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Dynamic Shear Behavior of Alumina-Filled Epoxy

MASTER

Laurence S. Costin

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Dynamic Shear Behavior of Alumina-Filled Epoxy*

L. S. Costin
Sandia National Laboratories**
Albuquerque, New Mexico 87185

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Abstract

Thin-walled tubular specimens of alumina-filled epoxy were loaded in torsion at a strain rate of approximately 10^3 s^{-1} using a stored-torque Kolsky bar. In addition to measuring the time resolved shear stress and shear strain in the specimen, the axial stress generated by the dilation of the material during shear deformation was also obtained as a function of time. Tests were conducted at room temperature and at -60°C . At room temperature, a moderate amount of plastic deformation occurred before failure. Material dilation was associated with the plastic flow. At -60°C , there was a marked increase in failure stress over the failure stress at room temperature. However, little or no plastic deformation or dilation occurred before failure.

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Table of Contents

	<u>Page</u>
Introduction	5
Experimental Procedure	5
Results	10
Summary and Conclusions	22
References	23

List of Tables

Table 1: Summary of Dynamic Test Results	19
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List of Figures

Figure 1: Photograph of specimens	6
Figure 2: Schematic diagram of Kolsky bar	8
Figures 3-10: Results of dynamic shear test on alumina-filled epoxy. Specimen number and test conditions are given on each figure	11-18
Figure 11: Post-test photograph of specimen #1. Fragments of the specimen gage section are in the foreground	21
Figure 12: Post-test photograph of specimen #4, tested at -60°C	22

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L. S. Costin
Sandia National Laboratories
Albuquerque, New Mexico 87185

Introduction

Explosively driven power supplies are used in weapon systems to provide a one-time, high rate burst of energy to power neutron generators. These power supplies consist of a ferro-electric element encapsulated in an alumina-filled epoxy potting compound. A complete understanding of the dynamic response of the encapsulant is a very important element in developing a predictive capability for power supply performance.

In this report, the intermediate rate dynamic behavior of an alumina-filled epoxy potting compound is examined. Dynamic tests at a strain rate of approximately 10^3 s^{-1} were performed using a stored-torque Kolsky bar. Tests were conducted at room temperature and at -60°C . The purpose of these experiments is to add to the data base of material behavior under a variety of loading conditions and strain rates which can be used to verify a recently proposed constitutive model (1). This model has been very successful in describing previous shock wave results. However, for completeness, the model should be compared to data generated by a variety of techniques and over a range of strain rates.

Experimental Procedure

Thin-walled tubes of alumina-filled epoxy, such as those shown in Figure 1, were loaded at a nearly constant strain rate using the torsional

Figure 1: Photograph of specimens.

Kolsky bar shown schematically in Figure 2. The specimens used in this test series were machined from a cylindrical casting of alumina filled epoxy. As shown in Figure 1, the specimens are thin walled tubes with integral flanges at each end. The flanges are acoustically impedance matched to the Kolsky bars and are used for cementing the specimen in place. The nominal specimen dimensions are 4.0 mm gage length with a radius of 8.5 mm and a thickness of 1.0 mm.

Since a complete description of the apparatus has been given by Lipkin and Jones (2), only a brief account need be given here. Referring to Figure 2, the sudden opening of the clamp at B releases the torque stored in the input bar between A and B. The torsional pulse propagates from the clamping point and interacts with the specimen which is bonded between the input and output bars at point C. The wave interaction at the specimen results in a portion of the input pulse being transmitted through the specimen with the remainder being reflected back into the input bar. Strain gages at D and E sense the incident, reflected and transmitted pulses which are recorded with a digital oscilloscope. These time-resolved stress pulse measurements are then used to calculate the stress-strain history of the specimen. Using analysis paralleling that of Kolsky (3) for the compressional bar, it can be shown that the stress (τ) and strain rate ($\dot{\gamma}$) in the specimen are related to the incident and transmitted torque histories, $T_1(t)$ and $T_2(t)$:

$$\tau(t) = \frac{T_2(t)}{2\pi r_h^2} \quad (1)$$

$$\dot{\gamma} = \frac{r}{l} \frac{2}{\rho J c} (T_1 - T_2) \quad (2)$$

Figure 2: Schematic diagram of Kolsky bar.

$$\gamma(t) = \frac{2r}{\ell \rho J c} \int_0^t (T_1 - T_2) dt \quad (3)$$

where r , ℓ and h are the mean radius, the gage length, and the wall thickness of the thin-walled specimen, respectively (Figure 1). The product $\rho J c$ is the torsional impedance of the elastic bars where ρ is the density, J is the polar moment of inertia, and c is the shear wave velocity. The strain rate of the test is set by adjusting the magnitude of the input pulse T_1 and the total strain to which the specimen is subjected is independently controlled by adjusting the initial pulse length (clamping distance A-B).

In addition to the shear gages used to record the incident and transmitted pulses, two sets of axial strain gages were also employed (Figure 2). As the specimen is loaded torsionally, it may tend to expand or dilate axially. In most brittle materials this is due primarily to the nucleation and growth of microcracks. However, in alumina-filled epoxy, a second mechanism is also operative: alumina grains sliding over one another during plastic flow result in a dilation of the material as it is sheared. Since the specimen is sandwiched between two bars, it cannot expand freely. Thus, an axial wave is generated by the inertial confinement force exerted by the ends of the bars. As the specimen begins to fail, relative rotation of the specimen ends is accommodated by the formation of large cracks. At this point, the response of the specimen is controlled by a mechanism wherein the saw tooth edges of the fractured tube slide over one another (4). This also results in an axial wave being generated. Thus, axial waves generated before failure are indicative of material dilation whereas axial waves accompanying failure are indicative

of a brittle failure mode in which large tensile cracks are formed at 45° to the applied shear direction. Any axial waves generated during the test were recorded so that a comparison between axial and shear behavior could be made.

In half of the tests a special set of end constraints was used. These end pieces are placed between the ends of the bars and the specimen flanges. Their purpose is to decrease the axial stiffness of the bar system and, thus, allow the specimen to expand axially with greatly reduced resistance. The end pieces are designed so that they have the same torsional impedance as the bar but are soft axially. It has been shown that reducing the axial constraint results in the specimen failing at a somewhat lower shear stress due to the fact that axial loads are not present to help hold fracture surfaces together (2,4). Thus, the use of the soft end pieces helps to better define the pure shear failure strength in brittle materials.

To achieve test temperatures below nominal room temperature, an insulated box is placed around the central portion of the bar system containing the specimen. A controlled flow of liquid nitrogen is used to cool the specimen with the temperature being measured by a thermocouple attached to the specimen flange. The specimen is allowed to set at the test temperature for at least fifteen minutes prior to testing in order to allow thermal equilibrium to be established.

Results

The results of the Kolsky bar tests are presented in Figures 3 through 10 and are summarized in Table 1. Each of the figures presents the results of one test under the conditions given at the top of the figure. In each figure, three quantities are presented, each as a function of the shear

Figures 3-10: Results of dynamic shear test on alumina-filled epoxy. Specimen number and test conditions are given on each figure. $\sigma(A1)$ and $\sigma(A2)$ are the axial stresses measured at the two gage stations shown on Figure 2.

Figure 4

Figure 5

Figure 6

ALUMINA-EPOXY SPECIMEN #6

Figure 7

Figure 8

Figure 9

Figure 10

Table 1. Summary of Dynamic Test Results

<u>SPEC #</u>	<u>END COND.</u>	<u>T °C</u>	<u>$\dot{\gamma}_c$ s⁻¹</u>	<u>γ_c</u>	<u>τ_c MPa</u>
1	FIXED	25	400	0.052	108
2	FIXED	25	550	0.060	114
4	FIXED	-60	150	0.030	134
5	FIXED	-60	370	0.025	136
6	SOFT	24	480	0.030	105
7	SOFT	24	500	0.040	107
8	SOFT	-60	200	0.028	140
9	SOFT	-60	150	0.035	130

Note: τ_c , $\dot{\gamma}_c$ and γ_c are the stress, strain rate and strain at the failure point.

strain in the specimen: shear stress, shear strain rate, and the axial stress in the specimen tube (measured at two different gage stations) resulting from dilation and failure.

In the tests at 25°C with the standard bar configuration (fixed ends), the deformation is nonlinear after about 30 MPa shear stress (Figures 3 and 4). Axial stress begins to build up at about 0.025 strain, well before the peak shear stress is achieved at 0.05 shear strain. This indicates that the specimen is trying to expand axially while being deformed in shear. At 0.05 to 0.06 strain there is a sharp drop in the shear stress indicating that brittle failure is beginning. Because of the axial stress imposed by the end conditions, the shear stress does not drop off as rapidly as one would expect for a brittle failure. Comparing Figures 3 and 4 with 7 and 8, it is apparent that the end conditions have some effect on the shear stress-shear strain behavior. With axially soft ends, the specimen can expand to a certain extent before axial stress begins to build. This results in failure beginning at a somewhat lower strain than with fixed end conditions (Table 1). In addition, the failure stress is slightly reduced when the axial constraint is lessened. Note that in Figures 7 and 8 the axial stress is not detected until failure occurs.

The tests conducted at -60°C (Figs. 5, 6, 9 and 10) show a marked increase in failure stress over those at 25°C as well as a more nearly linear behavior up to the failure point. Even with the fixed end conditions, axial stress was not detected until failure.

The dominant failure mode in all tests was brittle fracturing. For the tests at 25°C, a plastic bag was placed around the specimen so that the pieces resulting from the fragmentation of the specimen could be collected. Figure 11 shows the post-test condition of specimen #1. The

Figure 11: Post-test photograph of specimen #1. Fragments of the specimen gage section are in the foreground.

fracture surfaces on the remaining portion of the tube still attached to the flanges have a characteristic saw-tooth appearance. This arises because the principal tensile direction is at 45° to the tube axis. Thus, even though the tube is deformed in shear, it fails along planes of maximum tensile stress. Failure at -60°C occurred by the same mode except that there were far fewer fragments (Figure 12) indicating that the fracture propagation velocity is greater at -60°C than at 25°C . A greater crack velocity allows cracks to intersect more quickly resulting in fewer and larger fragments.

Summary and Conclusions

Dynamic torsional tests were performed on thin-walled tubes of alumina-filled epoxy at two temperatures, 25 and -60°C. The nominal shear strain rate during the tests was approximately 10^3 s^{-1} . At room temperature, a moderate amount of plastic deformation and dilation was observed to occur prior to failure. At -60°C, the failure strength was significantly greater than at 25°C and no dilation prior to failure was observed. The failure mode in all tests was fracturing along planes of maximum tension at 45° to the specimen axis.

Figure 12: Post-test photograph of specimen #4, tested at -60°C.

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