IMPACT TESTS AND SIMULATIONS FOR MULTIFUNCTIONAL MATERIALS

T. Mudric[1], C. Giacomuzzo[1], U. Galvanetto[1*], A. Francesconi[1], M. Zaccariotto[1], A. M. Grande[2], L. Di Landro[2]

[1]Center of Studies and Activities for Space – CISAS "G. Colombo", University of Padua, Via Venezia 15, 35131 Padova (Italy)
[2]Dept. of Aerospace Engineering, Politecnico di Milano, via La Masa 34, 20156 Milano (Italy)
**e-mail address: ugo.galvanetto@unipd.it*

Keywords: hypervelocity impact, ionomer, ballistic protection

Abstract
An experimental investigation of hypervelocity impacts on ethylene-methacrylic acid ionomer plates was carried out. Two impact velocities were considered, 2 and 4 km/s. At each velocity three ionomer and three aluminum targets with various thicknesses were impacted by an aluminum sphere. The objective of the experiment was to investigate the protective capability of the ionomer plates by comparing their impact behavior with that of aluminum plates with the same areal density.

1 Introduction
Vehicles moving in space are mainly subjected to two types of external forces potentially damaging the structure or the scientific equipment on board: thermal variations and impacts with micrometeoroids and space debris. The probability of impacts with debris is particularly high close to the earth where much man-made debris is present. The relative velocity of a spacecraft with respect to debris and or meteoroids depends on the vehicle's orbit and can range from few hundreds of m/s to several tenths of km/s. Above few km/s, impacts between orbiting objects are usually classified as hyper-velocity impacts.
Hyper-velocity impacts are one of the most damaging loading conditions affecting spacecraft, the effects of hypervelocity impacts are a function of impactor and impacted material, impact velocity, incident angle and the mass and shape of the impactor. The consequences of meteoroid and debris impacts on spacecraft can vary widely: from small surface indentation, due to micrometer-size impactors, to clear hole penetrations for larger millimeter-size objects, to mission critical damage for projectiles of one centimeter or more. Any impact of an object of 10 centimeters or more on a spacecraft will most likely cause a catastrophic disintegration of the target. Even if the structural integrity is not fully compromised clear hole penetrations could be extremely damaging if they affect tanks containing gases which are necessary to complete long lasting missions, even more so when human beings are on board. Therefore there is the clear need of self-healing materials capable of immediately closing holes generated by impacts. The authors are investigating experimentally and computationally new materials that could be used in modern spacecraft to reduce the consequences of hypervelocity impacts with millimeter-size aluminum alloy objects. The main objective of the authors is to develop a multifunctional composite panel that will be able to act as a load bearing structure,

repair holes generated by impacts, detect penetration or perforation of the panel and its location, and act as a gas barrier.

Ionomer polymers have the property of “self-healing” following projectile impact. This healing response is an inherent behavior of the ionomer [1]. The self-healing ability of the ionomers makes them very attractive for aero-space applications. The density of the ionomer is 0.95 g/cm^3, which is less than that of other materials used in the aerospace field (composite materials, aluminum,…). Even if its load bearing properties aren’t as good as that of the other commonly used materials, they can be used in combination with other materials to form a multilayer structure that, instead of performing only a structural function, would be also able to close a hole caused by an impact. Such an application would lead to a multifunctional system. Namely, multifunctional materials systems can perform more than one “primary” function simultaneously or sequentially in time and seek to achieve overall system-level performance enhancement through a reduction of redundancy between subsystem materials and functions [2].

This paper presents some preliminary results of impact experiments conducted onto a ionomer. In order to investigate the ionomer under impact, 1.5 mm aluminum spheres were launched at nominal speeds of 2 km/s and 4 km/s into ionomer targets by a two stage light gas gun. The same tests were repeated on aluminum targets for the purpose of comparison of the two. The experiments were performed at the CISAS hypervelocity impact facility (HVI).

2 Experimental procedure

Hyper velocity impact tests were carried out using a two-stage light-gas gun (LGG) at the CISAS hypervelocity impact facility (HVI) [3]. Figure 1 shows the schematic of the CISAS LGG. In a typical shot operation, high-pressure gas is stored in the first stage reservoir of the gun, until it is discharged on the back of the piston through the opening of a custom fast valve (shot valve) [4]. The driver gas coming from the first stage pushes the piston along the pump tube, thus compressing the propellant in the second stage up to very high pressure (e.g. 6000 bar) and temperature [4]. The compressed gas is canalized into the launch tube through a dedicated group of valves, that has been developed to achieve the optimal energy transfer from the second stage gas to the projectile [4].

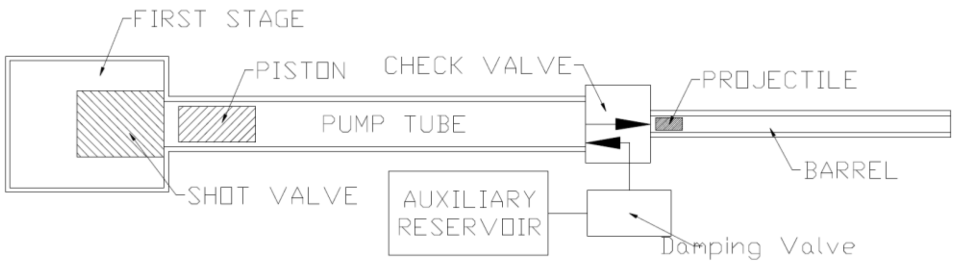

Figure 1. CISAS LGG schematic [4].

At the end of the barrel of the LGG a vacuum chamber is located, in which the target is placed. Two optical barriers detect the sphere pass before it enters in the vacuum chamber, and send signals to the computer, which makes possible to calculate the impact velocity.

Two different target materials were used. Namely, targets of ethylene-methacrylic acid ionomer and targets of aluminum were studied. Ionomer targets were made of a thermoplastic ionomer known by the trade name Surlyn® (DuPont). The polymer used was the Surlyn® 8940, characterized by a content of 5.4 mol% acid groups, of which 30% neutralized with sodium [5]. The density of this ionomer is 0.95 g/cm^3. All the targets were square plates with a side length 120 mm. Different target thicknesses were used. Ionomer targets were 2, 3 and 5

mm thick. Aluminum targets were 0.8, 1.0 and 1.5 mm thick, which correspond to the areal density of the ionomer 2, 3 and 5 mm thick targets, respectively.
The projectiles used in this study were aluminum spheres with a diameter of 1.5 mm.
The targets were attached to a steel frame by means of elastic springs. On the same frame, but behind the target, was mounted a ballistic pendulum with a witness plate made of copper mounted on it. The experimental configuration can be seen in Figure 2 and Figure 3.

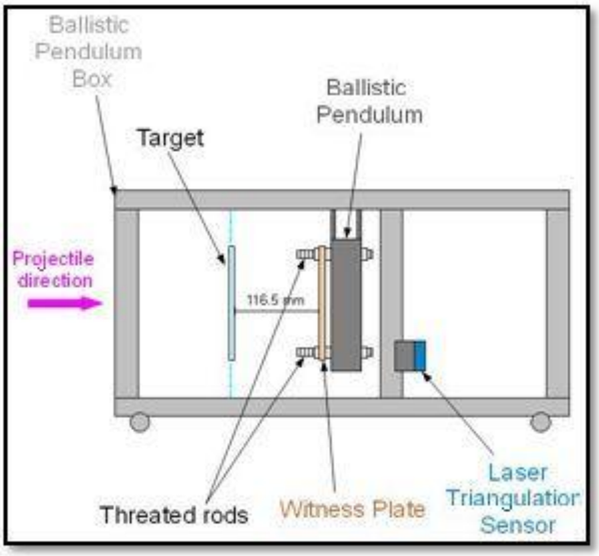

Figure 2. Experiment configuration scheme.

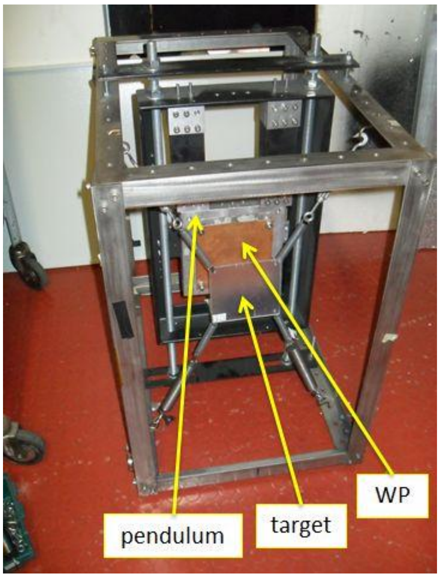

Figure 3. Target, pendulum and witness plate configuration.

The ballistic pendulum is used to measure the momentum transferred to a witness plate after the impact. In the case of perforation or spallation of the target the projectile and the impact debris will collide on the witness plate and cause a displacement of the pendulum. The momentum transferred to the witness plate can be obtained from direct measurement of pendulum maximum displacement. A laser sensor placed behind the pendulum was used to measure the displacement of the pendulum. Those data are still under analysis and are not given in this paper. Moreover, witness plates have been scanned before and after impact.
The impact velocities studied were about 2 km/s and 4 km/s, and all impacts were normal to the target, i.e. at 0˚ impact angle.

Experimental results
Fourteen tests were conducted for this study: six on the ionomer Surlyn 8940 and eight on aluminum targets. Test parameters are reported in Table 1.
After each impact target and witness plate damage was analised both by visual inspection and by using Matlab® codes developed for automatic damage recognition.
For ionomer targets different behaviors under hypervelocity impact were observed. The sketches of the ionomer targets cross sections are depicted in Figure 4, on the same figure also the measured crater diameters are shown. It was observed that at lower velocities (from 1.5 km/s to 2 km/s) a bulge was formed on both sides of the target if it was perforated, that occurred as a consequence of the self-healing ability of the ionomer. The bulge on the rear side was smaller than that on the front side.

Shot No.	**Projectile**			**Target**		**Perforated/Not perforated (P/NP)**
	d_p (mm)	**v_p (km/s)**	**Uv_p (km/s)**	**Material**	**Thickness (mm)***	
8813	1.5	1.93	0.05	Ionomer	2.0	P
8829	1.5	1.80	0.04	Ionomer	3.0	P
8833	1.5	1.64	0.05	Ionomer	5.0	NP
8836	1.5	4.10	0.20	Ionomer	5.0	P
8838	1.5	4.00	0.20	Ionomer	3.0	P
8839	1.5	3.90	0.20	Ionomer	2.0	P
8841	1.5	1.35	0.03	Aluminum	5.0	NP
8842	1.5	2.64	0.08	Aluminum	2.0	P
8843	1.5	1.37	0.03	Aluminum	2.0	P
8844	1.5	1.28	0.03	Aluminum	3.0	P
8845	1.5	3.70	0.10	Aluminum	5.0	P
8846	1.5	4.10	0.20	Aluminum	3.0	P
8847	1.5	4.10	0.10	Aluminum	2.0	P
8848	1.5	2.60	0.10	Aluminum	3.0	P

* For Aluminum targets the thickness is the equivalent thickness obtained assuming the same local density as Surlyn 8940 density.

Table 1. Summary of test parameters for impact on Ionomer Surlyn 8940 and Aluminum targets (d_p – projectile diameter, v_p – projectile velocity, Uv_p – projectile velocity uncertainty).

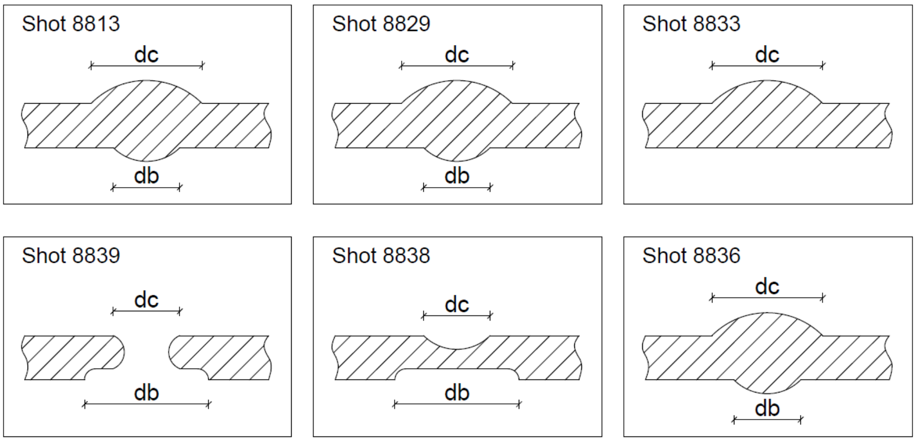

Figure 4. Sketch of the cross section of the ionomer specimens impact zone.

For higher velocities (around 4 km/s) a bulge was observed only for the 5 mm thick ionomer, while the 3 mm ionomer had a crater on both sides, and the 2 mm thick target had a hole through the thickness and did not repair [5]. More details on the self-healing performance of the ionomer in these tests can be found in [5]. At higher velocities and thinner targets (2 and 3 mm) a bulge was not formed most probably because a bigger amount of material was removed from the target, especially from the rear side. Indeed, by examining the surfaces of the ionomer specimens it was noticed that spallation occurred on the targets back side (Figure 5).

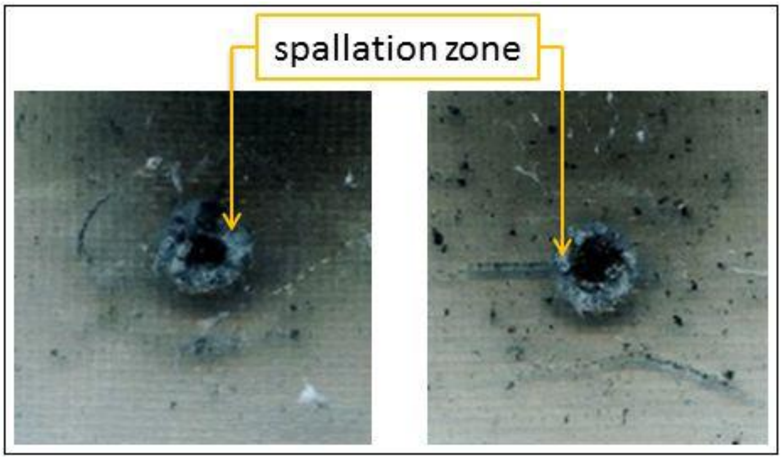

Figure 5. Spallation zone for: v=4,0km/s, t=3mm (left) and v=4,1km/s, t=2mm (right).

In Figures 6 and 7 results for two representative tests (8839 on ionomer and 8847 on aluminum) under same impact conditions are reported: the first refers to target shot-front side, while the second refers to copper witness plate.
A first visual inspection of damage on this two targets showed that hole produced on ionomer sample is smaller than that produced on aluminum plate. On the other side, the analysis of the copper witness plates revealed that the witness plate of ionomer test were hit by few quite large ejecta while that referred to aluminum test shows many small craters due to a large amount of ejecta. From this fact it can be argued that aluminum target induced a larger projectile fragmentation with respect to ionomer.
Similar results were obtained analyzing all 14 test targets and witness plates.

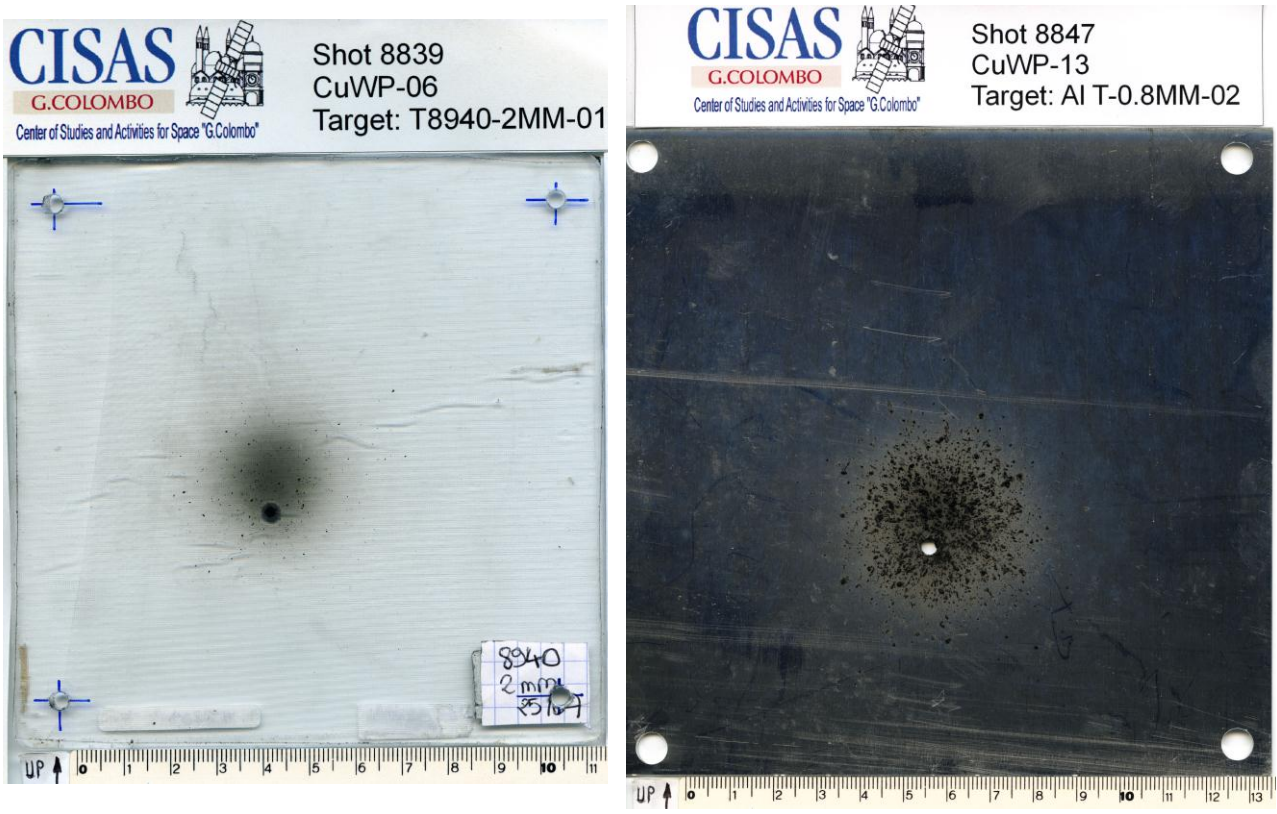

Figure 6. Example of comparison between ionomer (left) and aluminum (right) target after hypervelocity impact under similar impact conditions. Images refer to shots 8839 and 8847 respectively.

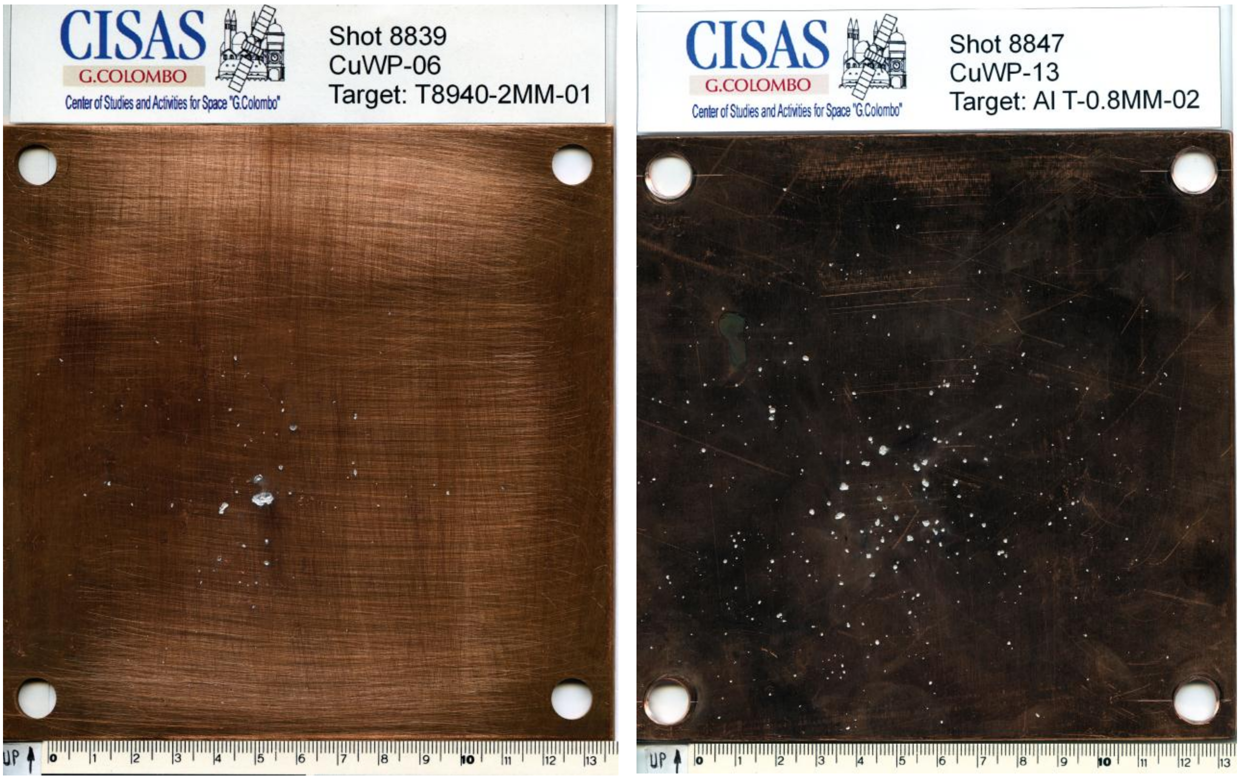

Figure 7. Example of comparison between Copper witness plates after test no. 8839 on ionomer (left) and test no. 8847 on aluminum (right) target. Tests were conducted under similar impact conditions.

Figures 8, 9 and 10 report the crater/hole produced on target plates of equivalent thickness of 2 mm, 3 mm and 5 mm respectively, as function of impact velocity. Aluminum equivalent thickess is that obtained assuming the same local density as Surlyn 8940 density. Blue circles represent front side damage, red square represent back side damage; empty markers refer to impacts on ionomer target while full color markers refer to impacts on aluminum plates.

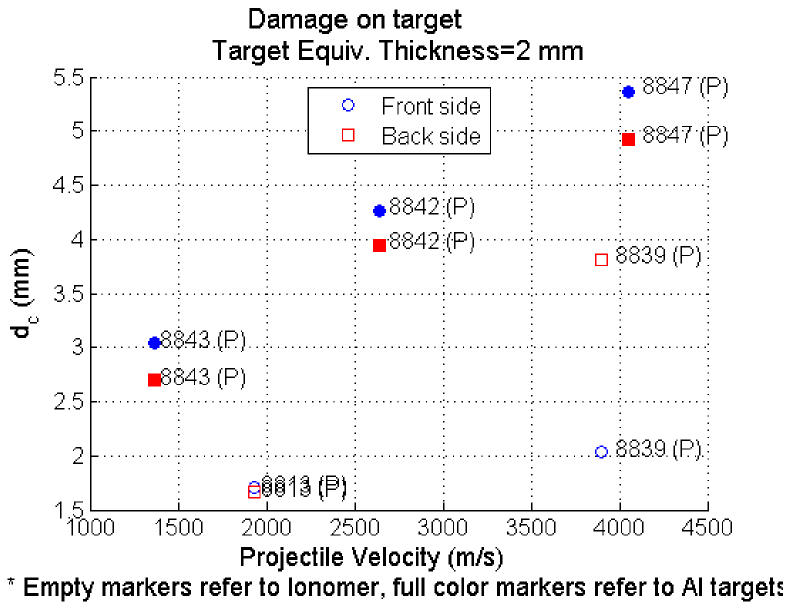

Figure 8. Target hole/crater diameter on front and rear shot side for tests on ionomer and aluminum plates with equivalent thickness of 2 mm as function of impact velocity.

Markers label reports the shot number and perforation or not perforation result (P/NP). Since it was not possible to analyse time evolution of ionomer healing process, it was not possible to distinguish between a not perforated target and a perforated-then-repaired one, so P/NP evaluation was performed by analysing the presence of craters on witness plate.

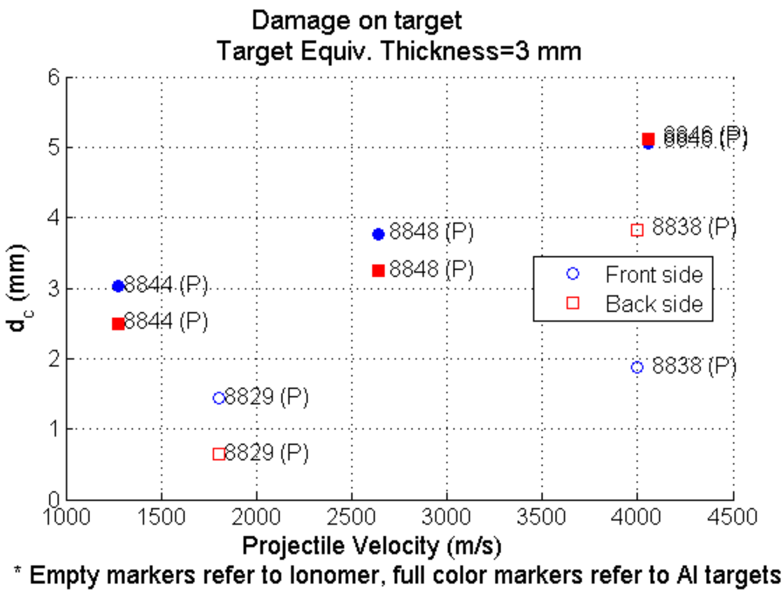

Figure 9. Target hole/crater diameter on front and rear shot side for tests on ionomer and aluminum plates with equivalent thickness of 3 mm as function of impact velocity.

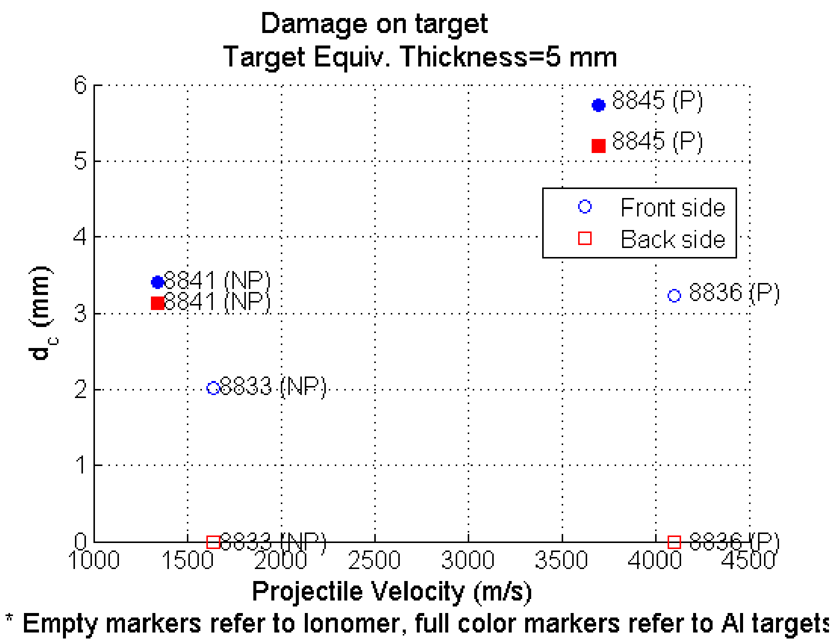

Figure 10. Target hole/crater diameter on front and rear shot side for tests on ionomer and aluminum plates with equivalent thickness of 5 mm as function of impact velocity.

Comparing shots with same impact conditions and same target equivalent thickness it results that damage on ionomer after impact is smaller than that on aluminum. This seems to suggest that a partial healing process occurred, but this process completed only in the case of thick target and not high impact velocity. About witness plate damage, visual and first numerical analysis seem to confirm the results obtained with tests 8839 and 8847, as plates present more and smaller craters in the case of aluminum tests than in the case of ionomer test. Since good

projectile fragmentation is a requirement for a material to be used effectively as a bumper, these results seem to suggest not to use ionomer as bumper but as an inner layer with anti-leakage purposes because of its self-healing properties.
These results need to be confirmed by ongoing deeper surface analyses on target and witness plates and also by ballistic pendulum motion study to infer information on the momentum transferred during the impact.

Conclusions

This study is part of the project for the identification of multifunctional materials by hypervelocity tests and simulations. This analysis focused on the characterization of a ionomeric material, Dupont Surlyn 8940. The objective of this study was to verify ionomer self-healing properties in hypervelocity regime and to identify Surlyn effectiveness in hypervelocity impact protection.
Some tests were performed on Surlyn targets with different impact conditions and target thicknesses. Surlyn behaviour was then compared to that of aluminum targets in the same impact conditions as ionomer tests.
Damage on target plates and witness plates was analysed and first results are reported.
Analysis on target plates showed small damage on ionomer samples with respect to aluminum plates suggesting a partial self-healing process occurrence. On the other side witness plate surface showed fewer and larger craters for ionomer tests than for aluminum tests. This suggests that projectile undergoes a better fragmentation during the impact onto an aluminum plate than on a ionomer sample leading to the conclusion that ionomeric plate is not suitable to be used as a bumper but it could be used as an inner layer for anti-leakage purposes. More data are needed to confirm these results and deeper analyses, involving also ballistic pendulum motion measurements, are in progress.

Acknowledgement: The financial support of CARIPARO under the Progetto di eccellenza IMBEMUS is gratefully acknowledged.

References

[1] Kalista S.J., WardT.C. *Self-healing of poly(ethylene-co-methacrylic acid) copolymers following ballistic puncture* in "Proceeding of *First International Conference on Self Healing Materials"*, Noordwijk aan Zee, The Netherlands, (2007).
[2] Thomas J.P., Qidwai M.A. Mechanical design and performance of composite multifunctional materials. *Acta Materialia*, **52**, pp. 2155-2164 (2004).
[3] Angrilli F., Pavarin D., De Cecco M., Francesconi A. Impact facility based upon high frequency two-stage light-gas gun. *Acta Astronautica* , **53**, pp. 185-189 (2003).
[4] Destefanis R., Faraud M., Gaurnieri V., Lobascio C., Nebiolo M., Rampini R., Angrilli F., Bettella A., Francesconi A., Giacomuzzo C., Pavarin D. Selecting materials to protect inflatable structures from the space environment.
[5] Grande A.M., Coppi S., Di Landro L., Sala G., Giacomuzzo C., Francesconi A., Rahman M.A. An experimental study of the self-healing behavior of ionomeric systems under ballistic impact tests.