Original Article

Effect of the impact geometry in the ballistic trauma absorption of a ceramic multilayered armor system

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A R T I C L E   I N F O

Article history:
Received 1 March 2018
Accepted 10 June 2018
Available online 23 August 2018

Keywords:
Ballistic test
Ceramic armor
Multilayered armor system
Impact geometry

A B S T R A C T

Ceramic armors are frequently used for protection against high energy projectiles, such as the 7.62 mm and 5.56 mm. Recently, it has been demonstrated that a modification in the geometry of the impact face, from flat to convex, enlarges the stress distribution zone created by the projectile-target interaction. This effect raises the projectile’s energy absorption and might improve the user’s safety. In the present work, the objective is to characterize ceramic armor plates with convex impact face, by means of the NIJ-0101.06 (2008) standard methodology, aiming to provide an eventual application in armor vests. The characterization is based on the measurement of the backface signature, a deformation behind armor imprinted in a reference material that simulates the consistency of the human body. The results showed significant improvement in the ballistic performance after the impact geometry modification.

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1. Introduction

Ceramic materials are widely employed for ballistic protection of individuals (ballistic vests) and structures, as alternative to reduce the weight of the armor, which has conventionally been made of steel. They integrate the multilayered armor systems (MAS), acting in conjunction with other materials for protection against high kinetic energy projectiles, such as the 7.62 and 5.56 mm ammunitions [1–3].

The ceramics are of great importance to a MAS. They are commonly used as the front layer, due to their high strength and hardness, having the ability of eroding the tip of the projectile. In this case, the stresses generated through the impact are distributed to a larger area, and thus a significant portion of the material responds and resists to the dynamic load. Also,
the ceramic spalling characteristics enables the absorption of a great amount of the projectile’s energy, in the production of fracture surfaces, which can reach 50% of the total kinetic energy of a 7.62 mm moving bullet [2–6]. In fact, ceramics are usually brittle materials with a tendency to shatter under impact loading. In many engineering situations, such as the case of concrete subjected to high strain rates [7–10] the impact impairs its integrity. By contrast, ceramic fragmentation under ballistic impact favors the dissipation of energy [11–16].

In a previous work, Monteiro et al. [17] investigated a ballistic ceramic based on alumina (Al₂O₃) doped with niobia (Nb₂O₅), either with flat or convex-shaped (80 mm radius) strike face. The authors measured the absorption of the projectile’s kinetic energy by the ceramic target, by measuring the penetration of the projectile in an 6061-T6 aluminum block positioned in the back face of the target (known as “depth of penetration test” or DOP). They found an improvement of 16% in energy absorption when the convex-faced ceramic replaces the flat one.

Finite element simulations were also performed by Monteiro et al. [17]. The result is illustrated in Fig. 1. This shows the decaying of the projectile’s energy after impacting the front ceramics, together with images of the damaged zones 25 μs, also relative to the impact. According to the authors [17], the impact interaction ceased at 30 μs, which represents perforation of the target. At this time, the difference in absorbed energies is 0.23 kJ, which represents 16% difference between flat and convex-faced ceramics. Fig. 1 also shows that the convex face contributes to enlarge the damaged area of the target, resulting in higher energy absorption. Those features contribute to the understanding that the difference in observed energy absorption (DOP test) is related to the impact geometry modification.

The oblique impact has been studied by several authors [18–21]. The motivation is mainly to develop lighter and safer protection systems. Therefore, the objective of the present work is to characterize the behavior of a MAS with convex ceramic front, when subjected to ballistic impact with 7.62 mm ammunition. It has been applied the methodology of the NIJ-0101.06 standard [22], which specifies the measurement of the indentation behind armor (also called “backface signature” or “trauma”) in a reference clay witness that simulates the consistency of the human body.

2. Materials and methods

The ceramic material investigated in the present work consists of alumina (Al₂O₃) containing 4 wt.% of niobia (Nb₂O₅). The alumina has been provided by the company Treibacher Schleifmittel and the niobia by Companhia Brasileira de Metalurgia e Mineração (CBMM). The ceramic processing included the mixing and milling of the powder in water suspension using polyethylene glycol as binder. The suspension was then dried at 60 °C for 48 h and sifted until 0.355 (42 mesh). The

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Fig. 1 – Decaying dissipated impact energy of the 7.62 mm bullet [17].

Fig. 2 – Ceramic powder pressing: (a) hexagonal steel mold; (b) epoxy putty adaptation for the production of convex-faced pieces.
The aramid fabric was provided by the Brazilian company LFJ Blindagens. It consists in a plain weave fabric composed by Kevlar 29 fibers, with areal density of 450 g/m². The laminates contained 18 fabric layers joined together with polychloroprene rubber. Some mechanical properties of the aramid fibers and fabrics are shown in Table 3.

The MAS were subjected to ballistic impact with 7.62 × 51 mm M1 ammunition, with 9.7 g of weight, commercially provided to the Brazilian Army. The shooting device, available in the Brazilian Army Assessment Center (CAEx), consists in a gun barrel with laser sight (Fig. 5a), located 15 m from the target (armor specimens). The shooting was performed horizontally, with the targets positioned in front of a Roma Plastilina type clay witness (Fig. 5b), with 1.7 g/cm³ density, simulating the consistency of the human body. The consistency of the clay witness is validated by the drop weight tests, which was performed following the procedure specified by the NIJ Standard [22]. The deformation behind armor, known as trauma or backface signature (BFS), was measured and used as parameter to compare the MAS specimens. This methodology is also specified in the NIJ-0101.06 standard [22]. Fig. 5 also shows the MAS with strike face with flat (Fig. 5c) or convex ceramic (Fig. 5d) fixed in the clay witness for the test.

The impact velocity (υ) of each projectile was measured using a HPI B472 optical barrier. This is specified by the NIJ standard [22] to avoid large variations in the impact kinetic energy, influencing the results.

After the ballistic tests, fragments of the MAS in the impact zone were microscopically evaluated by scanning electron microscopy (SEM), using a Quanta FEG 250 FEI equipment, using secondary electrons contrast.

### Table 1 – Characteristics of the ceramic.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Average value</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>3.51</td>
<td>0.06</td>
</tr>
<tr>
<td>Vickers microhardness (HV)</td>
<td>386</td>
<td>40</td>
</tr>
<tr>
<td>Grain size (μm)</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 2 – Characteristics of the 5052 H34 aluminum alloy.

<table>
<thead>
<tr>
<th>Mechanical property</th>
<th>Average value</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (MPa)</td>
<td>244</td>
<td>2</td>
</tr>
<tr>
<td>Total deformation (%)</td>
<td>19</td>
<td>2</td>
</tr>
<tr>
<td>Rockwell B hardness</td>
<td>20.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Chemical composition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Element content (%)</td>
<td>96.7</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>96.7</td>
</tr>
<tr>
<td>Mg</td>
<td>2.3</td>
</tr>
<tr>
<td>Ag</td>
<td>0.7</td>
</tr>
<tr>
<td>Cr</td>
<td>0.2</td>
</tr>
</tbody>
</table>

* Using 5 mm steel sphere and 750 g as load.

* Estimated by energy-dispersive spectroscopy (EDS).

The aramid fabric was provided by the Brazilian company LFJ Blindagens. It consists in a plain weave fabric composed by Kevlar 29 fibers, with areal density of 450 g/m². The laminates contained 18 fabric layers joined together with polychloroprene rubber. Some mechanical properties of the aramid fibers and fabrics are shown in Table 3.

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### 3. Results

Table 4 shows the values of impact velocity (υ) and backface signature (BFS) for the MAS with flat [12] and convex ceramic strike face. None of the MAS were perforated, and all the BFS values were below the 44 mm (1.73 in.) specified by the NIJ-0101.06 [22] for the level III of protection. Therefore, in terms of BFS, the performance can be considered satisfactory for both MAS.

By comparing the BFS values, the MAS with convex strike face had a better performance, with 19% lower average BFS than the flat one (decreasing the BFS from 21 ± 3 to 17 ± 1 mm).
Fig. 4 – Schematic diagram showing the multilayered armor system of the present work mounted for the backface signature test.

Table 3 – Properties of the aramid fibers and fabrics [23].

<table>
<thead>
<tr>
<th>Aramid fiber type</th>
<th>Fiber diameter (µm)</th>
<th>Fiber density (g/cm³)</th>
<th>Tensile strength (GPa)</th>
<th>Tensile modulus (GPa)</th>
<th>Elongation at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevlar 29⁰, DuPont</td>
<td>12</td>
<td>1.43</td>
<td>2.9</td>
<td>70</td>
<td>4</td>
</tr>
<tr>
<td>Kevlar 129⁰, DuPont</td>
<td>12</td>
<td>1.43</td>
<td>3.4</td>
<td>99</td>
<td>3.3</td>
</tr>
</tbody>
</table>

It is important to emphasize that, the lower the BFS, the better the ballistic performance, since less energy would be transmitted to the user, improving safety.

The general aspect of the different MAS were very similar, with total fragmentation of the ceramic tiles and partial penetration of the projectile in the aramid layer, as shown in Fig. 6. The projectile, as well as the ceramic, was totally fragmented. As can be seen in Fig. 6c and d, aramid yarns were broken in the impact zone, and ceramic fragments can be visualized all over fiber surfaces.

Fig. 5 – Ballistic test: (a) gun barrel; (b) Roma Plastilina type clay witness; (c) MAS with flat-faced ceramic front; (d) MAS with convex-faced ceramic front.
Larger ceramic fragments were collected and observed in the SEM, and the result is shown in Fig. 7. For both specimens (Fig. 7a and b), the fracture is essentially intergranular. This is attributed to grain boundary precipitates which are formed by the reaction of the ceramic components (alumina and niobia).

Fig. 8a and b shows the microscopic aspect in the aramid impact zone, for the flat-faced and convex-faced ceramic MAS, with high magnifications (5000× and 4000×, respectively). In these figures, the main features are the broken aramid fibers and the ceramic deposition over the fibers.

4. Discussion

The highest energy absorption of the convex-faced ceramic against the flat-faced, shown in Table 4, had already been demonstrated by Monteiro et al. [17], as previously discussed. The improvement in the performance is attributed to the fact that most of the convex impact surface is oblique relative to the projectile, and then the probability of orthogonal impact is almost negligible [17]. Besides that, the obliquity of the surface makes the impact energy to be distributed to a larger volume of the ceramic. This phenomenon can be visualized in the simulation (Fig. 1) by the longer and more numerous radial cracks in the (25 μs) stress calculations. According to Tasdemirci et al. [24], a larger energy absorption can be expected when the ceramic is being fragmented in smaller pieces. Since more cracks are being nucleated and propagated, more of the projectile’s energy is being consumed in the convex-faced material. That would be the same reason that the intergranular cracking could be beneficial to the ballistic performance of the ceramic. In this case, the cracks go through the grain boundaries, following a long and tortuous path, as can be seen in Fig. 7. Therefore, the niobia addition to improve brittleness and promote intergranular cracking is also important for a high energy absorption [17].

The fracture of the aramid threads, observed in Fig. 6c and d, can be attributed to the ceramic and projectile fragments moving cloud that impacts the fabric layer at a very high speeds. The detail of the fiber surfaces filled with ceramic particles can be better observed in Fig. 8a and b. Differentiation between ceramic and projectile fragments is relatively easy, however, fragments of the projectile are very scarce and could not be found among the ceramic particles. According to Braga et al. [25], in a similar ceramic MAS, the approximately 20 mm in length projectile is fragmented to particles smaller than 50 μm. In this previous work [25], the authors observed a small

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**Table 4 – Backface signature (BFS) measured in the ballistic tests for both ceramic geometries.**

<table>
<thead>
<tr>
<th>Strike face geometry</th>
<th>( v_i ) (m/s)</th>
<th>BFS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>840.45</td>
<td>17.56</td>
</tr>
<tr>
<td></td>
<td>842.78</td>
<td>21.79</td>
</tr>
<tr>
<td></td>
<td>849.90</td>
<td>23.16</td>
</tr>
<tr>
<td></td>
<td>842.07</td>
<td>25.04</td>
</tr>
<tr>
<td></td>
<td>856.16</td>
<td>20.10</td>
</tr>
<tr>
<td>Average</td>
<td>846 ± 7</td>
<td>21 ± 3</td>
</tr>
<tr>
<td>Convex</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>853.79</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>846.10</td>
<td>16.3</td>
</tr>
<tr>
<td></td>
<td>844.20</td>
<td>18.3</td>
</tr>
<tr>
<td>Average</td>
<td>848 ± 5</td>
<td>17 ± 1</td>
</tr>
</tbody>
</table>
projectile fragment bonded together with ceramic particles in a similar MAS, after 7.62 mm ballistic impact.

5. Summary and conclusions

In the present work, the ballistic behavior of a ceramic multilayered armor system (MAS) with either flat, or convex strike face, was investigated. The MAS was subjected to level III backface signature (NIJ-0101.06 tests), using 7.62 × 51 mm commercial ammunition.

- The ballistic performance of both MAS could be considered satisfactory in terms of backface signature tests, performed following the NIJ Standard 0101.06 [22], for the level III of protection.

- The convex-faced ceramic showed superior performance relative to the flat-faced, decreasing the backface signature of the armor in 19%. This system can thus be considered a safer solution in terms of trauma absorption.

- The observation of the fracture mechanisms together with a finite element simulation [17] could elucidate the reason for the higher energy absorption for the convex-faced ceramic. In this case, the impact is mainly oblique, and thus the stresses are distributed to a larger volume of material. This makes a larger number of intergranular cracks propagate and reach a greater distance from the point of impact, consuming more energy.

Conflicts of interest

The authors declare no conflicts of interest.
Acknowledgements

The authors of the present work wish to thank the Brazilian supporting agencies CAPES, CNPq and FAPERJ for the funding, and the CAEx, for performing the ballistic tests.

REFERENCES