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Fabrication and Characterization of Lightweight Ceramic/Polyurethane Composites

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Abstract: The paper presents the experimental results of fabrication and characterization of ceramic/ polyurethane composites. The composites were fabricated from preforms with gradient of porosity and different pores size. The composites obtained via infiltration of porous Al2O3 ceramics by urea-urethane elastomers poses a microstructure of percolated phases. In order to improve thermal resistance and mechanical properties of composites, fire retardants and silane coupling agent were used. The microstructure of ceramic/ elastomer composites was characterized using X-ray tomography as well as Scanning Electron Microscopy (SEM). The microscopic observations proved that the matrix pores are filled with the elastomer. It was found that residual porosity of composites was up to 5vol. %. Such composites exhibit high initial strength with the ability to sustain large deformations due to combining the ceramic stiffness and rubbery elasticity of elastomer. Static compression tests for the obtained composites were carried out and the energy absorbed during compression was calculated as the area under the stress-strain curve. The dynamic behavior of the composite was investigated using the split Hopkinson pressure bar technique in conjunction with high-speed photography. It was found that ceramic-elastomer composites effectively absorb the energy. Moreover, ballistic test was carried out using armor piercing bullets.

Key words: Composites, elastomer, infiltration, SEM, energy absorbing.

1. Introduction

A lot of works concerning of particle and fibre reinforced composites can be found in the literature. New class of structural materials comprise composite with percolation of phases [1-5]. They are obtained via infiltration of porous ceramics by materials in liquid form. As a result, the composites of two interpenetrating phases are fabricated. Because of combination of phases with totally different properties, stress - strain characteristics of composites are improved. The ceramic/polyurethane composites are characterized by high compressive strength together with the ability to achieve large deformation. Due to combining the ceramic hardness and stiffness with elasticity of polyurethane elastomer, the composites are capable to absorb the energy during deformation [6-8]. The materials can be used for lightweight armor in defense systems against ballistic threats.

Military industry is one of the most developing branches in the world. Security and military forces have been forced to adapt to new international terror threats. Application of lightweight and resistant protective systems is required as a military’s equipment. Ballistic panels must protect against a range of threats such as direct gun fire, shaped charges, fragmentation and land mines [9-11].

Generally, two requirements for materials applied for protective covers were determined. Materials should exhibit relatively low density. It allows to reduce in mass and thickness of the armored covers. In order to ballistic panels performed protective and energy-consuming properties, materials should be selected appropriately. Vehicles designed in traditional way are manufactured using high strength armor steel. New ideas establish replacement of steel by ceramic or protective sandwich system consisted of two or more layers. The most important ceramic materials for ballistic protection

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are alumina, silicon carbide, and boron carbide. The composite armor system is usually made of ceramic placed on the strike face and composite backing [9-11].

The paper concerns the composites fabricated via infiltration of porous alumina ceramics by urea-urethane elastomers. The properties of the composites were investigated. The effect of microstructure and stress-strain characteristic composites on the properties required for protective panels applications were also evaluated experimentally.

2. Materials

Porous alumina ceramics used for infiltration were obtained from the Al_2O_3 powders, mixed with binder ensured expected porosity gradient. Ceramic preforms were fabricated by sintering and high isostatic pressure method (HIP) at Institute of Ceramics and Building Materials. In this set-up the samples were sintered to maximum temperature of 1600℃ in the argon atmosphere and then 200MPa pressure was applied.

In the present paper the elastomer was synthesized from three substrates: 4,4’-diphenylmethane diisocyanate (MDI), ethylene oligoadipate (OAE), with an average molecular weight of 1908 a.u. and dicyandiamide (DCDA), as a chain extender. The elastomer structure and properties strongly depend on the hard and soft segments (H/S) ratio. The higher number of hard segments the better adhesion and compressive strength of the composites [13-15]. The poly(urea–urethane) elastomers with molar ratio of MDI/(OAE+DCDA) of 2.5 (H/S=1.50) were synthesized by a one-shot method [12].

The composites were made by the infiltration of ceramic preforms with the reactive mixture of substrates in the liquid form [16]. In order to ensure the elastomer’s higher thermal stability and fire resistance the addition of ammonium polyphosphate (trade name Exolit AP 422) as a fire retardant was used. Moreover, the N-2-(aminoethyl)-3- aminopropyltrimethoxysilane coupling agent (U-15) was applied to improve adhesion between ceramics and elastomer.

3. Methods

Microstructure of ceramic performs was characterized using X-ray tomography type SkyScan 1174 and a Hitachi TM 3000 Scanning Electron Microscopy (SEM). SEM observations of ceramic-elastomer composites were carried out on sections and fractured surfaces. Residual porosity of composites was measured using X-ray tomography and Archimedes method. Compression tests of composites, ceramic performs and elastomers were also performed to make a comparison between mechanical properties of these materials. Moreover, energy absorbed by the composite during compression was calculated as the area under the stress-strain curve. The dynamic behavior of the composite was investigated using the split Hopkinson pressure bar technique in conjunction with high-speed photography.

Ballistic testing was carried out using armor-piercing shell (AP). It is the straightest variety of the armor-piercing ammunition with steel core of the projectile. AP shelle are characterized by 7,62÷54R mm calibre B-32 type and 854m/s velocity.

4. Results

4.1 X- ray Tomografy

The X-ray tomography images were used to describe microstructure of alumina ceramic. Porosity’s gradient of ceramic performs was observed. The X-ray tomography results revealed that the volume fraction of elastomer phase was changed from 20vol.% to 40vol.%, while the pore size of the ceramic preforms was varied from 50 to 500 μm.

X- ray tomography also allowed to determined residual porosity of composites (Fig. 3). Ceramic is present as white phase, elastomer as grey phase and pores as black area. These studies allowed to quantitatively evaluated both of phases. For the porosity ranged of 20vol.% and 40vol.% the residual porosity averaged between 12vol.% and 8vol.%, respectively. These results were confirmed using Archimedes method.

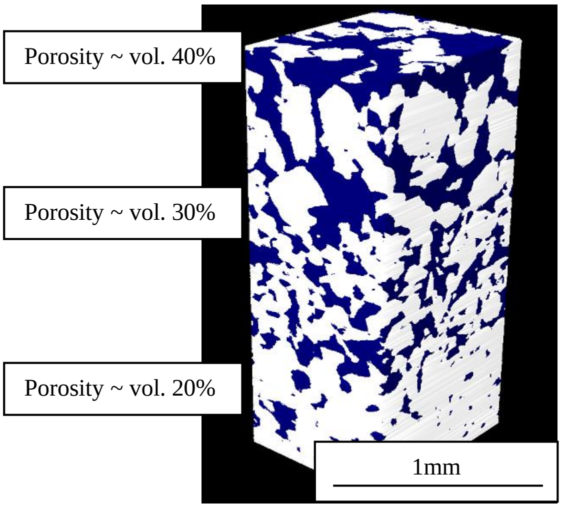


Fig. 1 X-ray tomography model 3D of Al_2O_3 gradient perform.

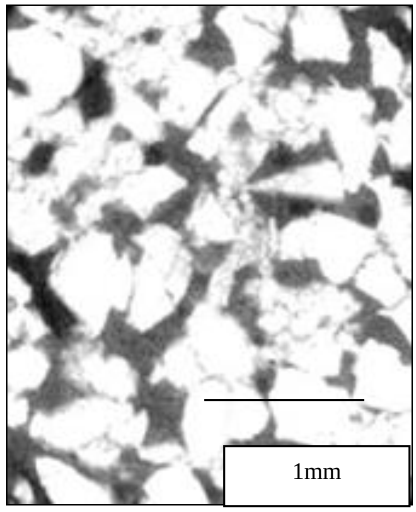


Fig. 3 Image of x-ray tomography of Al_2O_3/PU2,5 composites.

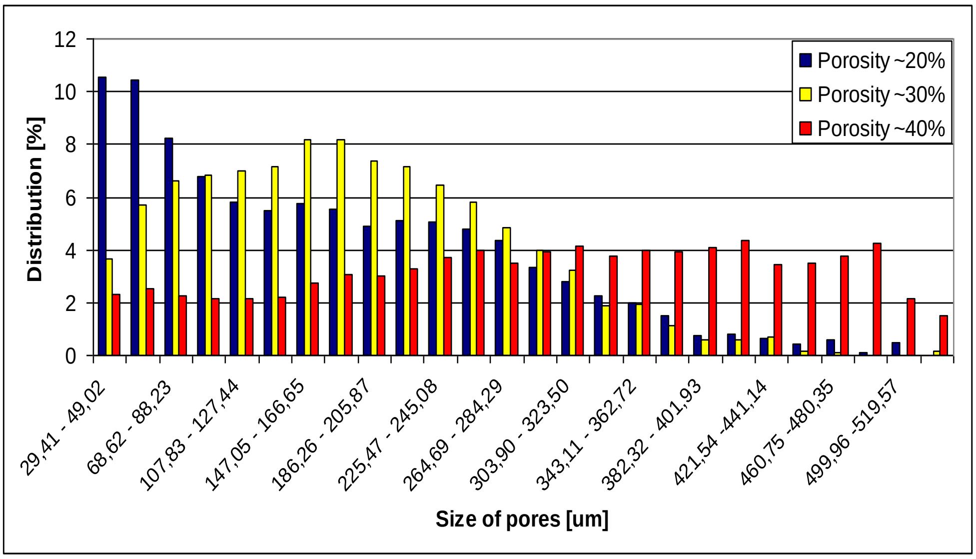


Fig. 2 Distribution of pores size of Al_2O_3 ceramic.

4.2 SEM Observations

Figs. 4 and 5 show the microstructure of ceramic-elastomer composites. The microscopic observations of composites indicated that the pores of matrix were filled by the elastomer, independently of ceramic preform porosity used to obtain composites. Also, small voids located at ceramic- elastomer boundaries can be observed. Moreover, SEM observation of composite's microstructure after compression tests was carried out (Fig. 6). It was observed that network of cracks in the ceramic phase was formed. The observations indicated that elastomeric phase blocked microcrack tip and ensured bridging effect.

4.3 Static and dynamic loading tests

The typical compressive stress–strain curves of the elastomer, porous ceramic and ceramic- elastomer composites are shown in Fig. 6.

Strain's velocity of static compression test was 0,001 s^{-1}. A stress peak and a stress valley can be observed in the early deformation stage of Al_2O_3/PU2,5 composites. The composites exhibit significantly higher compressive strength in comparison to ceramic preform

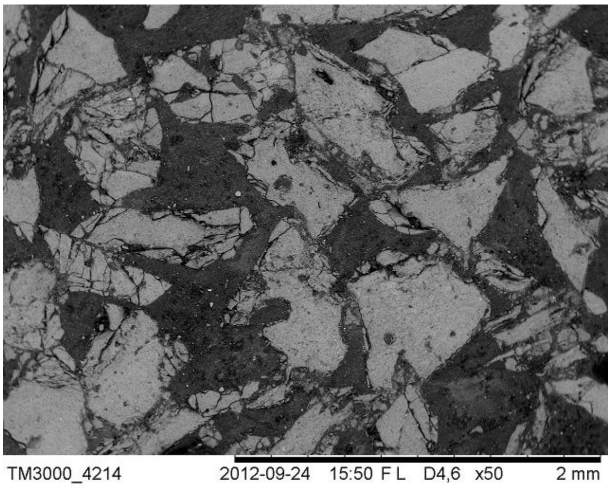


Fig. 4 SEM image of Al_2O_3 /PU2,5 composites, ceramic preform's porosity was 30vol.%.

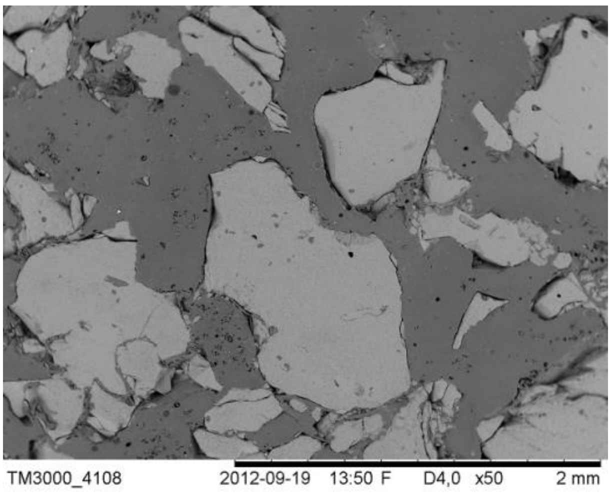


Fig. 4 SEM image of Al_2O_3 /PU2,5 composites, ceramic preform's porosity was 40vol.%.

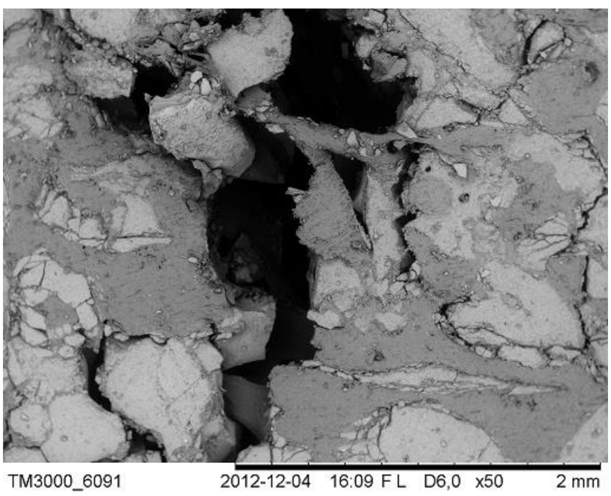


Fig. 6 SEM image of Al_2O_3 /PU2,5 composites after compression test.

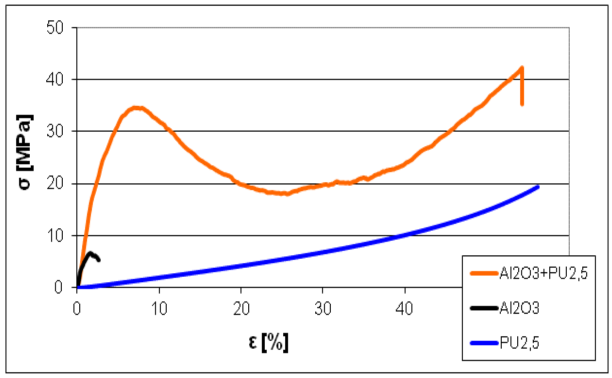


Fig. 6 Static compressive stress- strain curves of elastomer, ceramic preform and Al_2O_3 /PU2,5 composites.

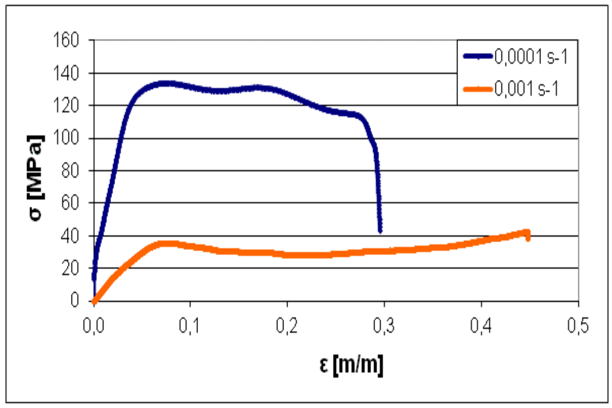


Fig. 7 Stress- strain curves of Al_2O_3 /PU2,5 composites.

and plateau area with constant stress vs. strain. The increase of mechanical properties of composites was caused by combination of ceramic stiffness and high elasticity of elastomer. While compression tests the porous ceramics were totally destroyed, but composite's failure was not observed due to the presence of elastomer in the ceramic pores.

In comparison static and dynamic compression tests were utilized. Strain's velocity of dynamic test was 0,0001 s^{-1}. Dynamic tests were carried out via generation of two-dimensional waves in uniaxial strain state. Results of both tests proved that increase of strain velocity caused improvement of compressive strength. Moreover, stress- strain curves were running in different ways (Fig. 7). The lower strain's velocity, the longer plateau region.

The energy absorbed by composite during loading was evaluated by integrating the area under the stress–strain curve as Fig. 8 presents [17].

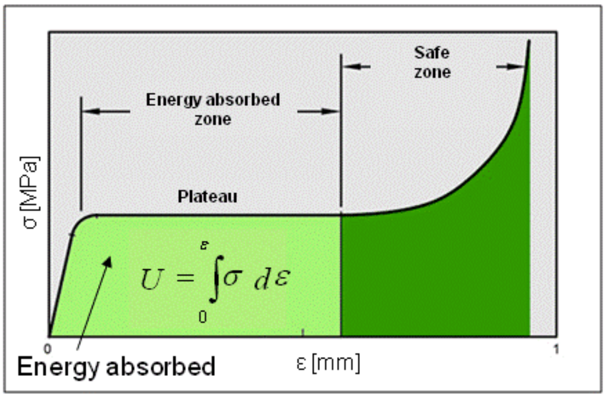


Fig. 8 Stress- strain curves.

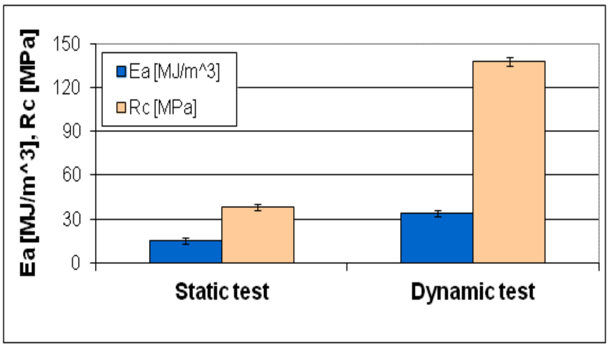
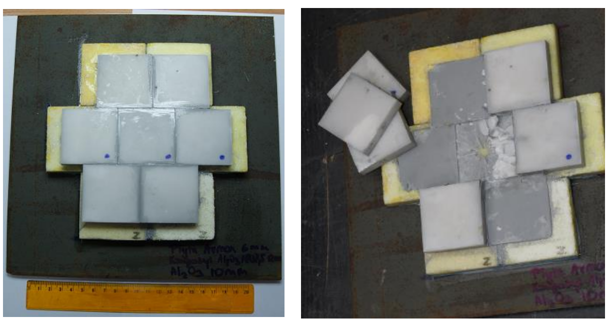


Fig. 9 Compressive strength and energy absorbed by Al_2O_3 /PU2,5 composites.



(a) (b)

Fig. 10 The front view of the panel with ceramic and composite layers (a) before and (b) after ballistic test.

Increase of strain's velocity ensured higher compressive strength and capacity of energy absorbed by the composites (Fig. 9).

4.4 Ballistic Tests

Typical protective sandwich system consists ceramic and steel layers. The ceramic is normally placed on the strike face. In these paper ballistic panels contained ceramic and composite layers was investigated. Ballistic testing was carried out using armor piercing bullets (AP). Fig. 10b shown results of ballistic tests. When the projectile impacted the surface of the ceramic, its kinetic energy is greatly reduced with penetrating the ceramic. Moreover, the shattered fragments of the projectile completely penetrate the ceramic. Additionally, composite's layer has not been destructed (Fig.10b).

5. Conclusions

The obtained results of SEM observation and mechanical properties showed that the infiltration method is useful for fabrication of composites with percolation of the phases. which exhibits higher strength and sustain large deformation. SEM observations of the microstructure of the composite's materials indicated that the porous ceramic preform was successfully infiltrated by elastomer. It was concluded that infiltration with elastomer significantly increases compressive strength of porous ceramics.

The static and dynamic compressive stress–strain curves of composites have been studied. It is possible to fabricate composites with the ability to absorb the impact energy by combining the porous ceramics stiffness and entropy-elasticity of elastomer.

In this paper, the ballistic behavior of the alumina ceramic and Al_2O_3/PU2,5 composites panel was investigated. Composite material located on the back of the ceramic can be used to replacement steel. According to the experimental results, utilization ceramic and composite layers ensured fully ballistic protection.

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