SELF-HEALING BEHAVIOUR OF IONOMERS AND IONOMER COMPOSITES UNDER BALLISTIC IMPACT TESTS AT DIFFERENT SPEEDS

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Abstract

This research work deals with the investigation of the self-healing behaviour after ballistic damage of ionomers and ionomer based multilayer composites under different impact conditions. The coupling of these polymers with fabric reinforcements or carbon foam has the aim to extend the field of application of such materials. The results obtained show that healing can be efficient in a wide projectile speed range.

1 Introduction

The development of self-healing materials has important scientific and technological implications, particularly in relation to cost-effective approaches toward damage management of structures. Thermoplastic materials, such as ionomers based on copolymers ethylene-methacrylic acid partially neutralized with sodium or zinc, have shown self-healing behaviour after ballistic impacts [1-5]. Blends of ionomer with diffente polymer were also investigated [6-9]. However, certain conditions in terms of proper temperature range, bullet speed and shape are necessary for the autonomic healing to occur.

In this research, the self-healing behaviour of ionomers plates, multilayer composites based on aramid fabric reinforced ionomer and plates with carbon foam backing was investigated under different ballistic impact conditions.

Aramid fabrics are widely used for flexible ballistic protections thanks to their tenacity and impact energy absorption capacity, while aramid reinforced composites and foam cored sandwich structures find extensive employment in rigid armour. Carbon foams present particular mechanical and thermal properties, which make them interesting in a number of structural applications [10,11]. They show remarkable ballistic performances for relatively small fragments impacts; researchers found that low density carbon foams were able to stop and in some cases hold a 5 mm diameter stainless steel sphere fired at a speed up to 240 m/s by a compressed air gun [12,13]. The coupling of aramid fabric or carbon foams with polymers able to restore, at least partially, the continuity of the material may significantly extend the performances of such systems.

The self-healing ability of plain ethylene-methacrylic acid copolymer, in which 30% of acid groups are partially neutralized with sodium ion (EMNa), and multilayer composites based on the same ionomer have been studied by ballistic puncture tests; different conditions were assessed by varying sample thickness, bullet impact velocity (from 700 m/s up to 4000 m/s), bullet shape and diameter.

At tested impact speed, EMNa presented self-repair ability up to a specific sample thickness/projectile diameter ratio even at highest impact speeds. Regarding multilayer systems, ballistic tests at the lowest speed prove that self-healing behaviour of ionomeric layers can be maintained also in composites.

After all impact tests, the healing efficiency was evaluated by applying a pressure gradient. Hole closure and tightness were tested by following vacuum decay and by checking for possible flow through the hole of a fluid droplet placed at the damage zone with the applied pressure difference. 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

The ethylene-methacrylic acid ionomers, grade Surlyn® 8940, was provided by DuPont™ Italy. This polymer is characterized by a content of 5.4 mol% acid groups, 30% of which neutralized with sodium and a density of 0.95 g/cm^3.

Two different materials were used as reinforcement or core, in particular carbon foam FPA-35, supplied by GrafTech International, with bulk density of 0.56 g/cm^3 and aramid fabric, STYLE 281, provided by Seal SpA. The fabric general properties are summarized in Table 1. This fabric follows also the AMS 3902 B specifications (Aerospace Material Specifications).

	threads x cm		**linear density (dTex)**		**thickness (mm)**	**weight (g/m^2)**			**weave**
	warp	*weft*	*warp*	*weft*		*warp*	*weft*	*total*	
STYLE 281	6.7	6.7	1270	1270	0.25	86.5	86.5	173	plain

Table 1. Aramid fabric properties.

2.2 Samples production

Ionomeric plates, 120x120 mm, were produced by compression moulding technique using a hot platens hydraulic press. Pelletized polymer was placed in the mould heated at 180 °C and then pressed in order to obtain plates of different thickness.

Multilayer composites were produced using the same technique; in the specific, previously produced polymeric plates, were used as external sheets in the stacking sequence of the composites (Figure 1). All layer were positioned within the mould and then lightly pressed for 10 minutes at 120 °C, in order to allow the adhesion between the different layers. In case of aramid reinforcement partial impregnation of the fabric was obtained.

After productions, samples were stored in temperature and humidity controlled chamber prior to testing.

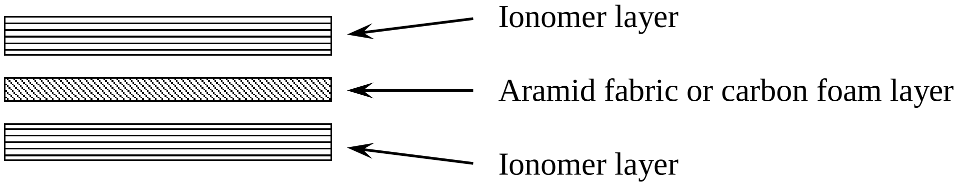


Figure 1. General representation of the different multilayer composites.

2.2 Ballistic tests

Ballistic puncture tests on ionomer plates and multilayer composites were performed at Fiocchi Munizioni Ballistic Laboratory by shooting 4.65x19.2 mm bullets through 120x120 mm square samples. The speed of bullets, measured using a laser beam, ranged between 700 and 730 m/s.

High energy impacts were performed on pure ionomer samples at CISAS Hypervelocity Impact Facility, at Padova University, using a two-stage Light-Gas Gun (LGG) [14]. In these tests, 1.5 mm aluminum spheres launched at 2 and 4 km/s speed were used. Sample thickness tested were 2, 3 and 5 mm.

2.3 Healing evaluation

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 ability of healing, leakage tests were carried out; a pressure difference of 0.9 bars was initially applied by a vacuum pump in a closed chamber, sealed with the tested polymer plate. 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 but for non-healed samples vacuum decay was observed within a few seconds. A sketch of the experiment system are showed in Figure 2.

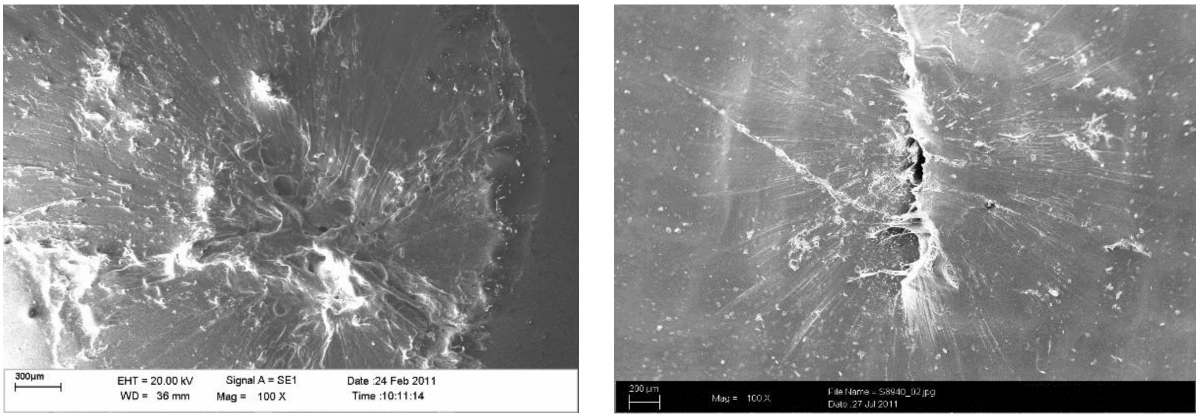
Figure 2. Sketch of the system for self-healing measurement.

3 Result and discussion

3.2 Healing evaluation

Previous experiments showed how pure ionomer exhibits self-healing after ballistic impact tests [15]; in Figure 3 SEM images of the damaged zones are shown. Microscope observations of pure ionomer after both ballistic tests with 4.65 mm diameter bullets (Figure 3.a) and low velocity impact with 5 mm sphere (Figure 3.b) evidenced complete hole closure, although in the first one a more extended viscous response of the material appears due to the greater energy exchanged during the impact. Either damaged areas show the characteristic striations radially distributed around the crater caused by an intense plastic deformation.

Hypervelocity impact tests showed a different morphology of the impacted areas; results are summarized in Table 2. At the lowest projectile velocity, all ionomer samples exhibited complete hole closure, but leakage tests showed a loss of pressure of the 3 mm thickness specimen. At the higher bullet speed instead only the 3 and 5 mm thickness samples exhibited complete hole closure.



(a) (b)

Figure 3. Pure EMNa ionomer tested with 4.65 mm bullet at 700 m/s (a) and 5 mm steel ball at 180 m/s (b), sample thickness 2 mm [15].

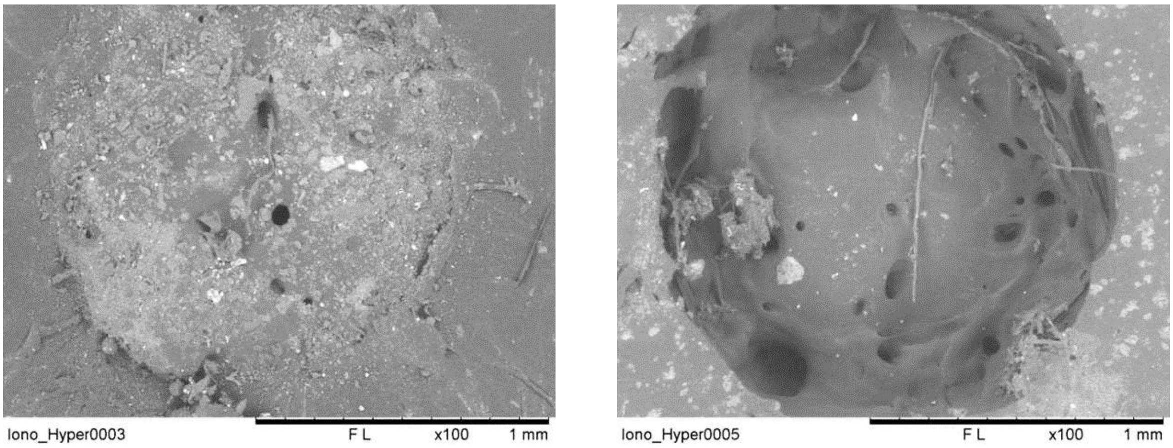
Morphological analysis after hypervelocity tests showed a different conformation of the impacted sites. On the inlet side, debris of the fired aluminium sphere can be observed (Figure 4.a), nevertheless on the other side there are no residues of the projectile (Figure 4.b). The morphology of the impact area on the back part of the samples exhibits a clearly defined molten zone of approximately the same diameter as the impacted sphere. In addition, the presence of voids, probably caused by the generation of volatile substances during the impact, can be clearly observed.

Diameter (mm)	**Velocity (km/s)**	**Thickness (mm)**	**Hole closure**	**Healing (leakage test)**
1.5	1.93	2	Yes	Yes
1.5	1.80	3	Yes	No
1.5	1.64	5	Yes	Yes
1.5	3.90	2	No	No
1.5	4.00	3	Yes	Yes
1.5	4.10	5	Yes	Yes

Table 2. Hypervelocity impact test results.

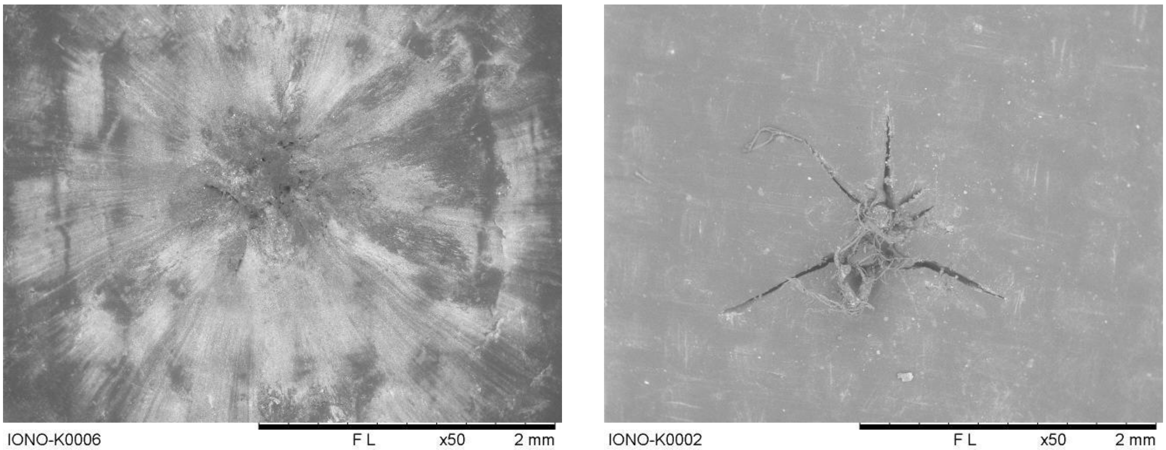
Regarding multilayer systems, it can be noted (Figure 6.a) that in aramid reinforced plate, delamination in the impact area (white halos) are evidenced. The reduced constrain exerted by the fabric in such area, allows for ionomeric polymer viscoelastic recovery and efficient healing (Figure 5.a).

Ballistic experiments carried out on carbon foam/EMNa sandwiches revealed a different behaviour in the self-repairing phenomenon of the ionomeric layers. Self-healing appeared only in the first EMNa layer hit by the bullet (inlet layer). When the bullet passed through carbon foam, the outlet ionomeric layer did not exhibited self-healing ability, as revealed by leakage tests. It is conceivable that the bullet passage through the first polymer plate and carbon core, reduces its energy so that no re-welding and healing of the ionomer is possible in the outer layer. Another possible cause of no healing of the outer EMNa layer could be attributed to the cloud of carbon microparticles generated during the impact of the projectile with the foam; these particles, deposited on the damaged area, lock the repair process of the ionomer. However also in these case complete hole closure was observed for all tested samples.



(a) (b)

Figure 4. Inlet (a) and outlet hole (b) on 2 mm thickness EMNa sample impacted at 1.9 km/s with an Al sphere.



(a) (b)

Figure 5. Inlet (a) and outlet hole (b) on the aramid fabric/EMNa multilayer sample.

(a) (b)

Figure 6. aramid fabric/EMNa (a) and carbon foam/EMNa (b) multilayer samples tested.

4 Conclusions

In this work the self-healing behaviour of different ionomeric systems was explored. Hypervelocity impact tests were performed on a commercial ionomer and it was found that self-repairing behaviour, already detected for impact at lower bullet speed, appeared also under these testing conditions up to a specific sample thickness/bullet diameter ratio.

Considering multilayer composites, performed ballistic impact tests showed that self-healing behaviour was well maintained in ionomer layers; these results encourage the study of ionomeric systems and the development of new complex structures yet able to maintain efficient self-healing ability. A further study could involve the response of these kind of structures under hypervelocity impact tests in view of possible space applications.

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