the additional propellant required due to system errors and external disturbing forces may far exceed this value. However, as the size of the vehicle, the length of the mission, or the propellant fraction is increased, the extra propellant required due to mass variance becomes more significant. The equations presented herein allow these propellant errors to be determined easily and thus they they can be considered in each individual design.

Reference

[1] Reeves, D. F., Boardman, W. P., and Baumann, H. A., "Pulsed rocket control techniques," ARS Paper 2704-62 (November 1962).

Application of Fiber Metals to the Meteoroid Protection Problem

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A SERIES of meteoroid simulation impact experiments was conducted to determine the feasibility of using fiber metals as meteoroid shield materials. Fiber metals have many other properties that make them attractive for spacecraft applications such as strength, rigidity, and ability to withstand high temperatures and light weight. They are also similar in some respects to plastic foams that have been found to be quite effective in stopping simulated meteoroid particles.

Fiber metallurgy is centered around a basic process in which metal fibers are felted as in paper making and the felted fibers are sintered as in powder metallurgy. That is, randomly interlocked, felted fibers are heated to form a metallic weld bond at each point of contact between them. The sintered bodies may be further compacted, rolled, machined, welded, brazed, or treated in a variety of ways to fabricate finished, useful components having porosities of 5 to 97%. Some of the materials that have thus been treated are lead, aluminum, copper, iron, stainless steel, nickel, and cobalt-base alloys, titanium, and molybdenum. It appears that no metal or alloy is impossible to treat fiber-metallurgically, although those that form stable surface oxide films (e.g., aluminum) are more difficult to sinter. A schematic illustration of how one might utilize fiber metal panels is shown in Fig. 1.

Because fiber metal structural panels had already been made and studied and because such panels had been shown to be efficient absorbers of some types of energy, it was decided to evaluate the ability of the material to absorb the energy of impacting meteoroids. Assuming that fiber metal is found to be competitive with plastic fills to absorb meteoroid impact on a strength-to-weight basis, then the following additional advantages of fiber metal are also accrued: 1) higher service temperature than plastics; 2) use as load-bearing structures; 3) higher thermal conductivities, compared to plastics, make them more efficient thermal sinks; 4) greater resistance to space radiation damage; and 5) lower susceptibility to degradation by evaporation.

Since fiber metal materials possess strength characteristics roughly proportional to their density, the possibility exists for using them in thin sheets for spaced bumpers. In this application, they may be effective in breaking up the impacting particle and absorbing the residual particles on subsequent collisions. The goal of this series of impact experiments was to gain a better understanding of the performance of fiber metal materials and possibly formulate a physical model of their function in energy absorption.

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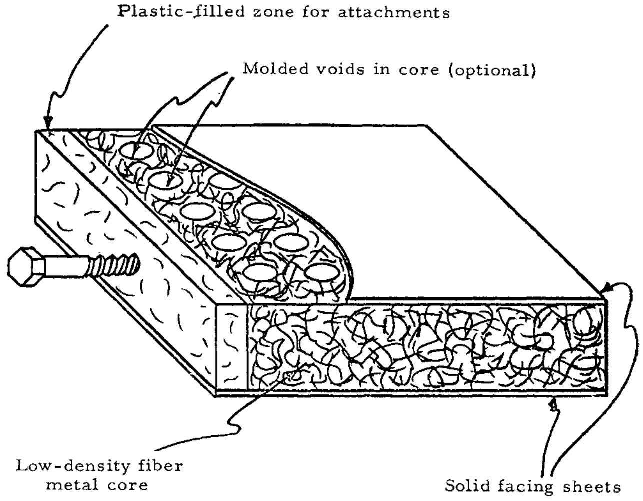

Fig. 1 Fiber-metal-core sandwich panel construction.

Several sets of hypervelocity impact experiments were conducted against fiber metal samples using the IITRI .22 caliber light gas gun. Simulated meteoroids ($\frac{1}{16}$-in. Pyrex spheres) weighing 4.54 mg were sabot-launched at velocities from 20,000 to 25,000 fps, and impact observations were made.

Fiber Metal Bumper Targets

In this series of firings, the targets were either thin, homogeneous metal sheets or fiber metal samples that were backed with an aluminum witness plate spaced 2 in. behind the primary target. Three sets of targets were used. In each set, a sheet of homogeneous materials was used as a control sample; then the varying relative densities of the same material in fiber metal form and the same area density were compared.

The first set used a control sample of 17-4 PH stainless steel, 0.031 in. thick, with an area density of 0.0176 psi. Three fiber metal samples of essentially the same area density, the same material, but with percentage densities of 64, 51, and 27 were then compared. It was found that as the percentage density of the fiber metal bumper decreased, the damage to the witness plate decreased accordingly. Penetration depth measurements were made on the witness plate to determine the greatest depth in all cases. Figure 2 shows that the maximum witness plate penetration generally follows a smooth curve as a function of percentage density.

The second set of targets made use of 1100 aluminum of the same area density as the stainless steel. A homogeneous control sample $\frac{3}{16}$ in. thick was used as were fiber metal samples of 51 and 30% density. It was found that the homogeneous aluminum in this thickness was sufficient to prevent damage to the witness plate even though the sheet suffered complete penetration. This demonstrates the relative efficiency of aluminum over stainless steel. The fiber metal samples completely stopped the projectiles without perforation and without any residual spray pattern.

Since the aluminum is a better bumper material than stainless steel from the weight standpoint, an additional aluminum series was fired using samples approximately one-half the area density. Control samples of two different types were used, one of 1100 and the other 7075 aluminum. The rest of this set included fiber metal samples of 1100 aluminum with relative densities of 60, 39, and 24%. The area densities were approximately the same as the control samples. A number of observations are possible: first, the higher strength aluminum bumper was slightly more effective in stopping the projectile in that the witness plate penetration was less; second, the lower the relative density of the fiber metal bumper, the shallower the penetrations of the witness plate. Witness plate penetration data (Fig. 2) are generally similar to those for the stainless steel, except that the aluminum is more protective even at one-half the area density.

Flash radiography was employed in these experiments in an effort to determine the energy absorption mechanisms involved in the fiber metal protection concept. It was found that residual particle velocity is much less behind a fiber metal bumper than it is in the case of the homogeneous sheet bumper. Apparently, the many inelastic collisions within the fiber structure absorb considerable energy. It is quite probable that the impact shock is greatly attenuated in the fiber metal because of the large zero pressure area that exists within the material. This reduced shock pressure is in turn less effective in discharging material from the region of the impact crater, thereby resulting in lower residual particle velocity. This is similar to the "mechanical atmosphere" concept, which has been advanced for plastic foam bumpers.

The fact that the fiber metal material is not capable of transmitting the full strength impact shock is advantageous from the vehicle design standpoint as well. For applications in which the fiber metal protection material is bonded, metallurgically or mechanically, directly to the item to be shielded, the impact shock will be sufficiently attenuated before it reaches the primary structure to prevent spalling from the opposite surface of the protected structure. If, on the other hand, the application of fiber metals to the bumper concept is considered, a similar advantage is gained. For example, for particles with insufficient energy to completely penetrate the homogeneous bumper, a damaging spall is often ejected from the rear of the bumper sheet at relatively low velocity but with a relatively large mass, and it may penetrate subsequent sheets. In the case of the fiber metal bumper, spalling is not experienced, but instead, a few low-velocity fibers or fragments from the impacting particles are ejected. These have been shown to do much less damage to subsequent sheets than the spall fragments.

Thick Fiber Metal Shields

The possibility of using relatively thick low-density fiber metal panels in direct contact with the structure to be shielded also exists. The approach has suggested itself in some parallel studies conducted at IIT Research Institute of impacts into various inorganic foams. The results of this work indicate that, if structural considerations can be minimized, the addition of a thin outer shield as in a composite structure is unjustified. Although the results are not conclusive, it appears that the added weight contributes little if any additional protection. However, the outer shield does seem to make the thickness required for equivalent protection less than in the case of unshielded filler.

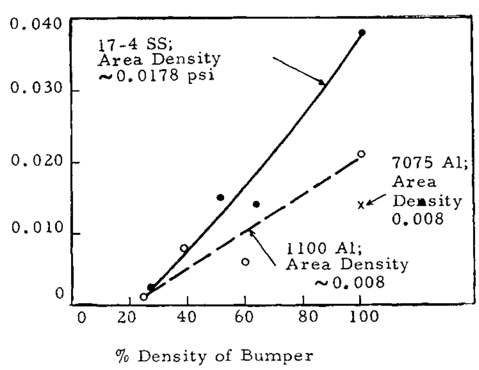

Fig. 2 Relationship between bumper density and maximum hole depth on witness plate.

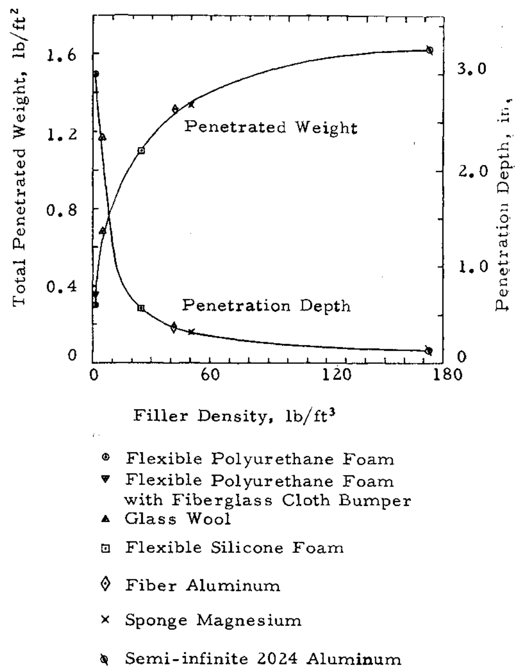

Fig. 3 Comparison of the resistance of various meteoroid bumper materials to penetration by a $\frac{1}{16}$-in. Pyrex sphere at ~22,000 fps.

Impacts into nonshielded fillers reveal some interesting comparisons. Data from firings into a wide assortment of materials including fiber metal are shown in Fig. 3. These experimental points represent the results of various impact programs that have been conducted at IIT Research Institute. The one exception is the sponge magnesium data that were obtained from J. L. Summers of the NASA Ames Research Center. For this data point only, the impacting particle was a $\frac{1}{16}$-in. aluminum sphere rather than Pyrex, as was the case for all other data points.

Rather than using the depth of penetration as a criterion of performance, a total penetration weight was chosen as a more meaningful indicator. Essentially, this is the area-density of this material required to prevent impact of an inner skin, and it is derived from the actual density of material and the penetration depth. However, the penetration depth is also plotted to show the actual thickness of various materials for a given amount of protection.

The weight of solid aluminum penetrated is only a benchmark, since it does not represent true protection. This point was obtained for an impact into a semi-infinite target and is only good for that case. If the equivalent protection was required in a thin sheet, the penetrated weight would increase by a factor of 1.5 to 2.0 because of the damaging spall produced from the rear of a thin sheet. This is not the case with the other targets that were considered.

A wide range of filler properties were involved in this examination. Both rigid and flexible organic materials were used as well as metallic and glasslike materials. Unfortunately, it was generally not possible to evaluate different materials at the same density to determine what influence other filler properties have on penetration resistance, but it appears likely that bulk density is the predominant factor. The limited aluminum fiber metal data fall in general agreement with other low-density materials. It is hoped that data will be obtained at other density levels and with other materials to compare the behavior of aluminum with other lightweight fillers.

Although this experimental series does not pinpoint the lightest weight fiber metal structure possible for protection against the chosen particle, the samples used in the aluminum series are competitive in weight with those encountered with other protection concepts.