Post-mortem microstructural characterisation of SiC materials after interaction with a kinetic energy projectile
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Abstract

Ceramic materials prove to be good candidates for armor application against medium kinetic projectiles. The optimization of a ceramic armor concept can be obtained by two different means: the experimental one (with ballistic tests) and the numerical one. In this last case, different models have been developed on physical bases. Nevertheless, values of the parameters used in the material behavior laws and damage criteria are often difficult to be experimentally determined and must be numerically fitted. This results from the lack of information on the physical behavior of projectile and ceramic materials during the interaction, especially in the case of battlefield medium projectile. This paper deals with an understanding of the interaction phenomenology, considering especially the physical mechanisms. A special target configuration has been designed to confine ceramic in order to recover the rubble of the target after the projectile interaction. Thus an approach is done by using a post-mortem microstructural analysis of both projectile and ceramic target.

1 Introduction

Against medium kinetic projectile, ceramic such as Silicon Carbide (SiC) seems to be a good candidate for armor applications. Nevertheless, the optimization of the ceramic armor concept using a numerical approach requires the determination of behavior law and damage criteria. Different models have been developed by Rajendran [1] or Cortes [2], for example, which present a physical basis but depend on empirical values. As a matter of fact, only few parameters could be measured during ballistic experiments. Thus it seems interesting to consider
some microstructural aspects after impact, in order to increase the number of experimental measurements to refine the simulation of impact. In a first approach, a post-mortem microstructural analysis of a ceramic target impacted by a medium tungsten penetrator has been carried out. The materials used, the test set-up and ballistic results obtained are presented in the first part. The second part of this work is devoted to the different post mortem analysis made on projectile and ceramic target to collect physical information on materials states.

2 Materials

The silicon carbide tiles used for this study are supplied by Céramiques & Composites society. Its thickness is 50 mm. Two different grades are studied. The first one is obtained by pressureless sintering process and is noted SiC. The other one is performed by a sintering process with a post hot isostatic pressure treatment and is called SiC HIP. This treatment reduces microstructural defects such as porosity. These two grades show equiaxed grains with a mean diameter of 6 μm composed by the 6H polytype phase. In order to improve the sintering process, carbon and boron are added which leads, during the process, to the formation of boron carbide (B₄C) particles as it is visible in figure 1. The mean size of the boron carbide is equal to 3±1.8 μm and particles are spaced by about 5 μm.

![Figure 1: SiC-Electron microprobe analysis showing the B₄C particles distribution](image)

Considering the tile dimension, it is difficult to reach the theoretical density even though with the HIP treatment. The pore volume fraction (fv) estimated by scanning electron micrographs image analysis of polished cross sections is indicated in table1. This parameter is assumed to be the same as the pore surface fraction [3]. Considering this value and taking into account the theoretical density of SiC (3.21), it is possible to evaluate a calculated density (Dc). The apparent density (Da), determined from a picnometry measurement is also reported. It is interesting to notice that Da is higher than Dc. This can be
attributed to the open porosity which is not taken into account with the \( D_a \) measurement.

Table 1. Influence of sintering process on microstructural characteristics

<table>
<thead>
<tr>
<th>( f_v (%) )</th>
<th>SiC</th>
<th>SiC HIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>( D_a /D_c )</td>
<td>3.13/3.07</td>
<td>3.17/3.13</td>
</tr>
</tbody>
</table>

Some mechanical and physical properties of SiC grades are indicated in table 2. It is possible to observe the influence of HIP treatment which reduces the level of defects and thus increases the physical properties. It is important to note that the bending stress is related to the maximum pore size which is difficult to be precisely determined.

Table 2. Physical properties of SiC grades

<table>
<thead>
<tr>
<th></th>
<th>SiC</th>
<th>SiC HIP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>longitudinal wave celerity (m/s)</strong></td>
<td>11800</td>
<td>12100</td>
</tr>
<tr>
<td><strong>transversal wave celerity (m/s)</strong></td>
<td>7600</td>
<td>7700</td>
</tr>
<tr>
<td><strong>Poisson ratio</strong></td>
<td>0,15</td>
<td>0,15</td>
</tr>
<tr>
<td><strong>Young modulus (GPa)</strong></td>
<td>415±30</td>
<td>450±30</td>
</tr>
<tr>
<td><strong>Ultimate bending stress (MPa)</strong></td>
<td>329±34</td>
<td>395±28</td>
</tr>
</tbody>
</table>

Projectile is made of W-Ni-Fe alloy. Strong tungsten particles are embedded in a Ni-Fe-W matrix. An optical micrograph of the cross section of this alloy is shown in figure 2.

Figure 2: Scanning electron micrograph of the projectile cross section

3 Test configuration and ballistic performances

To test ceramic material against medium kinetic projectile, ceramic tile is usually simply confined laterally and axially with steel. Nevertheless, after impact, ceramic targets simply confined are quite difficult to recover. For this reason, a
special target configuration has been designed to confine ceramic in order to recover the ceramic rubbles after the projectile interaction. This configuration is presented in figure 3 and has been used to test SiC and SiC HIP. The projectile geometry is a 10 mm diameter rod with a length of 220 mm. The impact velocity is around 1500 m/s.

![Figure 3: Ceramic target configuration used](image)

Ballistic tests reveal that SiC HIP presents a better ballistic behavior than SiC. Moreover, as presented in figure 3.b, the ceramic target is just perforated, which enables us to achieve a post-mortem microstructural analysis.

### 4 Post mortem analysis

#### 4.1 Target analysis

In order to allow a post mortem analysis, the front steel confinement of the targets was cut. On the top of the targets, whatever the grade of SiC, ceramic appears as a fine powder (figure 4.a). In the bulk of the target, on the inner side of the crater, ceramic is pulverized as it was previously observed by Tracy [4] and Shockey [5]. This damage indicates that high compression is achieved during impact [4]. Outside the crater, ceramic is just broken which is characteristic of a damage induced by tensile stress. The size of the fragments increases with the distance from the crater (figure 4.b).

![Figure 4: Ceramic target analysis](image)

Fragments were observed by scanning electron microscopy (figure 5). Whatever the two grades, crack path is transgranular and is induced by a cleavage mechanism. Some fragments have a very small size lower than 0.5 µm.

The fragment size distributions are determined by a laser diffraction particle size analyser, Coulter LS230. This equipment has a polarized intensity differential scattering which allows to measure particles size greater than 0.04 µm. With this equipment, the particles number per unit volume whose diameter has a given size is plotted as a function of the particle diameter. The
main number of fragments has a size lower than the grain size of the SiC. In figure 6, the total area per unit volume ($a_j$) is represented as a function of the particle diameter ($i$). This area is estimated by assuming that the particle is spherical.

![Figure 4: SiC HIP- Photograph of the target after the impact](image1)

*Figure 4: SiC HIP- Photograph of the target after the impact*

a) on the top b) in the bulk

![Figure 5: SiC HIP-Scanning electron micrograph of rubble showing transgranular crack path](image2)

*Figure 5: SiC HIP-Scanning electron micrograph of rubble showing transgranular crack path*

The main difference between the two microstructures is the double distribution of the surface particle observed for the SiC. As a matter of fact, it appears that the fragments are separated in two grades. The first one is composed of particles which have a mean diameter of 85 nm and the other one of particles with 1.5 μm mean diameter. This double distribution does not appear in the SiC HIP. Nevertheless, if this latest point is neglected, the mean
comprised of particles which have a mean diameter of 0.085 \( \mu m \) and the other one of particles with 1.5 \( \mu m \) mean diameter. This double distribution does not appear in the SiC HIP. Nevertheless, if this latest point is neglected, the mean diameter of the two microstructures is equal and is about 0.15-0.2 \( \mu m \). It is evaluated with the following equations,

\[
d_m = \left( \frac{s_m}{\pi} \right)^{-0.5} \quad (1) \quad \text{and} \quad s_m = \sum a_i / \Sigma n_i \quad (2)
\]

where \( s_m \) is the particle mean surface and \( n_i \) is the number of particles by unit volume which have a diameter \( i \).

In order to verify that no phases transformation occurred during impact, X ray diffraction analysis is done on a \( \theta/2\theta \) diffractometer. The results are indicated in figure 7. No phase transformation or polytypism transformation are evidenced. The new diffraction peaks obtained after impact, noted W in figure 7, correspond to the W phase peaks.
4.2 Residual penetrator material analysis

On the inner of the crater, a penetrator fragment remains. SiC particles and porosity are evidenced in the bulk of the residue. Moreover, important microstructural modifications have occurred.

First, the majority of the tungsten nodules are highly strained as it is observed for tungsten penetrator-metallic target by Shockey [5] and Valencia [6]. Moreover, in some areas, the volume fraction of the nodules decreases. In this case, a new phase appears in the binder as it is shown in the figure 9. It is important to note that the abundance of this new phase strongly depends on the SiC fragments or porosity position.

Figure 9: Scanning electron micrograph on penetrator residual material showing the decrease of the tungsten nodule size and the presence of a new phase in the binder

Unfortunately, this new phase is too small to be identified by electron microprobe analysis. Nevertheless, a Si (Kα) X rays image (figure 10.a) exhibits an important diffusion mechanism. This image is achieved at the interface between the penetrator residual material and a SiC fragments. When this image is compared with a Ni (Kα) X ray image (figure 10.b) obtained on the same zone, it appears that Si atoms diffuse only into the binder.

In order to identify this new phase, X ray diffraction experiment is performed on the total surface of the penetrator residual material cross section. The diagram obtained is presented in figure 11. The chemical composition of the phases which induce the most important diffraction peaks are referenced in the figure. X ray diffraction peak corresponding to two tungsten carbide (WC and W₂C) are exhibited. Thus it appears that SiC tends to decompose after penetrator interaction, when it is located near the tungsten alloy. Furthermore, X ray diffraction peak, which correspond to the binder, decreases.
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Figure 10: Electron microprobe analysis of penetrator residual material
a) Si (K\textsubscript{α}) X ray image  b) Ni (K\textsubscript{α}) X ray image

Figure 11: X rays diffraction intensity as a function of the double angle of incident beam (2θ) showing the presence of the two tungsten carbides after the interaction

5 Discussion

It is now well known that pulverized zone observed on the inner side of the crater in ceramic or brittle materials is essentially due to compressive stresses [4]. Meyers [7] indicates that microstructural effects are responsible for cracking under compression. As a matter of fact, microstructural inhomogeneities induce localized regions of tension, which then, lead to crack initiation. Nevertheless, crack cannot grow significantly because it propagates into the compressive stress field surrounding the flaw [4]. Thus, fragments induced by compressive state are much smaller than those observed after a tensile solicitation.
Furthermore, it is shown that the fragments size deeply depends on the pulse duration, strain rate, pressure and the size and the spacing of the initial flaws [7].

In order to simulate perforation experiments, models of pulverized ceramic behavior have been developed. Two main assumptions have been done:

1) from an energetic point of view, Grady [8] concludes that the fragment size is equal to the double of the initial flaw

2) the pulverized ceramic can be modeled as a powder which has an elastic plastic behavior. The elastic modulus is supposed to be correlated with the crack density [1]. The pulverized ceramic behavior is usually described by the mean of a Drucker-Prager law [1, 2].

In our experiments, on one hand, whatever the microstructure of the ceramic, the size of the rubble on the inner side of the crater is the same and is about 100 nm. On the other hand, the SiC HIP exhibits better ballistic performance.

Thus it seems that the fragment size is not only correlated with the initial flaw density. As a matter of fact, when the assumption ”1” is done, it is implicit that an infinity of flaws are present in the materials and, when the level of solicitation increases, the number of flaws which initiate a crack increases. On the other hand, it is often observed that bifurcation crack mechanism occurs under dynamic and high solicitation [9]. This mechanism is observed on the tip of microcracks on the same ceramic impacted at lower energy [10]. Moreover, in our case, the fragment size is much lower than the grain size or the spacing of porosity or boride carbide particles. If crack bifurcation mechanism is neglected, cracks can only be initiated from dislocation or planar fault. Nevertheless, no polytipism transformation is observed and isolated dislocation appears to be a very little flaw in order to induce important stress concentration. The importance of dislocation activity will be confirmed in a further TEM investigation. Then, it seems that the fragment size is perhaps more influenced by the crack branching process than by the initial flaw size.

Considering assumption "2" and the fact that after the pulverization process, the microstructure of the two grades is identical, it seems that the behavior of the two grades is the same during the penetrator erosion process. Then it appears that the better ballistic behavior of the SiC HIP is due to its higher tensile strength. Cagnoux [11] has shown that this property is important in order to prevent the damage due to the spherical tensile wave which propagates in the ceramic after the compressive one, but before the ceramic-projectile interaction.

Melting of the binder, silicon carbide decomposition and silicium diffusion are evidenced inside the penetrator residual materials. The first observation indicates that a temperature higher than 1500°C is reached during the impact. Taking into account the time needed for diffusion, is obvious that the two other mechanisms occur after the impact. Nevertheless, it appears that SiC has a great chemical reactivity with the tungsten alloy. This could have an influence on ballistic performance taking into account the high temperature reached during the impact.

6 Conclusion

Two different grades of silicon carbide are tested as armor application against a medium kinetic energy penetrator. An HIP post treatment of the ceramic induces a decrease of flaws volume fraction and an improvement of ballistic performance. A post-mortem analysis appears to reveal that the microstructure homogeneity improvement plays a most important role during the spherical
tensile wave propagation following the compressive one, than during the damaged ceramic-projectile interaction. Moreover, it appears that silicon carbide have a great chemical reactivity with the penetrator tungsten alloy.

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8 References

1. Rajendran A.M., Modelling the impact behavior od AD85 ceramic under multiaxial loading, Int.J. Impact Engn, 1994, Vol. 15, No 6, 749-768


4. Tracy C., Slavin M.& Viechnicki D., Ceramic Fracture during ballistic impact, Advances in Ceramics, 1988, 22, 295 - 305


[10] Beylat L., Endommagement du carbure de silicium après impact avec un projectile de faible énergie, rapport SERAM, 60126/2, Nov. 95