Rheological principles of development hetero-modulus and hetero-viscous complex materials with extreme dynamic strength

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Abstract. Materials with different crystalline and morphological compositions have different chemical, physical, mechanical and rheological properties, including wear protection, melting temperature, module of elasticity and viscosity. Examining the material structures and behaviors of different ceramic bodies and CMCs under high speed collisions in several years the authors have understood the advantages of hetero-modulus and hetero-viscous complex material systems to absorb and dissipate the kinetic energy of objects during high speed collisions. Applying the rheo-mechanical principles the authors successfully developed a new family of hetero-modulus and hetero-viscous alumina matrix composite materials with extreme mechanical properties including dynamic strength. These new corundum-matrix composite materials reinforced with Si₃N₄, SiN₆, SiAlON and AlN submicron and nanoparticles have excellent dynamic strength during collisions with high density metallic bodies with speeds about 1000 m/sec or more. At the same time in the alumina matrix composites can be observed a phase transformation of submicron and nanoparticles of alpha and beta silicone-nitride crystals into cubic-Si₃N₄ diamond-like particles can be observed, when the high speed collision processes are taken place in vacuum or oxygen-free atmosphere.

Using the rheological principles and the energy engorgement by fractures, heating and melting of components the authors successfully developed several new hetero-modulus, hetero-viscous and hetero-plastic complex materials. These materials generally are based on ceramic matrixes and components having different melting temperatures and modules of elasticity from low values like carbon and light metals (Mg, Al, Ti, Si) up to very high values like boride, nitride and carbide ceramics. Analytical methods applied in this research were scanning electron microscopy, X-ray diffractions and energy dispersive spectrometry. Digital image analysis was applied to microscopy results to enhance the results of transformations.

Keywords: ceramics, composites, diamond-like, elasticity, hetero-modulus, nanostructure, rheology, strength, viscosity

1. Introduction
In the last 10-15 years more and more ceramic materials and ceramic matrix composites (CMC) are developed and used in the leading and sophisticated industries [1-5]. In our days the relatively low density ceramics and CMC materials are willingly used by industry because of their excellent properties such as hardness [6-11], wear resistance [12-15], toughness [16-18] mechanical [19-25] and...
dynamic strength [26-32]. In our days several methods and technologies are used to produce ceramic and ceramic based composite items with required physical and mechanical properties [33-67]. Thanking to the several years research and investigation in development and processing of high-tech ceramics and ceramic matrix composites the following scientists have achieved considerable new results:

- S. Hampshire’s group in study and development of $\text{Si}_3\text{N}_4$ and $\text{SiAlON}$ [68-70],
- S N Kulkov’s and S P Buyakova’s group in $\text{ZrO}_2$, $\text{ZrWO}_8$ and zirconia based CMCs [71-77],
- E V Zharikov’s group in development of carbon nanotubes (CNT) and their application for reinforce ceramic nanocomposites [78-80],
- K Niihara’s group in high-pressure synthesis and in development and application of boron nitride (BN) nanocomposites and nanotechnology [81-84].

The papers of S G Chuklina, A I Pylinina and I I Mikhalenko [85, 86] also well represent the wide range application opportunities of ceramic materials and ceramic based composites especially the tetragonal $\text{ZrO}_2$ ceramics. In accordance to fracture and crack propagation in alloys, composites and porous materials T Sadowski with his colleagues have achieved remarkable new results. In 2004 [87] and in 2007 [88] they examined the crack length after thermal shock in functionally graded materials strip. In 2008 they described the damage state in porous ceramics under compression [89] and in 2012 successfully performed numerical analysis of the most loaded places in turbine blades under real working conditions [90]. In 2014 they described the fatigue [91] and dynamic [92] responses of composite materials and in 2015 the influence of geometrical parameters [93].

The rheological parameters and behaviors of materials are playing important roles not only during high speed collisions but in technology processes of polymers [94] and construction raw materials [95, 96]. Rheology is important also in physical, chemical and mechanical characterization of materials like porous ceramics [74] or complex materials [97] and living organism [98]. The authors of this paper also have several years experiments in development of alumina based ceramics and composite materials with increased mechanical properties [23, 27, 28, 41, 46, 99, 100] and in investigation and measurement of rheological properties of these complex materials [101-107].

On the basis of rheological principles, analysis of high speed collisions and experiments in development ceramic materials and ceramic matrix composites our aims are to develop ceramic based low density hetero-modulus, hetero-viscous and hetero-plastic materials for armor shells to save transport equipments against high speed (v>1000 m/s) collisions with flying objects having different densities and speeds.

2. Materials and experiments

Before choosing the materials and starting the experiments we have compared the modulus of elasticity and melting temperature of the most common technical materials including polymers, metals and ceramics (Fig. 1). Generally the polymers have very low melting temperatures and Young’s modulus, meanwhile the oxide and non-oxide ceramics have much higher modulus of elasticity and melting temperatures than metals and alloys. It is well known that most of the oxide and non-oxide ceramics and ceramic matrix composites have excellent mechanical properties including hardness and mechanical strength. Inspite of the high values of their compression strengths they do not have large enough dynamic strength, thanking to their microstructures with relatively large crystals of high rigidness and strong inclination to nicks, pitting and rigid fractures.

The advantages of material structures built from components having different modules of elasticity (Figure 1.b) and similar melting temperature were first described by D.P.H. Hasselman, P.F. Betzher and K.S. Mazdiyashni [108]. Actually the material structures built from components having different modulus of elasticity are capable dissipate the mechanical stresses better than others, and hereby stop the crack propagation under excess mechanical loadings and increase dynamic strength.
2.1. Materials
To create hetero-modulus composite materials with extreme dynamic strength alumina powders of different purity were used with grain size distribution from 50 nm milled powders to 100 μm large atomizer powders. The $\text{Al}_2\text{O}_3$ powders were polluted with different m% of $\text{SiO}_2$, $\text{TiO}_2$, $\text{MgO}$, $\text{CaO}$, thallium oxides and metallic Al powders. The specimens were compacted using uniaxial pressing and sintered in $\text{N}_2$ atmosphere at maximum temperature of 1600°C. Thanking to the reactive sintering in $\text{N}_2$ atmosphere the ceramic items were reinforced with $\text{SiAlON}$, $\alpha$-$\text{Si}_3\text{N}_4$ and $\beta$-$\text{Si}_3\text{N}_4$. These quadratic thin alumina matrix composite plates were tested under $v > 1000$ m/s high speed collisions with high density flying metallic objects of homogeneous and inhomogeneous densities. The typical damages of these ceramic composite plates after the collisions are shown in Figure 2.

![Figure 1](image1.png)

**Figure 1.** The melting temperatures and modulus of elasticity of most common technical materials

![Figure 2](image2.png)

**Figure 2.** Typical destructions of ceramic composites during high speed collisions

When the $\text{Al}_2\text{O}_3$ corundum based ceramic plates were reinforced with $\text{SiAlON}$, $\alpha$-$\text{Si}_3\text{N}_4$ and $\beta$-$\text{Si}_3\text{N}_4$ submicron and nano particles and tested under $v > 1000$ m/s high speed collisions with flying high density metallic objects we have observed the phase transformation of $\alpha$-$\text{Si}_3\text{N}_4$ and $\beta$-$\text{Si}_3\text{N}_4$ into cubic phase of high density diamond-like $c$-$\text{Si}_3\text{N}_4$ particles (Figure 3.a) [104, 109, 110, 111]. Thanking to the rapid and great local heating the melting of metallic parts also was observed (Figure 3.b).
2.2 Mechanical analysis of high speed collisions of objects

The energy engorgement of kinetic energy of high speed collision ($W_K$) by armor shells can be determined as:

$$ W_K = W_E + W_H + W_P + W_{PL} + W_S + W_V \quad [\text{Nm}] \quad (1) $$

where:

$W_E$: energy engorgement through elastic deformation [Nm]
$W_H$: energy engorgement through heating and phase transformation [Nm]
$W_P$: energy engorgement through fracture indicated by pressure stress [Nm]
$W_{PL}$: energy engorgement through plastic deformation [Nm]
$W_S$: energy engorgement through fracture indicated by shear stress [Nm]
$W_V$: energy engorgement through viscous deformation [Nm]

The kinetic energy of high speed impacting (flying) body with homogeneous density can be described as:

$$ W_K = \frac{m u^2}{2 g} = \frac{u^2}{2 g} \rho \cdot V \quad [\text{Nm}] \quad (2) $$

and with inhomogeneous density can be described as:

$$ W_K = \frac{u^2}{2 g} \sum_{i=1}^{n} m_i = \frac{u^2}{2 g} \sum_{i=1}^{n} \rho_i \cdot V_i \quad [\text{Nm}] \quad (3) $$

where:

$g= 9.81 \text{ m/s}^2$

$i=1, 2, \ldots, n$: the number of different density components of flying object

$\rho$: the density of flying object material [kg/m$^3$]

$\rho_i$: density of the “i-th” component of flying object [kg/m$^3$]

$m$: mass of flying object [kg]

$m_i$: mass of the “i-th” component of flying object [kg]

$u$: speed of flying object at the moment of collision [m/s]

$V$: volume of flying object [m$^3$]

$V_i$: volume of “i-th” component of flying object [m$^3$]

In case when the impacting body has homogeneous density and the armor shells (ceramic plates) are made from materials having only one (constant) value of Young’s modulus the engorgement of kinetic energy of flying object can be described as:
\[
\frac{u^2}{2g} \rho \cdot V = \frac{R_0^2}{2E} A_1 \cdot l_1 + \frac{R_2^2(v+1)}{E-\nu} \cdot A_2 \cdot l_2 + W_H
\]  \hspace{1cm} [\text{Nm}]  \hspace{1cm} (4)

where:
\( v_1 \): the Poisson ration
\( A_1 \) and \( A_2 \): surfaces of fractures [m\(^2\)]
\( l_1 \) and \( l_2 \): deep and “movement” of fractures [m]
\( R_0 \) and \( R_2 \): the pressure and shear strength of ceramic plates (tiles) [N/m\(^2\)]
\( W_H \): energy engorgement through heating and recrystallization of flying object particles and alumina based ceramic materials surrounding the collision [Nm]

In case when the impacting body has inhomogeneous density and the armor shells (ceramic plates) are made from materials having only one value of Young’s modulus the engorgement of kinetic energy of flying object can be described as:
\[
\frac{u^2}{2g} \sum_{i=1}^{n} \rho_i \cdot V_i = \frac{R_0^2}{2E} \sum_{i=1}^{n} A_{1i} \cdot l_{1i} + \frac{R_2^2(v+1)}{E-\nu} \sum_{i=1}^{n} A_{2i} \cdot l_{2i} + W_H \]  \hspace{1cm} [\text{Nm}]  \hspace{1cm} (5)

where:
\( v_1 \): the Poisson ration
\( \rho_i \): density of the “i-th” component of flying object [kg/m\(^3\)]
\( A_{1i} \) and \( A_{2i} \): surfaces of fractures caused by “i-th” density component of flying object [m\(^2\)]
\( l_{1i} \) and \( l_{2i} \): deep and “movement” of fractures, caused by “i-th” density component of flying object [m]
\( R_0 \) and \( R_2 \): the pressure and shear strength of ceramic plates (tiles) [N/m\(^2\)]
\( V_i \): volume of “i-th” component of flying object [m\(^3\)]

In case when the flying object (impact body) has homogeneous density and the armor shells (ceramic plates) are made from materials having several values of Young’s modulus the engorgement of kinetic energy of falling object can be described as:
\[
\frac{u^2}{2g} \sum_{j=1}^{N} \rho_j \cdot V_j = \sum_{j=1}^{N} \frac{R_0^2}{2E_j} A_{1j} \cdot l_{1j} + \sum_{j=1}^{N} \frac{R_2^2(v_j+1)}{E_j\nu_j} \cdot A_{2j} \cdot l_{2j} + W_H \]  \hspace{1cm} [\text{Nm}]  \hspace{1cm} (6)

where:
\( A_{1j} \) and \( A_{2j} \): surface of fractures of “j-th” Young’s modulus component of ceramic body [m\(^2\)]
\( E_j \): the Young’s modulus of the “j-th” component of ceramic body [N/m\(^2\)]
\( j=1, 2, \ldots, n; \) the number of different Young’s modulus component of ceramic body
\( l_{1j} \) and \( l_{2j} \): deep and “movement” of fractures of “j-th” Young’s modulus component of ceramic body [m]
\( R_{pj} \) and \( R_{sj} \): the pressure and shear strength of “j-th” Young’s modulus component of ceramic body [N/m\(^2\)]
\( \nu_j \): the Poisson ration of “j-th” Young’s modulus component of ceramic body [N/m\(^2\)]

In case when the flying object (impact body) has inhomogeneous density and the armor shells (ceramic based composite plates) are made from materials having several values of Young’s modulus the engorgement of kinetic energy of high speed collision can be described as:
\[
\frac{u^2}{2g} \sum_{i=1}^{n} \rho_i \cdot V_i = \sum_{j=1}^{N} \frac{R_0^2}{2E_j} A_{1j} \cdot l_{1j} + \sum_{j=1}^{N} \frac{R_2^2(v_j+1)}{E_j\nu_j} \cdot A_{2j} \cdot l_{2j} + W_H \]  \hspace{1cm} [\text{Nm}]  \hspace{1cm} (7)

where:
\( v_1 \): the Poisson ration of “j-th” Young’s modulus component of ceramic body [N/m\(^2\)]
\( \rho_i \): density of the “i-th” component of flying object [kg/m\(^3\)]
\( A_{1j} \) and \( A_{2j} \): surface of fractures of “j-th” Young’s modulus component of ceramic body [m\(^2\)]
\( E_j \): the Young’s modulus of the “j-th” component of ceramic body [N/m\(^2\)]
i=1, 2, … n: the number of different density components of flying object
j=1, 2, …, N: the number of different Young’s modulus component of ceramic body
\( l_{ij} \) and \( l_{2j} \): deep and “movement” of fractures of “j-th” Young’s modulus component of ceramic body [m]
\( R_{pj} \) and \( R_{sj} \): the pressure and shear strength of “j-th” Young’s modulus component of ceramic body [N/m²]
\( V_j \): volume of “j-th” component of flying object [m³]

3. Results and discussion

Metallic flying objects having inhomogeneous densities were used for high speed collision tests. Examining the collision process and the ceramic composite armor shells in the place and surrounding of the hits a considerable phase transformation could be observed both in \( \text{Al}_2\text{O}_3 \) and in \( \text{Si}_3\text{N}_4 \) components as it is shown in Figure 4.

Figure 4. Phase transformation of ceramic components of armor shells

Similar phase transformation could be observed in the metallic components (Figure 5) of the high speed flying objects.

Figure 5. Melting and phase transformation of metallic components of collisions

On the basis of Figures 4 and 5 the thermic part of the energy engorgement of high speed collision [27] can be described as:

\[ W_{H} = W_{HS} + W_{RC} + W_{RM} \quad [\text{Nm}] \]

where:

\( W_{H} \): energy engorgement through heating [Nm]
\( W_{HS} \): energy engorgement through heating and melting the surrounding of the collision and fall [Nm]
\( W_{RC} \): energy engorgement through recrystallization of ceramic particles surrounding the collision and fall [Nm]
\( W_{RM} \): energy engorgement through spraying and recrystallization of falling metallic body [Nm]
The melting of the high speed metallic components with inhomogeneous density gave the idea to create armor shells from components having the same or similar module of elasticity meanwhile their melting temperatures are different (Fig. 6).

![Figure 6](image)

**Figure 6.** The armor shells components have different melting temperatures

Thanking to the different melting temperatures of components this material structure has good ability to absorb not only elastic energy but absorb and dissipate the viscous energy during crack propagation. Although these materials have a certain “self-healing” properties thanking to the phase transformation (crystallization) of melted components during cooling after the hits.

Finally we decided to develop self-healing armor shells from ceramic-metal composites from hetero-modulus and hetero-melting components. These composite material structures are built from particles having different Young’s modulus, different viscosity and plasticity. For this we developed special high porosity (Fig. 7.a) or foam-like (Fig. 7.b) ceramic composites first and after impregnated them with different metals and alloys (Fig.8).

![Figure 7](image)

**Figure 7.** The developed new porous (a) and foam (b) ceramic composite structure
This kind of material structure can be mechanically and rheologically characterized as hetero-modulus, hetero-viscous and hetero-plastic complex materials in the moments of high speed collisions. The energy engorgements of this kind of materials during high speed collisions can be described as:

\[ \frac{u_i^2}{2g} \sum_{i=1}^{n} \rho_i \cdot V_i = \sum_{j=1}^{N} \frac{R_{pj}^2}{2E_j} \cdot A_{1j} \cdot I_{1j} + \sum_{j=1}^{N} \frac{R_{sj}^2(v_{j+1})}{E_j\nu_j} \cdot A_{2j} \cdot I_{2j} + \sum_{k=1}^{K} \eta_k \cdot A_{3k}l_{3k} + W_H \]  

(9)

where:

- \( \nu_j \): the Poisson ration of “j-th” Young’s modulus component of ceramic based armor body [m\(^3\)]
- \( \rho_i \): density of the “i-th” component of flying object [kg/m\(^3\)]
- \( A_{1j} \) and \( A_{2j} \): surface of fractures of “j-th” Young’s modulus component of the ceramic based composite armor plate [m\(^2\)]
- \( E_j \): the Young’s modulus of the “j-th” component of the ceramic composite armor plate [N/m\(^2\)]
- \( i=1, 2, \ldots, n \): the number of different density components of flying object
- \( j=1, 2, \ldots, N \): the number of different Young’s modulus components of the ceramic based composite armor plate
- \( k=1, 2, \ldots, K \): the number of different viscosity components of the ceramic based composite armor
- \( I_{1j} \) and \( I_{2j} \): deep and “movement” of fractures of “j-th” Young’s modulus component of the ceramic based composite armor plate [m]
- \( R_{pj} \) and \( R_{sj} \): the pressure and shear strength of “j-th” Young’s modulus component of the ceramic based composite armor plate [N/m\(^2\)]
- \( V_i \): volume of “i-th” component of flying object [m\(^3\)]

4. Conclusions

During this research the Authors successfully found some good pore forming additives which could decrease considerably the wetting angle between the ceramic matrices and the impregnated metals.

Thanking to the different values of heat conductivity and melting points of components these low density armor shells have not only excellent hardness, wear resistance and dynamic strength but good ability to self-healing and extra high tolerance to damage.

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