Dynamic Impact Behaviour of High Entropy Alloys Used in the Military Domain

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Abstract. AlFeCrCoNi high entropy alloys (HEA) feature significant compressive strength characteristics, being usable for severe impact applications in the military domain. The research paper presents the results obtained by testing the impact resistance of four HEA samples of different chemical compositions at perforation with 7.62 mm calibre incendiary armour-piercing bullets. The dynamical behaviour was modelled by numerical simulation based on the results of the dynamic tests conducted in the firing range, thus allowing the development of more efficient high entropy alloys, to be used for collective/personal protection.

1. Introduction

The materials used for ballistic protection have the role of collective or personal defence in the military tactical field. The main characteristics of the ballistic protection materials are the strong resistance to impact with ammunition, as well as the high capacity to absorb the kinetic and explosive energy developed. One of the classes of alloys that can ensure these performances is the high entropy alloys class (HEA) [1-4].

High entropy alloys are composed of n major alloying elements, n ≥ 5, introduced in equimolar or nearly equimolar ratios, easily leading to the formation of simple solid phase solutions with BCC or FCC, nano-structures or even amorphous states as cast [5-7].

The decision to use a certain high entropy alloy in military defense applications is adopted after a scientific analysis of the chemical composition, of the influence of the alloying elements and of the heat treatments which determine the impact resistance capacity. The design of ballistic protection systems is initially validated by simulations followed by experiments conducted in firing ranges. The application of numerical simulation methods results in the streamlining of the technical solutions, in reducing the time required for the completion of the products and in increasing the economic efficiency [8-11].
Numerical simulations are applied from the first steps of the investigation - the design of physical models, followed by the modelling of technological processes and, in the end, by the modelling of the ballistic impact behaviour of the composite structures analysed.

The accuracy of the solutions provided by numerical simulations is guaranteed by the correctness of the physical models used. At present, the mathematical support of numerical simulation methods - the mathematical model - is sufficiently developed. In this respect, the use in numerical simulations of current software packages: ABAQUS, ANSYS, AUTODYN, COSMOS M, LS-DYNA, NASTRAN etc. guarantees the correctness of the solutions, provided that the user correctly designs the physical models using discrete elements [12-15].

Given the diversity of high entropy alloys and their properties, a first step in putting in place is the design of physical models, which are defined by physical consistent patterns expressed by mathematical expressions in the form of constitutive equations. As rapid deformations are accompanied by local thermal effects as well, the material models also include the influence of the thermal regime on the behaviour of the material [4, 16, 17].

The elasticity of the material is generally expressed by the generalized Hooke’s law as a linear function between the elastic strain tensor and the stress tensor. The constitutive equations expressing the plastic behaviour of the materials have different forms, according to the plasticity models used. Currently, the plasticity model most commonly used is the plastic yield model [18]. In the case of high-speed deformation, the most commonly used model is the visco-elastic-plastic model. The constitutive equations of this model contain constants specific to each material and which can be determined experimentally [4].

The paper presents the results obtained by testing some high entropy alloys, used for collective/personal protection, subjected to dynamic stresses with high deformation speeds (impact resistance behaviour by perforation with incendiary armour-piercing bullet). The impact behaviour was numerically simulated based on the results of the dynamic tests conducted in the firing range, in order to choose the best alloy to be used for the above-mentioned applications.

2. Materials and methods

The high entropy alloys were obtained using a vacuum arc remelting equipment (MRF ABJ 900), located in the Laboratory ERAMET - Materials Science and Engineering Faculty from Politehnica University of Bucharest [1, 4]. For the experiments, there were considered four different compositions of high entropy alloys, varying the quantity of some elements (Al, Ni) considered as of significant influence on the properties. The chemical composition of the high entropy alloys obtained and selected for the experimental program is presented in Table 1 [4].

Table 2 presents the values determined for the compressive strength and the hardness of the high entropy alloys selected for the tests [4].

| Table 1. The chemical composition of high entropy alloys used in the experimental program. |
|----------------------------------------------|-----------------|-----------------|-----------------|-----------------|
| Element | HEA-1 AlCrFeCoNi | HEA-5 AlCrFeCoNi | HEA-12 AlCrFeCoNi | HEA-14 AlCrFeCoNi |
|---------|------------------|------------------|------------------|------------------|
| Al      | 10.67            | 8.72             | 9.76             | 8.99             |
| Cr      | 20.55            | 21               | 18.8             | 17.32            |
| Fe      | 22.13            | 22.61            | 20.24            | 18.65            |
| Co      | 23.32            | 23.82            | 21.33            | 19.65            |
| Ni      | 23.33            | 23.85            | 29.86            | 35.38            |

The full characterization of high entropy alloys subjected to dynamic stresses with high deformation speeds involves performing a number of tests, including the simplest tests, conducted in
mechanical testing laboratories, as well as special tests for analysing the material response to rapid stresses.

Table 2. The mechanical properties of the high entropy alloys used in the experimental program.

| Property               | HEA-1 AlCrFeCoNi | HEA-5 Al_{0.8}CrFeCoNi | HEA-12 AlCrFeCoNi_{1.4} | HEA-14 AlCrFeCoNi_{1.8} |
|------------------------|-------------------|-------------------------|-------------------------|-------------------------|
| Compressive strength, MPa | 2200              | 1350                    | 1600                    | 1200                    |
| Hardness HV_{0.1}      | 563               | 427                     | 456                     | 316                     |
| Hardness HB            | 535               | 406                     | 432                     | 300                     |

The purpose of the test experiments is also to determine the dynamic behaviour of HEA when impacted by incendiary armour-piercing bullets. The need for experimental approaches is due to the following main reasons:

- HEA are produced with the goal of building multilayered ballistic packages, consisting also of other materials such as ceramic, steel, aluminium, Dyneema;
- The phenomena associated with the impact of bullets/ballistic fragments/shock waves and various ballistic packages are extremely complex and occur at very high speeds;
- Numerical simulation is a mandatory stage for the design and delivery of optimal ballistic packages;

The execution of a simulated model, as close as possible to the real one, requires the dynamic characterization of the materials involved in the model.

Experimental tests were performed in the Ballistic Personal Protection Equipment Laboratory (Figure 1) of the CBRN and Ecology Defence Scientific Research Centre in accordance with the approved military procedures. There was tested the behaviour of the HEA structures under investigation to 7.62 mm incendiary armour-piercing bullet impacts. The HEA samples were placed on a polystyrene parallelepiped support placed in a metal frame, 5 m from the barrel’s muzzle.

Figure 1. Firing room picture.
A chronograph with photocell frames was inserted in the firing direction to determine the initial speed of the bullets. The test method assumed the variation in the bullets’ initial speed so as to obtain the speed at which all the kinetic energy of the bullet is consumed for its plastic deformation and total or partial penetration of HEA-type samples.

The test configuration is shown in Figure 2. The amount of powder in the cartridge was varied in order to obtain the desired initial speed. The limit speed was calculated as an average penetration speed for 10 firings in the steel discs and its value was 437 m/s.

The effect the impact with the target plate had on the bullets, required for the numerical simulation, was also monitored.

The impact with the incendiary armour-piercing bullet resulted in the partial or total penetration of the samples, with or without total fragmentation. In the case of partial penetration without total fragmentation, it is possible to measure the characteristic dimensions of the sample, i.e. the depth of penetration $H_1$ and the maximum thickness of the sample following deformation $H_2$, shown schematically in Figure 3.

3. Results and discussions

The conditions under which the tests were performed and the configurations of the HEA-type samples obtained after firing are shown in Figures 4 – 7. The results obtained after firing 7.62x39 mm steel core incendiary armour-piercing bullets in the firing range are shown in Table 3.
Figure 4. HEA 1 plate after the firing of a 7.62x39 mm steel core incendiary armour-piercing bullet: 
Alloy plate made of AlCrFeCoNi - HEA 1: 
Outer diameter Ø=65.80 mm 
Thickness g=6.70 mm 
7.62x39 mm steel core incendiary armour-piercing bullet: 
Bullet 8: Bullet speed $V_0 = 412$ m/s.

Figure 5. HEA 5 plate after the firing of a 7.62x39 mm steel core incendiary armour-piercing bullet: 
Alloy plate made of Al$_{0.8}$CrFeCoNi - HEA 5: 
Outer diameter Ø=65.80 mm 
Thickness g=6.60 mm 
7.62x39 mm steel core incendiary armour-piercing bullet: 
Bullet 9: Bullet speed $V_0 = 451$ m/s.

Figure 6. HEA 12 plate after the firing of a 7.62x39 mm steel core incendiary armour-piercing bullet: 
Alloy plate made of AlCrFeCoNi$_{1.4}$- HEA 12: 
Outer diameter Ø=65.80 mm 
Thickness g=6.80 mm 
7.62x39 mm steel core incendiary armour-piercing bullet: 
Bullet 11: Bullet speed $V_0 = 443$ m/s.

Figure 7. HEA 14 plate after the firing of 2 7.62x39 mm steel core incendiary armour-piercing bullets: 
Alloy plate made of AlCrFeCoNi$_{1.8}$- HEA 14: 
Outer diameter Ø=65.80 mm 
Thickness g=6.60 mm 
7.62x39 mm steel core incendiary armour-piercing bullet: 
Bullet 12: Bullet speed $V_0 = 457$ m/s 
Bullet 13: Bullet speed $V_0 = 419$ m/s.
Table 3. The results of the tests performed in the firing range.

| Armoured steel plate 1 | Bullet 1 impact effect, 553 m/s speed | Pierced | YES |
|------------------------|--------------------------------------|---------|-----|
|                        | H1                                   |         | -   |
|                        | H2                                   |         | -   |
| Bullet 2 impact effect, 360 m/s speed | Pierced | NO |
|                        | H1                                   |         | 5.6 mm |
|                        | H2                                   |         | 8.2 mm |
| Bullet 3 impact effect, 370 m/s speed | Pierced | NO |
|                        | H1                                   |         | 6.5 mm |
|                        | H2                                   |         | 8.8 mm |

| Armoured steel plate 2 | Bullet 1 impact effect, 388 m/s speed | Pierced | NO |
|------------------------|--------------------------------------|---------|-----|
|                        | H1                                   |         | 5.5 mm |
|                        | H2                                   |         | 7.8 mm |
| Bullet 2 impact effect, 426 m/s speed | Pierced | NO |
|                        | H1                                   |         | 6.8 mm |
|                        | H2                                   |         | 8.8 mm |
| Bullet 3 impact effect, 427 m/s speed | Pierced | NO |
|                        | H1                                   |         | 7.2 mm |
|                        | H2                                   |         | 9.1 mm |

| Armoured steel plate 3 | Bullet 1 impact effect, 491 m/s speed | Pierced | YES |
|------------------------|--------------------------------------|---------|-----|
|                        | H1                                   |         | -   |
|                        | H2                                   |         | -   |

| HEA1 plate | Bullet 1 impact effect, 412 m/s speed | Pierced | YES - the sample broke into 12 parts as detected |
|------------|--------------------------------------|---------|--------------------------------------------------|
|            | H1                                   |         | -                                                |
|            | H2                                   |         | -                                                |

| HEA 5 Plate | Bullet 1 impact effect, 451 m/s speed | Pierced | YES - the sample broke into 4 parts |
|-------------|--------------------------------------|---------|----------------------------------|
|             | H1                                   |         | -                                |
|             | H2                                   |         | -                                |

| HEA 12 Plate | Bullet 1 impact effect, 443 m/s speed | Pierced | YES - the sample broke into 4 parts |
|--------------|--------------------------------------|---------|----------------------------------|
|              | H1                                   |         | -                                |
|              | H2                                   |         | -                                |

| HEA 14 Plate | Bullet 1 impact effect, 457 m/s speed | Pierced | YES |
|--------------|--------------------------------------|---------|-----|
|              | H1                                   |         | -   |
|              | H2                                   |         | -   |

| Bullet 2 impact effect, 419 m/s speed | Pierced | YES |
|--------------------------------------|---------|-----|
| H1                                   |         | -   |
| H2                                   |         | -   |

Following the ballistic tests, there was found as follows:
• The steel samples were not pierced at low speeds during adjustment firings;
• The steel samples were perforated without fragmentation following impact at the set limit speed;
• The HEA 1, HEA 5 and HEA 12 samples were pierced with total fragmentation;
• The HEA 14 samples were pierced without total fragmentation.

4. Numerical simulation of the impact behaviour of high entropy alloys

The results of the ballistic firing into the samples made of high entropy alloys were interpreted using the numerical simulation method. For the four HEAs with known mechanical properties, simple dynamic material models were formulated. In order to formulate the dynamic plasticity model, the following coefficients were sufficient:

- \( \sigma_c \) hypothetical yield point, initial;
- \( E_T \) average tangent plasticity modulus;
- \( C \) deformation speed scaling coefficient;
- \( P \) deformation speed exponent.

The data obtained using statistic methods in previous research [4] was used for the measures \( \sigma_c \) and \( E_T \). The \( P \) exponent is given the value 1, considering a linear viscosity law. The \( C \) coefficient values are determined using successive numerical simulation methods. The \( C \) coefficient is adjusted until the result of the simulation overlaps the result obtained by experimental firing in the firing range.

The axial-symmetric model shown in Figure 8 was used both for calibrating the simulation method on the control interval and for the simulation of thresholds on the samples made of high entropy alloys. The firings were simulated in accordance with the experimental firing conditions.

![Axial-symmetric model: (a) Model; (b) Discretization detail.](image)

Figure 8. Axial-symmetric model: (a) Model; (b) Discretization detail.

Figure 9 shows an example of the calibration simulation results. The figure shows the bullet steel core speed variation graph when crossing the target and the section by model in the last recorded state.

After comparing the results of the simulations with the firing ones, it was found that the simulation model and method used needed no changes.

The dynamic characterization of high entropy alloys consisted in regulating the effects of the viscosity (parameter \( C \)) and of the actual plastic deformation following yielding when achieving the similar final states.
Figures 9 - 13 show the results of the numerical simulations by bullet steel core speed variation graphs and the final shapes of the assembly.

**Figure 9.** Simulation of calibration firing onto the steel sample.

**Figure 10.** Firing no. 1 into the sample made of HEA 1.
Figure 11. Firing no. 2 into the sample made of HEA 5.

Figure 12. Firing no. 4 into the sample made of HEA 12.
5. Conclusions
The parallel analysis of the results of the experimental firings in the firing range and of the simulated ones leads to some conclusions regarding the behaviour of high entropy alloys under dynamic stresses at high deformation speeds:

- Very high variations in behaviour are observed for the four types of alloys tested;
- The materials of the fragmented samples exhibit good resistance characteristics, although their tenacity is very high (HEA-1, HEA-5, HEA-12);
- The material of the pierced but not fragmented samples has lower resistance characteristics and better tenacity (HEA-12);
- The resistance and tenacity parameters of the HEA-5 and HEA-12 materials can be improved by appropriate heat treatments;
- The high entropy materials, HEA-5 and HEA-12, with the necessary improvements, especially for increased tenacity, can be used to build composite structures in different combinations, designed for ballistic protection.

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