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Elevated Temperature Ballistic Impact Testing of PBO and Kevlar Fabrics for Application in Supersonic Jet Engine Fan Containment Systems

J. Michael Pereira, Gary D. Roberts, and Duane M. Revilock
Lewis Research Center, Cleveland, Ohio

November 1997

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ELEVATED TEMPERATURE BALLISTIC IMPACT TESTING OF PBO AND KEVLAR FABRICS FOR APPLICATION IN SUPERSONIC JET ENGINE FAN CONTAINMENT SYSTEMS

J. Michael Pereira, Gary D. Roberts, and Duane M. Revilock, Jr.
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

Ballistic impact tests were conducted on fabric made from both Poly(phenylene benzobizoxazole) (PBO) and Kevlar 29 which were selected to be similar in weave pattern, areal density, and fiber denier. The projectiles were 2.54-cm- (1-in.-) long aluminum cylinders with a diameter of 1.27 cm (0.5 in.). The fabric specimens were clamped on four sides in a 30.5-cm- (12-in.-) square frame. Tests on PBO were conducted at room temperature and at 260 °C (500 °F). A number of PBO specimens were aged in air at 204 and 260 °C (400 and 500 °F) before impact testing. Kevlar specimens were tested only at room temperature and with no aging. The PBO absorbed significantly more energy than the Kevlar at both room and elevated temperatures. However, after aging at temperatures of 204 °C (400 °F) and above, the PBO fabric lost almost all of its energy absorbing ability. It was concluded that PBO fabric is not a feasible candidate for fan containment system applications in supersonic jet engines where operating temperatures exceed this level.

INTRODUCTION

The fan containment system in a jet engine is designed to prevent a fan blade from penetrating the engine nacelle in the event that the blade or a portion of the blade separates from the rotor during operation. The systems are generally classified as being "hardwall" or "softwall," depending on the means used to contain the blade. Typical hardwall systems consist of a metal case surrounding the fan rotor; that case is thick enough to prevent penetration. Softwall systems generally consist of an impact-resistant dry fabric wrapped around a relatively thin metal fan case. In the latter systems the major impact resistance comes from the fabric rather than the metal case. The systems may also include a honeycomb sandwich structure between the fabric and the metal case to provide extra stiffness and a region for the fan blade to "nest" or be captured during the impact event. In large turbofan engines metal containment systems can weigh as much as 250 kg (550 lb). Soft containment systems can be significantly lighter, providing a weight savings of 20 to 25 percent (Stotler, 1979).

All softwall containment systems in current commercial jet engines use the aramid fiber Kevlar (E.I. du Pont de Nemours and Company, Wilmington, DE). Kevlar has excellent impact properties and cutting resistance which makes it attractive for fan containment systems in subsonic engines, as well as for other applications such as personal body armor. However, because the properties of Kevlar degrade at elevated temperatures, it is not a suitable material for use in supersonic engines where temperatures in the fan section are expected to exceed 200 °C (400 °F). Recently, a relatively new fiber known as Poly(phenylene benzobizoxazole), or PBO (Dow Chemical Company, Midland, MI), has become available in small quantities. Fabric woven from this fiber has shown good impact properties in body armor applications as well as for jet engine turbine disk containment (Pepin, 1993). In addition to its good impact properties, the fiber has shown good thermal stability (Denny, Goldfarb, and Solaski, 1989). The objectives of this study were to measure the ballistic impact properties of PBO fabric at room and elevated temperatures and determine the effects of aging on its impact performance.

METHODS

Ballistic impact tests were conducted on PBO and Kevlar 29 fabrics that were selected to be similar in weave pattern, areal density, and fiber denier. The PBO fabric was a plain weave material (44-ends/in., 500-denier continuous filament fibers with an areal density of 203 g/m^2 (6 oz/yd^2)). The Kevlar 29 fabric was a plain weave material (48-ends/in., 400-denier fibers with an areal density of 170 g/m^2 (5 oz/yd^2)). Test specimens measuring 38 cm (15 in.) square were cut from the fabric. For the ballistics test a single specimen was clamped on the four sides in a 30.5-cm (12-in.) square fixture impacted by a projectile accelerated by the release of compressed helium in a gas gun. PBO specimens were tested at room temperature and at 260 °C (500 °F). The Kevlar specimens were tested only at room temperature. In addition, a number of PBO specimens were aged in air at 204 and 260 °C (400 and 500 °F) for 3 and 6 months, respectively. A limited number of specimens were tested after aging.

The projectiles used in these tests were 2.54-cm- (1-in.-) long 6061-T6 aluminum cylinders with a 1.27-cm (0.5-in.) diameter. A radius of 0.8 mm (0.0032 in.) was machined on the edge of the impacting face. The gas gun consisted of a pressure vessel with a pressure capacity of 10 MPa (1500 psi) and a volume of 2250 cc (140 in.^{3}), connected via a high-speed electric relay valve to a stainless steel hollow barrel approximately 2 m (6 ft) long (fig. 1). The barrel had an outside diameter of 2.54 cm (1 in.) and an inside diameter of 1.28 cm (0.505 in.). Helium was used as the propellant. The velocity of the projectile prior to impact was measured as it exited the barrel by the interruption of two laser beams a known distance apart.

The fabric specimens were heated by using an array of quartz lamps radiating upward and reflecting off of an aluminum foil reflector to heat the back of the specimen as shown in figure 1. The post-impact velocity of the projectile was measured by commercial light screens after the projectile penetrated the foil reflector. It was assumed that the reflector produced a negligible change in the velocity of the projectile. The temperature of the specimen was measured by using an infrared pyrometer focused on the impact side of the specimen. Prior to impact testing, scans were conducted to determine the temperature distribution in the specimens. The temperature was recorded at a grid of points 5 cm (2 in.) apart in the vertical and horizontal directions. Generally, within ±10 cm (±4 in.) of the center, the temperature of the specimen remained relatively uniform. At a nominal temperature of 260 °C (500 °F) the temperature in this region was typically within ±8 °C (15 °F), or 3 percent of the nominal. Near the corners of the specimens, the temperature was as much as 30 °C (54 °F) lower than the nominal.

The relative ballistic performance of PBO and Kevlar 29 at room temperature and PBO at an elevated temperature was evaluated by comparing the velocity required to penetrate the fabric. This velocity was determined by plotting the projectile exit velocity as a function of the impact velocity. An empirical relationship was fit to the data for cases where penetration occurred by making the assumption that the energy absorbed by the fabric was independent of velocity; that is,

$$\frac{1}{2}mv_i^2 - \frac{1}{2}mv_o^2 = \frac{1}{2}mu^2 \tag{1}$$

or

$$v_o = \sqrt{v_i^2 - u^2} \tag{2}$$

where m is the mass of the projectile, v_i is the impact velocity, v_o is the exit velocity, and u is a constant. When the exit velocity is zero, u corresponds to the velocity required to just penetrate the fabric v_p. Values for the penetration velocity for each of the fabric systems were determined by performing a least squares fit of equation (2) to the impact data for that system.

While the Kevlar 29 and PBO fabric weaves were similar, it was not possible to obtain fabrics with exactly the same areal density and fiber denier. The Kevlar 29 (with an areal density of 170 g/m^2 (5 oz/yd^2)) was somewhat lighter than the PBO (with a density of 203 g/m^2 (6 oz/yd^2)). Therefore, test results of the two fabrics could not be directly compared. However, results of impact tests on Kevlar fabrics using standard fragment simulators indicate that the energy absorbed by the fabric is proportional to the fabric areal weight (Figucia, 1980; Cunniff, 1992). To compare the two systems, therefore, the amount of energy absorbed by the Kevlar E_{abs} in the current study was scaled by the ratio of areal densities; that is,

$$E'_{abs} = \frac{\rho_1}{\rho_2} E_{abs} \tag{3}$$

where E'_{abs} is the scaled energy absorbed by the Kevlar, ρ_1 is areal density of the PBO, and ρ_2 is the areal density of the Kevlar. This led to the following modified empirical relationship for the Kevlar 29:

$$v'_o = \sqrt{v_i^2 - 1.2u^2} \tag{4}$$

RESULTS

The unaged PBO fabric was able to absorb greater energy at room temperature than either the PBO specimens at elevated temperature or the Kevlar 29 specimens at room temperature (fig. 2). The elevated temperature PBO performed better than the room temperature Kevlar. The data points falling on the curve in figure 2 correspond to impacts in which penetration did not occur; hence all of the energy was absorbed by the fabric. The maximum energy absorbed was 132, 92, and 50 J (97, 68, and 37 ft-lbf), respectively, for the room temperature PBO, elevated temperature PBO, and room temperature Kevlar. Scaling of the energy absorbed by the Kevlar to account for its lower areal weight (eq. (3)) increased the predicted maximum energy for an equivalent weight Kevlar to 60 J (45 ft-lbf).

A qualitative assessment of the fabric specimens indicated that the damage in the Kevlar fabric appeared to be more localized than in the PBO. In PBO specimens in which penetration had occurred, permanent deformation was evident over a relatively large area of the specimen.

The general nature of the results shown in figure 2 is similar to data in the literature (Cunniff, 1992) where it is shown that the energy absorbed by the fabric increases as the projectile velocity is increased until the penetration velocity is reached, after which there is an initial decrease in the absorbed energy. As the penetration velocity increases further, the absorbed energy may either decrease further, remain constant or begin to increase again. As a first approximation for the purpose of deducing a penetration velocity from the data, it was assumed that, for cases where penetration occurred, the absorbed energy was independent of the impact velocity. This assumption was the basis for the empirical relationship of equation (2).

The exit velocity as a function of impact velocity for the three test series is shown in figure 3. In this figure the straight line represents the limiting case where no energy is absorbed by the fabric. For a given impact velocity the exit velocity was lowest for the room temperature PBO and highest for the Kevlar 29. The figure shows a reasonably good fit between the data and the simple empirical function of equation (2). The penetration velocity v_p was taken to be the intersection of the empirical curve with the ordinate. The penetration velocities were found to be 155, 133, and 93 m/sec (509, 436, and 305 ft/sec), respectively, for the room temperature PBO, elevated temperature PBO, and room temperature Kevlar.

The empirical curves are shown in figure 4 with the curve for Kevlar scaled to correct for the lower areal weight. Again, in this figure the straight line represents the limiting case where no energy is absorbed by the fabric. The scaled relationship increased the predicted penetration velocity to 102 m/sec (335 ft/sec). Also shown in figure 4 are the results for three impact tests on aged PBO specimens, one aged for 3 months at 204 °C (400 °F), the second aged for 6 months at the same temperature, and the third aged for 6 months at 260 °C (500 °F). It is clear that there is a significant reduction in energy absorption in the aged specimens.

CONCLUSIONS

Unaged PBO has excellent impact energy absorbing characteristics. Its performance was somewhat degraded at elevated temperature. At 260 °C (500 °F) it was able to absorb approximately 70 percent of the energy that the room temperature fabric could absorb. However, both at room temperature and at 260 °C (500 °F), it was significantly better than a similar weight Kevlar fabric. It should be noted that, while steps were taken to scale the Kevlar results to a higher areal density fabric, a direct comparison of equal areal density and fiber denier fabrics was not made because of the constraint of production specifications of each fiber.

While PBO appears to be an excellent material for impact energy absorption, its performance is significantly reduced after aging at temperatures of 204 °C (400 °F) or above. This material, therefore, is not a feasible candidate for a fan containment system in supersonic jet engines where temperatures exceed this level.

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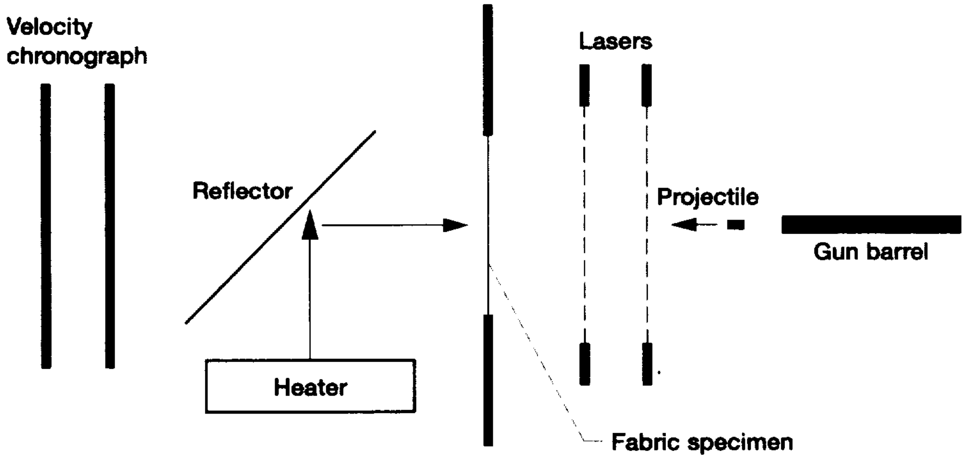

Figure 1.—Impact test facility.

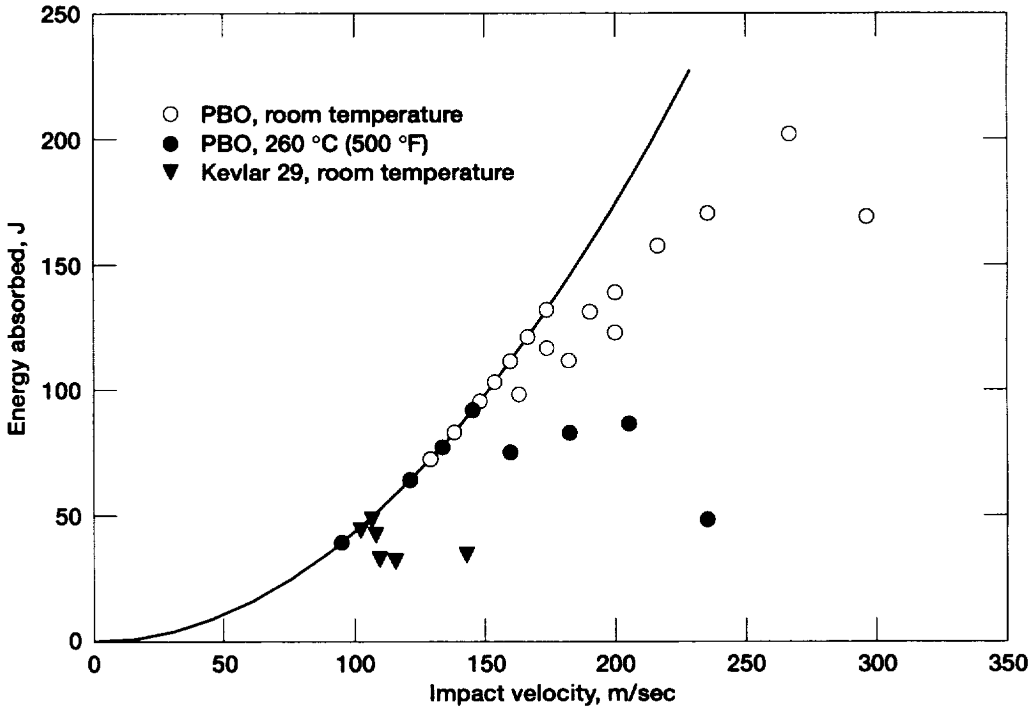

Figure 2.—Energy absorbed by Kevlar 29 and PBO at room temperature and PBO at 260 °C (500 °F) as a function of impact velocity.

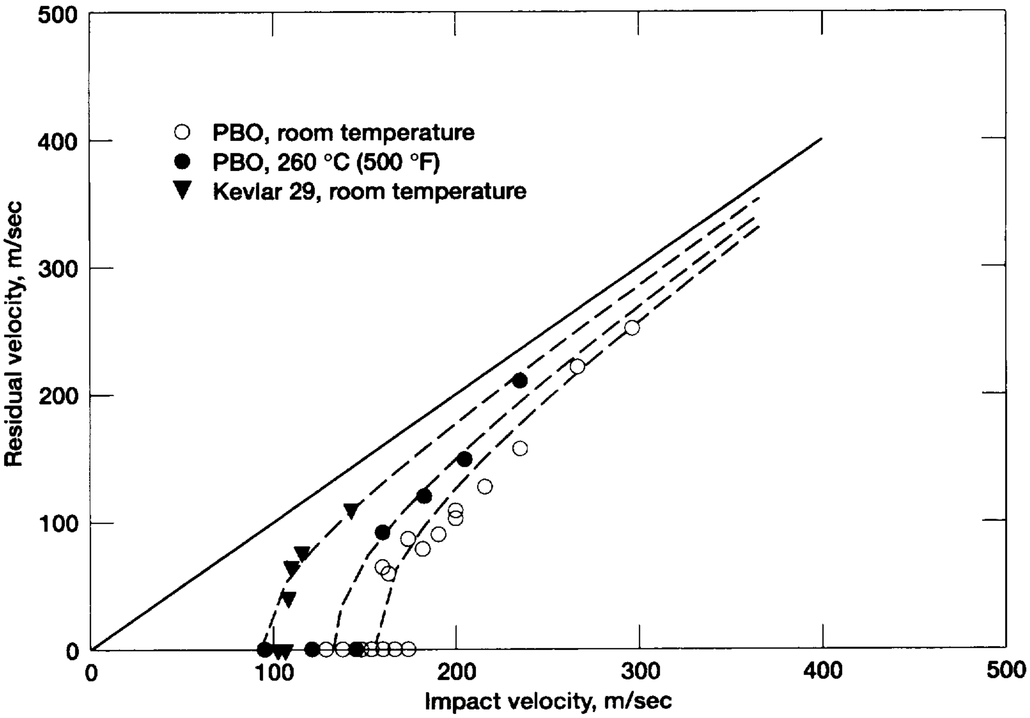

Figure 3.—Residual velocity after impact as function of impact velocity.

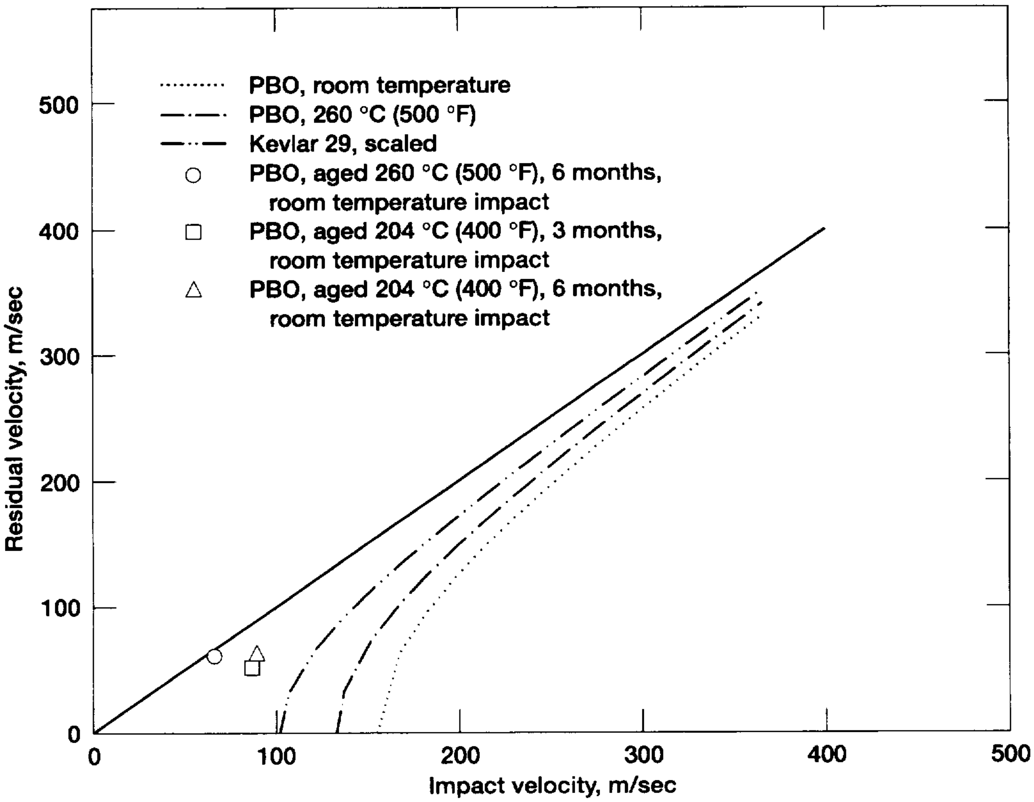

Figure 4.—Residual velocity for aged fabrics compared with empirical results for unaged specimens.

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J. Michael Pereira, Gary D. Roberts, and Duane M. Revilock

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Lewis Research Center
Cleveland, Ohio 44135-3191

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