EXPERIMENTAL RESEARCH ON PERFORMANCE OF AL-FOAM STUFFED WHIPPLE SHIELD AGAINST HYPERVELOCITY IMPACT

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ABSTRACT

Al-foam is a promising shielding material in the structural design of manned spacecrafts and satellites in the future. An Al-foam Stuffed Whipple Shield was presented under the concept of light-weight shield structure. Three different configurations were proposed with nearly the same total bumper areal density. Three porosities of Al-foam plate were adopted for each configuration with varying thicknesses to keep the same areal density. Hypervelocity impact tests were performed using two-stage light gas gun at 2km/s and 4km/s. The Al-foam Stuffed Whipple Shields have better performances than the equivalent Aluminum Plate Stuffed Whipple Shield and the Whipple Shield at the velocities tested. And Al-foam of higher porosity stuffed can provide better shield performance for the same configuration at a less significant level.

1. INTRODUCTION

All spacecraft in low earth orbit are subject to the risk of hypervelocity impact by meteoroids and space debris. These impacts can damage flight-critical systems, which can in turn lead to catastrophic failure of the spacecraft. The use of a shield can significantly decrease the probability of a catastrophic failure. The Whipple Shield was the first configuration developed to protect spacecraft against meteoroids and orbital debris. Considerable advances have been made in the development of constructive schemes based on the idea of a Whipple Shield at the present time. The performances of these shields developed are always compared with that of a Whipple Shield to have their capability evaluated against hypervelocity impact.

In spite of these advances, attempts continue to be made to find a structure and material for the bumper that will provide better fragmentation of the projectile. A possible solution can be the use of bumpers with inhomogeneous structures. It was reported in [1] that bumpers made from high-porosity copper with a density from 2.2 to 4.0 g/cm^3 disrupt a steel projectile better than duralumin bumpers of the same mass for impact velocities from 3 to 5 km/s. It was shown in [2] that a double-layer bumper made of high-porosity copper/ duralumin fragments a spherical steel projectile better than a duralumin bumper at the impact velocities in a range from 3 to 5 km/s at the same thickness and areal densities of the bumpers, and the former yields a secondary debris cloud constituting fragments in smaller sizes at lower velocities. The Enhanced Space Debris Shields Technology Program funded by European Space Agency carried out experiments of hypervelocity impact on shields containing aluminum-foam bumpers, whose results indicate that the by-layered Al-foam or Al-foam sandwiched configurations have outstanding capabilities to induce multiple shocks to the projectile in the completely velocity range [3-5]. The tests showed the multiple shocking process capable to completely melt the impacting projectile both at about 6 and about 4 km/s, and quite a good deal of melting was observed also at velocities as low as 2.6 km/s [3]. It was also reported in [3] that Al-foam can cause a strong radial dispersion of the secondary debris cloud, which coincide with the results of numerical simulations in [6]. As a result, Al-foam is a promising shielding material in the structural design of manned spacecrafts and satellites in the future.

However, the good performances of by-layered Al-foam sandwich was obtained for rather thick foam layers with a significant mass penalty with reference to a Whipple Shield configuration with Nextel stuffing [3]. In order to investigate the performance of light-weight shield structure containing thin Al-foam, an Al-foam Stuffed Whipple Shield was presented in this article and hypervelocity impact experiments were performed using two-stage light gas gun. The damages of the Al-foam stuffed and the rear wall were examined thoroughly after impact and compared to each other to evaluate the shield performance of different configurations and the influence of Al-foam porosities as well. All results were also compared with those of the classic Whipple Shield and the equivalent solid aluminum plate stuffed Whipple Shield with the same areal density to show the better performance of the Al-foam Stuffed Whipple Shield structure presented.

2. HYPERVELOCITY IMPACT TEST SCHEME

2.1. Test Facility

The tests were performed at the non-powder two-stage light gas guns of the Harbin Institute of Technology (HIT), which can accelerate a projectile up to 7km/s, as shown in Fig. 1. The gun comprises three parts, including projectile launch, velocity measure, and target

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chamber. The pump tube caliber is 57mm, and the launch tube calibers are 5.4mm, 7.6mm, 12.7mm and 14.5mm respectively. The drive gases of the first and second stage are nitrogen and hydrogen respectively. The projectile velocities can be measured by magnetic induction and/or laser beam cutoff instruments. Test specimens are fixed in the vacuumed target chamber which simulates space environments.

Figure 1. Two-stage light gas guns at HIT

2.2. Shield Configurations

Three Al-foam Stuffed Whipple Shield configurations were proposed with nearly the same total bumper areal density of 0.55 g/cm^3, as shown in Fig. 2. The total shield space was 100mm. The base material of the form used was Al-Si alloy ZL102 (AlSi12). The porosity of the Al-foam plate was made to be 50%, 60% and 70% respectively but varying in thickness to keep a same total bumper areal density. The foam has open cell with average hole diameter being 1mm. The three shield configurations used the same 5A06 aluminum alloy rear wall of 2mm in thickness. The Al-foams stuffed in Shields A and B possess the same area density as that of a 1mm thick solid 2A12 aluminum alloy plate. The Al-foam stuffed in Shield C has the areal density of a 1.5mm thick solid 2A12 aluminum plate. Thus the three shield configurations have the same total bumper areal density as that of a 2mm thick solid 2A12 aluminum plate.

For comparison purpose, two Aluminum Plate Stuffed Whipple Shield configurations were also presented with the same total bumper areal density as that of the Al-foam Stuffed Whipple Shield, which are shown in Fig. 3.

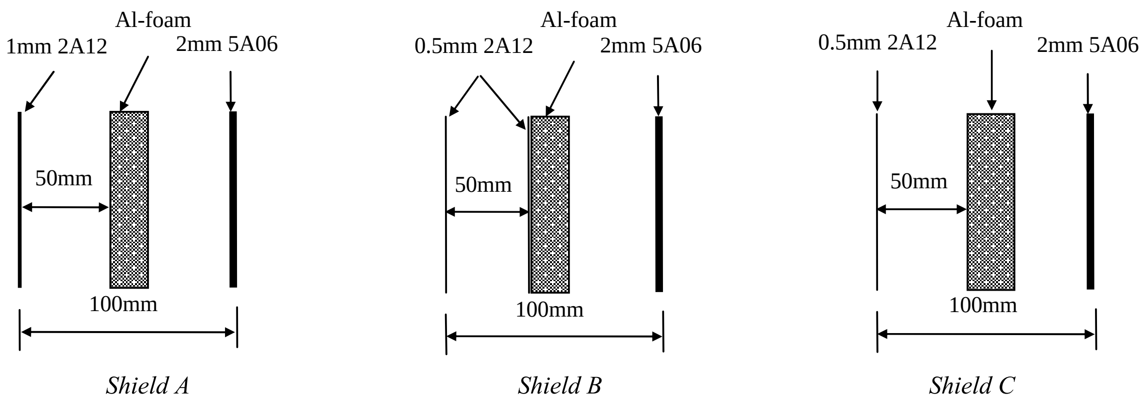


Figure 2. Al-foam Stuffed Whipple Shield configurations

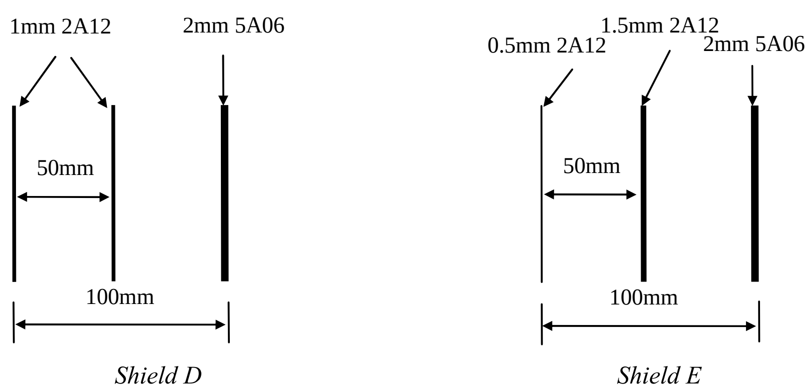


Figure 3. Aluminum Plate Stuffed Whipple Shield configurations

3. TEST RESULTS AND ANALYSES

The projectile launched was 2017 aluminum sphere with its diameter fixed to be 3.97mm. And the impact velocity was chosen to be 2km/s and 4km/s, i.e. below and above the projectile fragmentation speed respectively. The relative error of launch velocity was within 5%, and the incident angle was 0 degree. The test results for Shields A-E are listed in Tab. 1, where a test result of Whipple Shield is also listed for comparison. The Whipple Shield had a 2A12 aluminum alloy bumper of 2mm in thickness with other conditions the same as those of Shields A-E. Typical photos of specimen after impact are shown in Fig. 4.

Table 1. Test results for the shield configurations proposed

Test No. for Shield A	Impact velocity /km/s	Hole diameter of first bumper /mm	Al-foam bumper			Damage of rear wall		Total bumper areal density /g/cm^3
			Porosity /%	Thickness /mm	Hole size /mm	Hole size /mm	Number of bulges	
ZH-02	2.05	5.4	50	2.1	8×9	5.5×4.3	4 small	0.55525
ZH-14	1.999	5.26	60	2.6	6×8	Φ5mm	4 tiny	0.5526
ZH-18	2.042	5.3	70	3.3	12×9	5.4×4mm	6 small	0.53935
ZH-01	4.08	6.8	50	2.1	33×28	-	4 tiny	0.55525
ZH-03	4.02	6.6	60	2.6	35×26	-	11 tiny	0.5526
ZH-04	4.04	6.6	70	3.3	45×41	-	4 tiny	0.53935

Test No. for Shield B	Impact velocity /km/s	Hole diameter of first bumper /mm	Intermediate bumper				Damage of rear wall		Total bumper areal density /g/cm^3
			Hole diameter of front plate/mm	Al-foam bumper					
				Porosity /%	Thickness /mm	Hole size /mm	Hole size /mm	Number of bulges	
ZH2-11	2.026	4.68	5.92	50	2.1	8×8	5.86×5.38	3	0.55525
ZH2-12	2.026	4.74	6.12	60	2.6	8×8	5.18×4.44	2	0.5526
ZH2-10	2.1568	4.82	6.10	70	3.3	7×8	Φ5.54	6	0.53935
ZH2-38	4.093	5.68	12.66	50	2.1	Φ24	-	16 small	0.55525
ZH2-36	4.062	5.66	22×18	70	3.3	40×50	-	7 small	0.53935

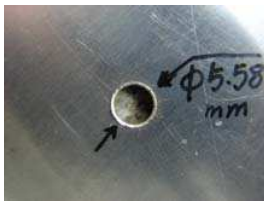
Test No. for Shield C	Impact velocity /km/s	Hole diameter of first bumper /mm	Al-foam bumper			Damage of rear wall		Total bumper areal density /g/cm^3
			Porosity /%	Thickness /mm	Hole size /mm	Hole size /mm	Number of bulges	
ZH2-09	2.0156	4.74	50	3.1	8×9	4.76×5.32	-	0.54925
ZH2-08	2.0056	4.76	60	3.9	6×8	4.06×4.68	6 tiny	0.5519
ZH2-06	2.057	4.76	70	5	7×8	3.74×5.44	4 small	0.536
ZH2-40	4.0805	5.64	50	3.1	20×26	-	7 small	0.54925
ZH2-39	3.98	5.58	60	3.9	22×20	-	1 big, 9 small	0.5519
ZH2-38	4.0065	5.62	70	5	17×11	-	5 small	0.536

Test No. for Shield D	Impact velocity /km/s	Hole diameter of first bumper /mm	Hole diameter of intermediate bumper /mm	Damage of rear wall		Total bumper areal density /g/cm^3
				Hole size /mm	Number of bulges	
ZH2-07	2.04	5.44	6.38	5.06×4.52	10	0.554
ZH-17	4.03	6.7	13	-	22	0.554

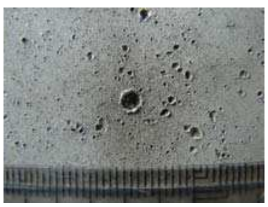
Test No. for Shield E	Impact velocity /km/s	Hole diameter of first bumper /mm	Hole diameter of intermediate bumper /mm	Damage of rear wall		Total bumper areal density /g/cm^3
				Hole size /mm	Number of bulges	
ZH2-03	2.026	4.76	6.4	5.66×4.92	4	0.554
ZH2-34	3.95	5.50	9	Φ2.94	28	0.554
Whipple Shield	4.0128	8.4	-	1×3, 1×2 (3 spalls)	76(including big)	0.554

3.1. Performance of different configurations

At the velocity of about 2km/s, it can be seen from Tab. 1 that all rear walls were perforated for Shields A-E, which indicate that the projectile is not fully fragmented at this velocity just as for the Whipple Shield. If the average size of holes in rear walls is considered for different porosities of individual Shield A-C, then it can be concluded that Shield C has the best shield performance among Shields A-E since it has the smallest hole perforated. But not all three Al-foam Stuffed Whipple Shield configurations A-C have better performance than the Aluminum Plate Stuffed Whipple Shields at this velocity. Shield C also has the smallest hole perforated through the Al-foam stuffed in Shields A-C, which implies that the thicker Al-foam stuffed might help to decelerate the projectile in intact status more effectively than thinner ones as well as solid Al-plate stuffed since it can induce more multiple shocks to the projectile.



Perforation of the first bumper *Perforation of the Al-foam*



Craters of the rear wall *Bulges of the rear wall*

Figure 4. Test results of No. ZH2-39

At the velocity of about 4km/s, it can be seen from Tab. 1 that all rear walls were not perforated for Shields A-D, which indicate that the projectile is fully fragmented at this velocity just as for the Whipple Shield. Shield E and the Whipple Shield failed, so they are not as good as Shields A-D at this velocity. All three Al-foam Stuffed Whipple Shield configurations A-C have better performance than Aluminum Plate Stuffed Whipple Shield D, different from the result at the speed of 2km/s, from comparison of average number and rough size of bulges on the back of rear wall which reflect indirectly the damage severity of rear wall. Thus it is implied that the multiple shocking effect produced by Al-foam is more effective on small impacters than big ones, owing to the projectile’s fragmentation or not, from the comparison of overall performance at between the speed of 2km/s and 4km/s for different shield types. And there should exist a rational range of ratio between impacter diameter and Al-foam average cell-wall width for the foam to have its multiple shocking capability fully worked. Shield A has the best performance among Shields A-C since it has the least and smallest bulges on rear wall. And Shield A has the largest hole perforated through the Al-foam stuffed in Shields A-C, just on the contrary of that at the speed of 2km/s, which suggest that the stronger radially dispersed debris cloud yielded by the thicker first bumper in this configuration gets even stronger after perforating through the Al-foam stuffed, though not as thick as that in Shield C, thus causing the weakest damage on the rear wall. This can be explained to be that the multiple shocking effect of Al-foam is more effective on the stronger radially dispersed debris cloud, in which more particles of smaller sizes are possible to exist so as to facilitate the multiple shocking effect. Thus a properly balanced combination of the first Al-plate and the Al-foam stuffed is expected to provide good shield performance at higher velocities, and this needs further experimental justification.

It should be noticed that there is no obvious evidence of projectile melting even at the velocity of 4km/s for all three Al-foam Stuffed Whipple Shield configurations. This is because that the Al-foam plates adopted are not thick enough to induce sufficient multiple shocks to melt the projectile, unlike the results in [3].

From above analyses it can be seen that the performance of shields containing Al-foam as a stuff are complicated. But the Al-foam Stuffed Whipple Shield configurations proposed do have better performances in an overall point of view than the Aluminum Plate Stuffed Whipple Shield and the Whipple Shield as well at the velocities tested.

3.2. Influence of Al-foam porosities

At the velocity of about 2km/s, it can be seen from Tab. 1 that the hole sizes of rear wall are very close to each other for the three porosities in each individual Al-foam Stuffed Whipple Shield A-C. It is hard to tell which porosity of Al-foam stuffed can help provide the best shield performance because the projectile is not fully fragmented and the Al-foam plates stuffed are not thick enough to load sufficient multiple shocks on the projectile in intact status to produce any notable differences. Thus it could be said that each shield configuration has the same performance for the three porosities of Al-foam stuffed at this velocity if the experimental measurement errors are considered.

At the velocity of about 4km/s, it can be seen from Tab. 1 that the Al-foam stuffed with the highest porosity of 70%, among the three porosities used, can help provide the best shield performance for each individual Al-foam Stuffed Whipple Shield A-C since it causes the least and smallest bulges on rear wall, though the differences not as significant as those yielded from different shield configurations. This also suggest that the thicker Al-foam stuffed, higher in porosity implied under same areal density, can help provide the better shield performance for the same configuration at this velocity due to it can load more multiple shocking on the particles in the debris cloud than thinner ones do. But there should exists a critical highest value of the porosity to help provide the best shield performance due to the existence of rational range of ratio between impacter diameter and Al-foam average cell-wall width.

As a result, the Al-foam stuffed with the highest porosity of 70%, among the three porosities used, can provide the best shield performance in an overall point of view for each individual Al-foam Stuffed Whipple Shield at the velocities tested. And the higher the porosity is within the critical value, the better performance can be expected.

4. CONCLUSION

The performances of shields containing Al-foam as a stuff against hypervelocity impact are complicated, but some rules can be found and explained basically on the multiple shocking mechanism of Al-foam stuffed.

At the velocity of 2km/s, the projectile would not be fragmented by the first Al-bumper, thus only the properly designed Al-foam Stuffed Whipple Shield configuration, the thicker Al-foam plate expected, can provide better performance than the Aluminum Plate Stuffed Whipple Shield with all the other conditions the same. The porosity of Al-foam stuffed seems to have not any influence on the performance of different Al-foam Stuffed Whipple Shield configurations at this velocity.

At the velocity of 4km/s, the projectile would be fragmented completely by the first Al-bumper, thus all three Al-foam Stuffed Whipple Shield configurations can provide better performance than the Aluminum Plate Stuffed Whipple Shield as well as the Whipple Shield. The shield configuration stuffing Al-foam plate of higher porosity, thicker in width implied under same areal density, can provide better shield performance than those of lower porosity at this velocity, at a less significant level than those yielded from different shield configurations.

The differences of performances between the three Al-foam Stuffed Whipple Shield configurations proposed are limited due to it is thin Al-foam plates that are stuffed in the shields, under the concept of light-weight shield structure, and they can not induce enough multiple shocks on the projectile to yield any distinct differences.

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