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RUBBER AND MAGNETORHEOLOGICAL FLUID APPLIED AS THE INTERLAYER IN COMPOSITE ARMOURS AGAINST HIGH-VELOCITY LOADINGS

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Abstract

Monolithic, homogenous ballistic shields consisting of a single thick, high-hardness and high-strength steel plate are rarely applied in modern combat vehicles. Currently, a popular armour concept is a multi-layered shield since it is expected that the kinetic energy of a threat may be dissipated by transmission through materials with different properties and also by multiple interface reflections. Searching for a maximum ballistic protection at minimum weight inspires applications of various materials which complementary behaviour provides a high protective efficiency without excessive mass. The preliminary experimental investigation presented in the paper aimed to verify behaviour of two prototyped laminated armours under impacts of small-calibre projectiles (cal. 7.62). The main interest lied in impact properties of materials proposed as the intermediate layer. The first tested concept was a laminated steel armour with the 10 mm thick rubber interlayer. In the second armour, the intermediate layer consisted of a magnetorheological fluid.

Keywords: energy absorption, rubber, magnetorheological fluid, protective properties.

1. INTRODUCTION

Compromise between requirements of high protection level and not excessive weight lies on the basis of modern armours. A single steel plate must be thick to assure a good level of protection, therefore in armoured vehicles, such simple solutions are rarely applied. A constant search for a maximum ballistic protection at minimum weight requires applications of various materials, which complementary behaviour provides high protective efficiency. Among different approaches applied in light-weight armour vehicles, laminated armours may be flexibly designed and they are relatively easy to assembly.

In a laminated amour, each armour-layer plays a specific role in a complete behaviour of the protective system. The objective is to dissipate the impact energy by using advantages of each applied material. Characteristics of the wave propagation are also changed by the impedance mismatch between plates' interfaces, which improves efficiency of armour.

The first plate is usually a high-strength, high-hardness material (ceramics, high-strength steels, titanium alloys), since it is responsible for projectiles shattering and dissipation of its kinetic energy due to penetration mechanisms. When a projectile hits a high-strength and usually brittle layer, a compressive stress wave is generated ant it propagates through the plate thickness. When it reaches the back face of the plate, it is partially reflected back as a tensile wave, which may cause damages and cracks of more brittle materials. The underlying layer should act then as a shock absorber and damp the transmitted impact energy to prevent damages of the first layer. Ceramics and very tough steels require such underlying dampers, which aim is to minimize an extent of cracks. In [1], an example of such a concept is discussed. It is reported that a polymeric interlayer ensured a good resilient bond between a ceramic and a composite and it prevented excessive cracking of the first layer.

The third layer is considered as a medium which captures fragments resulted from destruction of threats and the hard armour layer. Light, ductile alloys or fibre composites may be applied as the backing layer, [2]. Their plastic deformation dissipates kinetic energy of fragments and stops them.

The example of laminated armour discussed in the paper assumes application of a rubber layer between steels of different ductility and hardness properties. In elastomer-steels configurations, the visco-elastic glass transition of the rubber in conjunction with the difference of impedance between steel plates and a rubber results in a better protective performance, [3]. In [4], it was demonstrated that a few millimetres thick elastomeric layer coated on a high strength armour steel improved significantly the resistance to impacts of fragments – the ballistic limit of the tested armour increased. The author contributed the improvement to the fact that the glass transition zone of polymers is a regime of greatest energy dissipation.

In the second tested armour concept, as the interlayer a magneto-rheological (MR) fluid was applied. MR fluids in their neutral state are liquids with a viscosity ≈0.1–1 Pa-s and then they behave like regular motor oils. Under the influence of the magnetic field, ferro-elements dispersed in a carrier oil form a regular braid structure, [5]. The magnetic polarization causes the dipole-dipole interactions between particles which lead to formation of particle chains along the direction of the magnetic field. In the resulted solidified structure, a significant increase in the shear stress with a magnetically variable yield stress is observed, [6]. An instant change in the MR behaviour (few milliseconds) under the magnetic field makes this material attractive for damping and dissipative devices. Mostly, MRFs are used in control devices, such as semi-active MR dampers used in earthquake mitigation, [7]. Research on MR dampers has focused on low- velocity and frequency applications showing capability of MR fluids to handle impulsive loads, [8]. There are some works concerning applications of MRFs for absorption of blast and impact loadings, e.g. [9-10], but it is still not fully investigated if MR fluids are useful for absorption energy of high-velocity impacts. This was a reason to propose a MR fluid as the intermediate part of a metallic armour and to verify its behaviour under impact of small-calibre projectiles.

The presented paper aims to analyze two concepts of armours assumed to provide protection against impacts of small-calibre projectiles. The results of performed ballistic impact tests are discussed with a particular interest in behaviour of intermediate layers – a rubber and a MR fluid. Their effect on the protective performance of laminated armours is analyzed aiming to propose improvements in light-weight protective systems.

2. EXPERIMENTAL STAND

In the ballistic impact tests performed on purposes of the investigation, small-calibre projectiles were used as threats. To check the protective properties of the armour with an elastomeric layer, armour piercing incendiary (API) projectiles with calibre 7.62 × 54 mm R B32 (Dragunov) FMJ/PB/HC were shot. A 7.62 API projectile is a high-strength steel core (HC), round-nosed, full metal jacket (FMJ) pointed bullet (PB) with incendiary in the tip. Projectiles of this calibre are shot from the distance 30 m at the impact velocity 854 m/s as reference threats to evaluate the level III protection according to Stanag 4569, [11]. Their energy is assumed as higher than 3600 J.

Second kind of threats used in the study was 7.62 mm x 51 Nato Balls DM41. They are less powerful than 7.62 × 54 mm R API projectiles and they are recommended by Stanag 4569 to verify the protection level I. Projectiles of this calibre should have impact velocity close to 837 m/s. A Nato Ball DM41 is characterized by the impact energy slightly higher than 3300 J. They were shot to the amour with a MR fluid as the interlayer. DM41 bullets are soft core (lead), full metal jacket (tombac), pointed bullets.

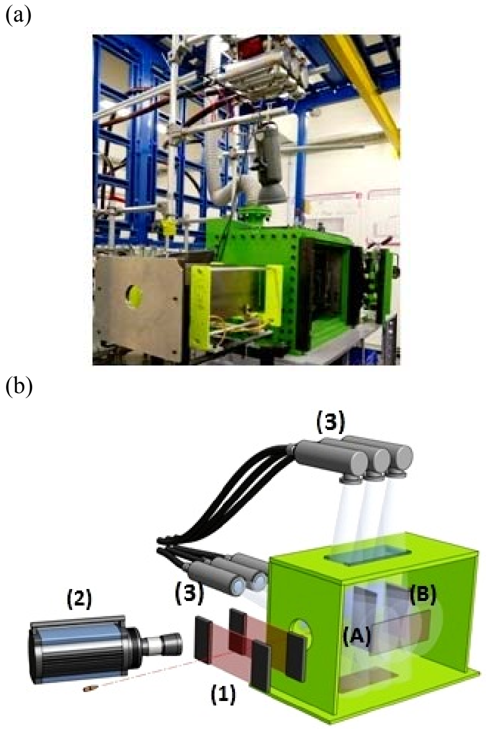


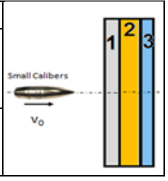
Fig. 1. (a) Experimental stand and (b) the instrumented catch-box: (1) dual-light barrier, (2) ultra-high speed camera, (3) triple flash X-ray

Projectiles were accelerated by a powder gun and it was assured that at the impact moment, they were perpendicular to the target. During the experiment, tested plates were mounted in a stiff frame in an instrumented catch box, Fig. 1. The projectile's impact velocity was measured by a light barrier. Basing on flash X-ray images, the projectile residual velocity was determined. The first X-ray image was taken just before the impact; the second and the third images showed the projectile position 50 and 130 mm behind a perforated target. Flash X-ray images can be made in two planes showing the side and the bottom view of the projectile trajectory.

3. ELASTOMER AS THE INTERMEDIATE LAYER

In the laminated armour with an elastomer as the intermediate layer, Mars® 300 of thickness 5 mm was applied as a front, striking-face plate. Among armour steels proposed by Industeel, Mars® 300 is a steel with the highest hardness, 600 HB, and the highest ultimate tensile strength, 2250 MPa, [12]. Because of a high ductility, the H500 steel was chosen as the third, backing plate – which function is to catch fragments. According to [13], the elongation may reach 51%.

Table 1. Tested laminated target with an elastomer as the intermediate layer.

Layer 1′	Layer 2′	Layer 3′	
Mars 300 t = 5 mm 60 HRC	Elastopal t = 5 mm 70 Shore	Forta H500 t = 5 mm A = 51%	
Aeral mass = 91 kg/m^2			

The intermediate layer for shock damping was a rubber – Elastopal EM (Polaris GmbH, Germany), a solid cast polyurethane with a high abrasion resistance and resilience. Initially, two configurations were prepared for testing, one with a rubber layer with the thickness 5 mm and the hardness 70 Shores (in A scale, this hardness describes a medium hard rubber) and another one with a rubber with thickness 10 mm and the same hardness, Fig. 2. The schema of the configuration with a 10 mm rubber layer is shown in Table 1. Three layers were bonded together by the adhesive 3M-Scotch-Weld™. It is a liquid, air-drying adhesive which bonds immediately upon application of contact pressure. The influence of an adhesive on impact properties of bonded laminates is discussed in e.g. [2]. In the presented investigation, a study on plates bonded by other adhesives was not made.

The aeral mass of laminate with a 10 mm rubber layer is equal to 91 kg/m^2. For comparison, a reference homogenous armour (RHA) plate must have thickness of 20 mm and the aeral mass equal to 156 kg/m^2 to provide the protection against 7.62 × 54 mm R API projectiles (value concerns Mars® 190 – a RHA steel proposed by [12]). The armour with the elastomeric layer inside provides the weight reduction of 42%.

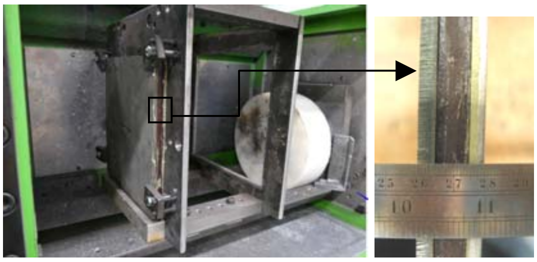


Fig. 2. Plate with the 10 mm rubber layer prepared to a shot

Conducted impact tests showed that laminates with the 5 mm rubber layer were perforated by 7.62 × 54 mm R API projectiles. However, the armours with the 10 mm thick rubber layer assured protection against impacts. None of several tested targets was perforated. In Fig. 3, a sample which withstood an impact of a 7.62 × 54 mm R projectile is shown.

As it was expected, the first steel plate caused projectile fragmentation. Mars® 300 did not crack impacted by an API 7.62 R projectile – the plate was perforated but was ductile enough to be not shattered (the producer assures elongation of 6%). A single 5 mm thick Mars® 300 plates impacted by this calibre were perforated but they did not crack, either. In all tested cases, most of bullet fragments was stopped between the rubber and the Forta H500 steel – which proves a proper behaviour of each applied layer. A localized bulge occurred on the rear side of the third plate; its height was close to 5 mm.

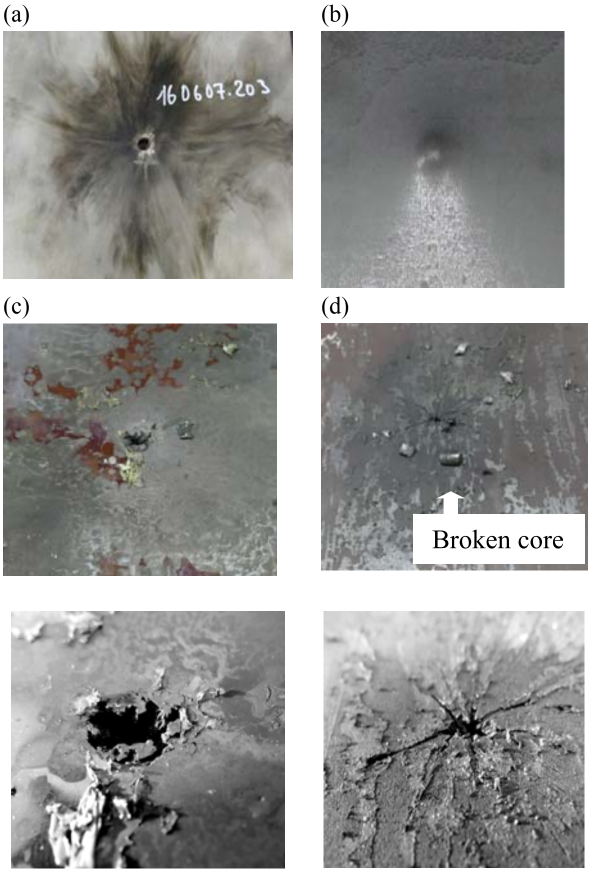


Fig. 3. The laminated armour impacted by a 7.62 × 54 mm R at impact velocity 855 m/s. a) The front plate: entry, b) the back plate: rear side. 10 mm thick rubber: c) its front side and d) rear side (with magnifications)

In Fig. 3 c – d, an entry and exit holes in the rubber layer are shown – the material failure looks brittle, which may mean that the rubber responded in a glassy fashion. During ballistic impacts, a rate of loadings can be higher than 10^5 s^{-1}. The glass transition temperature of rubbers is close to the temperature which occurs in them under impacts, [3-4]. Proximity of rates of the impact loading and of the polymer segmental motions can induce a transition of a rubbery polymer to the glassy state, which leads to large energy absorption and brittle fracture of the rubber, [3].

4. MAGNETO-RHEOLOGICAL FLUID AS THE INTERMEDIATE LAYER

Capability of magneto-rheological fluids to absorb and dissipate energy by varying the magnetic field intensity inspires their applications as an armour layer. When a fluid behaves like a solidified gel, a part of the energy transferred to MR fluid is stored while another portion is dissipated in the form of heat, [14]. In [15], there are shown concepts of armour modules containing MRFs designed for body-armours. MRF was filled into soft and flexible containers, which would increase movement comfort of soldiers. Under the influence of a magnetic field, a MRF becomes harder and more resistant to impacts. This change of a MRF state is an interesting possibility on a battle field. Results of experimental investigations shown in [15] proved efficiency of several solutions with MR fluids: padding or coating fabrics impregnated by a MRF and also rubberized aramid bag filled by a MRF.

In the current study however, a MR fluid was applied as the interlayer of a laminated armour foreseen for protection of light-armoured vehicles. In the tested MR fluid, LORD MRF-132DG, ferro-elements consisted of the carbonyl-iron powder. Spherical-shaped particles with average diameters of 5 μm were dispersed in a carrier liquid, polyalphaolefins. The density of the fluid was within a range 2.95 – 3.15 g/cm^3 and its viscosity measured at 40°C read 0.112 ± 0.02 Pa-s, [16]. The total concentration of ferro-particles was assumed as 81% of the fluid mass, [16].

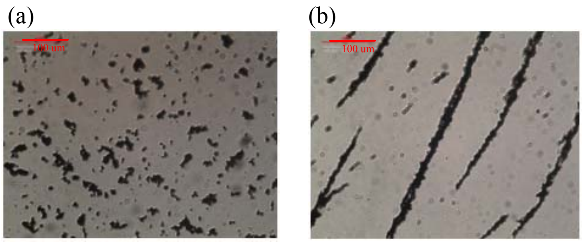


Fig. 4. Ferro-elements of the tested MRF in (a) the neutral state and (b) under the influence of magnetic field (LEM images)

Similarly to the first approach, the striking-face plate was supposed to cause the projectile shattering and the third, backing layer was assumed to be ductile to catch fragments. Both plates must have been non-magnetic, therefore a 5 mm thick titanium plate (grade 2) and a 5 mm thick aluminium 7065 plate were chosen. The titanium alloys are relatively ductile (20% elongation, [17]), so on the contrary to the previous study, in this case damping of the plate deformation was not necessary.

Hardening of fluid activated by the magnetic field and formation of ferro-chains was supposed to strengthen shattering of projectile initiated by the titanium plate. Magnets large enough to affect an entire suit would be heavy, so the MR fluid was filled into plastic ABS containers (20 x 20 x 5 mm). To limit leakages of fluid after the impact, modules were small enough so that they could be easily changed after their perforation. Neodymium magnets were inserted into containers each 20 mm and they were inducing a constant magnetic field with value 20 kA/m, Fig. 5b. Incoming projectiles were perpendicular to braids formatted after the magnetic field activation. Tearing of bindings between ferro-elements was supposed to decrease the velocity of a bullet. Similarly to shear-thickening fluid, the viscosity of a MR fluid causes the energy dissipation when the MR fluid is sheared, which also was supposed to be an important factor of a MR fluid applied as an impact energy absorber.

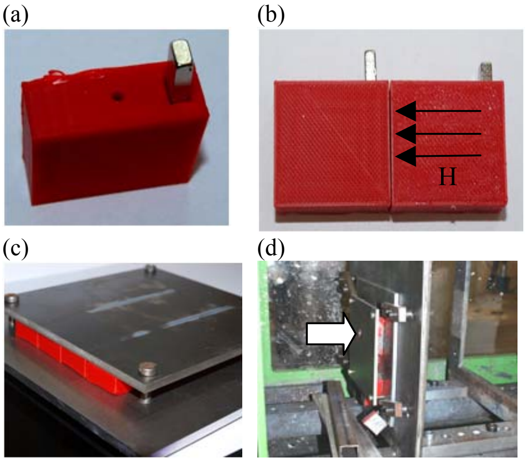


Fig. 5. (a) MR fluid in a single module, (b) two containers with indicated lines of the magnetic field (impacts were perpendicular to them), (c) MRF in modules arranged as the intermediate layer and (d) three-layered sample in the catch-box

The aeral mass of the armour with the MRF interlayer is estimated as close to 50 kg/m^2. Its protective properties were checked by impact tests started from verification of the lowest protection level, [11]. The first level of protection is provided by targets which withstood impacts of soft-core 7.62 NATO Balls DM41 at velocity 840 m/s. A multi-hit resistance was not tested; each target was submitted to one shot.

At first, shots were performed to the titanium-aluminium armour with a 5 mm air gap instead of containers with a MRF – treated as a reference configuration. Two-plated armours with the aeral mass 35 km/m^2 and thickness 15 mm were perforated by DM41 balls. The measured residual velocity of the bullet core was equal to 700 m/s. In average, for a few performed tests, projectile velocities dropped about 17%.

Next, a series of shots with the same threats was made to the laminates with MRF modules (Fig. 5d). In all cases, the plates were perforated by impacts with the velocity close to 840 m/s.

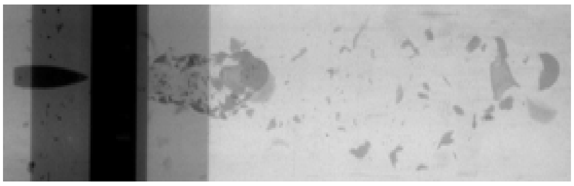


Fig. 6. Flash X-ray images taken at different time steps, before the projectile hit the plate and two times after its perforation

An exemplary flash X-ray image from one of impacts is shown in Fig. 6. It may be seen that the projectile jacket was partly peeled off and the core was highly deformed. The impact velocity was reduced to 655 m/s. The reduction of impact velocities for the configuration with the MRF was measured as 20 – 25%.

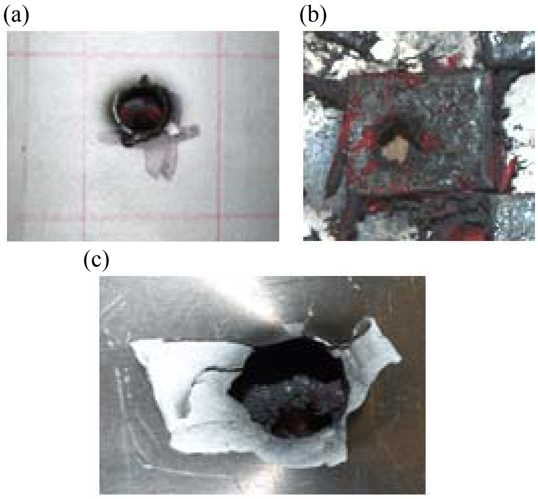


Fig. 7. Layers of the tested armour perforated by a Ball DM41: (a) entry hole in the Ti plate, (b) perforated container with the MR fluid, (c) exit hole in the Al plate

Fig. 7 shows the perforated layers of the tested three-layered armour. A ductile hole at the striking face of the titanium plate is seen. The AA7065 plate behaved in a more brittle manner – its rear face failed due to petalling and delaminations of the internal structure. In the presented example, a projectile hit in the middle of a MR fluid container (not in a magnet). The reduction of velocity was caused by the MR fluid and also by the plastic walls of the container. The shear hardening of the fluid did not have a strong influence on shattering of the bullet core.

The performed experiment did not prove high applicable capabilities of MR fluids to damp impact energy of small-calibre projectiles. Magnetic forces between ferro-elements of braids in the solidified MR fluid did not affect strongly projectiles. However, a presented study shows very early results of the conducted experimental investigation. To complete the study, a number of factors should be carefully analyzed. An influence of braids direction and power of magnetic bindings on bullet behaviour should be tested (in the study, braids were perpendicular to the impact direction and magnets caused a field with value of 20 kA/m). Another possibility would be an evaluation of the influence of impact rates on shear hardening of the fluid.

Some improvements might increase usefulness of MR fluids in application for armours. One of them would be cellular foams immersed with a MR fluid. A cellular skeleton would be supported by the structure of a MRF, which would additionally increase the performance against for example blast.

4. CONCLUSIONS

The physics of ballistic penetration is very complex – nonlinear phenomena included deformation and fracture of materials under increasing strain rates and temperatures; dependent also on interactions between targets and threat. This is a reason of a number various armour designs aiming for a better and lighter shield. As it is known that dissipation of impact energy is sensitive to boundary conditions, the tested in the study armours accounted for a combination of materials with different properties arranged in laminates. The prototype armours accounted for a rubber and a MR fluid as the intermediate layer.

The analysis of the results obtained due to the performed ballistic impacts proved that the application of rubbers to absorb impact energy of pointed bullets is worth further investigations, as the tested material configuration was not perforated by 7.62 API projectiles. The tested experimental configuration was 42% lighter than a reference RHA steel. The resistance to penetration of the laminate with an elastomer entails factors beyond direct energy dissipation (i.e. plastic deformation and fracture), such as impedance mismatching, strain delocalization and the impact-induced transition of the rubber to the glassy state.

In the second concept, containers filled by a MR fluid were assembled between the titanium and aluminium plates. MR fluid can change from a liquid to a hard gel under the magnetic field influence. It was also assumed that hardening of MR fluids under shearing could affect bullet shattering. But it takes about twenty thousandths of a second, which is too slow comparing to a range of rates of impact loadings. The impact test with DM41 Nato Balls did not prove that MR fluids provide high efficiency against high-velocity impacts but the measured residual velocities were lower than those from the reference configuration without a MR fluid. A number of factors which influences the behaviour of MR fluid under impacts is still not checked (like a magnetic field of higher strengths, for example).

Since the materials tested as intermediate layers are highly nonlinear, understanding of phenomena occurred during their penetration requires further analysis and deconvolution of the effects responsible for the resistance to impacts of small-calibre projectiles.

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