Ceramic based lightweight composites with extreme dynamic strength

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Abstract. On the basis of several years experiments in development of high performance technical ceramics and in investigation of hetero-modulus and hetero-viscous materials and ceramic matrix composites the authors successfully developed a new family of ceramic reinforced lightweight composites with extreme dynamic strength. To obtain these lightweight composites first the matrix materials were developed from different sort of sintered ceramics with high porosity and after the prepared items were re-sintered using reactive sintering methods or were impregnated with nanoparticles of Si₃N₄, SiAlON ceramics or light metal alloys having excellent mechanical strength and properties. Where it was necessary the pores and material structures of ceramic matrix materials anchored excellent wetting for a wide range of metal alloys, so it was possible to develop several types of ceramic reinforced hetero-modulus light metal composites with extreme dynamic strength of different density. In this work the authors present the c-Si₃N₄ diamond particles reinforced corundum matrix composite shield plate structures and some of the specially developed low density ceramic foams and high porosity ceramic matrix materials for lightweight metallic composites.

1. Introduction
Industry, transport and household enquire materials with increased mechanical, physical and chemical stability not only at normal but at high temperature or in corrosion environment in our days [1-4]. Whilst at the end of the ’90s the hardness and mechanical strength of materials were in the focus of researchers [5-7], today the corrosion [8, 9], wear [10, 11], thermal shock resistance [12-14] and dynamic strength at normal and high temperature [15-18] are more important. In their work Ershova and Kelina [19] experimentally examined and compared the wear-resistance of silicon nitride bearing balls and cylinders of diameters 12.7 mm, 15.8 mm and 23.4 mm, at temperatures 1000 °C, 1300 °C and 1500 °C, under mechanical forces of 850000 N, 1200000 N and 3200000 N, and 40000-72000 rpm. During the experiments the ceramic bearings worked for 47 minutes without lubrication. After 47 minutes working under extreme conditions the volumes of wears were measured and compared.

Most of the oxide and non-oxide ceramics and ceramic matrix composites have excellent mechanical properties including hardness and mechanical strength but thanking to the microstructures and relatively large crystals of high rigidness and strong inclination to nicks, pitting and rigid fractures they do not have enough dynamic strength. Thanking to this, substantial research has been done in ceramic industry to reduce the crystal grain sizes [20, 21] and increase mechanical properties like
toughness [22, 23] and dynamic strength [24, 25]. To increase density and dynamic strength the researchers often use hot isostatic pressing or spark plasma sintering [26-28], whilst Wang, Huang and Wu [29] applied two-step sintering process for Al2O3-ZrO2 ceramic materials. To increase mechanical properties Hernandez, Torre and Rocha-Rangel [30] have prepared corundum matrix cermets from Al2O3 and mechanically activated Al, Fe and Ti powder mix. The mechanically activated powder mixes were compacted into cylindrical samples and pressure-less sintered for 1 hour at 1500 °C. Incorporation of ductile metal into the hard ceramic matrix considerably improved the fracture toughness of Al2O3-Al, Al2O3-Fe and Al2O3-Ti cermets. At the same time, Khare, Sharma and Venkateswarlu have examined the effect of scandium addition on pressure-less sintering and final mechanical properties of Al matrix Ti3N4 reinforced composites [31].

The advanced technical materials including ceramics have different melting temperatures and elastic modulus as it is shown on figure 1 a. The advantages of material structures built from components having different modules of elasticity (figure 1 b) and same melting temperature were first described by D.P.H. Hasselman, P. F. Betzher and K. S. Mazdiyashni [32]. Actually the material structures built from components having different modulus of elasticity are capable of dissipating the mechanical stresses better than others, and hereby stop the crack propagation under excess mechanical loadings and increase dynamic strength.

Figure 1. The modulus of elasticity and melting points of some technical materials

Developing of SiAlON, α-Si3N4 and β-Si3N4 reinforced corundum matrix composites and examining them under \( \nu > 1000 \) m/s high speed collisions with flying high density metallic objects L. A. Gömez and L. N. Gömez were one of the first who described the phase transformation of β-Si3N4 into γ-Si3N4 diamond particles (figure 2 a) [25, 33, 34] and importance of the local heating and melting (figure 2 b).

Figure 2. Typical phase transformation and melting observed during high speed collisions

The aims of this work are to understand the physical, mechanical and chemical processes taking place during high speed collisions of objects and to develop hetero-modulus, hetero-viscous and hetero-plastic complex material structures with increased mechanical properties like hardness and dynamic strength.
2. Materials and experimental procedures
To create hetero-modulus corundum matrix nanoceramic reinforced CMC 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 Al₂O₃ content was higher than 92 % in each case and the powder was polluted with 2.0-4.0 % SiO₂, TiO₂, MgO, CaO, thallium oxides and metallic Al. The specimens were compacted using uniaxial pressing and sintered in N₂ atmosphere at maximum temperature of 1600 °C. Thanks to the reactive sintering in N₂ atmosphere the ceramic items were reinforced with SiAlON, α-Si₃N₄ and β-Si₃N₄. The such prepared quadratic surface thin alumina matrix CMC plate specimens were tested under v > 1000 m/s high speed collisions with high density flying metallic objects. The typical damages of CMC plates after the collisions are shown in figure 3.

![Figure 3](image)

**Figure 3.** Typical destructions of ceramic composites during high speed collisions

Under high speed collision the kinetic energy (W_K) of flying object during hit can be described by equation (1) [35].

\[ W_K = W_E + W_H + W_P + W_S + W_V \ [Nm] \]  

(1)

Where energy engorgement of kinetic energy:
- \( W_E \) - through elastic deformation [Nm]
- \( W_H \) - through heating and phase transformation [Nm]
- \( W_P \) - through fracture indicated by pressure stress [Nm]
- \( W_S \) - through fracture indicated by shear stress [Nm]
- \( W_V \) - through viscous deformation [Nm]

Thanks to the local heating a considerable growth of Al₂O₃ crystals (figure 4) and melting can be observed. Thanks to the different melting temperature of components in the surroundings of the hit absorption and dissipation of collision energy occurs, frustrating further crack propagation (figure 5).

![Figure 4](image)  
**Figure 4.** Growth of Al₂O₃ crystals during high speed collision

![Figure 5](image)  
**Figure 5.** Absorption of collision energy through melting of material components
3. Results and Discussion

The energy engorgement by destruction of hetero-modulus ceramic items during high speed collisions with flying objects of inhomogeneous densities depends strongly on values of Young’s modulus and local heating in the surroundings of hits, which can be described by equation (2) [17].

\[
\frac{u^2}{2} \sum_{i=1}^{n} \rho_i \cdot V_i = \sum_{j=1}^{N} \frac{R_{\rho}}{2 \cdot E_j} \cdot A_{ij} \cdot l_{ij} + \sum_{j=1}^{N} \frac{R_{R}}{E_j} \cdot \left( \frac{v_{ij} + 1}{v_j} \right) \cdot A_{2j} \cdot l_{2j} + W_H \quad \text{[Nm]} (2)
\]

Thanking to local heating and melting of some of the components the energy engorgement by destruction and viscous deformation of hetero-modulus and hetero-viscous material systems during high speed collisions with flying object of inhomogeneous densities depends strongly on values of Young’s modulus of elastic particles and viscosity of melted components, and can be described by equation (3).

\[
\frac{u^2}{2} \sum_{i=1}^{n} \rho_i \cdot V_i = \sum_{j=1}^{N} \frac{R_{\rho}}{2 \cdot E_j} \cdot A_{ij} \cdot l_{ij} + \sum_{j=1}^{N} \frac{R_{R}}{E_j} \cdot \left( \frac{v_{ij} + 1}{v_j} \right) \cdot A_{2j} \cdot l_{2j} + \sum_{k=1}^{K} \eta_k \cdot A_{3k} \cdot \frac{l_{3k}}{t_k} + W_H \quad \text{[Nm]} (3)
\]

Where:
- \( \eta_k \) - the viscosity of \( k \)th viscous (melted) component [Pas],
- \( v_j \) - the Poisson ratio of \( j \)th Young’s modulus component of ceramic body,
- \( \rho_i \) - the density of \( i \)th component of flying object [kg/m³],
- \( i \) - 1, 2…n the numbers of different density components of flying object hit into the shield plates,
- \( j \) - 1, 2…N the numbers of different Young’s modulus components of shield plates,
- \( k \) - 1, 2…K the numbers of different viscous (melted) components with different viscosity during hit,
- \( l_{1ij} \) - length of fractures caused by pressure stress on the \( j \)th Young’s modulus component of shield plates [m],
- \( l_{2ij} \) - length of fractures caused by shear stress on the \( j \)th Young’s modulus component of shield plates [m],
- \( l_{3k} \) - length of viscous deformation caused by mechanical stresses on the \( k \)th viscous component of shield plates [m],
- \( t_k \) - duration of viscous deformation of \( k \)th viscous component of shield plates [s],
- \( u \) - speed of flying object hit into the shield plates at the moment of collision [m/s],
- \( A_{1ij} \) - fracture surface caused by pressure stress on the \( j \)th Young’s modulus component of shield plates [m²],
- \( A_{2ij} \) - fracture surface caused by shear stress on the \( j \)th Young’s modulus component of shield plates [m²],
- \( A_{3k} \) - surface of viscous deformation caused by mechanical stresses on the \( k \)th viscous component of shield plates [m²],
- \( E_j \) - the Young’s modulus of the \( j \)th components of shield plates [Pa],
- \( R_{\rho j} \) - pressure strength of the \( j \)th Young’s modulus component of shield plates [Pa],
- \( R_{Rj} \) - shear strength of the \( j \)th Young’s modulus component of shield plates [Pa],
- \( V_i \) - volume of \( i \)th component of flying object [m³].

From equation (3) it is obvious that hetero-modulus and hetero-viscous material systems are working better under high speed collisions than only hetero-modulus material structures. Based on the rheo-mechanical properties of components, the authors developed new lightweight ceramic matrix composite shield plates as shown in figure 6 and figure 7.
Figure 6. The main components chosen to develop corundum matrix shield plates

Figure 7. The microstructure and main components of Al$_2$O$_3$ matrix shield plates developed by the authors

To achieve the material structure shown in figure 7, the authors first developed new, high porosity matrix materials based on alumina, and after impregnated the lightweight metal alloys using reactive sintering. Henceforward silicon-carbon-nitride and carbon-silicon-carbon foam (figure 8) were developed as matrix materials to increase dynamic strength and decrease density of hetero-modulus hetero-viscous lightweight shield plates.

Figure 8. High porosity ceramic matrix materials for shield plates

4. Conclusion
Based on rheological principles of the components the authors successfully developed low density hetero-modulus, hetero-viscous and hetero-plastic new composite material structures which have excellent ability to dissipate mechanical stresses and assuage the crack propagation during high speed collisions when $v > 1000$ m/s. Thanking to the enclosed light metal alloys on the surfaces and pores of ceramic matrix components these materials not only have excellent dynamic strength but increased thermal conductivity, thermal shock resistance and ability for ductile and viscous-elastic deformation.

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