



# Hypervelocity Impact Phenomenon in Bulk Metallic Glasses

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#### Abstract:

Collisions with debris are major cause of concern for spacecraft and satellites. Developing new materials that can combat these threats, while still providing low-density and sufficient toughness to survive launch loads, is important for future spacecraft design. In the current work, hypervelocity impacts are used to estimate the ballistic limit for bulk metallic glass and their composites and to investigate spalling behavior. The composites are shown to have excellent combinations of hardness and toughness for use as shields.

## 1. Introduction

Over the last 50 years, the number of space missions has substantially increased, as more countries have become space capable and as smaller, cheaper spacecraft have become more widely available. With this increase in space activity comes a dramatic increase in space debris, which has been exponentially increasing for the last 15–20 years. This results in an increasingly large amount of metal debris orbiting Earth, traveling at velocities ranging from 8 to 18 kms<sup>-1</sup> [1–4]. This debris





poses a serious and ever increasing threat to spacecraft, satellites, and manned space stations, as impacts with debris can cause loss of functionality or loss of life [4].

Although debris of all sizes is a concern for spacecraft collision, it is small, undetectable debris that poses the most serious threat to space missions. Micro-meteoroid and orbital debris (MMOD) is generally classified as debris less than 100mmin diameter, and is too small to be detected by groundbased radar systems, which track lager objects [2]. Shielding is therefore an integral component of spacecraft structural design to ensure the highest probability of survival during an MMOD impact. As such, spacecraft shielding is applied in such a manner as to vaporize an incoming projectile without penetration or detached spall occurring from the back wall of the shield. Standards for testing shield materials for the International Space Station (ISS) define shield failure as a complete penetration, a through-hole, a through-crack, or detached spall in the rear wall of the shield [3]. Assessing the performance of spacecraft shields requires ground-based hypervelocity impact testing, where various geometries of shields are subjected to impacts of particles that range from microns to centimeters in size fired at velocities from 0.5 to 10kms<sup>-1</sup>. A typical MMOD threat is generally considered to be an approximately 3mm diameter projectile, but groundbased hypervelocity facilities can only fire projectiles of this size up to 7 kms<sup>-1</sup>. This velocity is typically below that which would be seen during an actual MMOD impact, so groundbased testing must be used as a predictor for real impacts. In order to predict the hypervelocity impact response of materials at higher velocities (8–18kms<sup>-1</sup>), ballistic limit equations (BLEs) are developed using the slower ground-based tests. These equations allow for calculation of the critical shield thickness required to avoid penetration or detached spall, and they are a function of physical properties of the shield material (i.e., density, hardness, etc.) and properties of the projectile (i.e., density, diameter, velocity, etc.). BLEs are developed through a L. Hamill, S. Roberts, M. Davidson, W. L. Johnson, S. Nutt, D. C. Hofmann, Adv. Eng. Mater. 2013, 16, 85-93. DOI: 10.1002/adem.201300252





combination of empirical hypervelocity impact test results and analytical models and simulations [4].

Ballistic impact responses of common shielding materials such as aluminum, titanium, and stainless steel have been widely studied through extensive hypervelocity testing and computational simulation. The developed equations allow for the calculation of penetration depth as a function of projectile velocity, assuming a semi-infinite target. Critical shield thickness is then calculated based on the desired failure mode. Equations 1–3 give the well-established BLEs of aluminum, titanium, and stainless steel [5].

$$P_{\rm Al} \ge 5.24(d)^{19/18} (\text{BHN})^{-0.25} \left(\frac{\rho_p}{\rho_t}\right)^{0.5} \left(\frac{V\cos\theta}{C_t}\right)^{2/3}$$
 (1)

$$P_{\rm Ti} \ge 5.24(d) (\rm BHN)^{-0.25} \left(\frac{\rho_p}{\rho_t}\right)^{0.5} \left(\frac{V\cos\theta}{C_t}\right)^{2/3}$$
 (2)

$$P_{\text{Steel}} \ge 0.434(d)^{19/18} \left(\frac{\rho_p}{\rho_t}\right)^{0.5} (V \cos\theta)^{2/3}$$
(3)

In these equations, *d* is the projectile diameter (cm), BHN the Brinell hardness of the target (in this case the shielding material),  $\rho$  the density of the projectile (*p*) and target (*t*) (g cm<sup>-3</sup>), *C<sub>t</sub>* the speed of sound in the target (km s<sup>-1</sup>), *V* the projectile velocity (km s<sup>-1</sup>), and  $\theta$  is the impact angle from the target normal. Critical thickness, given in Eq. 4, can be determined based on the desired failure mode, where K = 1.8, 2.4, or 3.0 to prevent perforation, detached spallation or incipient spallation, respectively [5]. Here, *t<sub>s</sub>* refers to the critical thickness of the shield, and *P*<sub>∞</sub> refers to the ballistic limit of the shielding material assuming semi-infinite thickness.

$$t_s \le K^* P_{\infty} \tag{4}$$

Similarities between Eqs. 1–3 suggest that an ideal shield would consist of a material with high hardness and high density, even though practicality indicates that a low areal density is used

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to reduce the mass of spacecraft. As such, an optimal shielding material is one that combines high hardness with the lowest density possible. A ceramic would appear to be an optimal choice, but one material property that is not explicitly shown in these equations is that of low melting temperature. Using a material with a low melting temperature results in vaporization of the shield upon hypervelocity impact, decreasing the chance of solid particles making it through to the spacecraft wall [6]. Ceramic shields may not melt during impact and could threaten the spacecraft wall with debris. Moreover, the shielding material needs to possess a sufficient toughness to survive launch loads. These observations demonstrate why high-performance crystalline metals are typically used as shields.

Considering these requirements for effective shielding, amorphous metal (AM), also known as bulk metallic glass (BMG) when made thicker than 1 mm, appears to be a strong candidate for hypervelocity impact shielding. AMs are multicomponent alloys that are designed around deep eutectics such that they can be quenched from the liquid state into a noncrystalline, glassy state [7-10]. The amorphous microstructures created in these alloys allow for unique mechanical properties compared to crystalline metals. BMGs can exhibit carbide-like hardness (650 BHN, 60 RC), near theoretical yield strengths (>2 GPa), and high elastic limits (2%). They also exhibit polymer-like processability, allowing for complex shapes to be constructed [12]. BMGs can therefore have densities similar to other crystalline alloys (e.g., titanium) but with hardness typically found in ceramics. Moreover, BMGs can have much higher toughness than ceramics, which allows them to be used in structural applications. Monolithic BMGs are extremely hard, but brittle due to their inability to arrest a growing crack. Recent work has therefore focused on a new class of metal matrix composites. BMG matrix composites (BMGMCs) incorporate ductile, crystalline dendrites into an amorphous matrix which prevent shear bands that form in the L. Hamill, S. Roberts, M. Davidson, W. L. Johnson, S. Nutt, D. C. Hofmann, Adv. Eng. Mater. 2013, 16, 85-93. DOI: 10.1002/adem.201300252





glass matrix from evolving into opening cracks [11–13]. The result is high fracture toughness (>200MPa m<sup>1/2</sup>), increased fatigue endurance limit (30% of yield strength), and improved ductility (>10%). BMGMCs typically have a density comparable to that of titanium (5.1–5.8 g cm<sup>-3</sup> vs. 4.5– 5.0 g cm<sup>-3</sup>, respectively), while exhibiting more than twice the hardness (600 BHN vs. 250 BHN, respectively), leading to interest as a spacecraft shield [14–18].

In this study, we use hypervelocity impact testing to estimate BLEs for the BMG Vitreloy 1  $(Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5})$  and the BMGMC DH1  $(Zr_{36.6}Ti_{31.4}Nb_7Cu_{5.9}Be_{19.1})$ . We base our analysis and BLE development on data obtained from previous hypervelocity impact tests owing to the few number of impacts that were available for the current work.

Hypervelocity impact tests were conducted in November, 2011 at the NASA Ames Vertical Gun Range (AVGR) and consisted of nine total impact shots (outlined in Table 1). Figure 1 shows the AVGR facility and experimental setup. Using a 0.3 cal light-gas gun, impact velocities of 0.8-2.79kms<sup>-1</sup> were achieved with an aluminum spherical projectile 3.17mm in diameter. Although the AVGR facility is capable of firing 3.17mmaluminum projectiles at 5.5kms<sup>-1</sup>, the determination of BLEs require that some of the plates are not penetrated during impact. Based on the thickness of the available BMG sheets, the velocity was selected to be between 0.8 and 2.79kms<sup>-1</sup>. It should be noted that while these velocities are much slower than actually MMOD impacts, they are needed to determine the material's response, rather than a particular shield architecture response. The performance of a BMG in an actual shield configuration, with similar areal density to heritage shields, is outside the scope of the present work. Figure 1(a) shows the test frame used to hold the samples used for hypervelocity testing. The cutout in the top plate was added after a shadow was observed to have obscured an impact (as discussed below). Figure 1(b) shows a large plate of the BMG Vitreloy 1 (Vit 1) that was cut into several test pieces, approximately 100mm on a side. L. Hamill, S. Roberts, M. Davidson, W. L. Johnson, S. Nutt, D. C. Hofmann, Adv. Eng. Mater. 2013, 16, 85-93. DOI: 10.1002/adem.201300252





Figure 1(c) shows a long exposure image of the impact of a projectile into the center of the pate, with the clamps used to hold the sample to the fixture visible. Figure 1(d, e) show the arrangement of the three cameras used to capture the experimental data. Two are high-speed and one is setup for long exposures of the impact.

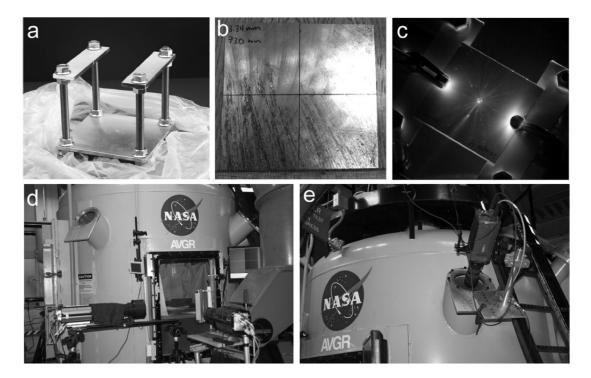


Figure 1: (a) The hypervelocity sample fixture used to support the BMG samples during impact. (b) A large plate of the BMG Vitreloy 1 was sectioned along the black lines to assure a constant test sample thickness of 3.34mm. These plates were cast commercially and donated by Liquidmetal Technologies. (c) A long exposure of a hypervelocity impact into a Vitreloy 1 plate. (d) The configuration of the two high-speed cameras used to capture the impacts and the test chamber at the NASA Ames Vertical Gun Range (AVGR). (e) A long exposure camera filming down on the test specimen from a port in the chamber.

Table 1 gives a description of each of the nine samples used in the study. Five tests were performed on monolithic BMG plates with the same thickness and four tests were performed on BMGMCs ranging in thickness and composition. Single sheets of Vit. 1 were fabricated by diecasting in a commercial process by Howmet. These sheets were donated for the study by Liquidmetal Technologies of Rancho Santa Margarita, Ca. The single-sheet Vit 1 samples were L. Hamill, S. Roberts, M. Davidson, W. L. Johnson, S. Nutt, D. C. Hofmann, *Adv. Eng. Mater.* **2013**, 16, 85-

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impacted at four different velocities (0.82, 1.25, 1.56, and 2.34kms<sup>-1</sup>). One test consisted of four stacked layers of Vit 1 sheets in a Whipple shield configuration and was impacted at a velocity of 2.79kms<sup>-1</sup> to simulate the impact of a multi-walled shield.

**Table 1:** The 9 hypervelocity tests were conducted at an impact angle of 0 degrees using a 3.17 mm diameter aluminium projectile. Three alloys were tested: the BMG Vitreloy 1  $(Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5})$  as well as the BMGMCs DH1  $(Zr_{36.6}Ti_{31.4}Nb_7Cu_{5.9}Be_{19.1})$  and DH3  $(Zr_{39.6}Ti_{33.9}Nb_{7.6}Cu_{6.4}Be_{12.5})$ . NP response stands for "no penetration", while DS denotes "detached spall".

Alloy	Sample description	Mass [g]	Thickness [mm]	Velocity [km s <sup>-1</sup> ]	Ballistic response	Penetration depth [mm]
Vit 1	Single sheet	174.085	3.37	2.34	DS	1.21
Vit 1	Single sheet	176.275	3.38	0.82	NP	0.39
Vit 1	Single sheet	183.549	3.38	1.56	DS	0.79
Vit 1	Single sheet	188.949	3.41	1.25	DS	0.74
Vit 1	4 Layer sheet	151.822	2.82	2.79	DS	1.07
DH1	Single sheet	7.869	0.76	2.34	DS	0.76
DH1	Single sheet	41.916	2.13	0.91	NP	-
DH1	Single sheet	41.190	2.15	1.25	DS	1.3
DH3	Single sheet	45.512	2.34	0.8	NP	-

In order to observe the difference in ballistic impact resistance between BMGs and BMGMCs, two BMGMC alloys were included in the study: DH1 (Zr<sub>36.6</sub>Ti<sub>31.4</sub>Nb<sub>7</sub>Cu<sub>5.9</sub>Be<sub>19.1</sub>) and DH3 (Zr<sub>39.6</sub>Ti<sub>33.9</sub>Nb<sub>7.6</sub>Cu<sub>6.4</sub>Be<sub>12.5</sub>). Both BMGMCs contain ductile crystalline dendrites for increased toughness with volume fraction of 40 and 66% in DH1 and DH3, respectively. Three single-sheet DH1 samples were impacted at three different velocities (0.91, 1.25, and 2.34kms<sup>-1</sup>). Finally, one single-sheet DH3 sample was impacted at a velocity of 0.8kms<sup>-1</sup>. The BMGMCs were fabricated using a semi-solid forging process developed jointly between Caltech and UCSD [12]. In this method, ingots of the various alloys are held isothermally between the solidus and liquidus temperatures to allow coarsening of the dendrites. The samples were then quenched by forging, allowing the remaining eutectic liquid to form a glassy matrix around the dendrites. Two water-cooled copper plates were used to produce thin sheets.

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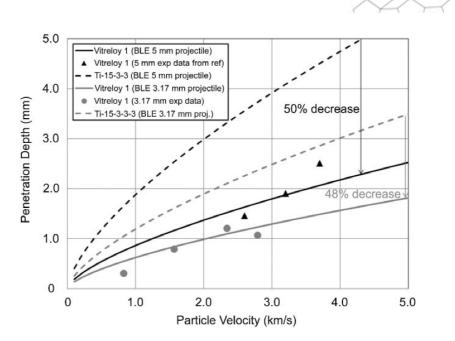




# 2. Penetration Depth

The first experiments performed on the AMs were designed to determine the penetration depth of the Al projectiles into the sheets of the BMGs at various velocities. In the current study, sheets of BMGs were impacted whereas the only penetration experiments from literature were into the ends of thick rods of Vit 1 [19]. Figure 2 compares experimental data from the Vit 1 single-sheet impacts for both the current study and the study from literature with the titanium (Ti-15-3-3-3) BLE (Eq. 2). To determine the penetration depth as a function of projectile velocity, the depth of the crater created by the Al projectile was measured (Table 1). Figure 2 shows penetration depth of Al projectiles on Vit 1 from the current study (using 3.17mm diameter Al projectiles) and from Yang et al. (using 5mm diameter Al projectiles). For each of the different projectile diameters, dotted lines are shown which represent the ballistic limit of Ti-15-3-3 measured from experiments but applied to the projectile diameter used in each study. The slope of the Ti-15-3-3 curves were adjusted to represent the solid curves through the results from the current work and from Yang et al. (the shape of the curves, which were developed using large numbers of impacts, were maintained from titanium) In both the current study and the study from Yang et al., Vit 1 exhibits an approximately 50% decrease in penetration depth compared to Ti-15-3-3. This result is expected since Vit 1 has both a higher hardness (653 BNH compared to 257 BNH) and density than Ti-15-3-3 (6.00 gcm<sup>-3</sup> compared to 4.73 gcm<sup>-3</sup>). At real MMOD impact velocities (8–18kms<sup>-1</sup>) shield melting or vaporization occurs instead of spalling and the material's hardness becomes the critical design property.





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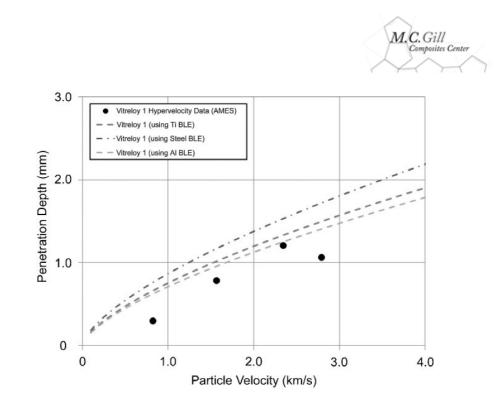
**Figure 2:** Plot of penetration depth versus particle velocity for an aluminum projectile impacting sheets of the BMG Vitreloy 1. The black data is from ref. [20] with a 5mm projectile, the grey data is from the current work with a 3.17mm projectile. In both cases, the dotted lines represent the ballistic limit of Ti 15-3-3 using equations from literature. Due to the limited number of impacts in the BMG, BLEs were not developed; however, they were estimated by modifying the Ti equations with a fitting parameter to match the data. In both cases, about a 50% decrease in penetration depth was observed in Vitreloy 1 compared to the Ti 15-3-3, which was expected from its much higher hardness.

### 3. Ballistic Limit Equation (BLE) Development

BLEs for commonly used shield materials, such as aluminum, steel, and titanium (Eqs. 1–3) have been empirically developed through statistics resulting from large numbers of impact experiments. In the current preliminary study on BMGs, the number of impacts was limited due to cost and availability of materials so some assumptions were used to compare the performance of the BMGs with other, well established materials. As a preliminary assessment, the respective material properties of the BMG Vit 1 were purely plugged into the BLEs for Ti, Al, and steel and plotted

for

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**Figure 3:** Penetration depth versus particle velocity for a 3.17mm Al projectile impacting a single-wall BMG shield. Penetration depth was estimated by digging the Al projectile out of the surface of the sample and measuring the depth with a probe. Since not enough data points were available to estimate the ballistic limit of the BMG, the material properties of the metallic glass were inserted into known equations for Ti, Al, and steel (shown as dotted lines). In all three cases, the variance in the predicted ballistic limit is low and the experimental data outperforms all three predictions. The high hardness of the BMG results in shallow penetration depths.

a 3.17mm Al projectile impacting between 0 and 4 kms<sup>-1</sup>, shown in Figure 3. What is immediately evident is that the three BLEs, which estimate the performance of Vit 1 using well established equations for other materials, are very similar with less than 10% difference in penetration depth. To compare the three equations versus experimental data, four impacts into sheets of Vit 1 were also plotted in Figure 3, at 0.82, 1.25, 1.56, and 2.34kms<sup>-1</sup>. Surprisingly, the experimental data shows a penetration depth lower than all three estimates using established BLEs, indicating that the hardness of the BMG is very effective at stopping penetration. The four shots also verify that the shape of the BLEs for Vit 1 are similar to those predicted from the BLEs for Al, Ti, and steel. Since Vitreloy 1 has a yield strength and a density similar to titanium alloys, the form of the BLE

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developed for Ti was used as an approximation for a BLE for Vit 1. This was done by adjusting the titanium BLE with a fitting parameter, N, which adjusted the shape of the Ti BLE to match the Vit 1 data. Using this method, the BLE determined for Vit 1 is given in Eq. 5 with N = 4.3 or 3.8 (for a 3.17 or 5mm Al projectile, respectively). This is compared to N = 5.4 in Ti.

$$P_{\text{Vit.1}} \ge N^*(d) (\text{BHN})^{-0.25} \left(\frac{\rho_p}{\rho_t}\right)^{0.5} \left(\frac{V\cos\theta}{C_t}\right)^{2/3}$$
(5)

## 4. Detached Spall Behavior

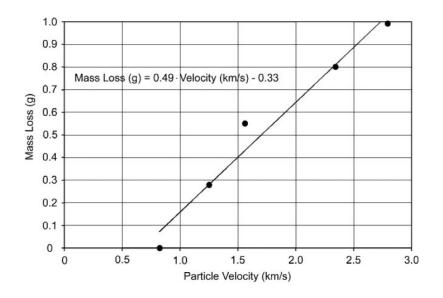
The BLEs for penetration depth assume a semi-infinite sheet of material upon impact and do not account for back surface affects [4]. The BLE for Vit 1 (Eq. 5) was developed purely on penetration depth and did not account for the behavior of BMGs subjected to impact-induced shock waves. Spall is a type of fracture that occurs simultaneously over an area of material. In the case of brittle materials, it is the result of nucleation and growth of many microcracks simultaneously. In hypervelocity impacts, this occurs due to the travel of shock waves through the material. Several groups have studied the spall strength, or resistance to spallation, in BMGs [21,22]. Yuan et al. found that spall strength in the BMG Zr<sub>41,25</sub>Ti<sub>13,75</sub>Ni<sub>10</sub>Cu<sub>12,5</sub>Be<sub>22,5</sub> decreases as impact force increases [23]. The difference in spall behavior between the BMG Vit 1 and the BMGMC  $\beta$ -Vit (Zr<sub>56,3</sub>Ti<sub>13,8</sub>Cu<sub>6,9</sub>Ni<sub>5,6</sub>Nb<sub>5,0</sub>Be<sub>12,5</sub>) was studied by Zhuang et al [24]. Due to the brittleness of BMGs, spalling in Vit 1 is a product of the nucleation, growth and coalescence of microvoids in the shear bands caused by the shock wave. The composite  $\beta$ -Vit, on the other hand, experiences ductile spalling, during which voids grow along the boundary between the ductile bcc  $\beta$  phase and the amorphous matrix. The more brittle a BMG is, the more likely it is to experience severe spalling.

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Figure 2 suggests that Vit 1 out-performs Ti-15-3-3-3 in a ballistic impact because of its increased hardness. However, this data represents only penetration depth and does not encompass all factors important in MMOD shielding and ballistic impact resistance; it does not account for detached spall. In order to quantify detached spall, we measured the total mass loss of each sample after impact. Mass loss as a function of impact velocity is given in Figure 4. The linear trend confirms conclusions from previous studies that detached spall increases with impact velocity. Using Eq. 5 with N = 4.3 to predict the critical shield thickness necessary for preventing detached spall, the data should satisfy Eq. 4 with K = 2.4. However, we observed the actual hypervelocity impact behavior of the Vit 1 samples to be worse than expected because Vit 1 is subject to spalling. At an impact velocity of 2.79kms<sup>-1</sup>, the Vit 1 plate loses 1.0 g of mass.

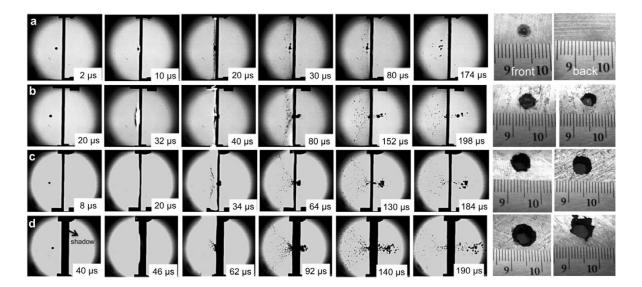


*Figure 4:* Mass loss versus particle velocity for impacts into single-wall BMG Vitreloy 1 sheets with thickness of 3.4 mm. In the case of the low-velocity impacts, the Al projectile was still attached to the plate after impact and the mass loss was due to spalling in the plate. In the 0.8 kms<sup>-1</sup> impact, the Al projectile displaced its exact mass in spall.





Figure 5 shows a series of still images from videos of each Vit 1 hypervelocity impact in increasing impact velocity. The samples are viewed from the side and are backlit to allow for contrast [it should be noted that Figure 5(d) was the first sample impacted and contained a shadow from the holding fixture. This shadow was removed during subsequent tests so that they looked like Figure 5(a-c)]. Figure 5(a) shows that at the lowest velocity of  $0.82 \text{kms}^{-1}$ , the Vit 1 sheet succeeds in catching the 3.17mm Al projectile without resulting in detached spall from the back side of the panel, so-called a "nopenetration" (which is denoted by a closed circle in Figure 6). As the velocity is increased (Figure 5b–d), spalling occurs from the back of the unsupported plate at velocities much lower than were predicted from the BLE in Eq. 5.



**Figure 5:** Hypervelocity impacts into single wall BMG sheets of Vitreloy 1 at (a) 0.82 kms<sup>-1</sup>, (b) 1.25 kms<sup>-1</sup>, (c) 1.56 kms<sup>-1</sup>, (d) 2.34 kms<sup>-1</sup>. The timestamp is the delay from when the laser was triggered by the projectile. The front and back of the plates after impact are shown at the right after the Al projectiles were removed. The only sample that experienced nopenetration was at 0.82 kms<sup>-1</sup>. At higher velocities, the sample spalled from the back and no penetration was observed (the projectile was still adhered to the surface). In (d) the sample holder is casting a shadow which hides the plate. This was removed for the other tests.

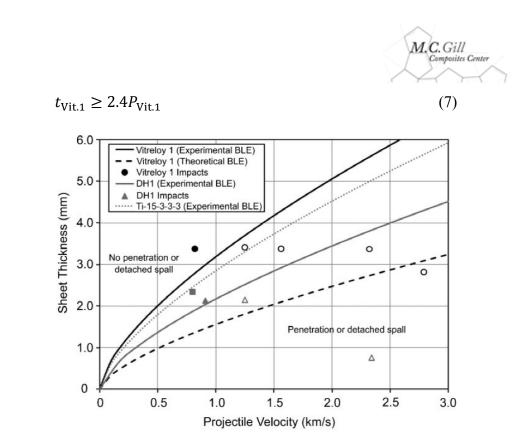




Although the impacts in Figure 5(b–d) appear as though the Al projectile has fully penetrated the plate, there is actually a slight delay in the formation of the spall from the high-speed video, indicating that a propagating wave is responsible for the spall, not the projectile penetrating the plate. In fact, the Al projectile was stuck into the surface of all the Vit 1 plates in Figure 5, indicating that there was not full penetration. These impacts are termed "detached spall," which is separate from "penetration." The still images from Figure 5 also show a debris cloud flying downrange and ejecta splashing backwards off the face of the plate. At these relatively low velocities, the debris cloud and ejecta are comprised of solid spalled material and no melting was observed (which was confirmed by analyzing the debris).

In order to adjust the estimated BLE for Vit 1 based on the penetration data, sheet thickness versus projectile velocity was plotted; closed circles were used to represent samples that experienced no penetration or detached spall and open circles to represent samples that experienced some penetration or detached spall (Figure 6). The blue circles in Figure 6 represent the impacts from Vit 1. The value of *N* in Eq. 5 was adjusted so that the critical thickness line for no-detached spall (Eq. 7) bisected the closed circle and the open circle (since the true ballistic limit must be between those values). The value of *N* was determined to be 9.2 instead of 4.3 as was previously determined from penetration measurements that were independent of spall. In Figure 6, the new ballistic limit with N = 9.2 is shown as a solid blue line, and it is compared with the previously determined (theoretical) limit with N = 4.3. The final BLE for Vit 1 is given in Eq. 6 (where it is noted that the equation has not been verified for changes in impact angle or for velocities above 3 kms<sup>-1</sup>).

$$P_{\text{Vit.1}} \ge 9.2(d) (\text{BHN})^{-0.25} \left(\frac{\rho_p}{\rho_t}\right)^{0.5} \left(\frac{V\cos\theta}{C_t}\right)^{2/3}$$
 (6)



**Figure 6:** Sheet thickness versus projectile velocity for the BMG Vitreloy 1 and the BMG composite DH1. The closed data points represent no-penetration or detached spall while the open data points represent penetration or detached spall. The ballistic limit is the curve that divides the two regions. The dotted black curve represents the theoretical BLE for Vitreloy 1 developing using penetration depth experiments. The actual BLE, shown with the solid black line, is far worse than the prediction, due to the low spall strength of the BMG. The performance of Vitreloy 1 is slightly worse than that of Ti-15-3-3, shown with the dotted grey line, even with its increased areal density. The solid black line is the estimated ballistic limit for the tougher BMG composite, DH1, with embedded crystalline dendrites to improve spall strength. Thinner plates were available for testing in the composite. The one square point is from an impact in an additional BMG composite with a similar composition to DH1, but with increased volume fraction of crystalline phase.

The dotted black line in Figure 6 shows the BLE for Vit 1 that was developed using the penetration experiments alone and the dotted grey line is the BLE for Ti-15-3-3-3 from the literature. Using the data on penetration alone, it appears that Vit 1 outperforms Ti in terms of penetration. However, once spalling was considered, the actual data shows that the performance of Vit 1 is slightly worse than Ti (the solid black line compared to the dotted grey line) and this does not account for the slightly increased density of Vit 1 compared to Ti. As expected from the





literature, Vit 1 is subject to poor shock spalling behavior, even resulting from impacts with small Al projectiles. To address this problem, BMGMCs have been developed by reinforcing the BMG with soft, crystalline dendrites for added toughness and ductility (the mechanical performance of these alloys is well-established in the literature by the current authors). The objective of the next set of hypervelocity experiments is to verify that the increased toughness of BMGMCs leads to an increase in spall resistance when compared to monolithic BMGs. Three single-wall plates of the BMGMC DH1 (a Zr-Ti BMGMC with >5% ductility in tension and a fracture toughness greater than 100MPam<sup>1/2</sup>) were tested. These alloys were fabricated into 25.4mm diameter plates through a semi-solid forging technique in thick sections (2.1mm thick) and thin sections (0.76mm thick), seen in Figure 7.

The three single-sheet samples of the BMGMC DH1 were impacted at three different velocities (0.91, 1.25, and 2.34kms<sup>-1</sup>), and the results from these tests are also plotted in Figure 6 alongside the results of the Vit 1 impacts. Figure 7(c) shows the impact of the 3.17mm Al projectile at 0.91kms<sup>-1</sup> exactly at the ballistic limit for DH1. Although it appears as though no spalling has occurred, a small piece of debris was shown to be traveling down range. As such, the parameter N in the BLE developed for Vit 1 was adjusted so that it passed just to the right of the data point (the impact is shown as a closed grey triangle in Figure 6 and the BLE is shown as a solid grey line). To verify this result, the velocity was increased to 1.25kms<sup>-1</sup> in a DH1 plate of the same thickness (shown in Figure 7d) and detached spall was, in fact, observed. The BLE of the BMGMC DH1 (the solid red line) now outperforms both Ti and Vit 1 substantially, indicating that the much higher toughness of the BMGMC results in a higher resistance to spalling. Moreover, the density of the composites can be tuned to be as low as 5.0 gcm<sup>-3</sup> by increasing the amount of Ti in these alloys and their hardness is still significantly higher than Ti, indicating that they should be L Hamill, S. Roberts, M. Davidson, W. L. Johnson, S. Nutt, D. C. Hofmann, *Adv. Eng. Mater.* **2013**, 16, 85-93. **DOI**: 10.1002/adem.201300252





excellent alternatives to crystalline Ti as shields. A third impact was performed on a thin (0.76mm) single wall sheet of DH1 at a much higher velocity (2.34kms<sup>-1</sup>) to verify that the material does become penetrated. In this impact, shown

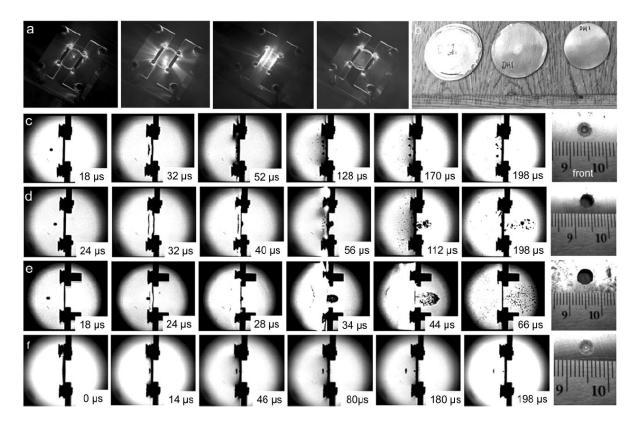


Figure 7: Hypervelocity impacts into single-wall sheets of BMG composites. (a) Long exposures of the impacts shown in (c-f), respectively. (b) Three plates of the BMG DH1 are shown before impact. The plates were made by semi-solidly forging ingots of the composite into a Cu o-ring. This created circular plates with uniform thickness and diameter. Details about the fabrication process can be found in Hofmann et al. JOM (2009). (c) Impact into DH1 plate at 0.91 km s\_1 showing a catch. The front of the plate is shown at the right after impact. (b) Impact into DH1 plate at 1.25 km s\_1 showing detached spall from the back of the sample. (c) Impact into a thin plate of DH1 at 2.34 km s\_1, showing complete penetration. (f) Impact into a BMG composite with a higher volume fraction of crystalline phase (66% vs. 40% in DH1) showing a catch. The higher toughness of the BMG composites decreases the effect of spalling.

in Figure 7(e), the sheet was penetrated by the projectile, leaving a circular hole. For the impacts in

DH1, it was found that the value of N equal to 6.3 best described the data, and the final BLE for





DH1 and the corresponding expression for critical shield thickness to prevent detached spall are given by Eqs. 8 and 9, respectively.

$$P_{\rm DH1} \ge 6.3(d) (\rm BHN)^{-0.25} \left(\frac{\rho_p}{\rho_t}\right)^{0.5} \left(\frac{V\cos\theta}{C_t}\right)^{2/3}$$
(8)  
$$t_{\rm DH1} \ge 2.4P_{\rm DH1}$$
(9)

One impact was also performed on the BMGMC DH3, which is comprised of the same composition BMG matrix as DH1 but with a much higher volume fraction of crystalline phase (66% vs. 40%). DH3 is notable for its ultra-high toughness (~200MPam<sup>1/2</sup>). One impact was performed at 0.8kms<sup>-1</sup> and no penetration or detached spall was observed [Figure 6 and 7(f)]. This verifies that increasing the volume fraction of soft crystals did not adversely affect the ballistic limit. However, with only one impact, and no penetration, a comparison between DH3 and DH1 was not possible. Figure 7 (a) shows long exposure images from the four BMGMC impact tests, Figure 7(b) shows the samples prior to impact testing, and the column on the right of Figure 7(c–f) shows images of the front surface of the plates after impacting.

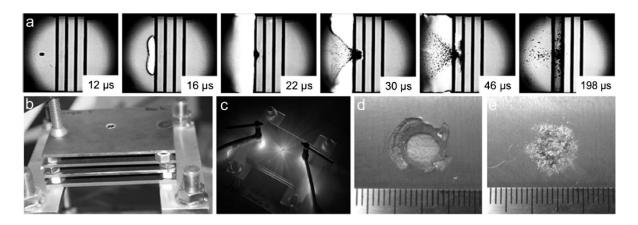
### 5. Shielding Geometries

The range of velocities in the current study (0.8–2.8kms<sup>-1</sup>) is much lower than the velocities of actual MMOD impacts (8–18kms<sup>-1</sup>). Using the final estimated BLEs for Vit 1 and DH1 (Eqs. 6 and 8), it can be seen that the critical thickness to prevent detached spall upon an impact of a 3.17mm Al projectile traveling at a velocity of 15kms<sup>-1</sup> is equal to 19.4 and 13.1mm for Vit 1 and DH1, respectively. As velocity increases, so does the critical thickness required to prevent detached spall, and thus, areal density is added to the shielding. Therefore, in order to effectively shield a spacecraft wall from perforation, multi-layer shield configurations (called Whipple L. Hamill, S. Roberts, M. Davidson, W. L. Johnson, S. Nutt, D. C. Hofmann, *Adv. Eng. Mater.* **2013**, 16, 85-93. **DOI:** 10.1002/adem.201300252





shields) are used to progressively diffuse and catch projectiles and debris. Figure 8(a) shows the performance of a 4-wall Whipple shield constructed of four stacked sheets of Vit 1 with a gap (called standoff) in between each layer (the standoff was approximately twice the thickness of the sheets in the current



**Figure 8:** (a) 2.79 kms<sup>-1</sup> impact into a 4-wall Vitreloy 1 Whipple shield showing penetration of only the first layer. (b) The sample holder after impact and (c) a long exposure of the entire impact. (d) The hole generated in the back of the first layer and (e) the debris embedded in the second layer.

test, 6 mm). The thickness of each sheet was 2.82mm, and the impact velocity was 2.79kms<sup>-1</sup>, the maximum velocity accessible using the current gun configuration. Equation 6 and Figure 6 show that a single sheet of thickness 2.82mm shot at a velocity of 2.79kms<sup>-1</sup> would result in penetration or detached spall; however, the four wall shield is able to completely arrest the impact using only one additional layer and standoff. The debris cloud is sufficiently diffuse after the impact with the bumper shield (or outer shield) that the second sheet does not experience a localized impact. In the design of actual spacecraft shields, wall thickness, standoff distance and material selection are all used to provide the maximum amount of shielding capability at the lowest possible areal density. Figure 8(b–e) show the post-mortem images of the Whipple shield impact.

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In this study, we determined approximate BLEs for the BMG Vit 1 and the BMGMC DH1. We observed the hypervelocity impact resistance of Vit 1, DH1, and DH3 single-sheet samples. In addition, we saw that multi-wall shields are effective in diffusing impact energy. Because there was a limited number of hypervelocity runs, the BLEs derived in this study are not meant to represent standard equations for the materials. Many more shots on each material are needed along with extensive computational simulation before a comprehensive set of equations can be developed. This work does, however, motivate the use of amorphous materials in spacecraft shields. Ongoing work in this area is focusing on developing new laminate composites, lowdensity panels using Ti-based

BMGs, and higher velocity impacts.

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#### **References**:

- 1. Committee on Space Debris, National Research Council, Orbital Depris: A Technical Assessment, Nat. Acad. Press, Washington, DC 1995.
- 2. Scientific and Technical Subcommittee of the United States Nations Committee on the Peaceful Uses of Outer Space, *Technical Report on Space Debris*, United Nations, New York **1999**.





- 3. E. L. Christiansen, K. Nagy, D. M. Lear, T. G. Prior, Acta Astronautica 2009, 65, 921.
- 4. E. L. Christiansen, in: *Handbook for Designing MMOD Protection*, National Aeronautics and Space Administration Johnson Space Center, Houston, TX **2009**, Ch. 1–4.
- 5. S. Ryan, E. L. Christiansen, *Micrometeoroid and Orbital Debris (MMOD) Shield Ballistic Limit Analysis Program.* TM-2009-2147 89, National Aeronautics and Space Administration Johnson Space Center, Houston, TX **2010**.
- 6. M. Davidson, S. Roberts, G. Castro, R. P. Dillon, A. Kunz, H. Kozachkov, M. D. Demetriou, W. L. Johnson, S. Nutt, D. C. Hofmann, *Adv. Eng. Mater.* **2012**, 15, 27.
- 7. W. L. Johnson, *MRS Bull.* **1999**, 24, 42.
- 8. R. Busch, W. Liu, W. L. Johnson, J. Appl. Phys. 1998, 83, 4134.
- 9. K. Jin, J. F. Löffler, Appl. Phys. Lett. 2005, 86, 241909.
- 10. Q.Wang, J. Qiang, Y.Wang, J. Xia, C. Dong, J. Non-Cryst. Solids 2007, 353, 3425.
- 11. A. Peker, W. L. Johnson, Appl. Phys. Lett. 1993, 63, 2342.
- 12. D. C. Hofmann, H. Kozachkov, H. E. Khalifa, J. P. Schramm, M. D. Demetriou, K. S. Vecchio, W. L. Johnson, *JOM* **2009**, 61, 11.
- 13. C. C. Hays, C. P. Kim, W. L. Johnson, *Phys. Rev. Lett.* 2000, 84, 2901.
- 14. D. C. Hofmann, J. Y. Suh, A. Wiest, G. Duan, M. L. Lind, M. D. Demetriou, W. L. Johnson, *Nature* **2008**, 451, 1085.
- 15. D. C. Hofmann, J. Y. Suh, A. Wiest, M. L. Lind, M. D. Demetriou, W. L. Johnson, *Proc. Natl. Acad. Sci. USA* **2008**, 105, 20136.
- 16. Y. Wu, Y. Xiao, G. Chen, C. T. Liu, Adv. Mater. 2010, 22, 2270.
- 17. S. Pauly, S. Gorantla, G. Wang, U. Kuhn, J. Eckert, Nat. Mater. 2010, 9, 473.
- 18. M. E. Launey, D. C. Hofmann, J.-Y. Suh, H. Kozachkov, W. L. Johnson, R. O. Ritchie, *Appl. Phys. Lett.* **2009**, 94, 241910.
- 19. J. P. Schramm, D. C. Hofmann, M. D. Demetriou, W. L. Johnson, *Appl. Phys. Lett.* **2010**, 97, 241910.
- 20. C. Yang, R. P. Liu, Z. J. Zhan, L. L. Sun, W. K. Wang, Mater. Sci. Eng., A 2006, 426, 298.
- 21. M. Martin, T. Sekine, T. Kobayashi, L. Kecskes, N. N. Thadhani, *Metall. Mater. Trans. A* 2007, 38, 2689.
- 22. S. J. Turneaure, J.M. Winey, Y.M. Gupta, Appl. Phys. Lett. 2004, 84, 1692.
- 23. F. Yuan, V. Prakash, J. Mater. Res. 2007, 22, 402.
- 24. S. Zhuang, J. Lu, G. Ravichandran, Appl. Phys. Lett. 2002, 80, 4522.