Simulation of Impact Phenomena on the Composite Structures Containing Ceramic Plates and High Entropy Alloys

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Abstract. Due to excellent mechanical properties, high entropy alloys from the system AlxCrFeCoNi can be used successfully to create composite structures containing both metallic and ceramic plates, which resists at dynamic load during high speeds impact (like projectiles, explosion). The paper presents four different composite structures made from a combination of metallic materials and ceramics plates: duralumin-ceramics, duralumin-ceramics-HEA, HEA-ceramics-HEA, HEA-ceramics-duralumin. Numerical simulation of impact behavior of the composite structures was performed by virtual methods, taking into account the mechanical properties of both materials. The best results were obtained using composite structures HEA-ceramics-HEA, HEA-ceramics-duralumin.

1. Introduction

The specifications regarding the security of the collective and individual defense equipment and structures in the military field have imposed increased requirements for the strength of the panels/flooring/protection elements to the penetration of different types of projectiles, due to the diversification of the types of interventions in the military activities. In order to ensure protection against impacts with high-speed projectiles, the materials must have both mechanical strength and impact energy absorption capacity. This can be accomplished by making materials that combine both requirements or by making composite materials that separately have the two characteristics [1].

The research directions in the field of ballistic protection have resulted in:

- Design and obtainment of modern and efficient devices for personal protection;
- Design and obtainment of protection devices for important facilities;
- Obtainment of new materials with special qualities compared to those considered conventional;
- Design and obtainment of adequate technical devices for intervention and neutralization of DEI;
- Establishing the conditions for testing materials and equipment so as they are fully useful, at a low cost price and with accessible technological possibilities [2 - 6].
Ballistic protection materials are used to obtain armored fighting machines - collective protection - and to manufacture individual protection systems. The main characteristic of the materials used for ballistic protection is the high resistance to the impact with kinetic and explosive ammunition. The provision of equipment for the protection of the armed forces, the police and the intervention structures has demonstrated their full utility during conflicts and events. In addition to the real protection it offers, this equipment also provides moral support for its use as a result of more advanced ergonomics and aesthetics.

Polyamide and polyethylene type polymeric materials, woven or non-woven, offer the best solutions for the production of soft armours, resistant to ballistic fragments and soft-core, sharp-nosed bullets. In order to stop steel-core, sharp-nosed bullets, metal armours or armours made of polymeric composite materials are required. In this area, a Kevlar composite armor with a mass of 28 kg / m² provides the same protection as a steel armour with a mass of 46 kg / m² [7].

To ensure protection against piercing bullets with a mass higher than 10 g and speeds exceeding 850 m/s, none of the solutions above is acceptable. The steel armour facing this threat is 14 mm thick and weighs 130 kg/m² and it cannot be used in the composition of bulletproof vests. The bullet protection problem has been satisfactorily solved by the use of structures that combine the high hardness properties of ceramic materials with the mechanical properties of the polymers used in ballistic protection [8]. Such a structure is composed mainly of a ceramic layer and a polymer composite layer. The two layers of strength are embedded with a polymeric fabric. The ceramics used are characterized by a hardness that exceeds 9 on the Moss scale. The Vickers microhardness of these materials is 2000 - 3000 VHN, compared to 750 VHN in the case of steel.

Currently, the best ballistic protection structures are made entirely of composite materials or incorporate, in part, material with outstanding features of impact resistance. The design and implementation of new structures for ballistic protection is based on the knowledge of the required properties of materials and the creation of composite structures for specific conditions of use. Composite structures for ballistic protection with the use of ceramic and metallic materials are proposed as a solution for effective ballistic protection. One of the classes of metal alloys that can be used for this purpose is the high entropy alloys class (HEA) [9-11]. By definition, high entropy alloys contain at least five main metallic elements with concentrations ranging from 5 to 35% atomic. High entropy alloys (HEA) are composed of n major alloying elements with n ≥ 5, introduced in equimolar or nearly equimolar ratios, which easily lead to the formation of simple solid phase solutions with BCC or FCC, nano-structures or even amorphous states as cast [12, 13, 14]. Therefore, the high entropy alloys are solid solutions with high strength, good thermal stability and hardening capacity above classical alloys, combined with superior strength characteristics under various environmental conditions [15, 16]. High entropy alloys, due to their high mechanical strength and high energy absorption capacity, provide multiple possibilities for use in individual protection applications or military or non-military armoured vehicles.

The paper presents four composite structures made from a combination of metallic materials and ceramics plates. The numerical simulation of impact behaviour of the composite structures was performed by virtual methods in order to assess the performance of the proposed structures.

In order to limit the material costs, the analysis of the ballistic protection performances of the constructive solutions of the composite structures, aimed at choosing the optimum solution, is done by virtual numerical simulation methods using a methodology for dynamic stress behaviour with high speeds of deformation of the composite structures [9]. The proposed methodology uses the Finite Element Method (FEM) for which there is a wide range of software packages [17]. The methodology is formulated in general terms, common to all finite element programs, and thus it can be applied to any program that has the analysis mode. The accuracy of the solutions given by numerical simulations is guaranteed by the correctness of the physical models used. Nowadays, the mathematical support of numerical simulation methods - the mathematical model - is well established. If used correctly, the mathematical support does not adversely affect the solutions [18 – 20]. In other words, the use for
numerical simulations of the current program packages: ABAQUS, ANSYS, AUTODYN, COSMOS M, LS-DYNA, NASTRAN etc. guarantees the correctness of solutions [17,19].

2. Composite structures made of metallic material – ceramic material used for the numerical simulation

For the virtual testing of the composite structures, there were analysed two types of metallic materials, i.e. high entropy alloys from the AlCrFeCoNi system and duralumin as well as ceramic materials. Thus, the composite structures for ballistic protection were designed in the following constructive variants:

- **VARIANT 1** - Composite layered structure consisting of a 2 mm thick duralumin layer and a 10 mm thick ceramic layer, joined with adhesive, as shown in figure 1;
- **VARIANT 2** - Composite layered structure consisting of a 2 mm thick duralumin layer, a 10 mm thick ceramic layer and a 6 mm thick layer of HEA, joined with adhesive, as shown in figure 2;
- **VARIANT 3** - Composite layered structure consisting of a 6 mm thick HEA layer, a 10 mm thick ceramic layer and a 6 mm thick HEA layer, joined with adhesive, as shown in Figure 3;
- **VARIANT 4** - Composite layered structure consisting of a 6 mm thick HEA layer, a 10 mm thick ceramic layer and a 10 mm thick duralumin layer, joined with adhesive, as shown in figure 4.

![Figure 1. Composite structure – VARIANT 1.](image1)

![Figure 2. Composite structure – VARIANT 2.](image2)

![Figure 3. Composite structure – VARIANT 3.](image3)

![Figure 4. Composite structure – VARIANT 4.](image4)
3. Input data for the virtual testing of the composite structures

As mentioned above, the analysis of the performance of the proposed composite structures variants was done using a method of numerical simulation. For each analysis variant there were made three virtual shootings at different speeds, using 7.62 x 39 mm caliber incendiary, armor-piercing bullets.

The virtual testing was made using the same kind of projectile, with the following values of the specific parameters:
- Bullet calibre of 7.62 x 39 mm;
- Shooting angle of 0°;
- Incendiary piercing bullet weight of 7.67g;
- Steel core weight of 4g.

The setting of the speed bullets was done so that the effects on targets to be at the limit of perforating. The speeds of projectiles were adjusted during simulations to fall within these limits, different for each of the four types of structures analysed.

4. Results and discussions

The results of the numerical simulation are presented in Figures 5, 7, 9, 11 and in the graphics from Figures 6, 8, 10, 12, according to the testing speeds. The analysis of these representations highlights the role of correctly positioning the materials relative to the direction of impact.

4.1. Variant 1 (duralumin – ceramics)

In the case of the constructive variant 1 (duralumin - ceramics), the shooting through numerical simulation highlighted the following aspects (figure 5): after 7.4 e-3 ms the aluminium plate was perforated and the bullet reached the ceramic layer. It is noted that after 14.6 e-3 ms cracks appeared and the material of the ceramic plate began to be displaced and after 27 e-3 ms the perforation was complete, the bullet and armour fragments still have high velocity (450 m/s) and can cause lesions or may be lethal. Following the simulation, the speed variation vs. time was plotted for two nodes, from the core of the bullet (node 20966) and of the ceramic plate (node 107237) that was dislocated (figure 6). After 5 μs from the impact between the bullet and the composite structure, the dislocation and acceleration of the considered node from the ceramic plate begins, finally increasing its speed up to 450 m/s while the bullet is slowed down from the impact speed of 1250 m/s at 400 m/s. Subsequently, the speeds of the two nodes reach the same value, establishing a balance between the remaining core and the element dislodged from the ceramic plate.

Figure 5. The behavior of the composite structure VARIANT 1 at impact with an incendiary armor piercing bullet (7.62 mm caliber) with initial speed of 1250 m/s.
This constructive solution does not provide adequate protection for personnel and fighting techniques.

4.2. Variant 2 (duralumin – ceramics – HEA)
Considering the situation in the previous case, the composite structure was modified by adding a layer of HEA to the previous structure. In this case, after $7.8 \times 10^{-3}$ ms the duralumin plate was perforated and the bullet touched the ceramic layer (figure 7).

It is noted that after $16 \times 10^{-3}$ ms cracks appeared and the process of dislocation of the material from the ceramic plate began and after $31.5 \times 10^{-3}$ ms the movement of the bullet and of the dislodged ceramic
element stopped, without cracks in the HEA layer. Following the simulation, the speed variation vs. time was plotted for the node in the bullet core (node 25572 - figure 8). After 30 μs from the impact between the bullet and the structure, its velocity is null and then it has a slight return motion.

This constructive solution can be considered for the obtainment of composite structures used for effective ballistic protection.

4.3. Variant 3 (HEA – ceramics – HEA)
After 6.2 e^{-3} ms the HEA plate was perforated and the bullet reached the ceramic layer (figure 9).

Figure 8. Variation of the bullet speed vs. time at the impact with the composite layered structure – VARIANT 2.

Figure 9. The behavior of the composite structure VARIANT 3 at impact with an incendiary armor piercing bullet (7.62 mm caliber) with initial speed of 1250 m/s.
It is noted that after $18 \, \text{e}^{-3}$ ms the core is consumed more than half without perforating the ceramic layer. It can be observed that the second HEA layer resisted and there is no perforation. After $26 \, \mu\text{s}$ from the impact between the bullet and the composite structure, its velocity is null and it has a slight return motion. The variation of the bullet speed versus time at impact with the composite structure 3 is shown in figure 10. This constructive solution can be considered for the obtainment of ballistic protection structures.

![Figure 10](image-url)

**Figure 10.** Variation of the bullet speed vs. time at the impact with the composite layered structure – VARIANT 3.

4.4. Variant 4 (HEA – ceramics – duralumin)

Another configuration used for virtual testing is made of HEA, ceramic and duralumin (figure 11).

![Figure 11](image-url)

**Figure 11.** The behavior of the composite structure VARIANT 4 at impact with an incendiary armor piercing bullet (7.62 mm caliber) with initial speed of 1250 m/s.
After 6 e-3 ms the HEA plate was perforated and the bullet touched the ceramic layer. It is noted that after 21 e-3 ms the core is consumed more than half without perforating the ceramic layer. At the same time, the other components of the bullet are consumed almost totally without the ceramic layer being cracked and dislodged. It can be observed that the duralumin layer resisted and there is no perforation. After 26 μs from the impact between the bullet and the composite structure, its velocity is null and then it has a slight return motion (figure 12).

![Figure 12. Variation of the bullet speed vs. time at the impact with the composite layered structure – VARIANT 4.](image)

This constructive solution can be considered for the obtainment of composite structures for adequate protection.

5. Conclusions
The composite structure of duralumin-ceramics does not provide adequate protection for personnel and fighting techniques.

The numerical simulations showed that the composite structure of duralumin-ceramics-HEA can be considered for building ballistic protection structures.

The research shows that the composite structure of HEA-ceramic-HEA behaves well during simulations.

Increased attention should be paid to the behaviour of the second HEA layer at the interference between the direct shock wave and the reflected one (it is possible to produce ballistic fragments from the second layer of HEA).

The composite structure of HEA-ceramics-duralumin behaves well at bullet impact and can be used for the obtainment of ballistic protection structures.

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