EXPERIMENTAL STUDY ON HYPERVELOCITY IMPACT CHARACTERISTICS OF NEW TYPES OF GONG-HOU SHIELD

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Abstract

Two new types of Gong-Hou shield, Al/Mg shield and Ti/Al/Mg/nylon shield, were studied by using two-stage light gas gun, to verify Gong-Hou shield had larger protection capacity than Whipple shield in defeating micro-meteoroid and orbital debris (MM/OD). Three impact velocities (3.5 km/s, 4.5 km/s, and 6.5 km/s) were chosen for Al/Mg shield. For Ti/Al/Mg/nylon shield, experiments were conducted at 4.5 km/s and 6.5 km/s. Petal-like perforations presented in both Al/Mg bumper and Ti/Al/Mg/nylon bumper. The normalized perforation diameters for Al/Mg shield and Ti/Al/Mg/nylon shield were approximately 1.3 to 2.1 times of those for Whipple shield. There were only 20-25 caters with diameter larger than 2 mm in Gong-Hou shield at 4.5 km/s, while more than 60 presented in Whipple shield. The critical diameters of aluminum spherical projectiles for Al/Mg shield were 5.0 mm, 5.5 mm, and 6.0 mm at impact velocities of 3.5 km/s, 4.5 km/s, and 6.5 km/s, respectively. Those for Ti/Al/Mg/nylon shield were 4.8 mm at 4.5 km/s and 5.9 mm at 6.5 km/s. However, the maximum diameters of projectiles that Whipple shield could defeat were only 2.7 mm, 3.3 mm and 4.5 mm at 3.5 km/s, 4.5 km/s and 6.5 km/s, respectively. The maximum performance increase was 85.2%, and the minimum was 31.1%.

Key words: Gong-Hou shield; hypervelocity impact; space debris; protection shield; functional-grade material

1. Introduction

Density-grade material is a kind of composite material which consists of different material in one direction. Hou et al. proved that it performed better than aluminum alloy in withstanding hypervelocity impact (HVI) by numerical simulation and experimental research [1,2]. Experimental results of Ti/Al/nylon-type Gong-Hou shield (short for Ti/Al/nylon shield) which comprised a Ti/Al/nylon density-grade bumper and a routine aluminum alloy showed that the performance of Gong-Hou shield was more than 50% higher than that of Whipple shield [2]. This new concept shield performed better than some enhanced shield such as Multi-Shock shield, Honeycomb shield and Mesh-Double Bumper shield [3-7]. It was comparable to Stuffed Whipple shield and Metal Foam Core Sandwich shield in defeating hypervelocity space debris [4,8,9].

Since Gong-Hou shield was put forward and the performance was validated by Ti/Al/nylon shield, researches on HVI characteristics of density-grade materials prevail among scientists in different fields and for different purposes. Works done by Huang, et al., Guo et al., Guo, et al. and Tamura et al. [10-13] were similar to Hou et al. [2]. Huang et al. used $Fe_{77}Si_{19}B_4$/LY12 Al density-grade material as bumper in Whipple shield, but they kept the total thickness of bumper constant, not the total areal density constant [10]. Although the concept they put forward approached the concept in Hou et al. [2], their conclusion that $Fe_{77}Si_{19}B_4$/LY12 Al performed better than aluminum alloy lacked of confidence, because the areal density of 0.15 mm $Fe_{77}Si_{19}B_4$+2.85 mm LY12 Al was larger than 3.00 mm LY12 Al. However, work done by Tamura, et al. [11] was much more convincing than Huang, et al. [10]. Tamura, et al.

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studied the debris cloud produced in projectile impacting SiC-fiber/3004 Al composite and found that SiC-fiber/3004 Al composite, compared with monolithic aluminum plate, can broke a projectile into more fragments and these fragments expanded in a larger area [11]. Similarly, the SiC-fiber/3004 Al composite took on petal-like perforation as those in Hou et al [2]. Unfortunately, they didn't study the performance increase when aluminum alloy was replaced by SiC-fiber/3004 Al composite in Whipple shield. Guo, et al. studied the Damage behavior of Al matrix composite reinforced with Ti-6Al-4V meshes [12] and Guo, et al. studied the Residual microstructure associated with impact craters in TiB_2/2024Al composite [13]. Although focuses were set on HVI characteristics of density-grade material in [12] and [13], they didn't study the performance in defeating hypervelocity projectile.

Efforts are also made on other materials to find the best candidate to apply in protection shield for spacecraft. Rudolph, et al. studied the ability of different flexible material i.e. Nextel 312, Kevlar 129 style 812, Carbon T300 PEN, Refrex 1420, and Dyneema CF10, to induce fragmentation of a hypervelocity projectile [14]. Experimental results illustrated that these material had smaller capacities in fragmenting projectiles compared with aluminum alloy. Baluch, et al. evaluated the specific energy absorption of carbon/epoxy composite and found that this composite absorbed 7% more energy than Al6061-T6 [15]. Ryan and Christiansen assessed potential of 12 kinds of materials (aluminium, titanium, copper, stainless steel, nickel, nickel/chromium, reticulated vitreous carbon, silver, ceramic, aramid, ceramic glass, and carbon fibre) arranged in single-, double- and triple-bumper shields [16]. The combination of outer aluminum bumper and inner aluminum foam bumper performed best amongst all structures with different materials. Francesconi, et al. studied the protection capability of a self-healing ionomeric polymer and found it performed worse than aluminum alloy in fragmentizing projectiles [17]. Zheng, et al. tested the HVI characteristics of $Zr_{51}Ti_5Ni_{10}Cu_{25}Al_9$ bulk metallic glass, but they didn't perform comparison with aluminum alloy and its performance in withstanding HVI is still unknown [18].

Developing new generation of enhanced shield is an eternal issue for scientists to protect spacecraft from micro-meteoroid and orbital debris. As new materials are applied, novel protection shields can be developed. Although enhanced shields are different, the primary theoretical method to develop enhanced shields remains same which is to raise shock pressure and prolong duration of shock wave in bumper. Hou, et al. had discussed this issue in [19]. Inklings can also be found in Huang, et al. [10] and Baluch, et al. [15].

This paper is to study the HVI characteristics of new density-grade materials (Al/Mg, Ti/Al/Mg/ nylon) and new types of Gong-Hou shield, and provide more evidences to validate that Gong-Hou shield is a promising candidate in protecting spacecraft.

2. Experimental setup and results

We have conducted experimental research on Ti/Al/nylon shield before [2]. The Al/Mg- and Ti/Al/Mg/nylon-type Gong-Hou shield (short for Al/Mg shield and Ti/Al/Mg/nylon shield) studied in this paper had same parameters to those of Ti/Al/nylon shield. The Al/Mg density-grade bumper consisted of 0.8 mm AL 2024-T4 and 1.1 mm MgAZ31B in thickness. The Ti/Al/Mg/nylon was made up of 0.4 mm Ti6Al4V, 0.3 mm AL 2024-T4, 0.3 mm MgAZ31B, and 0.9 mm nylon. The areal density of these three density-grade materials equaled 1.5 mm AL 2024-T4 plate in thickness. The parameters of Ti/Al/Mg/nylon and Al/Mg are listed in Tab. 1. The rear wall was 3.0 mm AL 2024-T4 (300 mm×300 mm in size). The overall spacing was 100 mm. Two 0.5 mm witness plates were set up behind rear wall. The sample used in experiments is illustrated in Fig. 1.

Table 1. Parameters of density-grade materials.

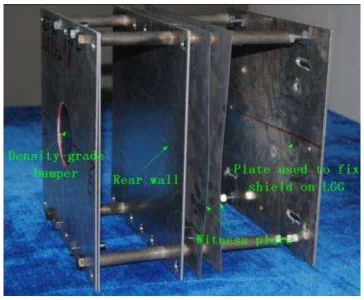
Density-grade Material	No.	Thickness of Ti6Al4V(mm)	Thickness of AL2024-T4(mm)	Thickness of MgAZ31B(mm)	Thickness of nylon(mm)	Diameter (mm)
Ti/Al/Mg/nylon	B-1	0.359	0.306	0.337	0.914	110.305
	B-2	0.369	0.304	0.314	0.944	110.170
	B-3	0.365	0.306	0.318	0.947	110.275
Al/Mg	A-1	/	0.818	/	1.150	110.000
	A-2	/	0.823	/	1.148	109.958
	A-3	/	0.813	/	1.096	109.935
	A-4	/	0.816	/	1.910	109.950
	A-5	/	0.815	/	1.148	109.928
	A-6	/	0.805	/	1.143	110.043
	A-7	/	0.813	/	1.091	109.918
	A-8	/	0.816	/	1.136	109.930
	A-9	/	0.814	/	1.140	110.095
	A-10	/	0.777	/	1.117	109.918

HVI experiments were conducted on two-stage light gas gun in National Key Laboratory of Science and Technology on Reliability and Environment Engineering. The projectiles varied between 4.5 mm and 6.5 mm in diameter. The velocities were carried out at 3.5 km/s, 4.5 km/s, and 6.5 km/s. The velocity uncertainty is less than 5‰. Projectiles normally impacted shield in all experiments. Results are summarized in Tab. 2.

Table 2. HVI experiments on new types of Gong-Hou shield.

Shot No.	Material No.	Projectile		Bumper① D_h (mm)	Rear wall damage	Failure②	Witness plate damage
		V_P (km/s)	D_P (mm)				
Shot A 1-1#	A-1	4.551	4.990	16.06	Bulge	No	No
Shot A 1-2#	A-2	4.486	5.490	19.28	Detached spallation	Yes	Crater
Shot A 1-3#	A-3	4.597	5.518	18.44	Bulge	No	No
Shot A 1-4#	A-7	4.537	5.518	18.80	Tiny detached spallation	Critical	No
Shot A 1-5#	A-9	3.549	4.989	12.76	Tiny detached spallation	Critical	No
Shot A 2-1#	A-4	6.383	6.481	30.12	Detached spallation	Yes	Penetration
Shot A 2-2#	A-5	6.345	6.003	29.44	Detached spallation	Yes	Crater
Shot A 2-3#	A-6	6.576	5.515	28.20	Bulge	No	No
Shot A 2-4#	A-8	5.967	5.991	29.00	Detached spallation	Yes	Crater
Shot B 1-1#	B-1	4.560	4.981	20.02	Penetration	Yes	Tiny crater
Shot B 1-2#	B-2	4.611	4.481	16.92	Bugle	No	No
Shot B 2-1#	B-3	6.40	6.0	28.36	Detached spallation	Yes	Crater

①: Only diameters of perforation in front surface were measured.
②: Failure criteria are chosen as penetration or detached spallation in rear wall.



(a) Sample before experiment

(b) Sample after experiment

Figure 1. Samples of Gong-Hou shield before and after experiment. The density-grade bumper is fixed by two aluminum plates.

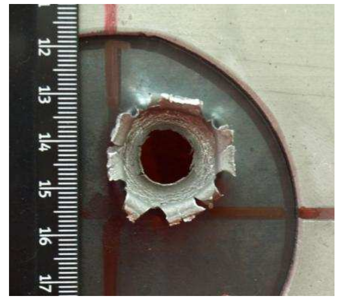
3. HVI characteristics of new types of Gong-Hou shield

The bumper of Gong-Hou shield is density-grade material rather than monolithic aluminum alloy. This novel design makes HVI characteristics of Gong-Hou shield different compared with those of Whipple shield.

3.1 Perforation in density-grade bumper

The representative morphologies of perforation in Al/Mg bumper and Ti/Al/Mg/nylon are shown in Fig. 2.

(a) Perforation in Al/Mg bumper for Shot A2-1#



(b) Perforation in Ti/Al/Mg/nylon bumper for Shot B1-1#

Figure 2. Representative morphologies of perforation in density-grade bumpers.

Petal-like perforations display in front surfaces of both density-grade bumpers. This is totally different from perforation in monolithic aluminum bumper which has a regular circle shape. In the back of Al/Mg bumper, there is a smaller perforation with rough edge. In addition a middle size crack compared with diameter of the hole is on the left. The perforation in the rear surface of Ti/Al/Mg/nylon bumper exhibits same character with Al/Mg bumper. Moreover a regular circle hole is in the middle of Ti/Al/Mg/nylon bumper, which is not observed in Al/Mg bumper. The petal-like lips in front are AL 2024-T4 of Al/Mg bumper and Ti6Al4V and AL 2024-T4 of Ti/Al/Mg/nylon bumper. The irregular holes in back are on MgAZ31B and nylon for AL/Mg and Ti/Al/Mg/nylon, respectively. The regular perforation in Fig. 2(b) is on MgAZ31B.

The perforation modes are typical characters for density-grade material when impacted by hypervelocity projectile. The interface hardness is much less than yield stress of material. The anisotropy makes density-grade material has different resistances in different directions. When a projectile normally impacted density-grade bumper, delamination in interface happened. This phenomenon was also observed in Ti/Al/nylon shield [2] and SiC-fiber-reinforced aluminum-alloy target [11].

The perforation diameter in density-grade bumper is larger than that in aluminum bumper. Fig. 3 summarized perforations in Al/Mg bumper, Ti/Al/Mg/nylon bumper, and monolithic aluminum alloy. The normalized diameters (perforation diameter divided by projectile diameter) of aluminum bumper are between 1.8 and 2.2 at velocity range 3 km/s-7 km/s. However, the normalized diameters of Al/Mg vary from 2.4 to 5.1, and those of Ti/Al/Mg/nylon are in the range 3-5. As is known to all, the larger the perforation is, the smaller the momentum of projectile fragments and the velocity of debris cloud are. If the perforation is big, the mass proportion of bumper fragments in debris cloud will be large. According to momentum equilibrium, the momentum of projectile fragments is reduced. Thus the velocity of debris cloud is reduced compared with the impactor.

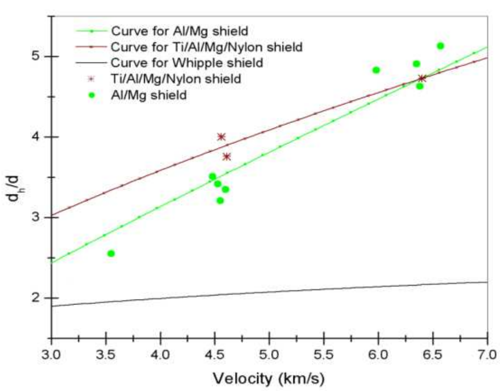
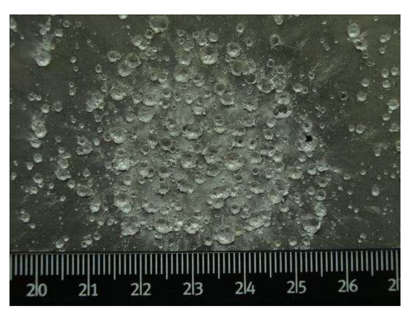


Figure 3. Normalized perforation diameters for Al/Mg bumper, Ti/Al/Mg/nylon bumper, and aluminum alloy bumper. Only penetrations in front surface of density-grade bumpers were measured. The colored curves were fitted by least square method. The green line represents result of Al/Mg bumper. The wine curve is result of Ti/Al/Mg/nylon bumper. The black solid line is calculated according to Hill [20].

3.2 Damage on rear wall

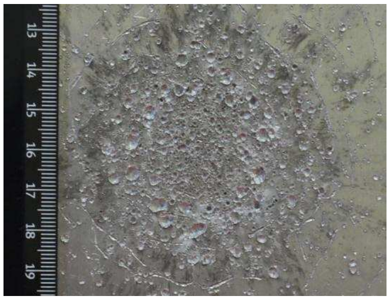
The damage on rear wall for Gong-Hou shield presents some unique characters. At 4.5 km/s, craters distribute discontinuously and homogeneously on rear wall of Whipple shield in Fig. 4(a). Each crater can be recognized by eyes. While the number of craters is much more on rear walls of Gong-Hou shield and craters overlap each other. There are about 25 craters with diameter larger than 3 mm in Whipple shield. However, only 2 craters with same size are on rear wall of Ti/Al/Mg/nylon shield and there is no crater larger than 3 mm in Al/Mg shield. The numbers of craters with size larger than 2 mm and 1 mm are 41 and 111, respectively, in Whipple shield. Surprisingly, the numbers are 10 and 42 for Al/Mg shield and 11 and 52 for Ti/Al/Mg/nylon shield, respectively. These facts illustrate that density-grade bumper broke projectiles into more fragments and reduced their size. Because projectile was fragmentized more finely, rear wall suffered less damage. Projectile with diameter of 4.00 mm at 4.795 km/s caused bulges on back of rear wall in Whipple shield. However, 4.48 mm projectile only caused small bulges in Ti/Al/Mg/nylon shield, and 5.48 mm projectile led to tiny detached spallation in Al/Mg shield.

Furthermore, big craters scatter in the central part of rear wall for Whipple shield. Those for Gong-Hou shield distribute in a ring zone off the center. The phenomenon suggests that fragments in central part of debris cloud are in small size. Density-grade bumper broke them into tiny pieces. In Fig. 4(c), black traces spread outside of the ring zone. It was caused by oxidated nylon fragment in hypervelocity impact. No obvious damage is observed in black traces.



(a) Whipple shield (V_P=4.795km/s, D_P=4.00mm)

(b) Al/Mg shield (V_P=4.486km/s, D_P=5.48mm)



(c) Ti/Al/Mg/Nylon shield (V_P=4.611km/s, D_P=4.48mm)

Figure 4. Damages on rear wall for Whipple shield and Gong-Hou shield at ~4.5 km/s.

At impact velocity of ~6.5 km/s, the morphology for both Whipple shield and Gong-Hou shield approach similar except for the ring zone with big craters. Also, craters in Gong-Hou shield are smaller than those in Whipple shield (0.3mm Vs 1.0 mm).

4. Ballistic limit curves for Gong-Hou shield

The ballistic limit curve (BLC) is the direct and prime evidence to judge performances of different shields. Fig. 5 summarized BLCs of Whipple shield and Gong-Hou shield. BLCs of Al/Mg shield and Ti/Al/Mg/Nylon shield are above that of Whipple shield. The fact suggests that Gong-Hou shield could defeat larger projectile at same impact conditions. At ~4.5 km/s, rear walls in Shot A1-1# and Shot A1-3# were not penetrated. The projectile diameters for Shot A1-1# and Shot A1-3# are 5.0 mm and 5.5 mm, respectively. While another shot's projectile diameter is 5.5 mm at 4.486 km/s (Shot A1-2#), which lead to detached spallation at back of rear wall. Shot A1-2# and Shot A1-3# restrict that the critical diameter is about 5.5 mm at 4.5 km/s. This is also validated by Shot A1-4#. Christiansen equation predicts that the maximum projectile diameter that Whipple shield can defeat is about 3.3 mm. The performance of Al/Mg shield is 66.7% larger than Whipple shield. At ~6.5 km/s, Rear walls of Shot A2-1# and Shot A2-2# suffered detached spallation, and witness plates also suffered penetration or crater for both experiments. Projectile diameters are 6.5 mm and 6.0 mm, respectively. These two experiments suggest the critical diameter is less than 6.0 mm at 6.383 km/s and 6.345 km/s. Shot A2-3# conducted at 6.576 km/s showed that 5.5 mm projectile didn't penetrate rear wall. The fitted diameter is 6.0 mm depending on these experimental results. The performance increases by 33.3% compared with 4.5 mm of Whipple shield. An experiment was also conducted at 3.5 km/s. Coincidentally, the diameter is 5.0 mm and at critical point. While Whipple shield can only defeat 2.7 mm projectile at 3.5 km/s.

Three experiments were conducted on Ti/Al/Mg/nylon shield. The BLC at velocity range 3-7 km/s can be fitted by at least four experiments. So the curve in Fig. 7 was drawn by hand and it can only give probable variation trend. At ~4.5 km/s, a 5.0 mm projectile penetrated rear wall, while the 4.5 mm projectile only caused bugle on rear wall. The critical diameter must be between 4.5 mm and 5.0 mm. Since the witness plate in Shot B 1-1# only suffered tiny crater, the critical diameter should approach 5.0 mm. The number read from the hand drawn curve is 4.8 mm at 4.5 km/s, which is 45.5% larger than 3.3 mm for Whipple shield. At 6.5 km/s, the read number is 5.9 mm. Whipple shield can only defeat 4.5 mm projectile at same velocity. The former's performance increases 31.1% compared with the latter.

HVI experiments on Ti/Al/nylon shield have verified that Gong-Hou shield has larger protection capacity than Whipple shield [2]. Experimental researches conducted on Al/Mg shield and Ti/Al/Mg/Nylon shield in this paper validate that conclusion further. Researches in [2] and this paper account for that the novel design of replacing the monolithic aluminum plate with density-grade bumper can promote the performance of Whipple shield.

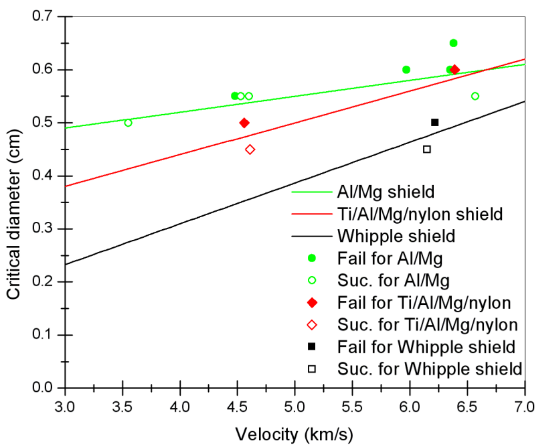


Figure 5. BLCs for Gong-Hou shield and Whipple shield. The green line was fitted by least square method. The red line was drawn by hand. The black line was calculated by Christiansen equation [4]. There are two experimental results for Whipple shield. Impact conditions are V_P=6.221 km/s, D_P=5.00 mm and V_P =6.150 km/s, D_P =4.50 mm, respectively, in normal incidence.

5. Conclusions

HVI experiments were conducted on Al/Mg shield and Ti/Al/Mg/nylon shield to verify the novel design of density-grade bumper in Gong-Hou shield. Perforation in density-grade and damage on rear wall were analyzed. These HVI characteristics are kind of different from those for Whipple shield. The perforation in density-grade bumper takes on petal-like shape and delamination of constitute materials in the edge across the perforation is observed. The perforation diameter is larger than that in Whipple shield at same impact conditions. Scattered craters with big size distribute homogeneously on rear wall of Whipple shield, while small craters overlap in the central area with a ring zone of big scattered craters outside. Thus the number of big craters is reduced markedly in Gong-Hou shield in comparison with Whipple shield.

BLC results validated the HVI characteristic of Gong-Hou shield. The protection capacities of Al/Mg shield are 33% to 85% larger than those of Whipple shield at velocity range 3~7 km/s. Ti/al/Mg/nylon shield also performs better than Whipple shield with performance increase of 31% to 45%.

Researchers [4-9] deduced that the performances of enhanced shields (Multi-Shock shield, Mesh Double-Bumper shield, stuffed Whipple shield and Metal Foam Core Sandwich shield) increased approximate 40% compared with Whipple shield. Since Gong-Hou shield performs much better than Whipple shield, it can be ranked as a kind of enhanced shield. However, Gong-Hou shield has only one bumper which makes it simplest amongst enhanced shields. This character enables Gong-Hou shield more promising in engineering application.

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References

[1] Hou M Q, Gong Z Z, Yang J Y, Zheng J D, Tong J Y, Xiang S H. A new concept density-grade type protection shield with high performance in defeating space debris. *Forum of space environment and material science in 2009*, pp.76-84, Beijing, China, 2009.

[2] Hou M Q, Gong Z Z, Zheng J D, Xu K B. A new concept shield withstanding hypervelocity impact. *The 29th*

Inter-Agency Space Debris Coordination Committee Meeting, Berlin, Germany, 2011.

[3] Shiraki K, Noda N. Evaluation of space station JEM MM-OD shield and structural design. *49th International Astronautical Congress*, Melbourne, Australia, 1998.

[4] Christiansen E L, Crews J L. Enhanced Meteoroid and Orbital Debris Shielding. *International Journal of Impact Engineering*, 17: 217-228, 1995.

[5] Cour-Palais B G, Crews J L. A Multi-Shock Concept for Spacecraft Shielding. *International Journal of Impact Engineering*, 10: 135-146, 1990.

[6] Christiansen E L, Herr J H. Mesh Double-Bumper Shield: A low-weight Alternative for Spacecraft Meteoroid and Orbital Protection. *International Journal of Impact Engineering*, 14: 169-180, 1993.

[7] Turner R J, Taylor E A, Anthony J, et al. Cost Effective Honeycomb and Multi-Layer Insulation Debris Shields for Unmanned Spacecraft. *International Journal of Impact Engineering*, 26: 785-796, 2001.

[8] Ryan S, Hedman T, Christiansen E L. Honeycomb vs. Foam: Evaluating Potential Upgrades to ISS Module Shielding. *Acta Astronautica*, 67: 818-825, 2010.

[9] Ryan S, Christiansen E L, Lear D M. Shielding Against Micrometeoroid and Orbital Debris Impact with Metallic Foams. *Orbital Debris Quarterly News*, 14(1), 2010.

[10] Huang X, Ling Z, Liu Z D, et al. Amorphous alloy reinforced Whipple shield structure. *International Journal of Impact Engineering*, 42: 1-10, 2012.

[11] Tamura H, Tanaka Y, Saito F, et al. Quantitative analysis of debris from SiC-fiber-reinforced aluminum-alloy targets impacted by spherical projectiles. *International Journal of Impact Engineering*, 38: 686-696, 2011.

[12] Guo Q, Sun D L, Han X L, et al. Damage behavior of Al matrix composite reinforced with Ti-6Al-4V meshes under the hypervelocity impact. *Materials Science and Engineering A*, 535: 136-143, 2012.

[13] Guo Q, Sun D L, Jiang L T, et al. Residual microstructure associated with impact craters in TiB_2/2024Al composite. *Micron*, 43: 344-348, 2012.

[14] Rudolph M, Schäfer F, Destefanis R, et al. Fragmentation of hypervelocity aluminum projectiles on fabrics. *Acta Astronautica*, 76: 42-50, 2012.

[15] Baluch A H, Park Y, Kim C G. Hypervelocity impact on carbon/epoxy composites in low Earth orbit environment. *Composite Structures*, 96: 554–560, 2013.

[16] Ryan S, Christiansen E L. Hypervelocity impact testing of advanced materials and structures for micrometeoroid and orbital debris shielding. *Acta Astronautica*, 83: 216–231, 2013.

[17] Francesconi A, Giacomuzzo C, Grande A M, et al. Comparison of self-healing ionomer to aluminium-alloy bumpers for protecting spacecraft equipment from space debris impacts. *Journal of Advances in Space Research*, 51:930-940, 2013.

[18] Zheng W, Huang Y J, Pang B J, et al. Hypervelocity impact on $Zr_{51}Ti_5Ni_{10}Cu_{25}Al_9$ bulk metallic glass. *Materials Science and Engineering A*, 529: 352– 360, 2011.

[19] Hou M Q, Gong Z Z, Zheng J D, et al. Hypervelocity Impact Mechanism of Gong-Hou Shield. *The 30th Inter-Agency Space Debris Coordination Committee Meeting*, Montreal, Canada, 2012.

[20] Hill S A. Determination of an Empirical model for the prediction of Penetration Hole Diameter in Thin Plates from Hypervelocity Impact. I*nternational Journal of Impact Engineering*, 30: 303-321, 2004.