

Birefringent coatings are generally employed to conduct photoelastic studies on opaque specimens. In this technique, displacements at the specimen/coating interface are transmitted without amplification or attenuation. A split-coating method is employed in this study in order capture isochromatic fringes on the opaque nanocomposite specimens. The coatings were 3mm thick polycarbonate sheets with vacuum deposited aluminum on the back surface.

Photoelastic Analysis

The photoelastic method is based on the stress-optic law that relates the optical properties of the material and the isochromatic fringe order to the stress field components. This relationship is given as:

$$\tau_{max} = \frac{\sigma_1 - \sigma_2}{2} = \sqrt{\left(\frac{\sigma_{yy} - \sigma_{xx}}{2}\right)^2 + \sigma_{xy}^2} = \frac{Nf_\sigma}{2h} \tag{1}$$

where τ_{max} is the maximum in-plane shear stress, σ_1 and σ_2 are in-plane principal stresses, N is the fringe order, f_σ is material fringe value, h is the length of the optical path through the material, and σ_{xx}, σ_{yy}, and σ_{xy} represent the stress fields around a moving crack tip. The stress intensity factor in the specimen is related to the stress intensity factor in the coating by the following relation:

$$K_{Id}^{S} = F_{CR} \frac{E^S}{E^C} \frac{1+\upsilon^C}{1+\upsilon^S} K_{Id}^{C} \tag{2}$$

where E is the Young's modulus, F_{CR} is a reinforcement correction factor, ν is Poisson's ratio, and the subscripts c and s refer to the coating and specimen, respectively. An appropriate reinforcement correction factor is then applied that accounts for the fact that the coating carries a portion of the load, causing the strain on the specimen to be reduced by a certain amount.

Specimen Loading

An INSTRON 5585 apparatus and a crack-line-loading were used to conduct experiments on SENT and MCT specimens, respectively. Specimens were statically loaded to predetermined force values corresponding to initiation stress intensity factor, K_Q. Upon reaching the prescribed load values, crack propagation was initiated by tapping a sharp razor blade on the specimen notch. Once crack propagation was initiated, crack detection gages mounted near the starter notch triggered an electronic circuit that caused a high-speed camera to commence taking a sequence of photographs of the isochromatics.

Photoelastic Setup

High-speed digital imaging from an IMACON 200 camera capable of taking 16 frames at a rate of 200 millions frames per second was coupled with dynamic photoelasticity to capture real-time, full field quantification of the dynamic fracture process. A schematic of the photoelastic configuration used for testing nanocomposite specimens is shown in Fig. 2. For the static and dynamic validations of the coating, an innovative method was used that permitted, in a single experiment, the simultaneous capture of isochromatics on the coating mounted on a transparent polyester specimen, and on the specimen itself.

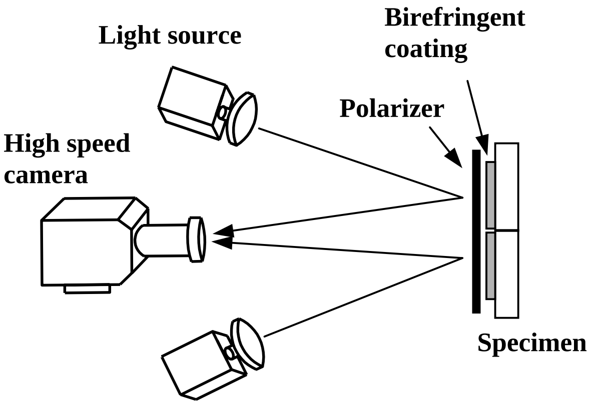
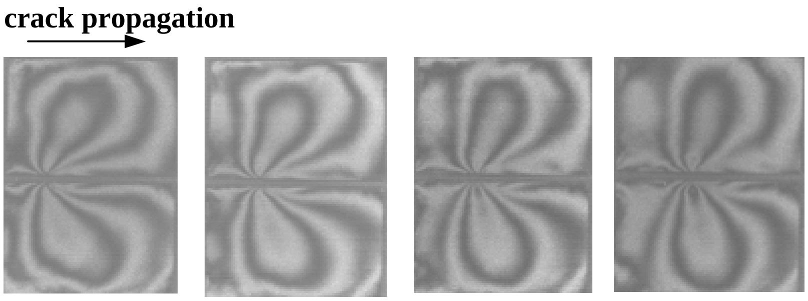


Figure 2. Photoelastic configuration for testing nanocomposite specimens.

Experimental Results

Static and dynamic validations of the photoelastic coating technique were initially conducted to instill confidence in the use of photoelastic coatings in the study of dynamic fracture of nanocomposites. Close agreement between stress intensity factors obtained in the coating and specimen were obtained.

Several experiments were conducted on SENT and MCT specimens in an effort to obtain crack propagation and run-arrest profiles. In the MCT specimens it was observed that the crack did not fully arrest. Instead, the entire arrest event was characterized by incipient arrest, followed by periods of brief re-initiation and subsequent incipient arrest, until such point as the crack traversed the specimen. Typical isochromatic fringes obtained during crack propagation in nanocomposites are shown in Fig. 8.



Frame 2
t = 70μsec

Frame 3
t = 80μsec

Frame 4
t = 90μsec

Frame 5
t = 100μsec

Figure 3. Typical isochromatics obtained using SENT nanocomposite specimens.

The results from the experiments mentioned above were compiled so that a constitutive relationship between crack velocity and dynamic stress intensity factor could be developed for polyester and polyester/TiO_2 nanocomposites. Such relationship is depicted in Fig. 4.

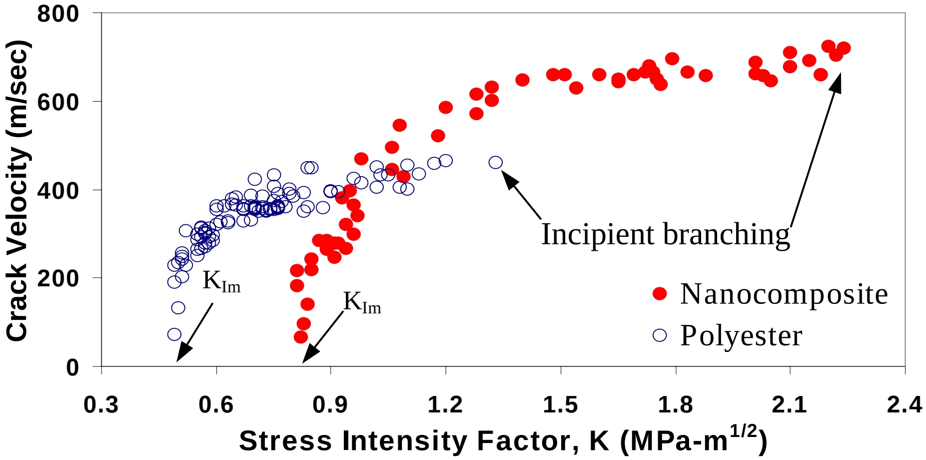


Figure 4. Crack velocity versus K_I relationship for polyester/TiO_2 nanocomposites and polyester.

It can be observed that the $\dot{a}$ - K_I profile consists of three distinct regions. In the low-velocity region (stem), K_I is nearly insensitive to velocity changes. The stem in the nanocomposite profile is more inclined than the nearly vertical stem in polyester, owing to the fact that nanoparticles in the nanocomposites behave as energy sinks. In the intermediate-velocity region, K_I becomes more sensitive to velocity changes. In the high-velocity region, large increases is K_I are required to produce small increases in velocity.

Conclusions

- Birefringent coatings were successfully employed to carry out dynamic fracture photelastic studies on polymer-based nanocomposites.
- A relationship was established between crack tip velocities and dynamic stress intensity factors for polyester and nanocomposites.
- Crack arrest toughness was found to be 0.5 and 0.82MPa-$m^{1/2}$, respectively, for polyester and nanocomposite specimens.
- Crack propagation velocities in nanocomposites were 50% greater than those in polyester.
- Incipient branching values in the nanocomposites were found to be 1.4 to 1.5 times those in polyester.

References

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