EPSC Abstracts
Vol. 8, EPSC2013-397, 2013
European Planetary Science Congress 2013

SPACECRAFT SHIELDING: AN EXPERIMENTAL COMPARISON BETWEEN OPEN CELL ALUMINIUM FOAM CORE SANDWICH PANEL STRUCTURES AND WHIPPLE SHIELDING.

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Introduction: Spacecraft shielding is generally provided by metallic plates in a Whipple shield type configuration [1] where possible. However, mission restrictions such as spacecraft payload mass, can prevent the inclusion of a dedicated protective structure for prevention against impact damage from micrometeoroids. Due to this, often the spacecraft's primary structure will act as the de facto shield. This is commonly an aluminium honeycomb backed with either glass fibre reinforced plastic (GFRP) or aluminium faceplates [2]. Such materials are strong, lightweight and relatively cheap due to their abundance used within the aerospace industry. However, these materials do not offer the best protection (per unit weight) against hypervelocity impact damage. A new material for shielding (porous aluminium foam [3]) is suggested for low risk space missions. Previous studies by NASA [4] have been performed to test this new material against hypervelocity impacts using spherical aluminium projectiles. This showed its potential for protection for satellites in Earth orbit, against metallic space debris. Here we demonstrate the material's protective capabilities against micrometeoroids, using soda-lime glass spheres as projectiles to accurately gauge its potential with relation to silicatious materials, such as micrometeoroids and natural solar system debris. This is useful for spacecraft missions beyond Earth orbit where solar system materials are the dominant threat (via hypervelocity impacts) to the spacecraft, rather than manmade debris.

Target Materials: The target material used here is an open cell aluminium foam (35 x 35 x 30 mm) sandwiched between two 1 mm thick aluminium plates . Aluminium foams are manufactured through the utilisation of a solid negative-image ceramic mould, which is then filled with a liquid aluminium alloy and then allowed to cool. The individual cells are typically 14 faceted polyhedral or solid tetrakaidecahedrons. When the foam has solidified, the thin membranes, are removed via a reticulation process which leaves behind only interconnected struts which form the open cell structure [4]. The tetrakaidecahedrons are referred to as cells, while the individual windows between the interconnected foam ligaments are the pores.

Fig. 1 Electron microscope images of Al. foam. Pores ~ 1 mm

The pore size controls the number and nominal size of foam ligaments, while the foam relative density controls their cross-sectional form and actual size [4]. The foam under investigation here has 40 pores per inch (PPI), yielding a porosity of 93%. This was selected over 10 and 20 PPI as the higher pore density foams seem to be less susceptible to individual fragments passing through the foam with few, or no, secondary impacts. The higher pore density foams also show an increased degree of densification (i.e. collapse of the foam cells, at the limits of the damaged zone, suggesting a greater level of energy partitioning into plastic work) although the effect of this on penetration limits was expected to be minimal. In general, the 40 PPI foams can be considered to perform approximately 5% better than the lower pore density foams (i.e. the critical projectile diameter is ~5% larger) [4]. The second target type was a Whipple style [5] configuration, that used four plates of aluminium (1 mm thick, Fig. 2) spaced evenly so that the front and back plates were the same distance apart as the plates sandwiching the aluminum foam targets. This configuration gave both target types the same total volume, and the same weight, and thus the same total density, but with different internal density distributions. However, the aluminium foam size was doubled in depth to 60 mm for the 3 mm projectile shots to allow for a more accurate penetration to be measured.

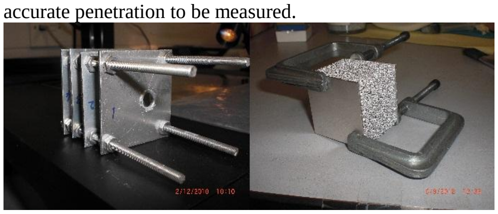

Fig. 2 Left: four plate Whipple target (post-impact). Right: Aluminium foam sandwich target (pre-impact). Plates = 35 mm^2.

Table 1. LGG shot parameters of shot program

Shot ID	Projectile size (mm)	Velocity (km s^{-1})	Approx Shock Pressure (GPa)
G260413#1F	1.56	4.71	149.08
G260413#2F	1.56	3.24	85.29
G010212#1F	2.00	2.00	43.66
G141011#2F	2.00	3.31	87.97
G201011#2F	2.00	4.91	158.97
G190413#1F	3.00	1.84	39.10
G190413#2F	3.00	3.15	81.89
G100413#1F	3.00	4.91	158.97
G010513#1W	1.56	4.54	140.90
G010513#2W	1.56	3.44	93.05
G080212#3W	2.00	1.89	40.50
G101111#2W	2.00	3.08	79.29
G171111#2W	2.00	4.96	161.49
G150112#3W	3.00	1.85	39.38
G011211#1W	3.00	3.12	80.77
G081211#2W	3.00	4.53	140.43

*F and W denote target type (Foam and Whipple respectively)

Experimental Methodology: A two stage light gas gun (LGG) [6] was used to accelerate projectiles (sodalime glass spheres) at a range of velocities to impact each of the two target types, see Table 1. The volume of material removed was then measured (see eq 1 for Foam, eq 2 for Whipple) and the crater depth. The volume of foam target excavated was calculated using the close packing of spheres method [7].

$$\text{Eq 1. } V_f = \sum_i^2 \pi \frac{d_i^2}{4}(1mm) + \left\{\left({}^{m}/_{\rho}\right)\left({}^{a}/_{b}\right)\right\} \quad \text{Eq 2. } V_f = \sum_i^4 \pi \frac{d_i^2}{4}(1mm)$$

d is diameter, m, ρ are mass (g) and density (g cm^{-1}) of the spheres, a is a porosity factor = 0.07 [3], and b is the packing fraction = 0.634 [8]. The approximate Shock pressures were calculated via:

$$\mathrm{P_H} = \rho_o u_p (C_o + S u_p) \text{ [9]}$$

Where ρ_o is target density (kg m^{-3}), u_p is projectile velocity (m s^{-1}), and C_o and S are parameters given in [9] as 5386 m s^{-1} and 1.339 respectively.

Results: **Table 2.** Table of measured results.

Shot ID	Kinetic energy (J)	Volume excavated (mm^3) +/- 3%	Penetration depth (mm)
G260413#1F	55.80	83.93	14.49
G260413#2F	26.30	50.39	11.20
G010212#1F	21.12	54.82	17.25
G141011#2F	57.85	99.24	17.21
G201011#2F	127.29	174.01	19.31
G190413#1F	60.25	160.19	32.82
G190413#2F	176.77	336.46	32.33
G100413#1F	428.79	563.17	30.66
G010513#1W	51.63	9.49	10.33
G010513#2W	29.64	6.77	10.33
G080212#3W	18.86	9.87	20.67
G101111#2W	50.09	19.21	20.67
G171111#2W	129.90	35.94	20.67
G150112#3W	60.97	22.75	20.67
G011211#1W	173.42	81.90	31.00
G081211#2W	365.58	129.40	31.00

Crater Volume: When impacted, there are significant differences between the volume evacuated by the two types of target for nominally identical velocities and projectile diameters. This is due to the nature of the materials, leading to a different dissipation of energy for the two types of targets. The Whipple plate targets show that the energy travels through the target in a conical shape with a small solid angle. However, the aluminium foam is structured such that as the projectile material travels through the foam, it is subjected to multiple secondary impacts on ligaments, and struts, which helps to dissipate the energy radially outwards. This leads to a bulbous cavity being formed within the foam, as opposed to the conical shape in the Whipple plates (see Fig. 3).

Fig. 3 Cross-sectional sketch of penetration path. Left: Conical in Whipple plates. Right: Bulbous cavity formed in aluminium foam.

This leads to a much larger volume of excavated material in aluminium foam targets than for Whipple plates (see Fig. 4).

Penetration Depth: Due to multiple secondary impacts of the debris cloud onto the ligaments within the foam structure, the projectile size is a crucial factor in the effectiveness of the foam targets for shielding. The trend of penetration depth vs kinetic energy changes depending on projectile size (see Fig. 4). Impacts of projectiles with diameters ~2 mm or less into the aluminium foam targets show penetration depths equal to, or less than those in the Whipple plates. However, in the foam targets, as projectile size or energy (and thus crater volume) increases, the rate of penetration depth slows, and can even halt, due to the compaction of material, i.e. ligaments and struts in the foam.

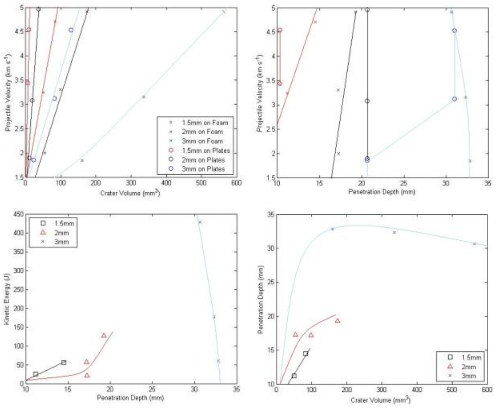

Fig. 4 Top: Foam and Whipple. Left: proj. velocity vs crater volume. Right: proj. velocity vs crater depth. Bottom: Foam. Left: Kinetic energy vs crater depth. Right: Crater depth vs crater volume.

Conclusions: The aluminium foam targets would be expected to provide similar or better levels of protection when considering small (< 2 mm) projectiles, than a traditional Whipple shield. However, as projectile size increases, the effectiveness of the foam sandwich panel significantly changes due to material compaction, thus a traditional Whipple shield will not necessarily perform any better for missions where the risk of impact is high for larger (> 2 mm) projectiles. Thus, metallic foam sandwich panels represent a possible alternative shielding structure for missions with extreme mass (or volume) restrictions, as well as unmanned missions where the risk assessment is deemed to be lower.

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