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DYNAMICAL TESTING OF COMPOSITE STRUCTURES MADE BY HIGH ENTROPY ALLOYS, ARMOUR STEELS, CERAMIC AND POLIMERIC MATERIALS

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***Abstract*:** The dynamical tests purpose is to obtain experimental data necessary to develop accurate numerical simulations for behavior of ballistic protection layered structures when are dynamically loaded at high strain rates by ballistics penetrators (bullets, projectiles, shrapnel) or by blast waves generated at explosive charges detonation. The tests were conducted in ballistic facilities with small caliber weapons. The experimental data was acquired by modern equipments. Acquired data was mathematical processed and analyzed trough numerical simulations of dynamical processes, giving a more complete image of the mechanical characteristics of tested materials.

Key words: dynamical testing, composite structures, numerical simulation.

1.INTRODUCTION

Today, most of the ballistic protection structures are made from composite materials or partially contains such materials. Outstanding properties of some classes of composite materials made them "ideal candidate" for ballistic protection systems manufacturing. Design and production of the modern protection structures is based on knowledge of useful properties of composite materials for specific conditions of armors: high strain rates, violent impact and extreme temperatures. The continuum competition between ballistic treats and protection systems has lead to a scientific research focused on obtaining new materials and structures complying with latest military requirements. Discover of new materials and configurations, becomes a necessary activity when higher performances are requested for ballistic protection systems. There are few important conditions that are generally imposed to the ballistic protection systems: penetration and blast wave proof; energy absorption and dissipation; tenacity; stable in time; low weight; easy maintenance and a low production price. The satisfaction of the basically requests for ballistic protection systems implies detailed knowledge of the mechanical and physical properties of contained materials, especially for those that are involved in interactions between treat and amour. The interaction phenomena is characterized by a fast transfer of mechanical and thermal energy from treat to armor, bodies shapes suffering important deformations that are propagated through materials at very high speeds. Unlike static loads, that are monotonous, in dynamic loads at high strain rates the materials response suffers important modifications. The modification of composite materials structures behavior at high strain rates is analyzed in this paper. The study is necessary for a better integration of composite materials in protection structures and based on conclusions, for designing and development of an optimum configuration, with performances equals to performances of products commercialized by world leading manufacturers. During the study development was evaluated the possibility to extent and to apply it on some materials and combinations, the use of which aims to increasing the performance of ballistic protection systems.

2. DYNAMICAL TESTING

The purpose of testing activity was determination of dynamic behavior of HEA 6 material plate, without thermal treatment, with no. 1 thermal treatment or with no. 2 thermal treatment, alone or in combination with ceramic materials, with Dyneema and amour steel, at impact with 7.62 mm caliber armor piercing incendiary bullet. The HEA 6 plate choosing was based on some previous trial tests, where this plate obtains the best results.

Experimental approach necessity is given by following reasons: HEA 6 materials are developed to be included in multilayered ballistic packages together with other materials like ceramics, steels, aluminum alloys or Dyneema. The phenomena associated to impact between ballistic treats and ballistic kits are very short in time and extremely complex. That numerical simulation became mandatory in design and development of optimum ballistic kits. An accurate simulation model requires dynamically characterization of implied materials. The tests were done in a specialized laboratory facility. The lab has developed its own testing procedures for almost all treats that menace ballistic protection systems (BPS): impacts (bullets, shrapnel), stabbing (knife, pinnacle) and impulsive loading (blast waves generated at detonation). The work methods follow the standards applicable in this scientific area and use the homemade studies and researches.

Table 1. Elastic-plastic bilinear models

Material	Part	Mechanical characteristics		
		Poisson coeff. ν	Yielding strength σ_y	Tangent modulus G_t
	MU	-	MPa	MPa
Hardened steel	Core	0.3	2800	15000
Hardened brass	Shirt	0.33	320	10000
Lead	Mantle	0.37	50	100
Low carbon steel	Glass	0.3	210	5000
Pyrotechnic substance	Pyrotechnic substance	0.49	10	20
HEA	Plate 1	0.35	1550	5000
Armor steel	Plate 2	0.3	1250	3000

Table 2. Johnson – Cook material models

Material	Mechanical characteristics						
	Johnson – Cook coefficients						
	A	B	n	C	m	T_m	T_0
	MPa	MPa	-	-	-	K	K
Hardened steel	2800	850	0.18	0.015	1.00	1763	300
HEA	1550	1200	0.24	0.032	1.00	1850	300
Armor steel	1250	3200	0.18	0.15	1.00	1763	300

During research project for the steel structures have being tested their behavior at the impact with 7.62 mm caliber armor piercing incendiary bullet. The steel samples were positioned at 5 m from barrel end in a parallelepiped polystyrene block on a metallic frame. The initial velocity of bullets was measured by a chronograph with a 1 m distance between photocell frames. Testing method consist in modification of initial bullet velocity in order to attain the limit velocity, when the entire bullet kinetic energy is consumed trough bullet plastic deformation and partial or complete steel samples penetration. The following equipments were used: shooting stand, target support, cal. 7.62 mm weapon, chronograph for projectile velocity measurement Oehler 35 (with photocell frames), 7.62x39 mm ammunition, armor piercing incendiary bullet, crimp installation, calipers and analytic balance XT220A. By changing the propellant powder quantity the initial velocity was modified. The limit velocity was calculated from a series of 10 rounds at 445 m/s value. During tests was also evaluated and recorded the effects of impact on the bullets, as supplementary information for an accurate numerical simulation.

In Fig. 2, 3 and 4 can be observed the modifications suffered after impact phenomena by the samples steel plates and bullets used in limit velocity determination.

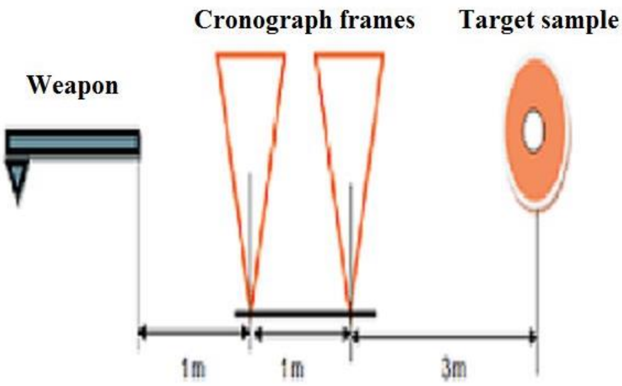

Fig. 1. Testing configuration

Fig. 2. HEA 6 sample, plate no. 9, thermal untreated (impact face, verso)

Fig. 3. HEA 6 sample, plate no. 2, thermal treatment no. 1 (verso)

Fig. 4. HEA 6 sample, plate no. 5, thermal treatment no. 2 (impact face, verso)

3. THE PORPOSE, GENERAL CONDITIONS AND NUMERICAL SIMULATION STEPS

3.1. The purpose

The purpose is to develop a methodology for modeling and numerical simulation of ballistic impact with multilayered structures (combinations between HEA and steel armor).

3.2. General conditions for simulation

In simulations of dynamic processes that appears at impact in protection layered structures are used both meshes, material meshes (Lagrange) and combined meshes (Arbitrary Lagrange Euler – ALE), associated to finite elements method.

3.3. Numerical simulation steps

Step I – Physic model – design of the applications that sustain technology consisting in a model with a combination between high entropy alloy plate (pos. 1) and armor steel plate (pos. 3), glued in a package by a thin layer of glue (pos. 2). The HEA plate is on the face that suffers bullet impact (pos. 4, Fig. 5). The lateral dimensions correspond to experimental model dimensions (200x200 mm). 7.62x39 mm armor piercing incendiary bullet is a treat of level 2 according to NATO standards. The physic model of this type of bullet is presented in Fig. 6.

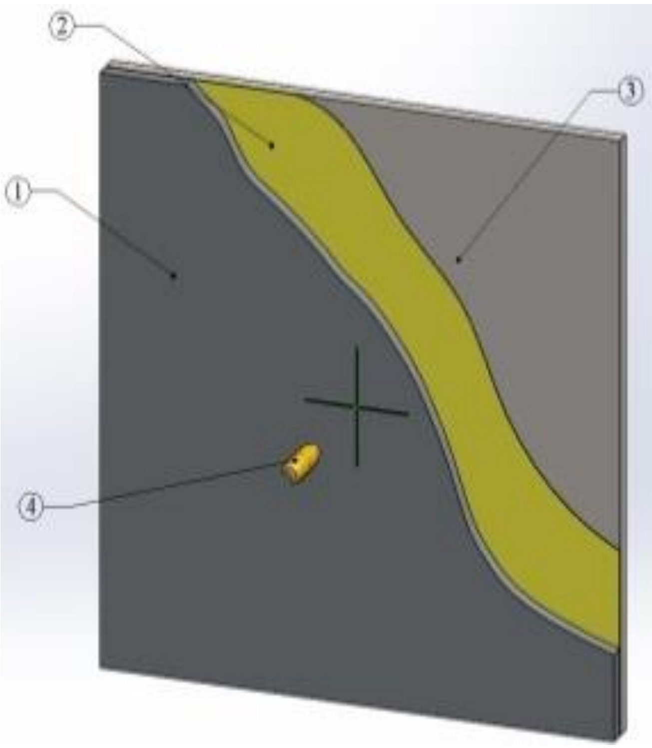

Fig. 5. Physic model of the HEA – Steel layered structure that suffers an impact with 7.62 mm armor piercing incendiary bullet

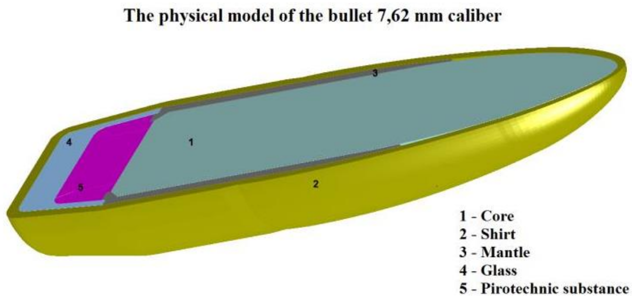

Fig. 6. Physic model of 7.62 mm armor piercing incendiary bullet

Step II – Mathematical model – The mechanics of deformable solid is governed by following equations:

1. Dynamic equilibrium differential equations are movement equations established for elementary volume, according to second principle in mechanics:

$$\frac{\partial \sigma_{ij}}{\partial x_j} + \rho\, f_i = \rho \frac{\partial^2 U_i}{\partial t^2}; \qquad (1)$$

The differential equations system (1) has following limit conditions:

-for stresses, on the border S_σ

$$\sigma_y\, n_j = p_i(t); \qquad (2)$$

-for displacements, on the border S_u

$$U_i = D_i(t); \qquad (3)$$

2. Geometrical equations have a differential form and make the connection between deformations and displacements:

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right); \qquad (4)$$

For large deformations, situation that appears at an impact between an projectile and a target, the approach is incremental. In that way, the deformed shape obtained at the time t becomes initial states for the next time step, that increases with the time increment dt. For incremental calculus the geometrical equations become

$$d\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial (dU_i)}{\partial x_j} + \frac{\partial (dU_j)}{\partial x_i}\right) \qquad (5)$$

where d represent elementary variations. The instantaneous deformations are obtained through summation of values gains registered for each calculus interval:

$$\varepsilon_{ij} = \int_0^t d\varepsilon_{ij} \qquad (6)$$

3. Physical equations are constitutive equations that reflect a physical relation between stresses, deformations, velocities and temperature. General form of physical equations is:

$$F\left(\sigma,\varepsilon,\dot{\varepsilon},T\right) \tag{7}$$

Step III – Meshed model – Variable structural mesh is often used in building of finite elements models of structures, that are analyzed by the methodology proposed here. Using this procedure have been meshed bullet components and layered plate. In Fig.7 is presented the way that was meshed the model in the impact region.

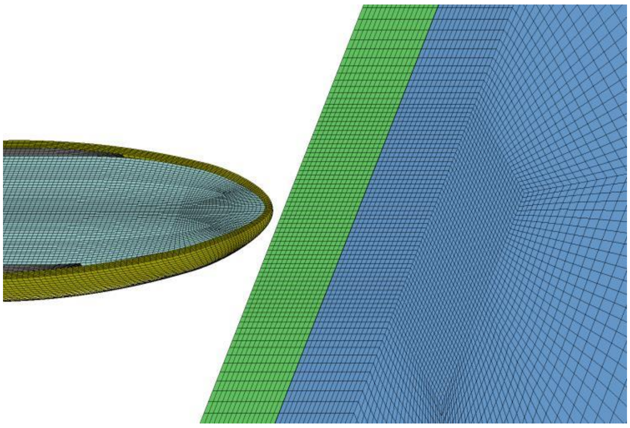

Fig. 7. Finite elements mesh – Impact area detail

Step IV – Numerical solution – the program SOLVER, following the given instructions; solve the algebraic equations system obtained by meshing process.
Step V – Data post-processing, consist in graphical representation of solution, solution analysis and conclusions formulation.

3.3. Case study

General physical model was particularized for a bimetallic plate obtained from HEA and armor steel subject to impact. Both plates' thicknesses are 4 mm and lateral dimensions 200 x 200 mm.
The layered plate was stricken by the 6.72 mm bullet in the centre at a normal angle at an impact velocity of 900 m/s.
Velocity value, higher than limit velocity determined for level 2 of STANAG protection, was chosen to assure plate perforation and to verify the methodology in a dynamic loading rough regime. Application was run, without any intervention, until the complete perforation was observed.
In Fig. 8 is graphically represented layered plate penetration at the end of the analysis. In a detailed view is illustrated the hole produced by hard core of the bullet.
Stress states in the bodies involved in perforation are showed in Fig. 9, where the von Misses stress is represented.
Evolution of bullet core velocity during the layered plate penetration process it is showed in the Fig. 10.

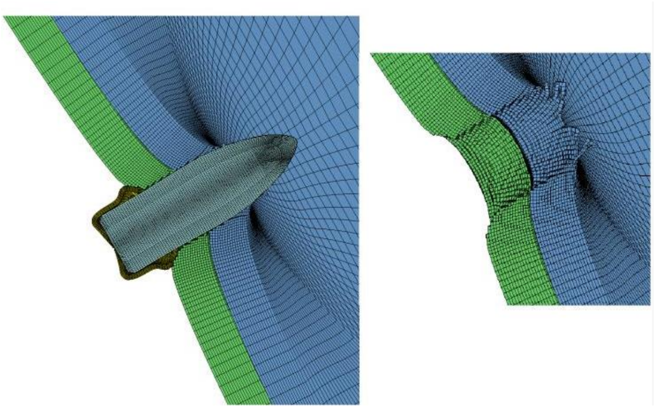

Fig. 8. Layered plate penetration – Final state of analysis

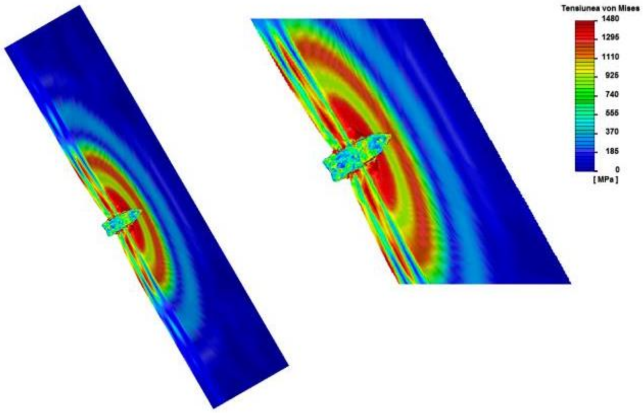

Fig. 9. Model von Misses stress – Final state of analysis

For the velocity control and observation were chosen three points on the core axis, as following: in core tip (1), in the middle (2) and at the end (3).

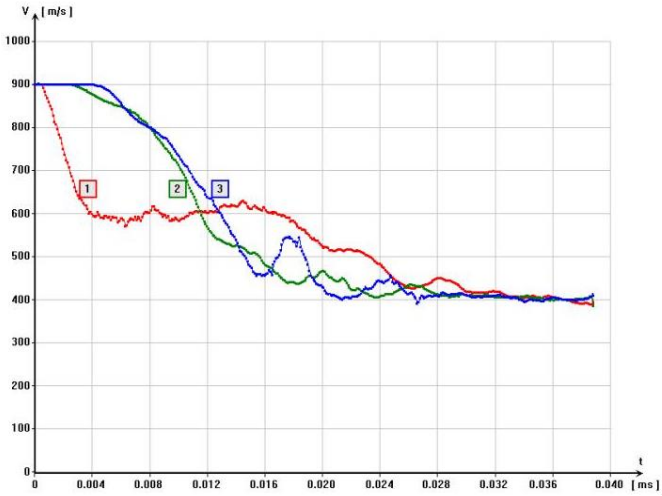

Fig. 10. Diagram of control points velocities from the 7.62 mm bullet core

4. CONCLUSIONS

4.1 Range tests

- In the case of thermal untreated HEA 6 plates, impacted at velocities equal or lower than V_{50} were obtained only partially perforations, and for velocities higher than V_{50} the complete perforations are obtained. The ballistic protection given by these plates, at the action of 7.62 mm armor piercing incendiary bullet, is similar with protection given by the steel armor;

- In the case of HEA 6 plates treated by thermal process no. 1 the results obtain in tests are unsatisfactory At the impact the plate samples were broken in pieces;
- In the case of HEA 6 plates treated by thermal process no. 2 the results are slightly better than those obtained with armor steel plates;
- In the case of HEA 6 plates treated by thermal process no. 2 used with Dyneema backing the ballistic protection is obtained even for velocities higher than V_{50};
- In the case of HEA 6 plates treated by thermal process no. 2 used with steel plates backing the ballistic protection is given even at a impact velocity of 537m/s;
- In the future work will be used layered protection packages compose by HEA, steel, ceramics and Dyneema, as the expected results for that configuration can be above the present study results.

4.2. Case study

- The methodology for modeling and numerical simulation of the processes that arise in the HEA/armor steel layered plates at impulsive loadings produced by impact of hard core bullets or shrapnel is designed for applications in that high strain rates and material erosion arise;
- Established methodology represent an advanced scientific approach for the mechanical and thermal phenomenon associated to terminal ballistics;
- 3D modeling, that is possible in present, when parallel processing and clustering permit short times of analysis, open a new perspective in the research and analysis of complex structures composed by high entropy alloys;
- Efficiency and accuracy of methodology used in modeling and numerical simulation have been tested with success on a support application;
- As the method is intended for use in applications with complex equipment designs, for the success of the modeling and numerical simulation is necessary to have a complete database with properties and thermo-mechanical characteristics of used materials;
- Designed methodology flexibility allow a generalization of the dynamic problems involving multilayered plates made from different materials subjected to large deformation, dynamic loads and material erosion, produced by impact with bullets (projectiles, kinetic and explosive driven fragments).

4.3. Future research development

Based on the obtained results and the simulation methodology set up, the research can be continued in order to obtain the material properties under dynamic conditions of experimentation. In general, these features are not made public.

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