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INTEGRATED SOLUTIONS FOR SAFE FUEL TANKS

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ABSTRACT

The integration of different tools for the prevention of fires or explosions due to impact or bullet damage may significantly improve the safety of fuel tanks. Self-healing polymers have demonstrated their ability to autonomous mending bullet punctures. The results of ballistic tests to check the response of multilayer structures based on self-healing ionomer and aramid fabric or carbon foam are presented in view of their potential employment as safety materials for dangerous liquids containment. Considerations related to the effect of coupling of different materials over self-healing response are discussed. A conceptual solution that integrates self-healing polymers or composites with cellular filler made of wrinkled aluminium foil for fuel tanks is proposed and discussed.
Keywords: fillers, fuel tanks, impact, self-healing.

1 INTRODUCTION

The availability of new materials with uncommon characteristics and functionalities gives the opportunity to develop and possibly integrate new conceptual solutions for the improvement of safety in the design and manufacture of containers for fuels and critical substances in general.

One of the causes of fatalities in case of accidents involving ground vehicles, as well as aircraft and vessels, is the development of fire consequent to fuel tank damage. Fire and deflagration, which may involve the full tank, start primarily from the leakage of the fuel due to the rupture or perforation of the tank walls followed by ignition of vapours by electric discharges or friction sparks. This suggests that possible solutions should focus on the following two issues: the limitation or avoidance of fuel leakage and the suppression of the explosion. Over the years many concepts, for the prevention or suppression of explosions, have been explored. Among these, foam and metallic fillers are the most used in military aircraft and helicopters. Complex inerting systems, which are usually based on the maintenance of inert atmosphere in the tank, over the fuel free surface, are employed also in civil aircraft [1]. Such systems are effective to reduce chances of deflagration starting within the tank but may reduce their efficiency in case of wall tank perforation and fuel spilling. A proper containment of liquid, even after accidental tank damage, is thus essential with regard to safety issues.

High-speed debris impact and bullet penetration of fuel tanks are two relevant examples, where specifically designed configurations, integrating different materials functionalities, may significantly improve safety margins over traditional solutions. In such situations, deflagration activated by sudden variation of internal pressure and liquid spilling due to wall container perforation can be final catastrophic event [1–3].

Cellular filler materials in the container can dispel fire heat, limit pressure wave peaks generated by a bullet explosion and slow down the liquid spilling rate. Moreover, the presence of an inner cellular structure can remarkably improve the overall response to impact loads in case of a crash, therefore, increasing ab initio the safety margins [4,5]. Different fillers with particular configurations, ranging from foams to porous structures to wrinkled aluminium foils, have been considered and tested as antisloshing and tank explosion suppression media for aircraft tanks as well as for vehicles with positive results [3–7]. Figure 1 shows an example of aluminium cellular filler for aeronautic safety tanks (Explosafe®).

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Figure 1: The expanded aluminium foil filler (Explosafe®).

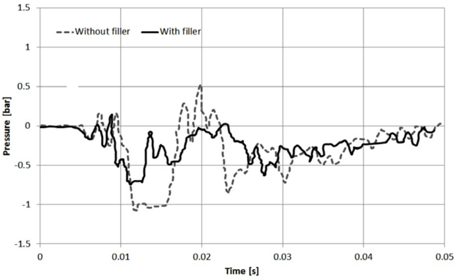

Figure 2: Internal average back side panel tank pressure–time traces recorded during impacts. Impact speed 5.7 m/s.

In multilayer wall fuel tanks for aerospace applications, fuel self-sealing after perforation can be obtained as a result of swelling or chemical reaction of rubber/foam layer when it comes in contact with the spilling internal liquid. A usual drawback of these materials is the limited resistance to ageing, which reduces their effectiveness with time. Moreover, the sealing material adds consistent weight to the component, yet giving no or negligible contribution to structural performance. Polymeric materials and composites with intrinsic self-healing capability may become a valid alternative to traditional configurations. The combination of aramid fabric or carbon foams with polymers able to restore, at least partially, the continuity of the material, may provide significant protection and fluid containment capacity even in particularly critical conditions. In this context, ethylene-methacrylic acid based ionomers have widely demonstrated their efficiency to autonomously repair after bullet punctures and can be taken into consideration as self-healing layers in tanks. Composites and sandwich structures based on ionomeric matrix can also be considered, provided the self-healing capability is maintained [8]. The coupling of such self-healing polymers or composites with rigid cellular fillers can have multiple benefits such as high impact resistance, repeatable and environmentally stable self-healing capability, lightness, mechanical stiffness and strength.

The behaviour of metal tanks filled with a particular expanded aluminium foil was studied by one of the authors through several deceleration and drop tests to investigate their response in case of a crash event. During some of these tests, accelerations, using a triaxial accelerometer, and pressures, using four pressure transducers on both side panels and three pressure transducers on the back panel, were measured and numerical models were developed to simulate interaction between the fluid and the filling material [4,5]. Results of these tests showed an overall good response during impact in terms of wall failure and pressure drop when the filler was present. Figure 2 compares the average pressure–time profiles recorded by all the transducers on the back side panel during the impact of the tanks with and without aluminium foil based filler; a reduction of pressure peaks is indicated. Besides, the observation of the

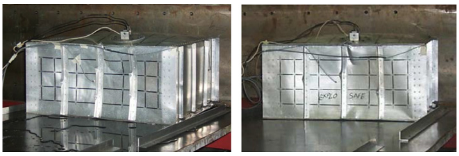

Figure 3: Impact tests: without filler (a) and with aluminium foil filler (b).

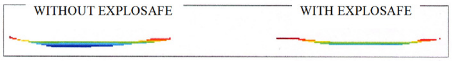

Figure 4: Comparison of backside panel deformation.

tanks with and without filler after impact tests evidenced a significantly reduced overall tank deformation in the former situation (Figs 3 and 4).

Also in case of bullet perforation, the cellular filler may significantly reduce the extent of spilling; on the other hand, consistent leakage of potentially dangerous fuel cannot be avoided. These considerations have suggested a new fuel tank concept in which both a cellular filler and tank walls made of a rigid self-healing material are employed. Thermoplastic ionomers or multilayer composites with self-mending capacity can be valid candidates for such wall materials.

The development of self-healing materials has found important scientific and technological implications, particularly in relation to cost-effective approaches towards damage management of structures. Thermoplastic materials, such as ionomers based on ethylene-co-methacrylic acid copolymers, partially neutralized with sodium or zinc, have shown self-healing behaviour after ballistic impacts [9–14]. Blends of ionomers with different polymers were also investigated: blending allows to get mechanical properties tuned over a wide range, yet maintaining self-mending ability [15–17]. However, certain conditions in terms of proper temperature range, bullet speed and shape are necessary for the autonomic healing to occur.

Aramid fabrics are widely used for flexible ballistic protections, thanks to their tenacity and impact energy absorption capacity; aramid reinforced composites and foam cored sandwich structures find extensive employment in rigid, bulletproof armours. Carbon foams present particular mechanical and thermal properties, which make them interesting in a number of structural applications [18,19]. They show remarkable ballistic performances coming from the formation of relatively small fragments during impacts: low-density carbon foams were able to stop, and in some cases hold, a 5-mm diameter stainless steel sphere fired by an air gun at speeds up to 240 m/s [20,21].

The self-healing ability of plain ethylene-methacrylic acid copolymer, partially neutralized with sodium ions (EMAANa), have been studied by ballistic puncture tests; different conditions were assessed by varying samples thickness, bullet impact velocities (from 180 up to 4000 m/s), bullet shapes and diameters [14]. Similar ballistic tests were applied to multilayer and composites, including aramid fabrics reinforced ionomer and composite/carbon foam/ionomer sandwich panels in various configurations.

At the tested impact speeds, EMAANa presented self-repair ability up to a specific sample thickness/projectile diameter ratio even at highest bullet rates. On the other hand, ballistic tests of multilayer systems showed that self-healing behaviour of ionomeric layers can be maintained also in composites only within defined impact speed limits. The analysis of healing efficiency was evaluated by leakage tests and microscopy observations. By applying a pressure gradient through punctured panels, hole closure and tightness were tested by following vacuum decay and by checking for possible flow of a fluid droplet placed in correspondence to damage. A morphology analysis of the impact zones was made observing all samples by optical stereomicroscope and scanning electron microscope both in the bullet entrance and exit sides.

2 EXPERIMENTAL

2.1 Materials and samples production

Ethylene-co-methacrylic acid based copolymers and ionomers are available on the market with different trade names (e.g. Nucrel® and Surlyn®). In this research, an ionomer partially neutralized with sodium (Surlyn® 8940, provided by DuPontTM Italy) was employed. The polymer is characterized by a content of 5.4 mol% acid groups, 30% of which is neutralized with sodium. The density is 0.95 g/cm^3.

Polymer pellets were dried in vacuum at 60°C for 5 h and square plates (120 × 120 mm) of 1–5 mm thickness were produced by compression moulding at 180°C. Before testing, flat specimens were stored in an environmental chamber at 23°C and 50% RH for 1 month in order to reach stable mechanical properties, non-variable as possible consequence of physical ageing [22].

Two different materials were used as reinforcement or core, in particular an aramid fabric, STYLE 281 (fabric thickness 0.25 mm), provided by Seal SpA and an open cell, carbon foam FPA-35, supplied by GrafTech International, with bulk density of 0.56 g/cm^3 and 10 mm thickness.

Ionomeric plates, 120 × 120 mm, were produced by compression moulding technique using a hot parallel platens hydraulic press. Pelletized polymer was placed in the mould heated at 180°C and then pressed to obtain plates of different thicknesses. Multilayer composites were produced using the same technique: previously produced 1 and 2-mm thickness polymer plates were used as external sheets in the stacking sequence of aramid-based hybrid composites and carbon foam core sandwich panels, respectively (Fig. 5). From 1–5 layers of aramid fabric were used and tested. All layers were positioned within the mould and then lightly pressed for 10 min at 120°C, to reach adhesion between the different layers. In case of aramid reinforcement, partial impregnation of the fabric was obtained.

After production, all samples were stored in temperature and humidity-controlled chamber before testing.

Aramid fabric layers (1–5) ionomer plates carbon foam (10-mm thickness).

2.2 Ballistic tests and healing evaluation

Ballistic puncture tests on ionomer plates and multilayer composites were performed at Fiocchi Munizioni Ballistic Laboratory by shooting 4.65 × 19.2 mm bullets through 120 × 120

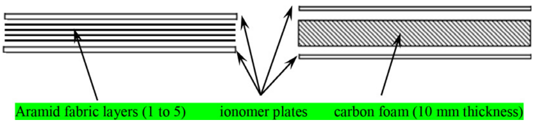

Figure 5: Schematic representation of the different multilayer composites.

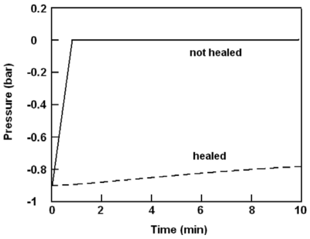

Figure 6: Vacuum decay recording during healing check tests.

mm square samples. The speed of bullets, measured using a laser beam, ranged between 700 and 730 m/s. Hypervelocity tests of ionomer plates were carried out up to 4000 m/s with a two-stage Light-Gas Gun; aluminium spheres with 1.5-mm diameter were used as bullets [13,14]. Low-velocity (180 m/s) and mid-velocity (400 m/s) impact tests were also performed by shooting steel balls of different sizes using an air gun and a shotgun, respectively [14].

An Infrared CCD Thermograph System Nikon LAIRD S270 was employed to record thermographic images during low-velocity impacts. A temperature measuring range between 60 and 140°C was set.

All specimens were observed by optical and scanning electron microscope (SEM) both in the bullet entrance and exit sides to have evidence of hole closures. SEM analyses were also performed to evaluate the morphology of the damaged surfaces of the specimens.

To check for the healing ability, leakage tests were carried out using a closed chamber, sealed on one side with a tested polymer plate. A pressure difference of 0.9 bars was initially applied by a vacuum pump across the impacted specimens; air tightness through the hole was tested following vacuum decay and by checking for possible flow of a fluid droplet placed at the damage zone with the applied pressure difference. When the hole was healed, no appreciable vacuum decay was detected within the specified time range (10–30 min), but for non-healed samples vacuum decay was observed within few seconds. Figure 6 shows an example of the vacuum decay test for healed and not healed ionomer plates after ballistic impact.

3 RESULTS AND DISCUSSION

Ballistic impact tests showed that in all cases the bullet energy employed was sufficient to perforate ionomer or multilayer plates. In the latter materials, however, the presence of a reinforcing fabric or foam efficiently adherent to ionomer, in some cases, reduced the self-healing efficiency. The healing mechanism of ionomers is well discussed in the literature [9–14]. It is the result of a ‘welding’ effect, where the energy dissipation due to material plastic deformation and projectile friction leads to local material melting; the following viscoelastic recovery and material solidification are able to close the hole and seal, at least partially, the damage. Figure 7 shows a thermographic picture of the temperature distribution in a ionomeric plate immediately after a ballistic puncture test with a steel ball. It can be observed that the temperature in correspondence of the impact site reaches the melting temperature of the material, thus allowing the welding and the hole closure. The heating effect is the result of deformation energy dissipation and friction forces.

An insufficient projectile impact energy or the presence of deformation constraints, such as reinforcing fabric or foam core, may impair the healing ability of the material.

Morphological analysis of multilayer panels after ballistic tests showed a different conformation of the impacted sites. In aramid reinforced plate (Fig. 8a), delaminations in the impact

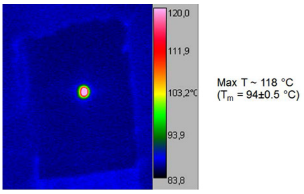

Figure 7: Thermographic image of an ionomeric plate right after puncture at 200 m/s impact speed.

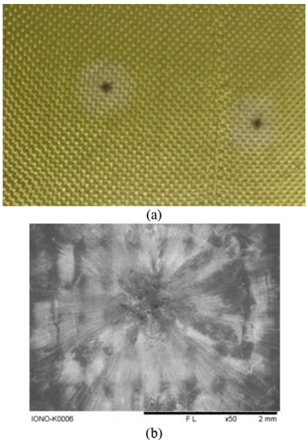

Figure 8: Aramid fabric/EMAANa multilayer sample (a) and bullet inlet side enlargement (b).

area (white halos) are evidenced suggesting a poor adhesion between layers. On the other hand, the limited constraint exerted by the fabric in such areas allows for ionomeric polymer viscoelastic recovery and consequent efficient healing. A complete hole closure with evidence of polymer melting and full welding was observed with one and two fabric layers (Fig. 8b).

Ballistic experiments carried out on carbon foam/EMAANa sandwiches revealed a different behaviour in the self-repairing phenomenon of the ionomeric layers (Fig. 9a). Complete hole closure with molten material appeared only in the first EMAANa skin hit by the bullet (inlet layer, Fig. 9b). When the bullet passed through the carbon foam, the outlet ionomeric layer did not exhibit self-healing, as confirmed by leakage tests. While the projectile energy is certainly sufficient for the effective healing of the inlet layer, the passage through the first polymer skin and the carbon core seems to reduce its energy so that re-welding and healing of the outer ionomer layer is no longer possible. A further cause of reduced healing capacity of the outer EMAANa layer could be attributed to the carbon micro-particles generated during the impact of the projectile with the foam: a cloud of such particles is deposited on the damaged area and may lock the repair process of the ionomer, thus preventing the full sealing of the hole.

Some of the healing results obtained in different panel/bullet configurations are summarized in Table 1. It should be observed that even when no full healing was obtained, the diameter of the remaining hole was consistently smaller than bullet diameter, indicating a general tendency to hole closure.

The results suggest that multilayer configurations for fuel containment can be efficient, provided quite limited coupling between self-healing and structural layers is granted. On

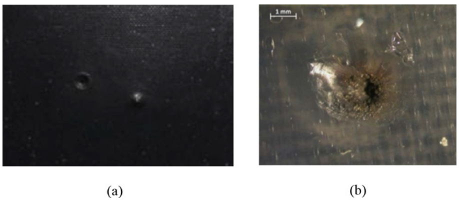

Figure 9: Carbon foam/EMAANa multilayer sample (a) and bullet inlet side enlargement (b).

Table 1: Results of ballistic tests on different panel configurations.

Configuration	Ionomer thickness (mm)	Sphere/bullet diameter (mm)	Bullet speed (m/s)	Full hole closure	Notes
Ionomer plate	2	Sph 1.5	1900	Yes	
Ionomer plate	2	Sph 1.5	4000	No	Small hole
Ionomer plate	3–5	Sph 1.5	4000	Yes	
Ionomer plate	1–3	Bullet 4.65	700	Yes	
Ionomer/aramid fabric (1 or 2 layers)	2	Bullet 4.65	700	Yes	
Ionomer/aramid fabric (3–5 layers)	2	Bullet 4.65	700	No	Small hole
Ionomer/CF	1	Bullet 4.65	700	Yes	Inlet side

the basis of these considerations, experimental evaluations of the healing ability in sandwich panels made of external ionomer skins, inner composite laminate and with honeycomb core have already given promising results. A next research activity considering coupled ionomer skin/cellular filler and composite wall/cellular filler as fuel containment materials is planned.

4 CONCLUSIONS

In this work, the self-healing behaviour of different ionomeric systems was explored. Ballistic impact tests on different multilayers and composites showed that although the coupling of mutually constraining layers may impair the healing efficiency, self-mending behaviour and hole closure can be preserved. These results encourage the study of ionomeric systems and the development of new complex structures yet able to maintain efficient autonomic repairing ability. The integration of self-healing structural walls and aluminium foil based filler is expected to significantly improve the safety levels of fuel tanks in case of perforation by high-speed objects. The self-healing capacity of such configurations is being experimentally investigated.

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