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WEAR TESTING OF α -Al₂O₃ OXIDE CERAMIC IN A DIVERSE ABRASIVE SOIL MASS

ANALIZA PROCESU ZUŻYWANIA CERAMIKI TLENKOWEJ α -Al₂O₃ W ZRÓŻNICOWANEJ GLEBOWEJ MASIE ŚCIERNEJ

Key words:

α -Al₂O₃ oxide ceramic, 38GSA martensitic steel, abrasive wear, soil mass

Słowa kluczowe:

ceramika tlenkowa α -Al₂O₃, stal 38GSA, zużycie ściernie, masa glebowa

Summary

This paper presents a comparative study of the intensity of α -Al₂O₃ oxide ceramic sand 38GSA martensitic steel wear in three types of abrasive soil masses, i.e. loose sand, sandy clay and heavy clay. The tests were carried out under laboratory conditions on a “spinning bowl” wear machine. Based on the obtained results, the intensity of ceramic material wear was many times lower than 38GSA steel wear. It was found that the granulometric composition had an important effect on the intensity of α -Al₂O₃ ceramics wear. The lowest α -Al₂O₃ oxide ceramics wear was obtained during friction in sandy clay, and it was 1.5 times lower than in heavy clay and 1.9 times lower than in loose sand.

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Differences in the types of tribological wear, depending on the granulometric abrasive mass composition, are described.

INTRODUCTION

Abrasive soil properties, which are the characteristics of the working element as an element working in the soil and the mechanics of this interaction, have a decisive effect on the intensity of the process of material deterioration of a working element on a soil mass [L. 8, 9, 11]. The intensive action of an abrasive soil mass and an active chemical environment cause the rapid wear of working elements, reaching 70 g per hour [L. 10, 13]. Wear occurs in an abrasive soil mass under the influence of the impact of abrasive particles against the surfaces of the abraded material (wear by de-cohesion, fatigue); however, in the case of compact abrasive masses, these particles can be treated as fastened grains causing material losses as a result of processes that are characteristic for abrasive wear (scratching, micro-cutting, and ridging). This paper [L. 11] demonstrates a connection between physical and chemical soil properties characterized by the granulometric composition, compactness, moisture and acidity, and the course of the wear process for structural materials. The problems of the wearing of elements used in an abrasive soil mass are very complex. The requirements that should be met by working elements in soil are often contradictory and often cause their production from classical structural materials to be ineffective. Under real operating conditions, the material properties of working elements particularly determine the durability of the used elements [L. 3, 6, 12]. Ceramic materials are increasingly becoming a substitute material for steel materials in the production of working elements [L. 4]. Many papers have been published to date on the wear of ceramic materials in different practical applications [L. 3, 7, 14], particularly, including α -Al₂O₃-based composites [L. 1, 2, 15–17].

Discussion of the structure and properties of engineering materials and their surfaces usually comes down to an analysis of the mechanisms connected with different technological processes and the effect of the obtained structures on their properties [L. 14]. The selection of structural/technological forms of working elements in an abrasive soil mass and planning the course of their operation is possible when the course of the depletion of their usable resources in a specific time and conditions is known. Therefore, discussion on the marking of engineering materials before starting to use them under operational conditions is obvious in this context. The conducted literature data analysis indicates that the properties of aluminium oxide-based ceramic layers in diverse abrasive soil masses have not been identified to date.

The aim of this paper is to evaluate the wear processes of α -Al₂O₃ ceramic material in abrasive soil masses with diverse granulometric compositions.

RESEARCH MATERIAL

Most ceramic materials are used in technology in a polycrystalline form, which are obtained during the sintering (burning) process. This is very often a monophasic-polycrystal or a polycrystal containing small percentages of other phases than the basic phase, which are the effect of the addition of compounds facilitating sintering or unremoved impurities. When manufacturing a material consisting of two (or more) phases, one should be prepared so that residual stresses arising from a difference in the coefficients of thermal expansion of the component phases will be introduced into it during sintering [L. 14]. During cooling, after sintering of a composite material, its different component phases shrink to different degrees. Maintenance of the coherence of the material causes the formation of stresses, which often have high values. Because of the relationship between the coefficients of thermal expansion of the ingredients of the composite, stresses in the matrix can have a compressing or stretching character. This can lead even to fractures in the composite. The state of stresses in the matrix influences the energy expenditure connected with the propagation of the fracture in the material (fracture energy). If the matrix is compressed, the propagation of the fracture requires an additional energy input. Mechanical strength properties will improve when the size of a critical defect decreases in the composite. Such a situation may happen, for example, by limitation of grain growth. The size of a critical defect is usually of the order of a grain size. A reduction of grain size while maintaining a good density allows the strength to increase considerably. The above-mentioned defects, raising the probability of brittle fracture of composites compared to monophasic materials in practical applications in a dynamic environment, are also seen in other functional characteristics. Abrasive wear resistance is a good example. Inclusions, on the other hand, contribute to increased abrasive wear resistance, particularly during friction in dry media [L. 14]. This effect is much weaker during abrasion in the presence of water, which is caused by the easy erosion of intergranular boundaries in aluminium oxide. Engineering ceramic materials are manufactured by sintering at a high temperature without the participation of the liquid phase of very pure compounds, such as oxides, carbides, nitrides, and elements in a solid state with a crystalline form without the participation of the vitreous phase. One of the compounds widely used for the manufacture of working elements of ceramic materials is α -Al₂O₃ aluminium oxide.

Chemically and thermally stable α -Al₂O₃ aluminium oxide (corundum) with the chemical composition Al₂O₃ ≥ 99.8, MgO ≤ 0.1, CaO ≤ 0.05, Na₂O ≤ 0.1, Fe₂O₃ ≤ 0.03, SiO₂ ≤ 0.07 was used for the tests. The addition of MgO was aimed at grain growth reduction. The microstructure of the oxide ceramics was a rhombohedral crystallographic system (Fig. 1). Ceramic samples were made in a dry-bag isostatic press. Powder densification took place in a plastic material mould as a result of the action of hydrostatic pressure, which was exerted uni-

formly on all sides of the mould. The press moulding pressure was 25 MPa. A triaxial stress state caused a good powder density and a uniform density distribution in the moulding. The material was press moulded and sintered at a temperature of 1650°C. A 60-minute sintering time at the maximum temperature was used.

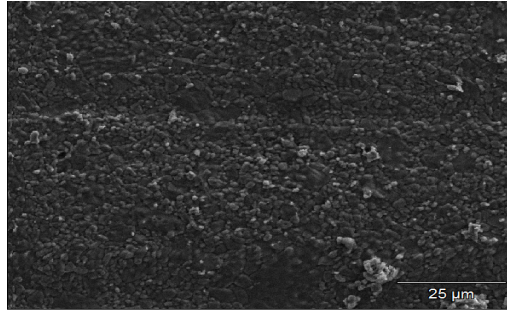


Fig. 1. Surface of the α -Al₂O₃ sample (Accelerating Voltage: 15.0 kV Magnification: 1000)
Rys. 1. Napięcie przyspieszające 15,0 kV, pow. 1000x

RESEARCH METHODOLOGY

The tests were carried out on a "spinning bowl"-type laboratory stand [L. 10]. The bowl of the wear machine was filled with a natural abrasive soil mass (Table 1). The aluminium oxide wear values obtained under diverse soil conditions were compared to the wear values obtained for 38GSA steel. The chemical composition of steel was as follows: C – 0.38%, Mn – 1.07%, Si – 1.17%, P – 0.028%, S – 0.02%, Cr – 0.18%, Cu – 0.16%, and Al – 0.022%. The steel microstructure was martensite with bainite and troostite. Aluminium oxide (α -Al₂O₃) and 38GSA steel wear were tested simultaneously in the wear machine during the friction test.

The sample was a cuboid with dimensions 30 × 25 × 10 mm. The samples were ground and polished before the tests. Friction tests were carried out at a load of 53 kPa, a cutting speed of 2 m/s, and a sliding distance of 10,000 m in six repetitions. Mass loss was measured using a laboratory balance with an accuracy up to $\pm 10^{-4}$ g. The hardness of layers was measured with a Vickers HV-10D hardness tester according to PN-EN ISO 6507-1:1999. The surface was evaluated after traveling the total sliding distance under a JEOL JSM-5310LV scanning electron microscope equipped with a digital system. The microscope was equipped with a reflected electron detector, a secondary electron detector, and a Thermo Scientific EDS Ultra DR7 X-ray spectrometer.

A constant soil reaction and soil moisture state (sandy soils 9–12%, clay soils 11–15%) were ensured during the testing. Granulometric composition evaluations were conducted using a Mastersizer 2000 laser particle size analyser + according to the EN ISO 14688-1:2004 and EN ISO 14688-1:2004 standards.

ANALYSIS OF RESEARCH RESULTS

The tested materials were characterized by homogeneous properties, because the hardness dispersion of top layers did not exceed 12%. The mean hardness of α -Al₂O₃ aluminium oxide was 1710.12 HV10 with a standard deviation of 91.53 HV10 and a mean range of 197 HV10. The mean hardness of 38GSA steel was 546.6 HV10, with a standard deviation of 31.54 HV10 and a range of 41.3 HV10.

Table 1. Characteristics of the abrasive soil mass

Tabela 1. Charakterystyka glebowej masy ścierniej

Name	Gravel ø 2–1.0 mm	Sand ø 1–0.1 mm	Dust ø 0.1–0.02 mm	Clay ø < 0.02 mm
Sandy clay	---	43.65	31.20	25.15
Heavy clay	---	19.02	29.68%	51.30
Loose sand	12.52%	73.82	11.14	2.52

Based on the obtained results, the highest α -Al₂O₃ ceramics wear was recorded in loose sand, followed by heavy clay, and the lowest was in sandy clay (**Fig. 2**). An inverse relationship was obtained for 38GSA steel, where the most intensive wear was found in sandy clay and the lowest was in loose sand (**Fig. 3**).

A comparative summary of wear per unit is presented in **Table 2**.

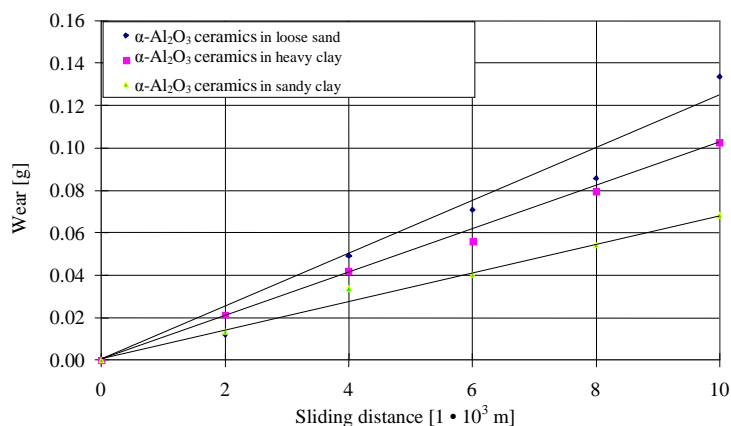


Fig. 2. Course of oxide ceramics wear depending on the type of the abrasive soil mass

Rys. 2. Przebieg zużywania ceramiki tlenkowej w zależności od rodzaju glebowej masy ścierniej

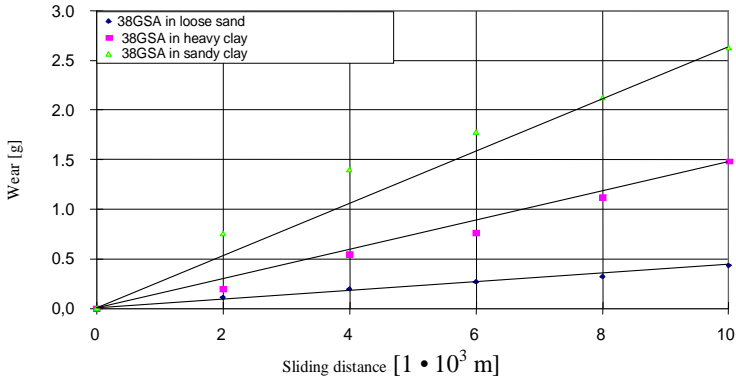


Fig. 3. Course of 38GSA steel wear depending on the type of the abrasive soil mass
 Rys. 3. Przebieg zużywania stali 38GSA w zależności od rodzaju glebowej masy ścierniej

Table 2. Summary of wear per unit for α -Al₂O₃oxide ceramics and 38GSA steel
 Tabela 2. Zestawienie zużycia jednostkowego ceramiki tlenkowej α -Al₂O₃ i stali 38GSA

Soil type	α -Al ₂ O ₃	[g/km]	38GSA	[g/km]
	Mean value	Standard deviation	Mean value	Standard deviation
Loose sand	0.0133	0.0014	0.0434	0.0088
Heavy clay	0.0102	0.0021	0.1483	0.0199
Sandy clay	0.0068	0.0011	0.2631	0.0224

Statistically significant differences in the wear of both oxide ceramics and 38GSA steel in diverse abrasive soil masses were found based on the conducted analysis of variance (**Table 3**).

Table 3. Analysis of variance for wear per unit in diverse abrasive soil masses
 Tabela 3. Analiza wariancji zużycia jednostkowego w zróżnicowanych glebowych masach ściernych

Source of variation	α -Al ₂ O ₃ ceramics			38GSA steel		
	Degrees of freedom	Sum of squares	Mean square	Degrees of freedom	Sum of squares	Mean square
Between objects	2	0.1064	0.0531	2	0.1064	0.0531
Inside objects	12	0.0329	0.0027	12	0.0329	0.0027

The comparative summary of the course of wear for α -Al₂O₃ oxide ceramics and 38GSA steel in individual abrasive soil masses is presented in **Figures 4–6**. 38GSA steel wear was considerably higher than α -Al₂O₃ oxide

ceramic wear in all the studied environments. Consequently, the spread of wear intensity was lowest in loose sand, 3.2 x, followed by heavy clay 14.5 x, and up to 38.5 times in sandy clay.

The granulometric composition of the worked soils was decisive for such wear values. Loose sand containing sharp-edged sand and gravel particles (most often quartz particles) causes wear in classical structural materials by fatigue processes as a result of the repeated action of sand grains on the top layer and scratching and sporadic ridging. For an abrasive mass of this type, the course of wear is also determined by the fastening of abrasive grains, because abrasive

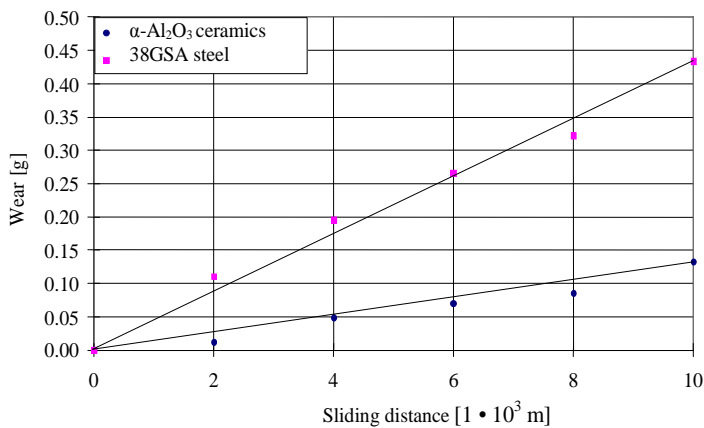


Fig. 4. Comparison of the course of 38GSA steel and α -Al₂O₃ wear in loose sand

Rys. 4. Zestawienie przebiegu zużycia stali 38GSA i α -Al₂O₃ w piasku luźnym

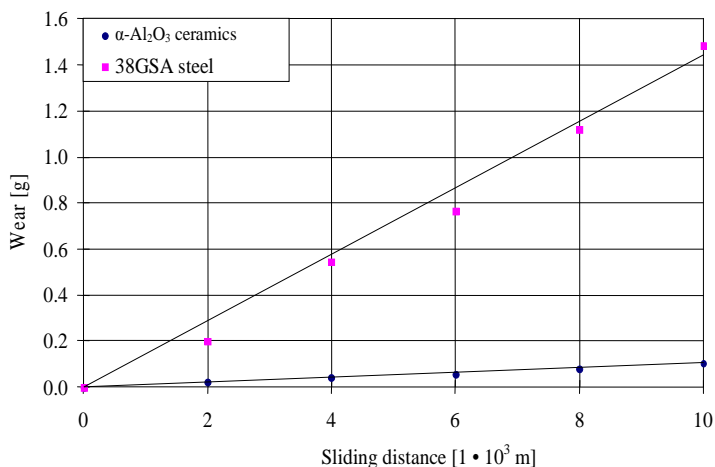


Fig. 5. Comparison of the course of 38GSA steel and α -Al₂O₃ wear in heavy clay

Rys. 5. Zestawienie przebiegu zużycia stali 38GSA i α -Al₂O₃ w glinie ciężkiej

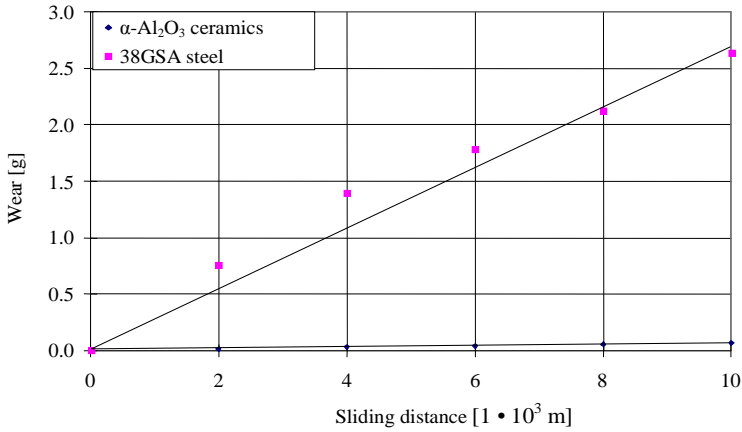


Fig. 6. Comparison of the course of 38GSA steel and α -Al₂O₃ wear in sandy clay

Rys. 6. Porównanie przebiegu zużywania stali 38GSA i α -Al₂O₃ w glinie piaszczystej

(quartz) grains have great freedom in moving on the top layer surface and wear intensity depends, above all, on the dynamics of the action of abrasive grains for these soils (with relatively low clay and dust contents). For materials with high hardness, higher than quartz hardness (ca.1300 HV10), considerable smoothing of the surface and blurring of crystallite boundaries was observed in the action of loose sand on the friction surface (**Fig. 7**). This process is similar to the classical process of dry grinding of ceramic materials. Although top layer porosity decreased as a result of friction, wear intensity was among the highest in the tested soil masses.

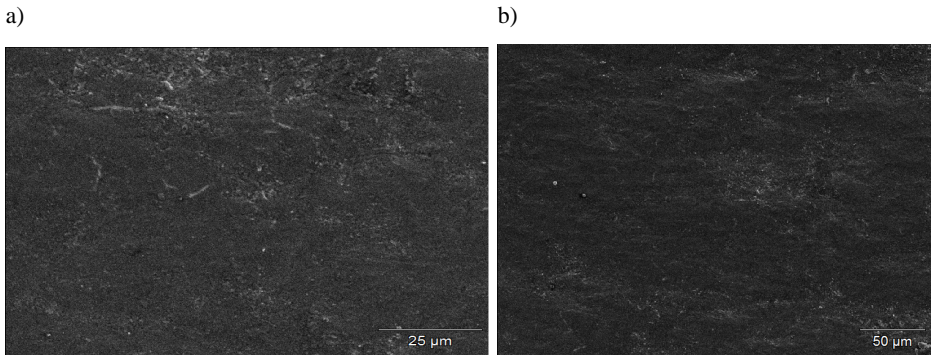


Fig. 7. Surface of α -Al₂O₃ oxide ceramics worn in loose sand (Accelerating Voltage: 15.0 kV): a) magnification 1000, b) a) magnification 500

Rys. 7. Powierzchnia ceramiki tlenkowej α -Al₂O₃ zużywanej w luźnym piasku (napięcie przyspieszające 15,0 kV): a) pow. 1000x, b) pow. 500x

Relationships concerning ceramic wear found during the testing diverge from relationships found for classical structural materials, where the highest wear intensity occurs in clay soils with a high content of sandy fractions. For heavy clay ceramics, wear takes place by surface spalling and grinding (**Fig. 8**). Spalling happens due to microfractures as a result of dynamic action of sand particles located in clay and dust. However, the intensity of this process is relatively low, taking into account the recorded wear values.

The highest difference in wear between the tested materials was found in the sandy clay soil mass (**Fig. 9**). This soil is characterized by the highest heterogeneity of the granulometric composition, and its abrasive properties change randomly with changes in the temporary configuration of the abrasive grains. The wear process consists of both tear-outs and surface grinding, but these processes are less intensive than for the other abrasive soil masses.

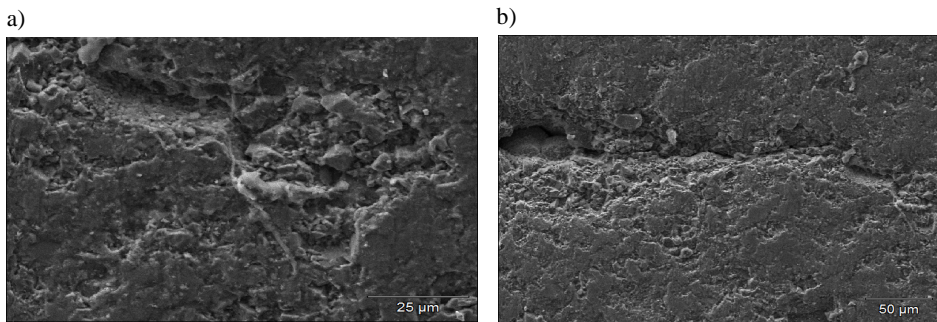


Fig. 8. Surface of $\alpha\text{-Al}_2\text{O}_3$ oxide ceramics worn in heavy clay (Accelerating Voltage: 15.0 kV): a) magnification 1000, b) a) magnification 500

Rys. 8. Powierzchnia ceramiki tlenkowej $\alpha\text{-Al}_2\text{O}_3$ zużywanej w glinie ciężkiej (napięcie przyspieszające 15,0 kV): a) pow. 1000x, b) pow. 500x

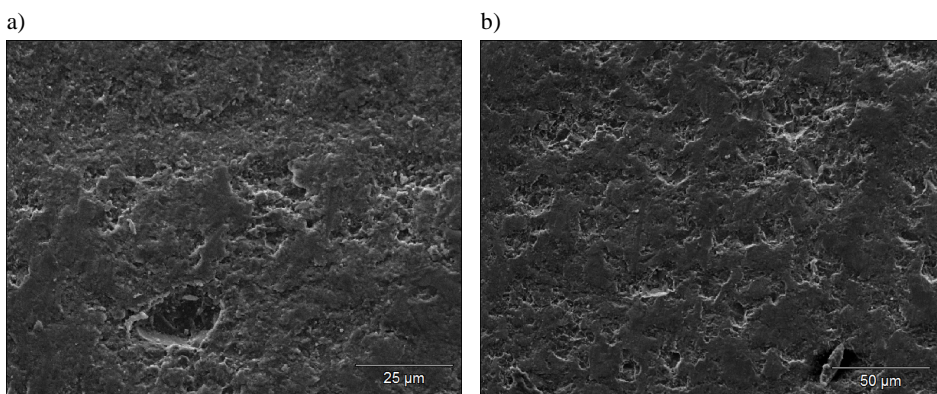


Fig. 9. Surface of $\alpha\text{-Al}_2\text{O}_3$ oxide ceramics worn in sandy clay (Accelerating Voltage: 15.0 kV): a) magnification 1000, b) a) magnification 500

Rys. 9. Powierzchnia ceramiki tlenkowej $\alpha\text{-Al}_2\text{O}_3$ zużywanej w glinie piaszczystej (napięcie przyspieszające 15,0 kV): a) pow. 1000x, b) pow. 500x

CONCLUSIONS

1. Based on the obtained testing results, it can be concluded that the granulometric composition is decisive for abrasion resistance in an α - Al_2O_3 oxide ceramic abrasive soil mass. The lowest α - Al_2O_3 oxide ceramic wear was obtained during friction in sandy clay, and it was 1.5 times lower than in heavy clay and 1.9 times lower than in loose sand. The course of ceramic wear in soil is described by linear dependences, and wear grows as the sliding distance increases.
2. α - Al_2O_3 oxide ceramic wear was lower than 38GSA steel wear in all the abrasive soil masses. Consequently, 38GSA steel wear was 3.2 times higher in loose sand, 14.5 times higher in heavy clay, and as much as 38.5 times higher in sandy clay.
3. The basic manner of wear was the grinding of the abraded surface and spalling for masses containing a high percentage of dust and clay due to microfractures. The intensity of the brittle cracking process was of no significant importance in the wear process in the conducted tests.
4. Properties of ceramic materials varies across quite a broad range, but their common characteristic is low crack resistance, and it is this characteristic that influences the way that they can be used in practice. The results obtained from the carried out tests indicate the rightness of using ceramics for working in soil masses without the presence of the dynamic loads leading to excessive cracking. The final evaluation of the suitability of ceramic layers α - Al_2O_3 in utilitarian applications require additional testing under normal operating conditions.

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Streszczenie

W pracy przedstawiono badania porównawcze intensywności zużycia ceramiki tlenkowej α - Al_2O_3 i martenzytycznej stali 38GSA w trzech rodzajach glebowych mas ściernych tj. piasku luźnym, glinie piaszczystej i glinie ciężkiej. Badania przeprowadzono w warunkach laboratoryjnych na maszynie zużyciowej „wirującej misy”. Na podstawie uzyskanych wyników stwierdzono, że intensywność zużycia materiału ceramicznego była wie-

lokrotnie mniejsza od zużycia stali 38GSA. Stwierdzono, że skład granulometryczny ma istotny wpływ na intensywność zużywania ceramiki $\alpha\text{-Al}_2\text{O}_3$. Najmniejsze zużycie ceramiki tlenkowej $\alpha\text{-Al}_2\text{O}_3$ uzyskano podczas tarcia w glinie piaszczystej i było ono 1,5-krotnie mniejsze niż w glinie ciężkiej i 1,9-krotnie mniejsze niż w piasku luźnym. Opisano różnice w sposobach zużywania tribologicznego w zależności od składu granulometrycznego masy ścierniej.