ABSTRACT

In recent years, ceramics is a substantial element of the modern systems for protection from high-speed impact. An overview of the ceramic types used and the influence of the physical and mechanical parameters on their functionality is made.

The use of ceramics for ballistic protection in vests and armored helicopter seats dates back to the 1960s and discussions upon that issue become available by the end of the 80s. The ceramics is the main component in the systems for protection against HE projectiles of increases piercing ability developed recently.

Keywords: ceramics, ballistic protection.

RECENTLY USED COMPOSITIONS OF CORRUNDUM CERAMICS

The efficacy of a given protection system can be judged by comparing its surface weight with that of conventional armor steel of the same level of protection, since in most cases the weight restrictions are limiting. Although the efficacy of ceramics protection systems revealed in [1] can contain a certain element of company publicity, we assume that the recent state of art is exhibited here. The comparison between ceramics and armor steel is shown in Fig. 1.

The information about the use of different ceramics: oxide (mainly corundum ones with different content of Al₂O₃) and non-oxide (carbides, borides, nitrides and their combinations) is found in [2-10]. The main requirements to ceramic armors used to be low weight (lower than the equivalent metal protection) and the ability to arrest small armor piercing ammunitions [11-18]. The main properties of ceramics for ballistic protection are revealed in [19-21]. The oxide ceramics, and in particular corundum ceramics, exhibit physic properties making them appropriate for ballistic protection. The corundum ceramics is cheaper and can be manufactured using different methods. It is appropriate for ballistic protection despite its high density (3.95 g/cm³). As a whole, the non-oxide ceramics exhibit high physical and mechanical properties and has comparatively low density (excluding TiB₂), which make them more advantageous than the corundum but are manufactured through hot pressing, which is more expensive and unproductive. Nevertheless, the hot pressing ensures high mechanical properties. The mechanical properties of hot pressed corundum are comparable with those of the non-oxide ceramics. The ceramic-matrix composites behave very well as ballistic material due to their mechanical properties, and especially the fracture resistance. They offer a better ballistic integrity after stroke compared with monolithic ceramics.

ENERGY CALCULATIONS

The balance of energies and the work for piercing a single-layer screen can be presented as:

\[ W_o = A_1 + A_2 + A_3 + W_1 + W_2, \]
The condition \( H_1 > P_k \) is valid during time \( t_p \), after which penetration of the partially deformed and destructed projectile in the broken ceramics continues until the pressure on the contact surface exceeds its hardness \( P_k > H_1 \). In the moment \( t = t_p \) the pressure in the contact area becomes equal to the hardness of the broken ceramics \( P_k = H_1 \) and the penetration is ceased. The penetration modes are determined by the mutual layout of curves \( H_1(t) \) and \( P_k(t) \) describing the dependences hardness-time and contact pressure-time and are shown in Fig. 3.

On the final stage the ceramics has lost a significant part of its strength but in combination with the supporting rear layer decreases the speed through alteration of the impulse of the penetrator. The monolithic ceramic tiles are the most appropriate for initiation of the destruct-

MECHANICAL PROPERTIES AND PROTECTION ABILITIES

The hardness \( H_1 \) of ceramics subjected to high-speed hit rapidly decreases due to in the process of formation of shear and tension stress fields due to its fracture. However, penetration of the projectile is not observed until the hardness of ceramics exceeds the contact pressure.

Fig. 1. Surface weight of ceramics and steel of equivalent protection level.

where:

- \( W_o \) – initial kinetic energy of projectile;
- \( A_1 \) – work for deformation and fracture of projectile;
- \( A_2 \) – work for deformation and fracture of screen;
- \( A_3 \) – work for arresting the piercing projectile;
- \( W_1 + W_2 \) – kinetic energies of remainders of projectile and fragments of screen.

It is experimentally determined that in case of piercing in thin and brittle screens the kinetic energies of projectile are distributed as follows:

\[
A_1 = (0.45...0.5)W_o;
A_2 = (0.02...0.03)W_o;
W_1 + W_2 = (0.4...0.45)W_o.
\]

It is noteworthy that in case of hard and brittle screens the part of work for deformation and destruction \( A_2 \) within the overall energy balance is negligible. As for the work \( A_3 \), in the case of single-layer ceramics screen it is equal to naught. Consequently the use of multi-layer protection systems is required. The interaction of an armor piercing projectile with such system is exhibited in Fig. 2.

Fig. 2. Interaction between projectile and three-layer screen with ceramic outer layer: a – destruction of the projectile’s tip; 1 – ceramics layer; 2 – polymer backing; 3 – metallic layer; b – formation of broken ceramics cone; c – penetration of the remainders of the core within the broken ceramics, deformation of the backing and formation of rear swelling.
tion effect due to their high hardness and low density. However, ceramic armor requires a backing component to support it and to impede the damages during the initial hit/fracture interaction. The backing component also serves to absorb the remaining parts of projectile and ceramic fragments. Consequently, for protection against small ammunitions typical are small two-component ceramic surface composite armors designed for use as tiles in protection vests, armored helicopter seats and additional armoring of metallic or composite bodies of battle vehicles.

The area of fractured ceramics is shaped as truncated cone with its large base facing the backing and small base of diameter insignificantly exceeding the diameter of projectile. The angle of the cone is within the range 110°-130°. On initial stage of formation and acceleration of the conic area, the broken ceramics can be regarded as porous body with fragments tightly arranged to each other, which possesses certain strength in conditions of pressure stress. If the stresses exceed the friction forces, plastic deformation is possible with additional fracture, as well as with increased volume of fractured ceramics due to shifting of single fragments. The penetration of remainders of projectile within the fractured ceramics is accompanied both by inertia and strength resistance.

The fracture cone is accelerated like a solid body and interacts with the backing even before reaching it. The residual strength observed in fractured ceramics is important factor characterizing its protection effect. The role of ceramic layer is to damage the tip of projectile, thus increasing the surface of interaction onto the following layers of the screen and to absorb part of kinetic energy of the remainder of projectile during arresting it within the already fractured ceramics. On order to keep the fractured ceramics in state of pressure and to prevent the fragments from scattering, a strong enough and energy absorbing backing is provided, which arrests the remainders of the damaged projectile and fractured ceramics during its deformation without disintegration.

Fig. 3. Variations of hardness of ceramics and contact pressure in dependence of time in the process of penetration of projectile in ceramic screen.

Table 1. Parameters affecting the protection properties.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>EXERCISES EFFECT ON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-structure: Grain size; Minor phases; Phase transitions and amorphism during dynamic impact; Porosity.</td>
<td>All the rest parameters in the left column bellow.</td>
</tr>
<tr>
<td>Density</td>
<td>Weight of protection system</td>
</tr>
<tr>
<td>Hardness</td>
<td>Extent of destruction of projectile</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>Speed of shock waves</td>
</tr>
<tr>
<td>Strength</td>
<td>Resistance to multiple impact</td>
</tr>
<tr>
<td>Fracture resistance</td>
<td>Resistance to multiple impact</td>
</tr>
<tr>
<td>Character of destruction</td>
<td>Energy absorption</td>
</tr>
</tbody>
</table>
and within the frames of rear swelling admissible for the target protected. Since the beginning of the 1980s increase is observed of the number of patents in which in one form or another ceramics materials are used for ballistic protection. There are a variety of types of ceramic used, as well as methods of arrangement and attachment, backings, ranges for application, degree of protection. Currently realistic assessment of protective properties of ceramics based of their mechanical properties and physicochemical structure in static conditions can not be done. However, some key features can be used to guide the initial selection of ceramics for ballistic protection [20]. They are shown in Table. 1.

The physical- mechanical characteristics of different types of ceramics and the steels used for bullet cores are shown in Table 2.

Unlike steel, ceramics compared to steel, the density of ceramics is about 2-3 times lower and modulus of Young is about 2 times higher. This results to high speed of propagation of longitudinal elastic waves of the order of 10.0-13.0 km/s. It is obvious that ceramics combines high hardness with low impact toughness. It is difficult to make direct correlation between each of these indicators and ballistic impact behavior since the process of destruction of ceramics is not well understood and its duration is very short.

Selected ceramic samples with uneven grain size and presence of at least two crystalline phases exhibit higher protection properties with no decrease in their mechanical properties. It is difficult to formulate general requirements to all types of ceramics due to significant differences in the manner of destruction and dissipation of energy in the impact area. It is more appropriate to determinate optimal parameters of different groups of ceramics.

A semi-empirical criterion to assess the degree of dissipation of energy during ballistic impact can be represented by the equation:

$$D=0.36 \left( \frac{HV.c.E}{K_{IC}^2} \right)$$ [8].

Taking into consideration that the product

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, $\rho$ [g/cm$^3$]</th>
<th>Elasticity modulus E, [GPa]</th>
<th>Hardness of ceramics HV [GPa]</th>
<th>Poisson’s ratio, $\mu$</th>
<th>Longitudinal sound speed, $c$, [Km/s]</th>
<th>Crack-resistance ratio, $K_{IC}$ [MN. m$^{3/2}$]</th>
<th>Relative work for destruction, $W$ [J/m$^2$]</th>
<th>Bending strength $\sigma$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corundum</td>
<td>3.9</td>
<td>407</td>
<td>18.0</td>
<td>0.22</td>
<td>10.4</td>
<td>3.5±0.3</td>
<td>180.500</td>
<td>220</td>
</tr>
<tr>
<td>Boron carbide</td>
<td>2.4-2.52</td>
<td>475</td>
<td>28</td>
<td>0.2</td>
<td>12.4</td>
<td>4.0</td>
<td>260</td>
<td>350</td>
</tr>
<tr>
<td>Boron carbide</td>
<td>2.45-2.52</td>
<td>440-460</td>
<td>29-35</td>
<td>0.2</td>
<td>13.0-13.7</td>
<td>2.0-4.7</td>
<td>200-300</td>
<td></td>
</tr>
<tr>
<td>Silicon carbide</td>
<td>3.0</td>
<td>350</td>
<td>20</td>
<td>0.17</td>
<td>10.5</td>
<td>3.2</td>
<td>240</td>
<td>440</td>
</tr>
<tr>
<td>Hot pressed silicon carbide</td>
<td>3.2-3.45</td>
<td>440-450</td>
<td>-</td>
<td>-</td>
<td>11.0-12.0</td>
<td>5.0-5.5</td>
<td>-</td>
<td>600-730</td>
</tr>
<tr>
<td>Hot pressed silicon nitride</td>
<td>3.2-3.45</td>
<td>-</td>
<td>16-19</td>
<td>-</td>
<td>6.3-9.0</td>
<td>-</td>
<td>690-830</td>
<td></td>
</tr>
<tr>
<td>Hot pressed titanium diboride</td>
<td>4.48-4.51</td>
<td>550</td>
<td>22-25</td>
<td>-</td>
<td>11.0-13.0</td>
<td>6.7-6.95</td>
<td>-</td>
<td>270-400</td>
</tr>
<tr>
<td>Steel 10</td>
<td>7.86</td>
<td>206</td>
<td>Up to HB 143</td>
<td>0.3</td>
<td>6.0</td>
<td>-</td>
<td>235x10$^4$</td>
<td>400</td>
</tr>
<tr>
<td>Steel U12</td>
<td>7.83</td>
<td>206</td>
<td>Up to HRC 68</td>
<td>0.3</td>
<td>-</td>
<td>18.0</td>
<td>200x10$^3$</td>
<td>1600</td>
</tr>
<tr>
<td>Steel 45</td>
<td>7.82</td>
<td>206</td>
<td>Up to HB 500</td>
<td>0.3</td>
<td>-</td>
<td>120</td>
<td>550x10$^3$</td>
<td>1500</td>
</tr>
</tbody>
</table>

Table 2. Physical-mechanical characteristics of different types of ceramics.
\[ B = \frac{HV.E}{K_w^2} \]

is a criterion for brittleness of ceramics introduced by [21], then the criterion for energy dissipation can be expressed as

\[ D = 0.36(Bc) \]

Consequently, the brittleness is a decisive property for the behavior of ceramics. These formula can be applied for homogenous dense ceramics too.

**CONCLUSIONS**

Materials of increased brittleness, e.g. carbide ceramics, do not withstand multiple hits and exhibit increased susceptibility to cracks formation. The criterion \( B \) is equal to: i/ 350 - 500. \( 10^6 \) m\(^{-1} \) for corundum ceramics ii/ 840 - 1200. \( 10^6 \) for silicon carbide; and iii/ 840 - 1200. \( 10^6 \) m\(^{-1} \) for boron carbide. For heterogeneous materials like reaction-bonded SiC and B\(_2\)C the behavior under ballistic impact is determined mainly by phase content and structure, i.e. content and distribution of residual Si and the size of grains of the main phase of SiC, and the related crack propagation.

For corundum ceramics the content of Al\(_2\)O\(_3\) is determining, as well as the properties of the initial material and the manufacture technology, the flows during manufacture, e.g. local non-homogeneous distribution of glass phase, micro-cracking, etc., being of the heaviest impact.

During the impact between projectile and ceramics, the kinetic energy of projectile decreases almost 3 times within ~ 20 \( \mu \)s at the expense of deceleration and weight loss during fracture. It is found that the fractured coarse-grained reaction-bonded SiC based ceramics and in this case the deceleration and weight loss of projectile are more pronounced than in sintered SiC samples [20].

It is impossible to recommend some particular ceramic material as “the most appropriate” for ballistic protection, especially in relation to weight and price. For each particular case the combination of physical and mechanical characteristics, manufacture mode, production process, as well as design and manufacture of the system for ballistic protection shall be considered.

**REFERENCES**