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Alumina–mullite ceramics for structural applications

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Abstract

New dense alumina–mullite ceramics developed using two formulation approaches have been studied. They include the materials based on alumina with a remarkable content of mullite and the materials based on alumina and containing mullite, zirconia and zircon formed via high-temperature interaction of alumina and zircon. Both types of materials have uniform fine-crystalline microstructures, a remarkable level of physical properties, high ballistic performance and high wear resistance. Ballistic performance and wear resistance are considered as a function of phase composition and microstructure of the studied ceramics.

Keywords: C. Wear resistance; D. Al_2O_3; D. Mullite; Ballistic performance; Microstructure

1. Introduction

Dense alumina ceramics are widely used for structural applications, including for armour, wear resistance applications and some others where they are in situations of severe mechanical stresses often coupled with corrosive and thermal actions. Alumina ceramics are relatively low cost, and the ceramic components may be manufactured with high output using different methods, e.g. by slip casting, pressing, injection moulding, etc., without the use of expensive equipment such as kilns with special controlled atmosphere. These ceramics have a high level of mechanical properties; for example, some materials can be successfully used in abrasion and erosion environments [1–4]; armour systems based on some kinds of alumina ceramics can defeat high-velocity projectiles with steel, lead and even tungsten carbide cores [5–7].

One of the directions of modification of alumina ceramics in order to attain desirable properties is creating a secondary crystalline phase. For example, materials with two crystalline phases may have increased fracture toughness that provides their wear resistance improvement. Regarding armour, one of the important tasks is to decrease the weight of ceramics that may be achieved by the presence of the crystalline components with lower specific gravity in the alumina system. As such ingredient, mullite ($3Al_2O_3{\cdot}2SiO_2$) may be considered due to its relatively lower specific weight (approximately 3.2 g/cm^3 versus 3.95 g/cm^3 for alumina). Alumina–mullite ceramics with a low content of a glassy phase may have a high potential for armour and wear resistance applications if these ceramics have an optimal ratio between two major crystalline phases and, therefore, a remarkable level of physical properties.

A presence of the mullite phase in alumina ceramics may have a positive effect on ceramic properties if the Al_2O_3 content does not exceed 98 wt.%. For instance, alumina ceramics with an Al_2O_3 content of 72–76 wt.% containing mullite and aluminosilicate or aluminoborosilicate glassy phase demonstrated remarkable mechanical properties, e.g. flexural strength up to 350 MPa [8]. Alumina ceramics AL91 which contained some quantity of mullite phase reinforcing a glassy phase exhibited high wear resistance [3,4]. Wear resistance of this material is superior comparatively to different kinds of alumina ceramics with higher Al_2O_3 contents but containing only corundum crystalline phase bonded by a glassy phase. As another example of a positive influence of mullite on properties of alumina ceramics is dense alumina ceramic AL97ML with a rather high level of ballistic protection and density reduced to

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3.74–3.76 g/cm^3 [5,6]. A lower density of this material was achieved by addition of a small amount of a mullite-based component, which also promoted the development of a glassy phase. Further density reduction using this methodology did not allow to achieve the required high ballistic performance due to a remarkable decrease of mechanical properties connected with the formation of a considerable amount of a glassy phase. In order to maintain high ballistic performance, but to decrease density of ceramics to a considerable extent, alumina–mullite ceramics with a higher content of mullite phase but with a lower content of a glassy phase should be considered. An optimal ratio between contents of corundum and mullite crystalline phases may provide a relatively high level of physical properties.

In order to attain a significant amount of mullite in alumina ceramics, two directions may be considered. As the first direction, a proper mullite-containing material with a lower content of glassy phase-forming ingredients may be added. As the second direction, a proper silicate-based material may be used as additive. Using this approach, after high-temperature transformation with this material and after reaction between forming silica and alumina, mullite and residual crystalline phases will be obtained. The second direction was studied previously by the authors [9,10] who developed zirconia-toughened mullite ceramics using zircon ($ZrSiO_4$) as an additive to alumina ceramic mixes. In this case, the high-temperature transformation occurs in accordance with the reaction:

$$2ZrSiO_4 + 3Al_2O_3 \rightarrow 2ZrO_2 + 3Al_2O_3 \cdot 2SiO_2$$

However, the ratio between alumina and zircon, as well as a selection of a zircon particle size, should be optimized in order to obtain a proper ratio between crystalline phase and glassy phase. Besides, the formation of monoclinic zirconia may deteriorate overall ceramic properties; therefore, this negative effect should be neutralized. The development of both types of mullite-containing alumina ceramics have been undertaken in order to reduce armor weight while maintaining satisfactory ballistic performance and to obtain ceramics with satisfactory wear resistance.

2. Experimental

The considered and studied alumina ceramics were based on the system of Al_2O_3–SiO_2 with sintering aids selected from earth-alkali silicates or borosilicates (AM materials) and based on the system of Al_2O_3–SiO_2–ZrO_2 with sintering aids promoting mullite formation and ZrO_2 stabilizing (ZAS materials). The major starting materials were commercially produced by Pechiney-Altech (France), Alcoa World Chemicals (USA), Nabaltec GmbH (Germany) and Continental Mineral Processing (USA). Experimental studies allowed to develop and optimize the following manufacturing steps:

- ceramic batch compositions, including selection of raw materials with proper particle size distributions;
- ceramic water-based slurry preparation depending on the batch composition, including selection and optimization of dispersant and binder, that result in the achievement of 77–80 wt.% of solid in the slurry;
- slip casting process providing manufacturing of large-size tiles and plates and some other ceramic components with different configurations;
- drying and firing in the production gas-fired kilns with a firing temperature less than 1550 °C providing full densification of ceramics (water absorption not greater than 0.02%);
- bonding process of ceramics with backing materials (in the case of armour systems manufacturing).

The batch compositions have been selected not only to reduce the density of ceramics and to maintain high levels of ballistic performance and physical properties, but also in order to fire the ceramics at the same temperature and with the same firing profile, used for high-alumina ceramics as currently produced by the manufacturer.

Microstructure was studied using scanning electron microscopy. Density, porosity and water absorption were tested using the water immersion method based on Archimedes law. Vickers hardness was tested in accordance with ASTM C1327 at an indentation load of 10 kg. Rockwell hardness was tested in accordance with ASTM E18 at the load of 60 kg (HRA testing). Fracture toughness K_{Ic} was determined using the indentation technique under the load of 10 kg and calculated using the following well-known formula

$$K_{Ic} = 0.941Pc^{-3/2}\ (\mathrm{MPa\,m^{1/2}})$$

where P is the indentation load (N) and c the crack length (m) measured using a microscope. Sonic velocity and Young's modulus were tested by the ultrasonic technique measuring the longitudinal ultrasonic velocity in accordance with ASTM C769 (Poisson ratio for the Young's modulus calculation was assumed as 0.2). Four-point flexural strength was tested in accordance with ASTM C1161. Brittleness factor (B) was defined as [11]

$$B = \frac{\mathrm{Hv}\,E}{K_{Ic}^2}$$

where Hv is the Vickers hardness, E the Young's modulus and K_{Ic} the fracture toughness. The coefficient of thermal expansion was measured in the temperature range of 20–100 °C using known quartz dilatometer technique. Test samples with required dimensions were cut from actual products or from test tiles with a size of 100 mm × 100 mm × (7–10) mm prepared by the mentioned technology. The quantity of the measurements was in accordance with related testing procedures indicated in the corresponding ASTM methods. In the case of K_{Ic} determination (non-standard method), measurements are based on a minimum of five indentations.

Ballistic performance of ceramics bonded with appropriate backing materials was tested in accordance with the NIJ 0101.03 and NIJ 0101.04 standards using the weapon M16. Depending on the application and the required level of protection, the ammunition 5.56 × 45 SS109 with a steel tip ball, 7.62 × 51-mm NATO Ball Full Metal Jacket (FMJ) with a lead core, 7.62 × 39-mm Russian Ball FMJ with a steel core, 7.62 × 54R Russian Ball LPS, 7.62 × 63-mm AP M2 FMJ with a tungsten carbide core were used. Depending on the ammunition, the bullet weight, velocity and energy were varied. The projectile velocity was controlled using a chronograph. The trauma after shooting was measured using a Roma Plastilina modeling clay supporting armor systems on the back; the trauma in clay duplicated the trauma in the armour. The damage zone of the ceramics, including ceramic fragmentation, and the bullets after shooting were observed. The flat tiles with sizes of 100 mm × 100 mm × (7–9) mm and 155 mm × 200 mm × (7–9) mm as well as actual body armour plates of different configurations were used for the ballistic testing; the actual plates were used for multi-hit testing (with approximately 50 mm spacing between hits). Also ballistic energy dissipation ability (*D*-criterion) for the studied ceramics was calculated in accordance with the formula proposed by Neshpor et al. [12]

$$D = \frac{0.36(\mathrm{Hv}\,Ec)}{K_{\mathrm{Ic}}^2}$$

where Hv is the Vickers hardness, E the Young's modulus, c the sonic velocity, and K_{Ic} the fracture toughness.

Wear resistance testing was conducted by three different methods under various conditions [4,13] where the weight loss was measured after each wear test and then was converted to the volume loss using known density values. The lower the volume loss indicates the higher the wear resistance.

Abrasion resistance was tested in accordance with ASTM B611 and ASTM G65.

- Wet slurry abrasion test ASTM B611 consisted of the continuing action of hard abrasive media (30-mesh alumina grit with water) that was supplied between the sample and the rotating steel wheel. The testing time was 400 revolutions.
- Low stress sliding abrasion was determined using the dry sand rubber wheel test ASTM G65 (Procedure A). Abrasive media (AFS 50–70-mesh silica sand) was continuously fed between the sample and the rotating rubber lined wheel. The testing time was 6000 revolutions.

Slurry jet erosion testing (SJET) was conducted using a custom-designed system described previously [13]. Erosive slurry consisting of 10:1 wt.% of AFS 50–70 silica sand in water was re-circulated through a piping loop via a mixing tank/reservoir. It was projected at the rectangular sample from a tungsten carbide nozzle with a 5 mm diameter orifice in a high velocity (16 m/s) jet. Three different impingement angles (20°, 45°, and 90°) were used at this testing. A computer-controlled electronic valve maintained the required velocity, while pressure was controlled manually with an adjustable by-pass valve. The distance between the spraying nozzle and a sample was 100 mm. The test duration was 120 min.

Thermal shock resistance of the experimental materials was evaluated based on formula proposed by Kingery et al. [14]

$$R = \frac{\sigma_{\mathrm{f}}(1-\mu)}{\alpha E}$$

where σ_{f} is the fracture stress, μ the Poisson ratio, α the linear coefficient of thermal expansion and E the Young's modulus.

Assuming that thermal shock resistance of brittle materials is also defined by the resistance to crack propagation, i.e. by fracture toughness, the sensitivity to thermal stresses was evaluated using the formulae

$$R^* = \frac{K_{\mathrm{Ic}}(1-\mu)}{\alpha E} \quad \text{and} \quad R^{**} = \frac{K_{\mathrm{Ic}}(1-\mu)d^{-0.5}}{\alpha E}$$

where d is the maximum grain size that may be determined by the microscopic studies.

3. Results and discussion

All studied ceramics are fully dense (water absorption and open porosity not greater than 0.02% and 0.075%, respectively) after firing at temperatures less than 1550 °C. As predicted, their density values were less than density of high-alumina ceramics (3.5–3.75 g/cm^3 depending on composition). The ceramics developed in the system of Al_2O_3–SiO_2 with sintering aids have two major crystalline phases, i.e. corundum and mullite, cemented by aluminosilicate or aluminoborosilicate glassy phases uniformly distributed between grains (AM2 and AM5 materials are typical examples, where crystalline phases are bonded by aluminosilicate or aluminoborosilicate glassy phase, respectively). The additives resulting in a formation of an aluminoborosilicate glassy phase are more "active", and they promote more intensive dissolution of alumina in a liquid phase during sintering. It is confirmed by similar values of densities of AM2 and AM5 ceramics, although AM5 material contains a higher content of alumina in the batch composition. The ceramics developed in the system of Al_2O_3–SiO_2–ZrO_2 have corundum, zircon, mullite and zirconia crystalline phases bonded by a glassy phase; as expected, mullite and zirconia are formed during high-temperature transformations with starting materials that correlates with the results of the authors [9,10] (ZAS materials). In this case, reaction-bonding processes occur during sintering and phases formation. The formation of new phases is confirmed by the lower shrinkage of this type of ceramics. The glassy phase is formed due to a use of small amounts of additives in the batch compositions and at the zircon–alumina particle interfaces. Due to the presence of zirconia and zircon, density values of ZAS ceramics are greater as compared with alumina–mullite AM ceramics (3.6–3.75 g/cm^3 versus 3.5–3.56 g/cm^3, respectively). Due to a use of specially selected additives in the batch compositions, microcracks dealt with the presence of monoclinic zirconia are not observed. The ceramics with a greater content of zircon in the batch compositions have lower densities. That may be explained by more intensive liquid phase development and a partial dissolution of forming zirconia in the liquid phase during sintering, i.e. these ceramics have less amounts of crystalline phases and a higher amount of the glassy phase. As an example of the mentioned, the ceramic ZAS2 with a lower content of zircon in the batch composition than the ceramic ZAS3 or ZAS4 has higher density. The intensive vitrification was observed only in the case of a relatively high content of zircon in the batch composition (approximately 20 wt.% or greater as for materials ZAS3 and ZAS4); other types of the studied alumina–mullite and alumina–mullite–zirconia–zircon ceramics had rather limited contents of a glassy phase. Probably, in order to increase the yield of mullite and zirconia due to more completed high-temperature interaction between alumina and zircon that may improve properties of ZAS ceramics, the firing temperature of these materials should be increased.

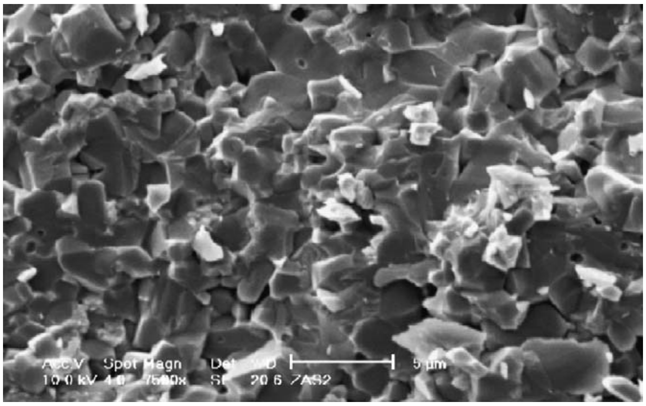

Fig. 2. Microstructure of ceramics ZAS2 prepared in the system Al_2O_3–SiO_2–ZrO_2.

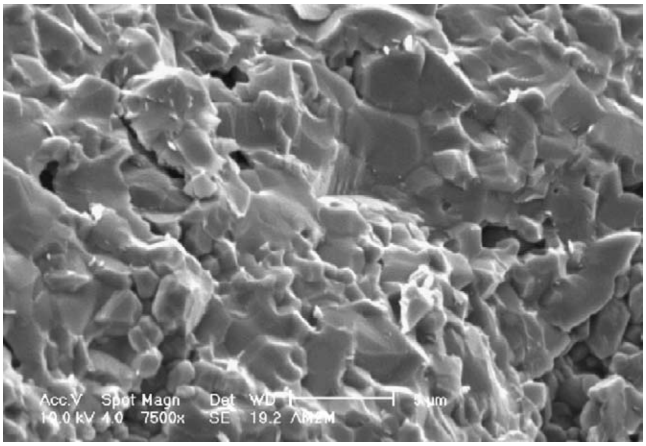

Fig. 1. Microstructure of alumina–mullite ceramics AM2.

In general, the studied ceramics have uniform microcrystalline structures. The grain size of the ceramics depends on the initial batch composition and initial particle size and particle size distribution of starting materials. The experimental studies focused on the selection of starting materials with different particle sizes and the optimization of their contents in the ceramic mixes allowed to reach a high level of compaction between grains and dense homogeneous microstructures. The grain size of alumina–mullite ceramics is 2–4 µm (mostly isometric) with a presence of larger grains (up to 6 µm); smaller grains with a size of 0.5–1 µm are also observed (Fig. 1). The grain size is greater if the ceramics have a higher content of a glassy phase (e.g. in the case of an aluminoborosilicate glassy phase); short prismatic grains may be also formed due to re-crystallization process. The grain size in the Al_2O_3–SiO_2–ZrO_2-based ceramics with a relatively high content of alumina and, accordingly, with a lower content of forming mullite, zirconia and a glassy phase (e.g. ZAS2 ceramic, Fig. 2), is also rather small; it ranges from 0.5–1.5 to 2–4 µm (mostly isometric), and occasional grains have a size up to 6 µm. The grains of the phases formed due to high-temperature transformations have a size up to 0.5 µm. Microscopic studies and density values analysis indicate that some amounts of residual zircon are present. If a content of zircon in the initial batch is rather high (e.g. greater than 20 wt.%), the ceramics has a higher content of a glassy phase enriched with zirconium silicate (e.g. ZAS3 ceramic). In this case, the ceramics have less uniform and relatively coarser microstructures (e.g. grain sizes range from 5–7 to 10–12 µm, see Fig. 3) due to more intensive re-crystallization during sintering; however, small grains with a size of 1–2 µm and grains of formed crystalline phases with a size up to 0.5 µm, are also observed.

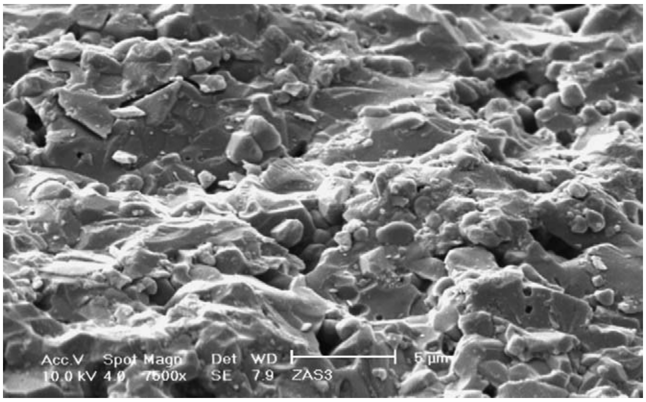

Fig. 3. Microstructure of ceramics ZAS3 prepared in the system Al_2O_3–SiO_2–ZrO_2.

Phase composition and microstructure affect physical properties, ballistic performance and wear resistance of ceramics. The major properties of some experimental compositions are presented in Table 1. The studied ceramics have lower hardness and some other properties in comparison with high-alumina ceramics; however, our studies show that they may be beneficially comparable with the properties of alumina ceramics with even higher Al_2O_3 content but with a higher content of a glassy phase. Factor of brittleness (B) calculated for the experimental materials is on the level with some high-alumina ceramics performed in [15]. The alumina–mullite ceramics with approximately the same content of Al_2O_3 and with a lower amount of a glassy phase have higher values of hardness and fracture toughness. Comparing the studied compositions, the ceramics with an earth-alkali aluminosilicate glassy phase (material AM2 from the Table 1, as an example) are more beneficial from the mechanical standpoint than the ceramics with an aluminoborosilicate glassy phase (e.g. material AM5). This is due to the former materials have higher contents of crystalline phases and more uniform and microcrystalline structures. The mechanical properties of the Al_2O_3–SiO_2–ZrO_2-based ceramics with a relatively high corundum content are comparable with ones of the alumina–mullite ceramics (they have even higher values of fracture toughness and lower brittleness factor due to a presence of the zirconia phase); however, these materials have higher density values. The Al_2O_3–SiO_2–ZrO_2-based ceramics with lower corundum contents and, accordingly, with higher glassy phase contents, and less uniform microstructures and larger grain sizes have lower mechanical properties (e.g. material ZAS3 from Table 1).

The studied ceramics exhibited high ballistic performance despite their mechanical properties are decreased in comparison with high-alumina ceramics. It may be explained by a remarkable ballistic impact energy dissipation ability that is provided by the presence of two or three crystalline phases. These phases do not have equal mechanical properties (e.g. the presence of the mullite phase decreases hardness and some other properties of alumina ceramics), but these "weaker" phases are significantly "stronger" than a glassy phase. The approximate values of the ballistic energy dissipation criterion (D) for some experimental ceramics exhibited in Table 1 indicate that the developed materials may have a benefit in comparison with high-alumina ceramics (the latter have the D-criterion values of $(1.5–2.4) \times 10^{12}$ 1/s depending on composition [5,6]).

The studies showed that alumina–mullite ceramics with a lower amount of crystalline phases and, accordingly, with a higher amount of a glassy phase, demonstrate lower ballistic performance, especially against armour piercing projectiles. The obtained results confirm the point of view that satisfactory ballistic performance of ceramics may be achieved if the ceramics possess the appropriate combination of mechanical properties, including hardness, brittleness (higher brittleness factor denotes more brittle material), sonic velocity and others, as well as an optimal microstructure. Among studied, the most promising armour material with high ballistic performance and density reduced to 3.52–3.56 g/cm^3 is the alumina–mullite ceramics developed in the Al_2O_3–SiO_2 system with earth-alkali–aluminosilicate glassy phase (denoted as AM2 in Table 1). The armour systems (actual body armour plates) based on this ceramics bonded with appropriate backing materials are capable of defeating 5.56 × 45-mm SS109, 7.62 × 51-mm NATO Ball FMJ, 7.62 × 39-mm Russian Ball FMJ, 7.62 × 54R LPS and 7.62 × 63-mm AP M2 ammunition at the tested velocities, and they provide ballistic performance to NIJ Level III or Level IV dependant on the ceramic and backing materials thickness (Level IV in conjunction with a Level IIIa vest). The armour systems have satisfactory multi-hit performance, withstanding up to six rounds of the Ball FMJ to one plate without penetration with an acceptable size of trauma (not greater than 44 mm

Table 1
Properties of selected alumina–mullite ceramics

Property	AM2	AM5	ZAS2	ZAS3
Density (g/cm^3)	3.52–3.56	3.52–3.55	3.70–3.75	3.58–3.62
Vickers hardness Hv10				
kg/mm^2	1130	1030	1180	940
GPa	11.1	10.1	11.6	9.2
Rockwell hardness HRA	90.5	89	90	85
Fracture toughness K_{Ic} (MPa m$^{1/2}$)	2.54	2.32	3.03	3.08
Sonic velocity (m/s)	8615	8765	9040	8385
Young's modulus (GPa)	237	241	275	228
Flexural strength (MPa)	350	300	350	275
Coefficient of thermal expansion, ($\alpha \times 10^6$, 1/°C)	5.5	5.5	4.5	4.0
Brittleness ($B \times 10^{-6}$, 1/m)	408	452	347	221
Ballistic energy dissipation criterion ($D \times 10^{-12}$, 1/s)	1.3	1.4	1.1	0.7
R value (°C)	215	181	226	241
R^* value (m$^{0.5}$ °C)	1.56	1.40	1.96	2.70
R^{**} value (°C)	640	570	800	780–850

The values of properties presented are average.

Fig. 4. Ballistic test result of the armour plate (7.62 × 51-mm NATO Ball FMJ). Left: front view and right: back view.

backface deformation of the plate, see Fig. 4). The armour based on AM2 ceramics had the same design and thickness as the armour based on high alumina AL98 ceramics but lower weight.

Observed fragmentation and crack formation from ballistic impacts for the studied ceramics have a similar character as for the high-alumina ceramics described previously [5,6]. The ceramic plate zone close to the impact point consists of the chunks of various sizes to fine powder with a locus of conoidal coaxial cracks with a presence of radial tensile and spall cracks (Fig. 5). The cracks propagate through the glassy phase, as the weakest component of the ceramics, and the secondary crystalline phases. Due to the presence of two or more crystalline phases, the crack propagation is not as intensive as was demonstrated for the alumina ceramics with one major crystalline phase and a relatively high amount of a glassy phase.

The studied ceramics demonstrated a high level of wear resistance tested using different methods (ASTM B611, ASTM G65 and SJET), i.e. under various testing conditions, that is comparable with high alumina ceramics (see Ref. [3,4]). As Table 2 exhibits, the highest values of wear resistance among the studied ceramics were obtained for alumina–mullite ceramics AM2 where corundum and mullite grains were cemented by aluminosilicate glassy phase. Alumina–mullite ceramics with a higher content of a glassy phase (AM5) with lower hardness and fracture toughness and higher brittleness factor demonstrated lower wear resistance. The fine-grained ‘‘secondary’’ crystalline phase, such as mullite, reinforcing the boundary glassy phase, prevents crack propagation in a glassy phase under abrasion and erosion actions and results in the delay of a wear process. The achieved level of wear resistance for the developed ceramics may be explained by the formation of the microstructure with an ‘‘optimized’’ phase composition despite these ceramics demonstrate lower values of physical properties than high alumina ceramics. The positive influence of the presence of mullite grains in the ceramic microstructure on wear resistance of alumina ceramics is in a good correlation with the data received in the previous work [3,4]. Alumina–mullite ceramics contained zirconia and residual zircon grains (ZAS materials) have lower values of wear resistance than AM2 ceramics. Probably, the presence of residual zircon and zircon-based glassy phase results in more intensive crack occurring and crack propagation during the action of the abrasive media. Considering ZAS ceramics, it was obtained that wear resistance decreases with an increase of the content of zircon in the starting compositions, i.e. with an increase of the formed zircon-based glassy phase (i.e. ceramic ZAS2 demonstrated a higher level of wear resistance than ZAS3 and ZAS4 materials). Although brittleness of ZAS ceramics with high contents of zircon in the batch compositions is very low, that may be considered as a positive factor, physical properties of these ceramics (e.g. hardness and Young’s modulus) are also not high enough. These lower values of the properties, as well as a higher content of a glassy phase, do not provide a high level of wear resistance. Especially it is noted for the tests with more severe conditions, such as SJET with a high impingement angle and as ASTM B611 where hard alumina particles are used

Fig. 5. Fracture image of the AM2 ceramic (view of a backface of the plate) after ballistic impact with 7.62 × 51-mm NATO Ball FMJ (backing material was taken out).

Table 2
Wear resistance test results (volume loss) for selected alumina–mullite ceramics

Material	ASTM G65 (mm^3)	ASTM B611 (cm^3)	SJET (mm^3) at impingement angle		
			20°	45°	90°
AM2	10.9–11.6	0.32–0.35	15	32	43
AM5	12.0–12.5	0.33–0.38	19	36	45
ZAS2	13.3–14.1	0.33–0.40	20	37	46
ZAS3	14.8–18.8	0.38–0.50	21	43	62
ZAS4	19.9–20.9	0.50–0.75	25	57	68
Air hardening 460HB steel[a]	173	–	50	62	80

[a] Wear resistance test results for the steel are performed for comparison.

as the abrasive medium. The studied alumina–mullite ceramics may have a higher potential in sliding abrasion applications due to very satisfactory wear resistance results demonstrated after testing at these conditions (tests ASTM G65 and ASTM B611).

Performance of ceramic components for power generation applications often depends on not only mechanical properties, but also on thermal shock resistance and an ability to serve under mechanical and thermal stresses. Thermal shock resistance was evaluated using the formula proposed by Kingery et al. [14] and the formulae utilizing the sensitivity to crack propagation. Comparing values R and R^* for the studied alumina–mullite ceramics using the data of σ, K_{Ic}, E and α from Table 1 for approximate calculations (Poisson ratio μ is assumed as 0.2 for all the studied materials; a maximum grain size for the studied ceramics was determined under microscope), it is possible to assume that ZAS ceramics will have higher thermal shock resistance. ZAS ceramics demonstrated elevated fracture toughness; their coefficients of thermal expansion are lower than of AM ceramics (zircon-based ceramics usually have low values of coefficient of thermal expansion). This conclusion was confirmed by the practical evaluation, when the ZAS ceramic components demonstrated better performance and longer service cycle at elevated temperatures and thermal shocks than the high-alumina and AM ceramic components. This may be explained by the presence of a few crystalline phases with different coefficients of thermal expansion and associated microstructure of ZAS ceramics.

4. Summary

New dense alumina ceramics with reduced density have been developed and studied. These ceramics with two or more crystalline phases have a remarkable level of physical properties and low brittleness, and they may be used for armour and wear resistance applications. Alumina–mullite ceramics (e.g. AM2 composition) with a uniform microcrystalline structure and a low content of a glassy phase are the most promising for armour applications due to a high level of ballistic performance and lower density (3.52–3.56 g/cm^3 versus 3.8–3.9 g/cm^3 inherent to high alumina ceramics). These ceramics also demonstrated the highest wear resistance among other studied materials. The presence of zirconia and residual zircon ingredients in the alumina–mullite ceramics (ZAS compositions) results in an increase of density, and, therefore, of weight of ceramic components. Although the ceramics with a relatively low content of zirconia and zircon (e.g. ZAS2 material) demonstrated high mechanical properties and lower brittleness than the ‘‘two-phased’’ alumina–mullite ceramics, their ballistic performance and wear resistance were still lower. However, ZAS ceramics are less sensitive to thermal stresses. Satisfactory ballistic performance and wear resistance of the developed alumina–mullite ceramics may be explained by their high impact energy dissipation ability and low brittleness dealt with a presence of the mullite crystalline phase uniformly distributed among the corundum phase and a low content of a glassy phase. The appropriate armour systems based on these ceramics demonstrated the ballistic protection to NIJ Level III or Level IV that is comparable with the systems based on high alumina ceramics but with lower weight.

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