BALLISTIC TEST OF MULTILAYERED ARMOR WITH INTERMEDIATE EPOXY COMPOSITE REINFORCED WITH JUTE FABRIC

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ABSTRACT

Multilayered armors with a front ceramic followed by aramid fabric are currently used against high speed ammunition. In these armors, a front ceramic layer that erodes the bullet is followed by an intermediate layer, usually made of aramid fabric, which dissipates the fragments energy. In the present work, the intermediate aramid fabric layer was replaced by an equal thickness layer of jute fabric reinforced epoxy composite. Ballistic impact test with 7.62 caliber ammunition revealed that the jute fabric composite, although not as efficient as the aramid fabric attended the NIJ standard for body protection. The mechanism of jute fabric composite protection was analyzed by scanning electron microscopy. The results indicate that both the rupture of the brittle epoxy matrix and the interaction of the jute fibers with the fragments from the front layer contribute to dissipate the incoming impact energy.

Keywords: Ballistic test, multilayered armor, jute fiber composite, bullet penetration analysis.
1. INTRODUCTION

Armor vests for human protection against relatively heavy ammunition, such as the 7.62 mm x 51 caliber bullet, require a light shielding system with high impact absorption and resistance to penetration. Monolithic layer, typically a steel plate\(^1\), are not able to provide the necessary protection unless with a comparatively larger thickness, which compromises lightness and portability. Multilayered armor systems (MAS) combining relatively lighter materials are currently extensively investigated\(^2\text-}^4\) and used as portable vests. The MAS aims not only to absorb the impact energy of the projectile but also to impede the penetration of fragments\(^5\). Indeed, a portable armor vest for body protection should be a low cost and lightweight wearable garment system with ballistic impact resistance\(^6\). The NIJ standards\(^7\) specify that body armor should stop a projectile and prevent its penetration into a clay witness backing the armor to a depth not exceeding 1.73 inches (44 mm). Beyond this depth the penetration can potentially cause serious blunt trauma to the body armor wearer\(^8\).

MAS are usually composed of a harder front ceramic tile with the ability to deform and erode/fracture the projectile\(^9\). Owing to this ceramic frontal layer, a great deal of the projectile energy is dissipated through dynamic fragmentation involving nucleation, growth and coalescence of micro cracks\(^10\). It is known that once a high energy projectile strikes the front ceramic tile, a compressive wave propagates and reaches the back of the tile\(^11\). There, the wave is partially reflected as a tensile pulse, which normally breaks the ceramic tile regardless of the interlayer material connecting the following layer\(^4\). A second MAS layer backing the ceramic tile might be chosen as a lighter composite material, which reduces even further the impact wave by absorbing part of the fragments (projectile or ceramic) kinetic energy. For this second layer, glass fiber composites have originally been preferred\(^12,13\) and carbon fiber composites investigated\(^14,15\). Today, however, aramid fabric such as Kevlar\textsuperscript{™} and Twaron\textsuperscript{™}\(^6,16\) as well ultra high molecular polyethylene fiber such as Spectra\textsuperscript{™} and Dyneema\textsuperscript{™}\(^17,18\) reinforcement are becoming the choices for lightweight body armor composites.

As the lighter component of a body armor vest, the intermediate composite layer is not only intended to provide comfort and mobility to the wearer but also to improve the absorption efficiency of the projectile impact. Indeed, upon the projectile
impact a compressive wave is generated and travels through the several layers of a MAS. At the interfaces between different materials (ceramic/composite/metal) the propagating energy pulse is reflected back as either a tensile or a compressive wave, depending on the impedance of the two layers\textsuperscript{19}. In the case that a lower shock impedance composite stands behind the interface, the proceeding compressive wave will be comparatively lower in transmitted energy. Since the shock impedance is directly related to the material's density, a greater ballistic impact energy reduction should be provided by a comparatively lighter composite backing the ceramic tile. The substitution of an even lower density fiber reinforced composite for the aramid should, in principle, be an alternative to improve the impact absorption. A possible candidate might be a lighter polymer composite reinforced with natural fibers. Natural fibers obtained from plants, also known as lignocellulosic fibers, in addition to a lower density than aramid, are much less expensive and regarded as environmentally friendly. In recent years, polymer composites reinforced with lignocellulosic fibers have been extensively investigated\textsuperscript{21-24} and applied in several engineering sectors particularly the automotive industry\textsuperscript{25}. In particular, the jute fiber extracted from the stern of the plants in the genus Corchorus, native of the India, was reported to have a density of 1.3 g/cm\textsuperscript{3} and tensile strength of 393 to 773 MPa\textsuperscript{28}.

In the present work, the ballistic performance of armors composed of ceramic, composite and aluminum layers was investigated in terms of penetration into clay witness simulating a human body. Ballistic tests were conducted in MASs with a front Al\textsubscript{2}O\textsubscript{3} tile. As the following intermediate layer, lighter jute fiber reinforced epoxy composite plates were compared (same thickness), to plain epoxy plates and aramid fiber plies. The contribution of each material was also assessed by individual ballistic tests. The fracture aspects of the different types of intermediated layer materials were analyzed by scanning electron microscopy.

2. MATERIALS AND METHODS

The multilayered armor system (MAS) arrangement used in this investigation was compound for:

(i) a front layer of 15 mm thick hexagonal tile with 31mm of side dimension and made of 4 wt% Nb\textsubscript{2}O\textsubscript{5} doped Al\textsubscript{2}O\textsubscript{3} impact resistant ceramic. Ceramic tiles were fabricated by sintering Al\textsubscript{2}O\textsubscript{3} powder (0.3 μm of particle size) supplied by Treibacher
Schleifmittel as commercial purity mixed with Nb₂O₅ powder (0.69 μm of particle size) supplied by the Brazilian firm CBMM as 99% pro-analysis. Sintering was carried out at 1,400 °C for 3 hour under air.

(ii) A intermediate layer with 10 mm in thickness and square sides with 150 mm was either: 8 plies of aramid fabric, or 30% vol of continuous and aligned jute fibers reinforced epoxy matrix composite (jute composite for short) plates, or plain epoxy plate. The aramid fabric plies were supplied by the Brazilian firm LFJ Blindagem Com. Serv. S.A. The jute fiber was supplied by the Brazilian firm Amazon Paper in the form of a bundle. Fibers were separated from the bundle, dried at 60°C in a laboratory stove for 2 hours, and aligned with the correct amount inside a steel mold. An initially fluid diglycidyl ether of the bisphenol-A (DGEBA) epoxy resin, mixed with a phr 13 stoichiometric fraction of triethylene tetramine (TETA) as hardener, was poured onto the mold. A pressure of 5 MPa was applied and the composite plate cured for 24 hours. In a similar procedure, plain DGEBA/TETA epoxy plates were also fabricated.

(iii) The back layer was a 150 x 150 mm 6061-T6 aluminum alloy sheet with 5 mm in thickness. These layers were bonded in the composite with commercial Sikaflex™ glue from Sika Co..

In direct contact with this metallic back layer, a block of clay witness simulated a human body protected by the MAS. Modeling clay, compressed to avoid air bubbles, was commercially supplied by American Express. The trauma in the clay duplicates the plastic deformation imposed by the projectile impact on the aluminum back layer. The corresponding indentation was measured with a rigid ruler and caliper with an accuracy of 0.01 mm. In order to prevent ceramic fragments to fly away an aramid spall shield was attached to the armor front.

The ballistic tests were conducted at the Brazilian Army shooting range facility, CAEX, in the Marambaia peninsula, Rio de Janeiro. All tests, 3 for each type of MAS, were carried out according to the NIJ 0101.03 and NIJ 0101.04 standards using 7.62 x 51 mm NATO military ammunition. The 9.7 g projectile, ammunition bullet, was propelled from a velocity test barrel. Tests in which the target was totally perforated, allowed the residual velocity of the outcoming projectile or fragments to be was also measured. Fractured samples of each MAS component after the ballistic test were analyzed by scanning electron microscopy (SEM) in either a model FSM 6460 LV.
Jeol or a model QUANTA FEG250 Fei microscopes operating with secondary electrons at 20 kV.

3. RESULTS AND DISCUSSION

3.1. Multilayered Armor Ballistic Performance

All ballistic tests conducted in the MASs failed to perforate the target. Consequently, the projectile was always stopped and its kinetic energy was dissipated inside the multilayered armor in association with an indentation in the clay witness. To evaluate the individual ballistic behavior of each distinct intermediate layer, tests were separately performed in the ceramic tile, aramid fabric plies, jute composite plate and plain epoxy plate. In these tests, contrary to the MAS tests, the target was always perforated. Therefore, in addition to the impact velocity, the projectile residual velocity after perforation could also be measured.

The three materials tested as the intermediate layer that follows the front ceramic layer, showed corresponding indentation depth below the NIJ\(^7\) limit of 44 mm for serious blunt trauma. The aramid fabric with 13.50 mm displays the best result (smaller indentation) in confront to both the jute composite with 16.42 mm and the plain epoxy with 19.84 mm. The jute composite indentation corresponds to a 17.8 % penalty, as compared with the aramid fiber ballistic performance. However, the jute composite is significantly lighter and less expensive than the aramid fabric\(^{26,27}\). These are advantages that might be considered as practical compensations for the higher ballistic performance of aramid fabric plies.

3.2. Ballistic Penetration

The ballistic performance of the MAS’s investigated was a consequence of the energy absorption by the different layers. Both the first Al\(_2\)O\(_3\) ceramic layer as well as the second layer, either aramid or composite were perforated by the projectile. However, a significant amount of energy was absorbed by these first and second MAS layers. After crossing the second layer, fragments (projectile or ceramic) were only able to cause a relatively small plastic deformation in the aluminum sheet back layer, causing the indentation in the clay witness.

The perforation of the first ceramic layer, which is responsible for most of the energy dissipation\(^7,9\), was associated with shuttering of the brittle ceramic tile.
In the damage region of an aramid fabric plies observed of fabric yarn pullout, fiber stretching and fiber rupture reported by Lee et al\(^6\). Additionally, was noted that bright and white particles of Al\(_2\)O\(_3\) are attached to the fibers. This indicates that the aramid fabric contributes in the energy dissipation by stopping ceramic fragments. Small metallic particles from the projectile were also found entangled in the aramid fibers and so contributing to dissipate the energy.

The fracture region of a jute composite after penetration showed the separation of jute fibers in thinner fibrils, which is a characteristic of its mechanical rupture\(^{20}\). This contributes significantly to absorb the impact energy. Moreover, the fracture of the brittle epoxy matrix, pointed by arrow, is another source of energy dissipation. Similar to what was found in the damaged aramid fabric, the ballistic penetration of fragments also impregnated the jute composite fracture by the bright and white particles.

The fracture of a plain epoxy presented mechanisms for dissipating energy as the nucleation and propagation of cracks in a typical brittle polymer “river pattern”. Consequently the plain epoxy rupture is not as efficient in reducing the energy or stopping fragments from the initial ballistic impact. This explains the higher indentation, Tab. 1, as compared with aramid fabric or jute composite.

3.3. Individual Components Ballistic Performance

The contribution of each MAS component was assessed by individual ballistic tests using the same ammunition, 7.62 x 51 mm NATO, and methodology described in the previous section. The average impact velocity of 846 m/s corresponds to a projectile kinetic energy of 3,471 J. Individual targets with same thickness of the separate component layers: Al\(_2\)O\(_3\) ceramic tile, aramid fabric plies, jute composite plate and plain epoxy plate, were tested in 3 samples of each. All targets were completed perforated after these individual tests. Not only the projectile impact velocity but also the residual velocity of the fragments passing through the target were measured by the Doppler radar system.

For aramid fabric jute composite and plain epoxy targets, the residual velocities were found to be relatively closer to the corresponding impact velocities. It was observed a much greater decrease in the ceramic impact to the residual velocity, about 33%, as compared to less than 3% for the other components. The possible explanation for the relatively low individual absorption energy of the aramid fabric in
the present ballistic tests might be associated with the easy penetration in between the aramid fabric weave by simply separating or pulling out the yarns. Therefore, individually, an aramid fabric is not as effective barrier to a 7.62 bullet as compared to jute composite or a plain epoxy, in which the brittle matrix is able to dissipate more energy by fragmentation. Once again, the reader should be reminded that a jute composite attends the NIJ\textsuperscript{(7)} standard limits for body trauma and sensibly reduces the MAS weight and price.

**CONCLUSIONS**

- A multilayered armor with epoxy matrix composite reinforced with jute fiber attended the NIJ trauma limit after ballistic tests with 7.62 x 51 mm ammunition.
- The ballistic performance of the jute composite is 18% less effective than the aramid fabric but might be compensated by being 5% lighter and 31% cheaper.
- The addition to fiber rupture and stretching that occur in the aramid fabric, the jute composite also contributes to dissipate the fragments (projectile or ceramic) energy through crack nucleation and propagation in the epoxy matrix.
- Ballistic tests of each individual (separated) components revealed that the Al\textsubscript{2}O\textsubscript{3} ceramic tile dissipates around 55% of the 7.62 bullet impact energy while the other components dissipate less than 3%. The lowest energy dissipation of aramid might be attributed to the easy penetration of the sharp-pointed bullet in between the yarns of the fabric weave.

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**REFERENCES**


