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Analysis of ballistic resistance of composites based on EN AC-44200 aluminum alloy reinforced with Al_2O_3 particles

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ABSTRACT

The work presents the research conducted on the impact resistance of newly developed metal-ceramic composites with aluminum matrix on firing with 5.56 × 45 mm caliber intermediate ammunition. For this purpose, materials based on AC-44200 alloy reinforced with Al_2O_3 particles were made using the squeeze casting method. The ballistic resistance was compared between the shot composites with 20% vol. and 40% vol. of Al_2O_3 particles and the shot material of the non-reinforced matrix. The ABAQUS program was used to carry out the preliminary analysis of ballistic resistance of the composites. The performed works also included homogenization through the Representative Volume Element (RVE), the 3D geometry of the 5.56 mm SS109 projectile and the simulations in the scope of shooting through materials. In the basic research, the shot samples of composite materials were subjected to the thorough metallographic analysis with the explanation of the mechanism of scrap formation while being shot. As a result of the tests and analyzes, conclusions were drawn on the application possibilities of aluminum composites reinforced with Al_2O_3 particles in construction of add-on-armor protection structures.

1. Introduction

In the engineering applications of impact resistant materials (ballistic impact), composite materials occupy a significant position [1–5]. The energy absorption in materials impacted with ballistic velocities in the range of 300–1000 m/s is a complex mathematical process [6–10]. The knowledge of the physical processes involved is directed towards the search for new material solutions, which should exceed the traditional material with their mechanical properties, etc. [11–13]. Ballistic shields used today are mainly layered composites, [14–19] the surface layers of which are usually composed of a hard element such as ceramics. This is primarily due to the special properties of this material with regard to kinetic effect of high-impact ammunition, namely: high hardness causing damage and fragmentation of striking projectiles, very high compressive and bending strength, especially transverse, very high stiffness coefficient and longitudinal modulus of elasticity and others. Ceramic materials such as aluminum oxide (Al_2O_3), boron carbide (B_4C), silicon carbide (SiC), silicon nitride (Si_3N_4) and combinations thereof are used to build this layer [20–23]. Ballistic ceramics are characterized by a surface mass of 32–55 kg/m^2 and usually contain about 97% of $A1_2O_3$. Aluminum oxide and other ceramic components used for their production must be of exceptional purity. The search for alternative construction materials has been directed at combining properties of metals and ceramics, thereby alloys on the basis of intermetallic phases, the so-called intermetallics, are obtained [24,25]. These alloys are primarily referred to as refractory materials. However, due to their other assets, i.e. resistance to abrasion, corrosion, they are expected to be more widely applied. Works on the use of these materials for ballistic protection have been conducted [26,27]. The comparative analysis of properties of intermetallics and properties of classical materials places the first mentioned ones in a favorable position in terms of mechanical properties. Low density is the essential feature of these materials, where titanium or silicon are the basic alloying components for aluminum; then a high value of the relation R_T/ρ and E/ρ is obtained, which is of significant importance for air transport applications.

The disadvantages of alloys based on intermetallic phases include

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low plasticity, low fracture resistance and propensity to intergranular fracture at ambient temperature. Works in this area are aimed at improving the negative characteristics of innovative energy-consuming materials. Materials of the cermet group can be a positive response to search for such solution. Cermets can largely replace the standard material in the form of classic ballistic ceramics, and conducted works, inter alia [28–32], are focused mainly on finding proper structures absorbing the impact energy in the velocity range of up to 1700 m/s to improve the yield strength. Recognition of damage mechanisms in the scope of low and high velocities can result in the production of optimal material that exceeds the behavior of ceramics under the ballistic impact [33–42].

The subject matter of the study covers metallic composites reinforced with aluminum oxide (Al_2O_3) particles. The behavior of material shot with 5.56 mm SS109 ammunition and the effect of the amount of corundum admixture on the impact energy absorption were studied. For the study purposes the ballistic impact was modeled and simulation results were compared to real damage. Due to the introduction of new solutions as to innovative materials, the results obtained were compared with the currently used solutions based on corundum ceramics and traditional armored sheet in order to evaluate their optimal adoption in composite ballistic shields.

2. Preparation of samples and methods of their evaluation

2.1. Materials and impact specimen configurations

The composite castings made on the base of EN AC-44200 alloy normally designed for use in the construction of heavily loaded components of machines and devices constitute the research object. The alloy chemical specification is given in Table 1 and the exemplary structure in Fig. 1.

The α-Al_2O_3 ceramic particles with the specifications given in Table 2 were used as reinforcement of composite materials.

2.2. The production of hybrid composites

Composite materials produced using the squeeze casting method underwent tests on ballistic resistance to shooting from 5.56 × 45 mm intermediate ammunition with SS109 projectile – Fig. 2. The preforms infiltration process was carried out under the molding pressure of 90–110 MPa.

In the first stage rectangular preforms of 14 mm thickness were used in order to produce composite materials from α-Al_2O_3 particles. The preforms were characterized by open porosity guaranteeing their complete infiltration with the liquid matrix alloy. The dimensional stability of the preforms under the pressure of the liquid metal and their respective strength were achieved due to the application of the manufacturing technology described in detail in the work [43–45]. In the next stage, the preforms were placed in the mold and subjected to infiltration with EN AC-44200 liquid matrix alloy. The description of the materials thus produced is given in Table 3, while their strength characteristics performed in other works [44–45] are presented in Table 4.

Composite materials of the structure shown in Fig. 3 were obtained as a result of the infiltration. The microstructure of these materials consists of alternatingly arranged zones of non-reinforced matrix with areas containing Al_2O_3 particle clusters. The amount of non-reinforced areas in the structure is dependent on the assumed volume of particles contained in the infiltrated preform.

Table 1
Chemical composition of base material EN AC-44200.

Weight fraction [%]	Si	Fe	Mn	Cu	Ti	Zn
EN AC-44200 Al – remainder	10.5–13.0	0.55	0.35	0.05	0.15	0.10

2.3. The ballistic test

The samples were overshot along the ballistic track from the assault weapon caliber 5.56 mm – Beryl produced in Poland. The ammunition 5.56 × 45 mm with the SS109 projectile produced by MESCO in 2005 was used for the test (Fig. 4). The velocity was measured using the Doppler Waibel SL-525P radar and CED Millennium Chronograph. The test parameters are summarized according to The Euro Standard EN 1522 [46].

3. The approach to the issue and the numerical simulation

The cracking mechanics of particle-reinforced materials can be described by the commonly used equation for the stable crack evolution, which is a development of the crack propagation criterion [47,48]. It is assumed that the increase in the crack length Δc is related to the extortion of the external force ΔP represented global loading of the structural material. The evolution equation can be written as:

$$X(\sigma_a, c, k) = X_R(\Delta c) \tag{1}$$

where:

$X(\sigma_a, c, k)$ – local measure of external extortion, X_R – material's resistance to crack propagation, k – is local parameter associated with the flaw.

The bridging mechanism of the crack front propagation is shown in Fig. 5. Crack propagation occurs mainly on the material matrix and interphase boundaries, although sometimes the crack runs through the loaded particle. The matrix strength can be described by the strength of the adjacent atoms of the matrix as a result of the applied external force causing tension. The break occurs when two adjacent atoms under external stress are pushed away at a distance greater than the mutual attraction forces. The exemplary crack path of the composite material subjected to the impact load is shown in Fig. 5.

Ceramic material in the first phase (elastic range) is characterized by the elastic model in can be considered within the issues of the theory of linear elasticity.

The considered object of volume V limits the surface S, and inside the volume forces $g^T = \{g_x, g_y, g_z\}$ act, which are distributed continuously. The column matrix of stresses σ, deformation ε and the displacement u takes the form:

$$\begin{aligned} \sigma^T &= \{\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{zx}\} \\ \varepsilon^T &= \{\varepsilon_x, \varepsilon_y, \varepsilon_z, \gamma_{xy}, \gamma_{yz}, \gamma_{zx}\} \\ u^T &= \{u_x, u_y, u_z\} \end{aligned} \tag{2}$$

The shear matrix **D** takes the form:

$$\mathbf{D} = \frac{2G}{1-2\nu}\begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & 0 & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-\nu}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \tag{3}$$

where: G – shear modulus, ν – Poisson's ratio

The second phase was considered as a brittle material model. A method of modeling the authors presented in [49], where was analyzed model consists of grains formed as the Kelvin shape, matrix of aluminum 44200 with a cubic addition of Al_2O_3.

The static test of the projectile compression was performed on the composite samples on the MTS 810 testing machine in order to