Shielding Against Micrometeoroid and Orbital Debris Impact with Metallic Foams

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For the past 50 years, the protection of manned spacecraft against micrometeoroids and orbital debris (MMOD) has, for the most part, been performed by the Whipple shield or derivatives thereof. Although highly capable, the installation of Whipple-based shielding configurations requires a significant amount of non-ballistic mass for installation (e.g., stiffeners, fasteners, etc.), that can consume up to 35% of the total shielding mass. As NASA's vehicle design focus shifts from large pressurized modules operating for extended durations in relatively debris-polluted low-Earth orbits, to small-volume lower-duration craft, new protective concepts are being designed and evaluated to address the new threats.

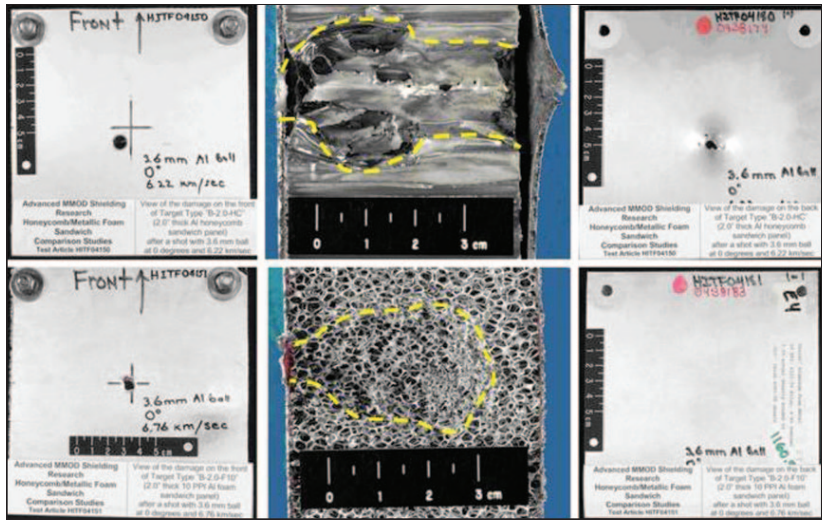

Fig. 1. Comparison of damages in a honeycomb core (top) and open-cell foam core (bottom) sandwich panel impacted by 3.6-mm-diameter aluminum spheres at 6.22 km/s (honeycomb) and 6.76 km/s (foam) with normal incidence (0°). From left to right: bumper (front view); core cross-section (emphasis added); and rear wall (rear view).

One possible solution involves the use of structural components that have intrinsic shielding capability. Traditional primary structures such as honeycomb sandwich panels are unsuited for use in manned vehicles due to their poor shielding performance. Metallic foams, however, are a relatively new material with low density and novel physical, thermal, electrical, and acoustic properties that offer a promising alternative for MMOD protective systems. There are two competing types of metallic foam: open cell and closed cell. Although closed-cell foams are capable of retaining some residual atmosphere, which may aid in the deceleration of penetrating fragments via drag, open-cell foams are considered the more promising technology due to their lower weight and higher degree of homogeneity. Preliminary investigations have demonstrated the potential of open-cell foam core structures, as shown in figure 1, compared to a traditional honeycomb core sandwich structure.

Researchers at Johnson Space Center's Hypervelocity Impact Technology Facility performed the following experimental investigations to comprehensively evaluate the performance of open-cell foams during hypervelocity impact: a fundamental study to investigate penetration and failure mechanisms in open-cell metallic foam structures; an application study evaluating the performance effect of modifying International Space Station-representative shields with open-cell metallic foams, and; a study comparing the performance of open-cell foams of varying materials with alternate MMOD shielding materials and structures.

Hypervelocity Impact Performance of Open-Cell Foams

An advantageous property of open-cell metallic foams, in terms of MMOD shielding, is their periodic structure of small diameter, low mass pores. During a hypervelocity impact event, the isentropic (constant value of entropy) shock and non-isentropic release process acts to raise the thermal state (internal energy) of the impacting particle. As a projectile penetrates through an open-cell foam structure, repeated impacts on individual foam cell ligaments induce multiple shock and release events, resulting in the fragmentation, melt, and vaporization of meteoroid or debris particles at impact velocities significantly lower than with traditional shields. The multi-shock shield used a similar concept, demonstrating potential weight savings of 30% to 40% over traditional Whipple shields for equal levels of protection. Although enhanced fragmentation and melting was clearly observed in experiments on foam core sandwich panels, rear facesheet failure was almost exclusively caused by the penetration of individual solid (or molten) fragments, even at impact velocities above 7 kilometers per second (km/s). Given the non-homogeneity of the foam structure on a micro scale, it is considered that these individual fragments have propagated through the foam core with minimal secondary impacts. Subsequently, the degree of experimental scatter for these structure types may be greater than that of traditional configurations.

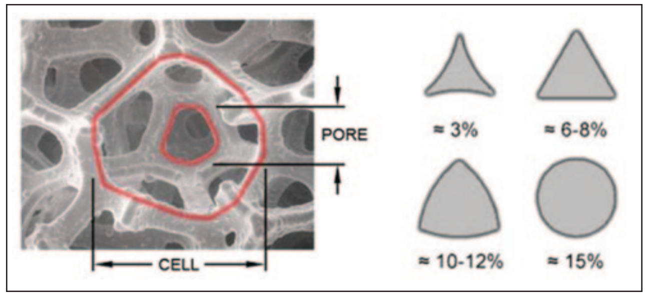

Fig. 2. *Foam pore size, cell size, and ligament cross-section (variation with relative density). © ERG Aerospace*

The number and size of foam ligaments is a function of material pore density (i.e., pores per linear inch [PPI]), which is specified in the manufacturing process. Additionally, the relative density of the foam (also adjustable during manufacturing) controls both the panel weight and the cross-sectional form of the foam ligaments (figure 2). It was found that increased pore density led to minor improvements in protective capability. For instance, 40 PPI foam core sandwich panels were found to be approximately 5% more capable than 10 PPI configurations. The effect of ligament shape was found to be minimal, with 3% to 5% (nominal) relative density cores providing equal levels of protection as heavier 6% to 8% (nominal) panels.

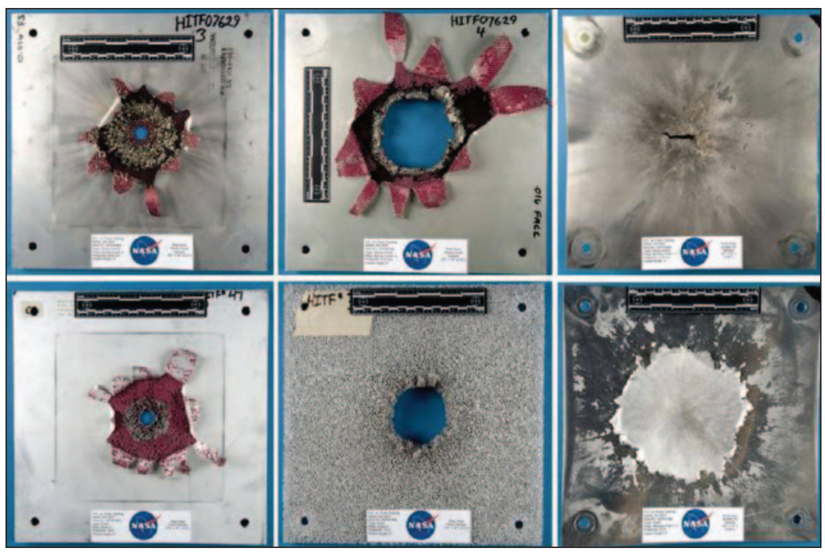

Fig. 3. *Comparison of impact damages induced by impact of 0.833-cm-diameter Aluminum spheres at approx. 6.9 km/s (0°) on the double layer honeycomb (top) and foam (bottom) targets. From left to right: outer sandwich panel (rear view); second panel (rear view); and rear wall (front view).*

Improved Shielding Performance Through use of Metallic Foam

Metallic open-cell foams provide comparable mechanical and thermal performance to honeycomb structures, without the MMOD shielding detrimental through-thickness channeling cells. A double-layer honeycomb sandwich panel shield, with a mesh outer layer and monolithic aluminum rear wall was modified to include aluminum open-cell foam, and thus evaluate the effect on shielding performance. The aluminum honeycomb core of the outer sandwich panel was replaced with 10 PPI foam, while the second honeycomb sandwich panel was replaced with an equal thickness foam panel (no facesheets), maintaining approximate totals for shield standoff and weight. The foam modified shield was found to provide a 3% to 15% increase in critical diameter for impacts normal to the target surface (0°). For oblique impacts, the performance gain was more substantial, particularly at low velocities. A comparison between impact damages induced by 0.833-cm-diameter Al2017-T4 (aluminum) spheres at approximately 6.9 km/s with normal incidence is shown in figure 3. In addition to reduced rear wall damage, clear evidence of enhanced fragment melting is visible on the foam-modified target.

Evaluation of Advanced Shielding Materials and Structures

The performance of aluminum, titanium, copper, stainless steel, nickel, nickel/chromium, reticulated vitreous carbon, silver, and ceramic open-cell foams was evaluated in an extensive experimental impact campaign. Configured in single-, double-, and triple-bumper shields, their protective capability was assessed against metal plates, meshes, and various flexible fabrics via a figure of merit based on cratering and impulsive failure modes. Further ballistic limit-based evaluations were performed, in which the advanced shield configurations were compared against equivalent weight all-aluminum shields. The top performing configurations were found to generally include monolithic aluminum outer bumper plates, with metallic foam and/or Kevlar® fabric inner bumper plates. Of the various foam types investigated, copper was found to provide the best protection, with reticulated vitreous carbon providing the worst.

The generation of ejecta during MMOD impact on a shield outer bumper is of concern due to the danger of secondary impacts, and the general pollution of the orbital environment. For impact on common shielding materials (i.e., aluminum, carbon-fiber reinforced plastic), ejecta can constitute up to 30% of the total expelled mass (ejecta + fragment cloud). Impact on foams, meshes, and fabrics was found to generate almost no ejecta of any significance, providing a substantial reduction in ejecta mass over monolithic structures (figure 4).

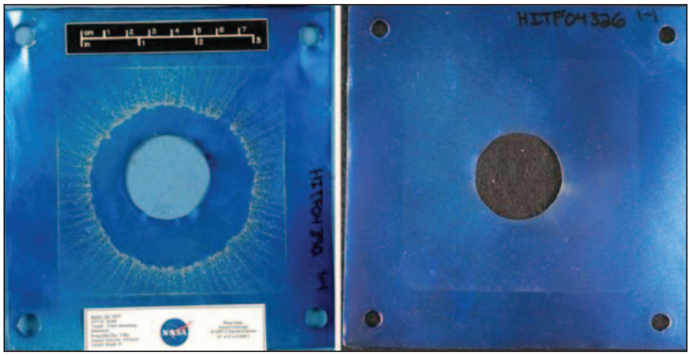

Fig. 4. *Comparison of ejecta plate damages following impact of 0.3175-cm-diameter aluminum spheres on a monolithic aluminum outer bumper (left) and stainless steel foam outer bumper (right) at hypervelocity (approximately 6.8 km/s).*