Low and High Strain Rate Experiments on Model Kevlar–Epoxy Microcomposites

I. GILATH, S. ELIEZER, Y. GAZIT AND N. BARNEA
Soreq Nuclear Research Center
Yavne 70600, Israel

H. D. WAGNER
Weizmann Institute of Science
Rehovoth, Israel

ABSTRACT: Fracture modes at low and very high strain rate impact experiments were studied using model unidirectional composites. The model microcomposites consist of a set of single fibers embedded in an epoxy film such that the interfiber distance, number of fibers, interface and resin properties can be controlled.

The impact tests at ultra high strain rate were performed using short pulsed laser induced shock waves. To avoid laser ablation of the thin samples, the shock wave was delivered through a thin aluminum foil.

Dynamic experiments were compared with mechanical quasi-static failure tests.

1. INTRODUCTION

TWO NEW EXPERIMENTAL methods were used to investigate model microcomposites for quasistatic and dynamic fracture behaviour.

The fracture behaviour of fibrous composites is characterized by the combination of complex events such as fiber breakage, interface decohesion, matrix failure, and is depending on internal geometrical features of the composite, applied loading, etc. As a direct consequence of the complexity of the damage encountered in real-life composites, only simple geometrical and loading cases may be at first studied. Microcomposite monolayers can demonstrate basic failure modes of reinforced composites.

The simplest geometry for a fibrous composite is a monolayer tape made of equidistant parallel continuous fibers embedded in a matrix (see also Figure 1). The preparation of controlled geometry model composites was possible due to a new method developed by Wagner et al. [1–3].

The quasistatic deformation and fracture modes were tested using a specially designed custom-made miniature tensile testing machine [2]. The sequences of the fracture events were recorded using a colour video camera fitted to a polarised light stereo zoom microscope.

The dynamic tests at ultra high strain rate were performed using short pulsed

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Figure 1. Quasistatic testing of Kevlar 29/epoxy microcomposite.

laser induced shock waves. This new method developed by Gilath et al. [4–8] for metal foils, was applied to study the fracture mode of thin tapes of model microcomposites. To avoid laser ablation of the thin samples, the shock wave was delivered through a thin aluminum foil. Due to the small diameter of the laser beam, high shock wave pressure and very fast energy deposition, the short pulsed laser experiments are the most suitable to study dynamic fracture for small samples such as microcomposites.

The second advantage of laser induced shock wave experiments is the possibility to obtain very close energy density steps at the amplifier stages of the laser system thereby enabling the intermittent monitoring of the various failure modes in the sample.

2. EXPERIMENTAL PROCEDURE

2.1 Microcomposite Preparation and Quasistatic Testing

The matrix used in our experiments was a bisphenol A based epoxy resin (Araldite CY223) mixed with a polyamine hardener (HY956) from Ciba Geigy. The fiber was Kevlar 29 produced by du Pont de Nemours. The single fibers were carefully separated from spools.

Microcomposite monolayers containing eight single fibers (see also Figure 1) in epoxy matrix were manufactured by a two stage procedure [1,3]:

(a) The fibers were accurately positioned using a specially designed single fiber positioner mounted on an optical rail. The alignment was made with fiber guides under a stereozoom microscope. The center to center distance between single fibers is 550 μm. When the positioner is rotated, the distance is reduced to $550 \times \cos\theta$. We used a rotation angle of $\theta = 80°$, and the average final distance between fibers was 93 μm. The fiber array was fastened with cyanoacrylate adhesive on a silicone oiled PVC plate.
(b) Freshly prepared epoxy was poured on the fibers and a second PVC plate was then placed on top and a pressure of 5 KPa was applied for a few days. The mold was opened and samples were cut to size.

The testing of mechanical properties was performed using a miniature tensile testing machine with a load cell of 20 kg. The force was measured with an accuracy better than 3 gr via digital amplifier and an analog recorder. The single fibers were tested in an Instron machine.

The fiber content of the first generation of microcomposite monolayers used in this work was low, and the experimental results for Young modulus and strength followed the rule of mixtures.

2.2 The Laser System and Dynamic Tests

The Advanced Laser Amplifier Design Integration System at Soreq N.R.C. is capable of delivering 7.5×10^{-9} seconds, up to 80 joule pulses in the 1.06 μm wave length. The focused beam intensity on the target is up to 10^{14} watt/cm^2, corresponding to ablation pressures of the order of about one Mbar in aluminum.

Lower pressures can be obtained at lower irradiances and larger laser spots, by moving the target out of focus. To avoid laser ablation of the thin microcomposite samples, the laser induced shock wave was delivered through a 300 μm aluminum foil. The thin tape of microcomposite was therefore directly cast on the aluminum foil and the laser pulse was delivered to the other free side of the foil.

A 2 and 3 mm laser spot diameter was used for energy deposition. This large laser spot ensured one dimensional shock wave conditions [7], necessary to use our one dimensional laser–matter interaction code for shock wave pressure estimation.

The damage transmitted to the microcomposite was always in the form of a circular spot, equal to the laser beam spot. This fact demonstrates the planarity of our shock wave experiments and also the lack of side effects.

The following values were measured:

(a) The energy density necessary to lift the epoxy film from the aluminum support
(b) The energy density necessary to induce damage in epoxy film when reinforcement is undamaged
(c) The energy density for complete rupture of epoxy and fibers in microcomposite

3. RESULTS

The mechanical properties in quasistatic conditions of single components and microcomposites are presented in Table 1. Since the failure strain of the epoxy is slightly lower than that of Kevlar 29, the probability of having fiber breaks before matrix (or interface) failure is very low, as indeed observed.

For our low volume percent of fibers in matrix, the rule of mixture gives a good description of the measured data which demonstrates the good quality of the microcomposites.

The sequence of photographs in Figure 1 demonstrates typical failure process in Kevlar 29/epoxy microcomposites for eight single filaments. The crack develops from a large matrix edge flaw and approaches the first fiber where debonding occurs.

After penetrating the fiber rich zone via successive debonding events, the crack

Table 1. Mechanical properties of single fiber, matrix and microcomposite.

Material	Young Modulus, E (GPa)	Failure Strain, %	Strength [MPa]
Kevlar 29	58.9	4.0	2640
CY223/HY956	2.0	3.0	31
8 fiber monolayer	2.8	3.2	65

Table 2. Energy densities and pressures obtained in pulsed laser experiments.

Experiment	Energy Density Delivered, J/cm²	Pressure in Aluminum at Interphase, kbar (Simulation)	Pressure Transmitted to Epoxy, kbar
A	75 ± 10	9	3.5
B	206 ± 10	15	5.7
C	300 ± 10	20	7.6

growth speed increases till catastrophic failure occurs in the microcomposite. More details on this can be found in Reference [2].

In laser impact experiments, the threshold laser energy densities were measured to obtain epoxy-foil detachment from the aluminum support (see experiment A, Table 2), epoxy-foil rupture (see experiment B) and microcomposite failure (see experiment C). When a shock wave passes through a laminate (aluminum and epoxy) with different acoustic resistances (impedances) the transmitted and reflected shock wave must be accounted for. The impedances $p.c$ (p is density and c is the sound velocity) is known for aluminum and epoxy. The transmitted pulse to the second material (epoxy) will be accordingly only about 38%.

Results are summarized in Table 2.

The pressure needed to detach the epoxy foil from the aluminum support is substracted from the pressure necessary for the foil and microcomposite failure. The net values obtained at ultra high strain rate are as follows:

100 μm epoxy foil failure at 2.2 ± 0.5 kbar

100 μm microcomposite tape failure at 4.1 ± 0.5 kbar

In Figure 2 a circular hole in epoxy is shown, corresponding to experiment B in Table 2. The poor quality of the picture is due to surface morphology of rolled aluminum as seen through the thin transparent epoxy film.

In Figure 3 the microcomposite failure can be seen (see experiment C in Table 2).

4. CONCLUSION

A new approach has been presented to study composite properties starting from model microcomposites. The microcomposites were tested in quasistatic tensile tests and also in dynamic ultra high strain rate conditions. The dynamic tests are still preliminary and need further investigation.

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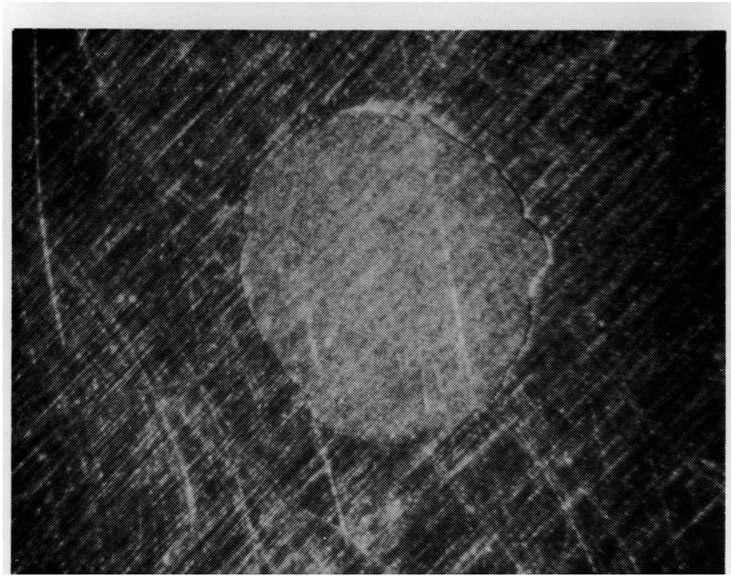

Figure 2. *Epoxy foil failure in dynamic experiments (× 15).*

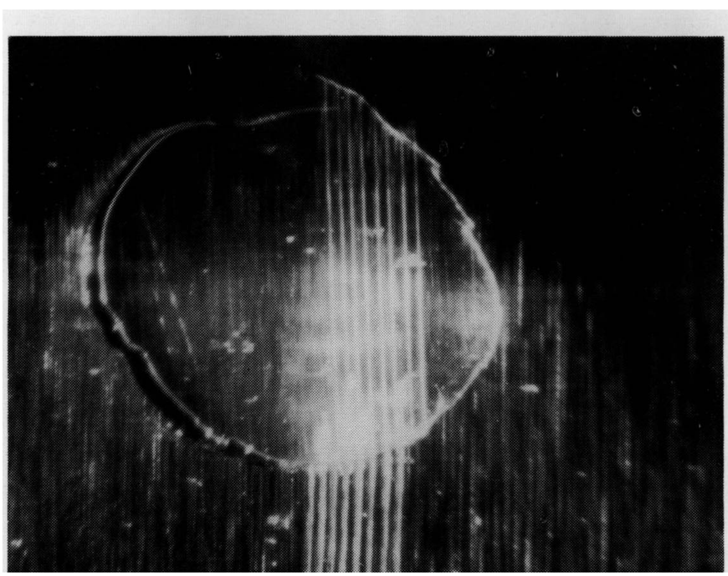

Figure 3. *Microcomposite failure in dynamic experiments (× 20).*

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