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Comparison of self-healing ionomer to aluminium-alloy bumpers for protecting spacecraft equipment from space debris impacts

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Abstract

This paper discusses the impact behavior of a self-healing ionomeric polymer and compares its protection capability against space debris impacts to that of simple aluminium-alloy bumpers. To this end, 14 impact experiments on both ionomer and Al-7075-T6 thin plates with similar surface density were made with 1.5 mm aluminium spheres at velocity between 1 and 4 km/s.

First, the perforation extent in both materials was evaluated vis-à-vis the prediction of well known hole-size equations; then, attention was given to the damage potential of the cloud of fragments ejected from the rear side of the target by analysing the craters pattern and the momentum transferred to witness plates mounted on a ballistic pendulum behind the bumpers.

Self-healing was completely successful in all but one ionomer samples and the primary damage on ionomeric polymers was found to be significantly lower than that on aluminium. On the other hand, aluminium plates exhibited slightly better debris fragmentation abilities, even though the protecting performance of ionomers seemed to improve at increasing impact speed.

Keywords: Ionomer; Protecting capabilities; Space debris; Hole size; Witness plates; Momentum transfer

1. Introduction

Since many years, laminated composites are finding an increasing role in many engineering applications for their excellent properties per unit mass; in particular, they are used in aerospace structures where the limitation of weight is remarkably important. However, their impact behavior is still under scrutiny because it can pose serious risks of critical local damage as well as structural collapse. This is of special concern in space applications, where man-made space debris traveling at several km/s represent a serious hazard for existing spacecraft. Many works are reported to describe the damage due to hypervelocity impact on both simple composite plates (Yew and Kendrick, 1987; Schonberg, 1990, 2000; Christiansen, 1990; Lamontagne et al., 1999, 2001; Francesconi et al., 2012) and sandwich panels with honeycomb core and composite face-sheets (Taylor et al., 1999; Schaefer et al., 2005; Ryan et al., 2008), and this loading condition is recognized to permanently degrade the components strength. In this framework, new cost-effective solutions to make composite structures less vulnerable to space debris impacts are highly desirable, including techniques for damage inherent reparation.

Laminated composites equipped with self-repairing capabilities belong to the class of multifunctional structures: usually various layers of the panel play different roles so that the whole laminate can simultaneously carry loads

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and perform additional functions. An extensive review on multifunctional structures and materials can be found in Gibson (2010). In particular, self-healing capabilities are currently the object of a considerable research effort (Wu et al., 2008; Norris et al., 2011; Zhang and Rong, 2011; Pingkarawat et al., 2012; Zhang and Rong, 2012) and can be classified as extrinsic and intrinsic. In the case of extrinsic self-healing, the repairing agent is different from the main structural material and is stored in capsules incorporated into the main matrix in advance. As soon as a crack path intersects the capsules, it destroys them and the healing agent is released into the cracks due to capillary effect, thus re-binding the fractured surfaces (Zhang and Rong, 2011). The so-called intrinsic self-healing materials, usually polymers, are based on specific polymers properties that enable crack reparation under certain stimulation such as increased temperature or stress. In the intrinsic case, no additional healing substance is present, but the repairing capability is located in the structural material itself. Moreover, healing is said to be autonomic if no manual intervention is required to trigger the process whereas non-autonomic otherwise (Zhang and Rong, 2011).

Few papers on self-healing after impact damage have been published so far, mainly for the case of low energy impacts. Patel et al. (2010) described autonomic self-healing of impact damage in composite materials using a microencapsulated repairing agent, whereas Williams et al. (2008, 2009) studied the compression after impact of self-healing Carbon Fiber Reinforced Plastics (CFRP) and the restoration of compressive strength after impact in sandwich panels. Other self-healing technologies specific to space applications were discussed by Brandon et al. (2011).

In such a context, the authors are investigating the possibility of realizing a multifunctional panel with damage reparation abilities, in which self-healing is provided by one or more layers of ionomeric polymers. Ionomers are thermoplastic ionic polymers, e.g. hydrocarbon polymers bearing pendant carboxylic acid groups that are either partially or completely neutralized with metal ions (Holiday, 1975). Ionomers' intrinsic self-healing properties have been known for sometime (Varley and Zwaag, 2008; Varley and Van der Zwaag, 2008) and have been also investigated after high energy impact or puncture test such as bullet penetration (Kalista and Ward, 2007; Kalista et al., 2007). This ability is an inherent material response and occurs automatically and instantaneously without the need for manual intervention but it is limited to specific conditions, e.g. temperature, bullet shape and speed. In order to overcome these limits, recent research activities have shown how different blends of Surlyn® with 30% of acid groups neutralized by Na ions and epoxidized natural rubber also showed complete self-healing behavior after ballistic impacts with pointed bullets (Penco et al., 2011; Rahman et al., 2011a; Rahman et al., 2011b).

With this background, this paper reports the results of a preparatory study on the intrinsic, autonomic, self-healing capabilities of the ionomer subjected to high-velocity impacts, when it is not inserted in any laminated panel. In particular, the experiments were conceived to compare its ballistic protection with that provided by a more traditional plate of aluminium Al-7075-T6 alloy of comparable weight per unit area.

In the remainder of this paper, the selected ionomer material and the experimental methods are described in Section 2. Results are then presented in Section 3, as regards the primary damage on the target (i.e. hole size) and the secondary damage to neighboring structures from ejected debris. This latter aspect was investigated by analysing the craters pattern and the momentum transferred to witness plates mounted on a ballistic pendulum behind the bumpers. Conclusions are finally given in Section 4.

2. Target materials and test setup experimental methods

A total of 14 impact experiments were conducted on dual-wall target systems composed by a thin bumper plate (Al-7075-T6 or ionomer of various thickness, see Table 1) and a 2 mm thick copper witness plate (WP) mounted on a ballistic pendulum at a stand-off distance of 116.5 mm (Fig. 1). Copper was chosen to help identifying aluminium debris coming from projectile fragmentation.

The ionomeric polymer employed for the study is commercially known as Surlyn® (Van der Zwaag, 2007) and was purchased from DuPont. Surlyn® is an ethylene-co-methacrylic acid co-polymer with 30% of acid groups neutralized with sodium ions. The ionic species in the polymer can aggregate in the form of clusters (Eisenberg et al., 1990).These ionic domain and the related order-to-disorder transition phenomenon of the clusters (Tadano et al., 1989) have a deep effect on the mechanical and physical properties of the polymer (Van der Zwaag, 2007). Density and

Table 1
Targets designation, size (a, b are the lateral dimensions, t is the thickness of the samples), density and surface density.

Target designation	Size			Density (kg/m^3)	Surface density (kg/m^2)
	a (mm)	b (mm)	t (mm)		
Al-7075-T6/1	150	150	0.8	2810	2.25
Al-7075-T6/2	150	150	1.0	2810	2.81
Al-7075-T6/3	150	150	1.5	2810	4.22
Surlyn®/1	120	120	2.0	950	1.90
Surlyn®/2	120	120	3.0	950	2.85
Surlyn®/3	120	120	5.0	950	4.75