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Influence of the type of strengthening particles on the tribological and material properties of sintered copper matrix composites

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ABSTRACT

This paper presents a comparison of the material and tribological properties of sintered copper matrix composites. Aluminum oxide and titanium were used as reinforcing particles. Commercial powders of copper, aluminum oxide and titanium were used to manufacturing the composites. Composites were tested on cylindrical samples with the content of strengthening particles 2.5, 5, 7.5, 10% by weight. Before the sintering process, the powder mixtures were subjected to a single pressing using a hydraulic press at a compaction pressure of 624 MPa. The samples obtained after the pressing process were sintered in a tubular furnace with silite heating elements. The maximum sintering temperature was 900 °C. Dissociated ammonia was used as a protective atmosphere. The samples were heated for 60 minutes. After the sintering process was completed, the samples were slowly cooled at a rate of approximately 70 °C/min. The produced sinters were subjected to material tests including measurements of hardness, density and electrical conductivity. Tribological tests were also carried out including measurements of the coefficient of friction and resistance to abrasive wear. Microstructural observations were performed using optical (OM) and scanning electron microscopes (SEM). After the tribological tests, the surface morphology was observed in the abrasion areas. The introduction of aluminum oxide and titanium particles significantly increased the hardness of the composites while reducing the density and electrical conductivity. The tribological tests showed that the introduction of aluminum oxide particles reduced the abrasive wear resistance, while the introduction of titanium particles significantly increased it. In addition, the introduction of aluminum oxide and titanium particles resulted in an increase in the coefficient of friction compared to the sample made of copper powder. The obtained results showed that the copper-titanium composite is characterized by high material and tribological properties, while maintaining relatively high electrical conductivity.

Keywords: copper matrix composites, powder metallurgy, copper, alumina, titanium, intermetallics.

INTRODUCTION

The continuous development of technology has resulted in research around the world to produce modern materials with specific properties. A single material, despite the use of many treatments aimed at improving its strength or tribological properties, does not meet the assumed expectations. For this reason, composites, i.e. materials consisting of several phases differing in strength, physical or tribological properties, have been gaining more and more interest in the field of machine design and maintenance for many years [1,2]. In recent years, an attractive direction for engineers are metal matrix composites (MMCs) made, among others, by powder metallurgy and casting methods. Among them, copper matrix composites are very popular. High thermal and electrical conductivity, as well as corrosion resistance in many environments, makes copper useful in many industries. It is used, among others, in the construction industry (pipelines, air conditioners, lighting, roofs), the electrical and energy sector (wind farms, transformers, electric generators), telecommunications (wires, computer connectors), the automotive industry, and also in coinage. Due to its excellent electrical conductivity, copper is also used for electrical contacts, electric motor components, and resistance welding electrodes [3,4]. Copper in its pure form has low strength and tribological properties, which limits its use in industry. In order to strengthen the copper, alloying additives are introduced to it. By introducing alloy additions to copper, strength and tribological properties are increased, however the electrical conductivity decreases, because the introduction of even relatively small amounts of alloy additions reduces its conductivity. For example, the electrical conductivity of most bronzes and brasses is around 20 MS/m while that of pure copper is around 59 MS/m [5]. In order to improve the material and tribological properties, particle-reinforced copper matrix composites are manufactured. The most commonly used particles include metal oxides (TiO_2, ZrO_2, Al_2O_3, SiO_2, MgO, BeO) [6,7], nitrides (BN, TiN) [8], borides (ZrB_2, TiB_2, CrB_2) [9,10], and carbides (TiC, SiC, Cr_3C_2, Cr_7C_3) [11]. In addition to the above-mentioned ceramic materials, in recent years scientists have been investigating the use of zeolite and volcanic tuff as a strengthening phase for sintered copper matrix composites (CMCs) [12]. Another method of strengthening sintered metal matrix composites is the introduction of pure metals, which in combination with the matrix form intermetallic phases. The world literature contains the results of research on the manufacturing of CMCs strengthened with copper-titanium, nickel-aluminum and iron-aluminum intermetallic phases [13,14]. The latest research on the manufacturing of sintered CMCs includes composites reinforced with high-hardness steel particles, graphene, and carbon tubes [15,16]. Metal matrix composites are most often produced by powder metallurgy methods. One of the advantages of using powder metallurgy to produce sintered metal matrix composites is very good distribution of strengthening particles in the metal matrix, as well as the possibility of producing composites with a variety properties [17,18].

This work presents a comparison of the materials and tribological properties of sintered copper matrix composites (CMCs), in which Al_2O_3 and titanium particles were used as reinforcing phases. The manufactured composites were tested for hardness, density and electrical conductivity. Structural studies were carried out using scanning electron (SEM) and light microscopy (OM). The tests of resistance to abrasive wear and the observation of geometric structure of the composite surface after tribological tests were also carried out. All tests of the produced composites were carried out in order to assess the application possibilities for elements of electric motors, such as electric brushes. Currently, materials such as graphites, electrographites, bakelite-graphites and metal-graphites are used for the production of electric brushes [19]. The use of a specific material is related to the power of the device. Electric brushes are subject to intensive wear during operation, so they must be replaced from time to time. For this reason, research is underway to produce a material with greater wear resistance while maintaining high electrical conductivity [20]. The aim of the work was to determine, based on the obtained test results, which of the used materials has properties that allow it to be potentially used for electric brushes and electrical contacts.

RESEARCH METHODOLOGY

Elementary powders of copper, titanium and aluminum oxide were used to produce the composites. The basic powder constituting the matrix of the manufactured composites was copper powder, while the other powders were used as reinforcing phases. Electrolytic copper powder with an average particle size of 35 μm, alumina powder with an average particle size of 50 μm, and titanium powder with an average particle size of 750 μm were used to fabricate the sinters. The difference in the size of the reinforcing particles resulted from the fact that the use of small titanium particles caused a significant decrease in the electrical conductivity of the composites. The decrease in electrical conductivity was related to the dense distribution of titanium particles that diffused into the copper matrix. On the other hand, the use of large-sized alumina would result in uneven distribution of particles in the metal matrix. The chemical purity of all powders used was about 99.5%. Before the sinters were produced, the powders were observed using a scanning electron microscope to determine the shape and size of the particles. The shape and size of the particles used to fabricate sinters are shown in Figure 1.

The first step in the production of composites was the preparation powders mixtures. Mixtures of powders with different content of strengthening

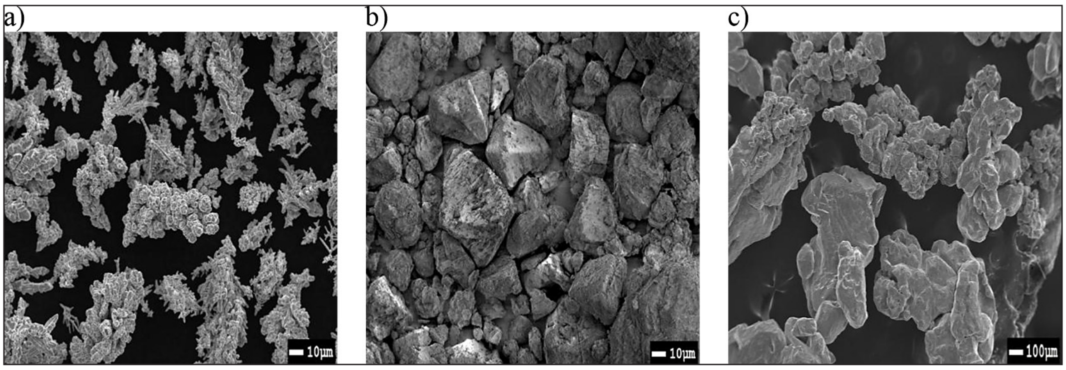


Figure 1. Shapes of the particles used in experiments: (a) copper, (b) alumina, (c) titanium

phases (2.5%, 5%, 7.5%, 10% by weight) were prepared. The finished powder mixtures were pressed using a hydraulic press at a compaction pressure of 624 MPa. The ϕ20 × 5 mm compacts were sintered in a tube furnace in an atmosphere of dissociated ammonia. Two samples were produced for each variant. The copper-alumina composites were sintered at 900 °C, while the copper-titanium composites were sintered at a maximum temperature of 895 °C (so that sintering does not occur with the participation of the liquid phase). The sintering temperature of the copper-titanium composites was selected on the basis of the copper-titanium phase equilibrium system [21]. The sintering time was 1 hour. After sintering, the composites were cooled in a cooler that was part of the furnace equipment. The finished composites were subjected to tests of material properties. Hardness, density and electrical conductivity were tested. The produced composites were also subjected to tribological tests, after which observations of the surface morphology were carried out. The density of the composites was determined using Archimedes' principle using a hydrostatic scale. The measurements were carried out in accordance with the PN EN ISO 2738:2001 standard. The hardness of the composites was measured using the Brinell method in accordance with the PN EN ISO 6506-1:2014-12 standard. The measurements were made at a load of 2452.4 N using a 5 mm diameter steel ball as an indenter. The hardness of the intermetallic phases which formed in the copper-titanium composites was determined using a Vickers microhardness tester using a load of 0.1962 N in accordance with the PN EN ISO 6507-1:2018-05 standard. Measurements of the electrical conductivity of the produced composites were carried out using a GE Phasec 3D flaw detector using the eddy current method. Observations of the microstructure of the fabricated sinters were carried out using a Nikon ECLIPSE MA 200 light microscope and a JEOL JSM-7100F scanning microscope integrated with the EDS X-ray microanalysis system. Abrasive wear resistance tests were carried out on the Anton Paar TRB3 tribometer using the „ball on disc" method in accordance with ASTM G 99.

Abrasive wear resistance tests were carried out using the following parameters:

- friction pair: 6mm diameter ball made of 100Cr6 steel and counter samples made of manufactured sinters (Cu+ 2.5–10% of Al_2O_3 and Ti);
- ball load P = 5 N;
- sliding velocity v = 0.1 m/s;
- friction path distance: for copper- titanium composites s = 1000 m, for copper- alumina composites s = 200 m;
- humidity 50 ± 1%;
- ambient temperature T_0 = 20 ± 1 °C;
- atmospheric pressure 1000 ± 5 hPa.

Abrasive wear resistance tests were performed without lubricant. The weight loss of the composites was determined by weighing them before and after the tests. After the tribological tests, observations of the geometric structure of the wear surface using a Leica DCM8 optical profilometer were carried out.

ANALYSIS OF THE RESULTS

Microstructural investigations

Microstructure studies of the produced sintered copper-based composites reinforced with aluminum oxide and titanium particles were conducted to assess the distribution of particles in the metal matrix, the connection of particles with the matrix, and also to check whether the particles do not combine into clusters. In the case of the copper-titanium composite, chemical composition studies were also conducted because as a result of mutual diffusion of copper and titanium, different intermetallic phases were formed. Figures 2 and 3 show exemplary microstructures of the produced composites.

Analyzing the microstructures of the sintered copper-alumina composite, it can be stated that the particles are evenly distributed in the metal matrix. In order to avoid particle agglomeration, the powders should be properly mixed before the composite manufacturing process. Particles of different sizes and shapes are visible in the microstructures. No merging of particles into larger clusters was observed. The alumina particles are well connected to the matrix despite the lack of diffusion with the copper matrix.

In the case of the copper-titanium composite, a worse distribution of particles in the metal matrix was observed. This is due to the much larger size of titanium particles than aluminum oxide. Titanium particles are visible in the microstructures around which various intermetallic phases have formed. These phases were identified during the examination of the chemical composition using a scanning microscope with an X-ray microanalysis system. The studies showed that the highest concentration of titanium is located in the center of the particle and decreases towards the copper matrix. Figure 4 shows the results of the linear analysis of the chemical composition of a titanium particle in a copper matrix.

A layer rich in titanium was formed around the particle, which is the effect of diffusion of titanium atoms into the copper matrix. The highest concentration of copper is in the matrix and drastically decreases towards the center of the titanium particle, where it is about 3%. In the center of the particle there is a structure similar to the Widmanstätten structure. This is probably a solid solution of copper in α and β titanium. Copper stabilizes the β phase, so during rapid cooling it may not have completely transformed into the α phase [22,23]. Figure 5 shows the microstructure of the center of the titanium particle

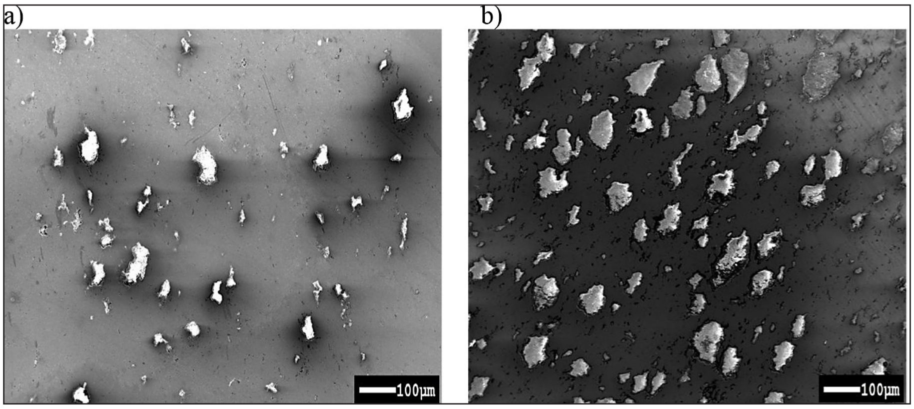


Figure 2. Microstructures of sintered copper-alumina composite: (a) 2.5% of alumina, (b) 10% of alumina

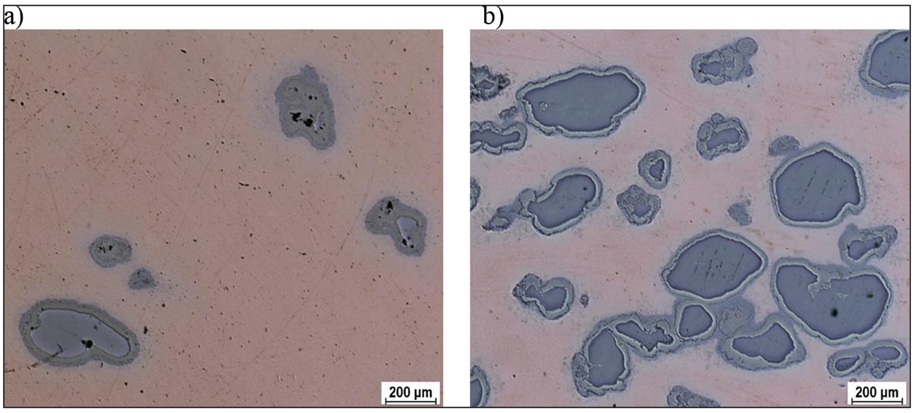


Figure 3. Microstructures of sintered copper-titanium composite: (a) 2.5% of titanium, (b) 10% of titanium

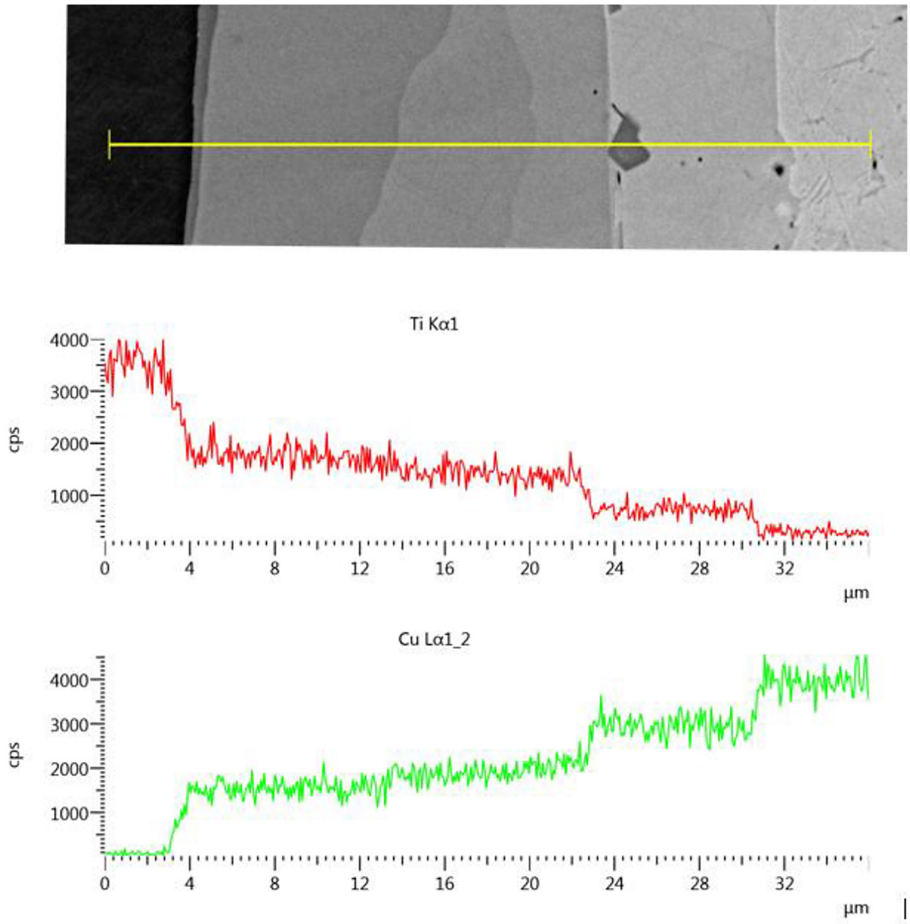


Figure 4. Linear analysis of the chemical composition of titanium particles in a copper matrix

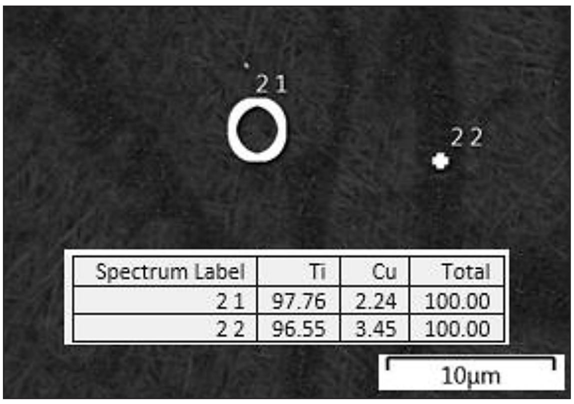


Figure 5. Microstructure of the center of the titanium particle

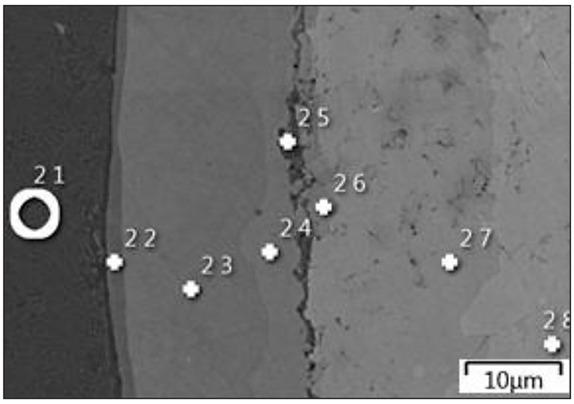


Figure 6. Microstructure of the titanium particle-copper matrix connection with marked EDS analysis points

along with the results of the point analysis of the chemical composition.

Akbapour et al. [21] identified eight intermetallic phases occurring in the Cu-Ti system. In the presented own studies, the presence of five intermetallic phases was found. Based on the obtained results of the point analysis of the chemical composition, the characteristics of the individual intermetallic phases were made using the studies performed by Konieczny [24]. Figure 6 shows the microstructure of the connection of the copper-titanium intermetallic phase particle with the copper matrix with marked places where the point analysis of the chemical composition was performed. Table 1 presents the results of the point analysis of the chemical composition.

Table 1. Chemical composition and phases occurring at the boundary of the copper-titanium intermetallic phase particle and the copper matrix

Point in Figure 6	Ti,%	Cu,%	Possible phase
21	96.92	3.08	Copper solid solution in titanium
22	52.34	47.66	TiCu
23	42.26	57.74	Ti_3Cu_4
24	38.38	61.62	Ti_2Cu_3
25	33.42	66.58	$TiCu_2$
26	18.06	71.94	$TiCu_4$
27	19.62	80.38	$TiCu_4$
28	4.92	95.08	Titanium solid solution in copper

Density and hardness measurements

Density and hardness tests of sintered copper-matrix composites were performed to estimate the effect of the amount and type of reinforcing particles on the above properties. For each sample of a given material, 10 measurements were performed. The results are presented as an arithmetic mean of 10 measurements with an accuracy of 0.01 in the case of density tests and 0.1 in the case of hardness tests. The relative density of the fabricated composites was also determined. The density values of the materials used were used to determine the relative density: Cu – 8.91 g/cm^3, Al_2O_3 – 3.95 g/cm^3, Ti – 4.5 g/cm^3. Tables 2 and 3 present the density and hardness measurements results of the produced composites.

Due to the lower density of the reinforcing particles than the density of the matrix material, the composites density decreases with the amount of reinforcing particles. The density of the composites is also influenced by the porosity that occurs at the boundaries of the matrix-particle connections. A similar phenomenon was also observed by other researchers in their work [2,4]. Hardness measurements of the fabricated composites showed that with the increase of amount of reinforcing particles, the hardness increased. In the case of the copper-alumina composite, the highest hardness was obtained for the composite with 10% of reinforcing particles, which was 50.7 HB (38% more than in the case of sintered copper). A significantly higher hardness was obtained for a composites reinforced with titanium particles, similarly to the copper-alumina composites, the highest hardness was measured for the composite with 10% of reinforcing particles (92.8 HB, which is over 150% more than in the case of sintered copper). Such high hardness of copper-titanium composites is related to the high hardness of copper-titanium intermetallic phases that were formed during the sintering process. The hardness of the formed intermetallic phases

Table 2. Density and hardness test results of copper-aluminum oxide composites

Material	Density, g/cm^3	Relative density, %	HB
Cu	8.17±0.02	92.11	36.6±1.5
Cu+ 2.5% Al_2O_3	7.82±0.02	90.87	46.3±1.2
Cu+ 5% Al_2O_3	7.71±0.04	88.83	47.9±1.7
Cu+ 7.5% Al_2O_3	7.59±0.01	89.16	49.9±1.1
Cu+ 10% Al_2O_3	7.42±0.03	88.13	50.7±1.4

Table 3. Density and hardness test results of copper-titanium composites

Material	Density, g/cm^3	Relative density, %	HB
Cu	8.17±0.02	92.11	36.6±1.5
Cu+ 2.5% Ti	7.79±0.02	88.87	68.9±1.6
Cu+ 5% Ti	7.75±0.04	89.79	78.4±1.2
Cu+ 7.5% Ti	7.58±0.01	87.03	87.6±1.4
Cu+ 10% Ti	7.36±0.03	86.85	92.8±1.3

ranges from 150 to 230 $HV_{0.2}$, while the center of the particle, where the solid solution of copper in titanium probably occurs, is characterized by hardness from 250 to 340 $HV_{0.2}$. The increase in the hardness of composites associated with the presence of intermetallic phases has also been observed by other researchers [13,14].

Electrical conductivity measurements

Electrical conductivity tests of sintered copper matrix composites were performed to estimate the effect of the amount and type of strengthening particles on electrical conductivity. For each sample of a given material, 10 measurements were performed. The results are presented as an arithmetic mean of 10 measurements with an accuracy of 0.01. The obtained results were compared with the electrical conductivity value obtained for the sintered copper sample (50.41 MS/m). The results of electrical conductivity tests are presented in Table 4 and 5.

It is a natural phenomenon that with the increase in the content of particles in the copper matrix, the electrical conductivity decreases. Additionally, porosity has an effect on electrical conductivity. Copper in the cast state has an electrical conductivity of about 58 MS/m or 100% IACS. A sinter made of copper powder with a purity of 99.5% has an electrical conductivity of about 50 MS/m or 87% IACS. In the case of copper-alumina composites, a relatively high electrical conductivity was obtained, the addition of 2.5% caused a decrease of only about 10 MS/m in comparison with copper in the as-cast state. This was achieved due to the lack of diffusion between the alumina particles and the copper matrix. In the case of copper-titanium composites, in which diffusion of copper and titanium particles occurred during the formation of intermetallic phases, a significantly lower electrical conductivity was observed. The decrease in electrical conductivity values after introducing particles into the copper matrix was also observed by other researchers [9,15].

Wear characterization

In order to assess the application capabilities of sintered copper-based composites, abrasive wear resistance tests were conducted using the “ball on disc” method. The weight loss of the composites was determined by weighing them before and after the abrasive wear resistance tests. After the tribological tests, the samples were subjected to observations of the geometric structure of the surface of the abrasion site to assess the characteristic of wear. The tests were conducted without the use of lubricant. The parameters of the abrasion resistance tests for each type of material used in the experiments are given in the “Research Methodology” chapter. The exceptions are copper-aluminum trioxide composites, for which, due to high wear, the friction path had to be shortened to 200 m. All samples reinforced with different phases were compared with a sample made of sintered copper. The mass loss for the sintered copper sample was 0.0123g. The friction coefficient was also determined for each tested composite. Figure 7 shows the geometric structure of the surface of a sample made of pure copper after abrasive wear resistance tests.

Analyzing the geometric structures of the surface of the sample made of pure copper presented in Figure 6, one can see a smooth trace of abrasion due to the lack of reinforcing particles. Small depressions appearing in the trace of abrasion are related to the porosity of the sample made of pure copper. Table 6 presents the results of measurements of the mass loss of sintered copper-matrix composites.

Analyzing the results of mass loss measurements, it should be noted that copper-titanium composites are characterized by a low tendency to abrasive wear. The introduction of 2.5% titanium

Table 4. The results of the electrical conductivity measurements of the copper-alumina composites

Material	Electrical conductivity, MS/m	IACS, %
Cu	50.41	86.91
Cu+ 2.5% Al_2O_3	47.94	82.65
Cu+ 5% Al_2O_3	40.63	70.05
Cu+ 7.5% Al_2O_3	34.64	59.72
Cu+ 10% Al_2O_3	28.62	49.34

Table 5. The results of the electrical conductivity measurements of the copper-titanium composites

Material	Electrical conductivity, MS/m	IACS, %
Cu	50.41	86.91
Cu+ 2.5% Ti	41.17	70.98
Cu+ 5% Ti	35.42	61.06
Cu+ 7.5% Ti	34.39	59.29
Cu+ 10% Ti	25.06	43.20

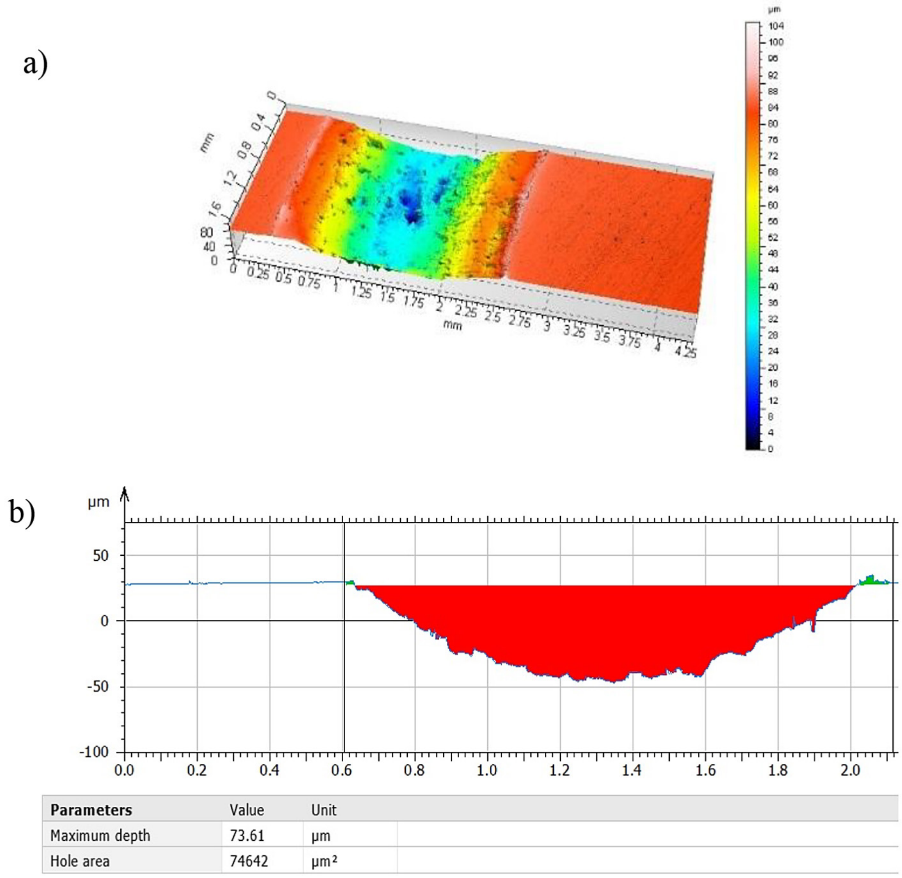


Figure 7. Geometric structure of the surface of the sintered copper sample after abrasive wear resistance tests: (a) isometric image, (b) surface profile

Table 6. Results of mass loss measurements of sintered copper-matrix composites

Material	Weight loss, g			
	2.5%	5%	7.5%	10%
Cu-Al_2O_3	0.0413	0.0289	0.0127	0.316
Cu- titanium	0.0101	0.0069	0.0052	0.0042

to the copper matrix increased the resistance to abrasive wear by about 20% compared to the sintered copper sample. The results of the measurements of the loss of mass of the copper-aluminum oxide composite showed that with the increase of the content of Al_2O_3 particles to 7.5%, the wear of the composites decreased. However, in the case of the composite containing 10% Al_2O_3, a considerable increase in wear was observed. This is due to the fact that aluminum oxide is an abrasive material with high hardness. The reason for the high wear is the lack of diffusion connection of Al_2O_3 particles with the copper matrix, which causes the pulling out of the strengthening particles and a rapid increase in wear. Based on the obtained results, it can be stated that the copper-titanium composite, despite the 5 times longer friction path, is characterized by a much higher resistance to abrasive wear in comparison with copper- alumina composites. The high abrasive wear resistance of the composite is related to the high hardness of the copper-titanium intermetallic phases, as well as to the diffusion bonding of the intermetallic phase particles with the copper matrix.. Figure 8 shows the results of friction coefficients of sintered copper-matrix composites. The friction coefficient for the sinter made of copper powder was 0.79.

Analyzing the obtained results of friction coefficient measurements, it can be stated that in the case of copper-based composites reinforced with alumina particles, the friction coefficient increases with the increasing content of reinforcing

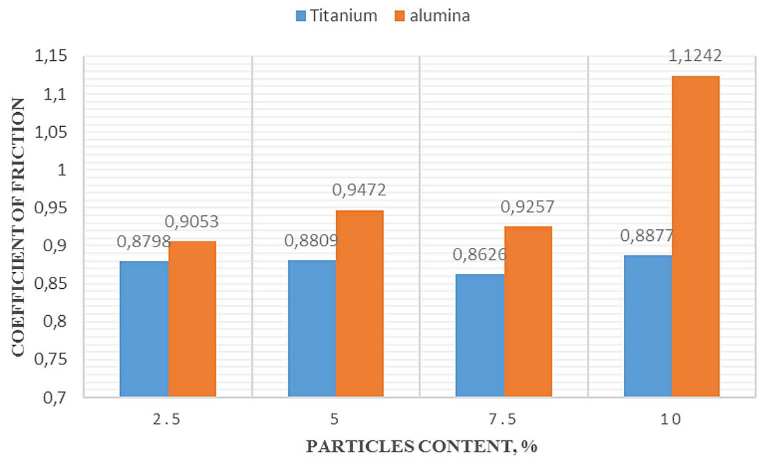


Figure 8. Friction coefficient results of sintered copper-matrix composites

particles. In the case of copper-based composites reinforced with titanium particles, the friction coefficient oscillates at a similar level. Figures 9–16 show the geometric structures of the composite surfaces after abrasive wear resistance tests.

The geometric surface structures shown in Figures 9–12 confirm the results obtained during the mass loss measurements. A reduction in abrasive wear was observed for composites containing up to 7.5% alumina compared to sintered copper, and a significant increase in wear for the composite containing 10% alumina. The friction traces visible on the geometrical surface structures show numerous tear-outs of particles.

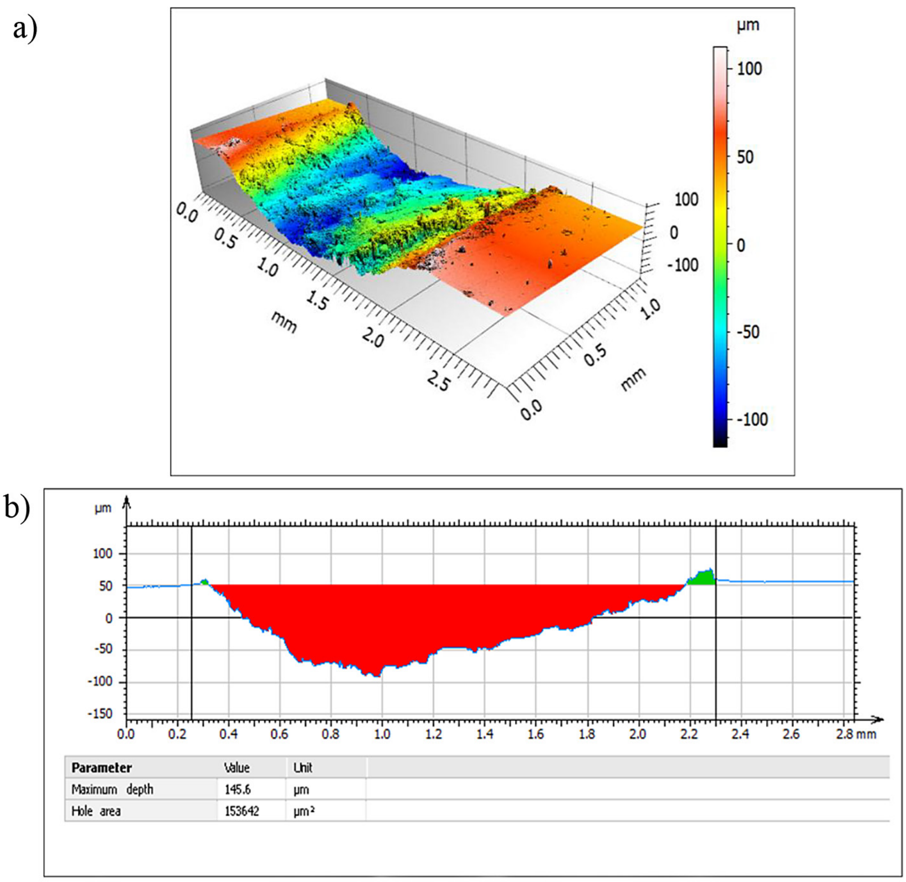


Figure 9. Geometric structure of the surface of the Cu– 2.5% Al_2O_3 composite after abrasive wear resistance tests: (a) isometric image, (b) surface profile

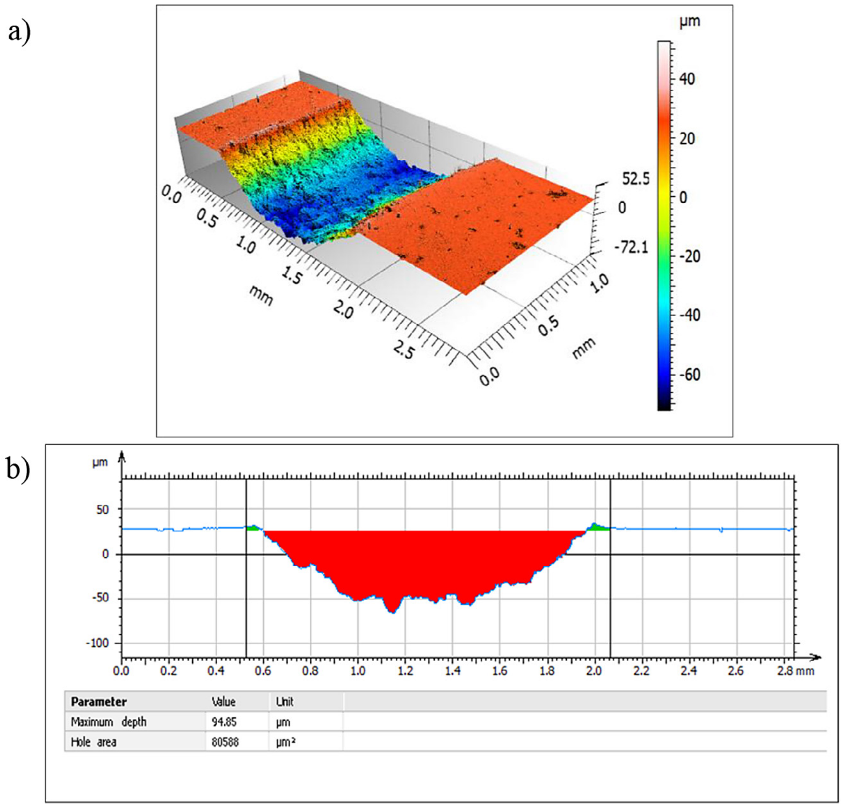


Figure 10. Geometric structure of the surface of the Cu– 5% Al_2O_3 composite after abrasive wear resistance tests: (a) isometric image, (b) surface profile

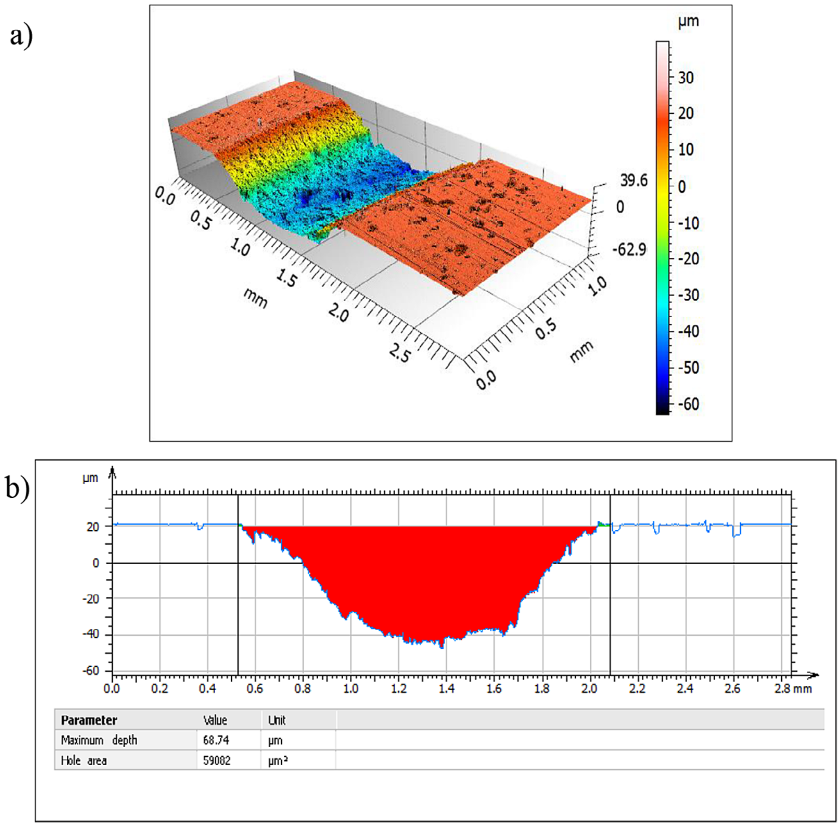


Figure 11. Geometric structure of the surface of the Cu– 7.5% Al_2O_3 composite after abrasive wear resistance tests: (a) isometric image, (b) surface profile

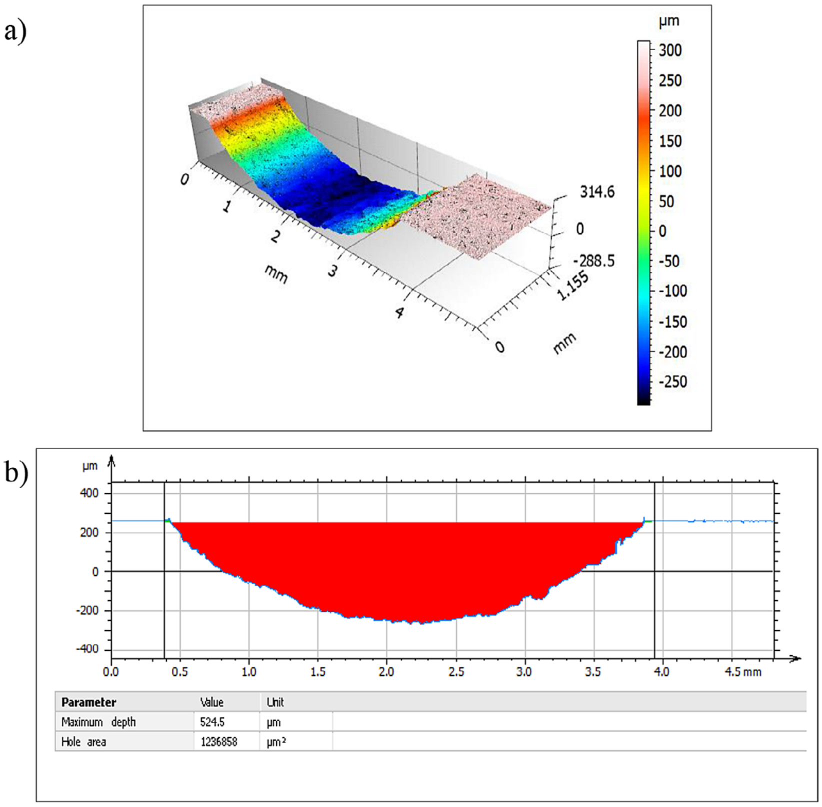


Figure 12. Geometric structure of the surface of the Cu– 10% Al_2O_3 composite after abrasive wear resistance tests: (a) isometric image, (b) surface profile

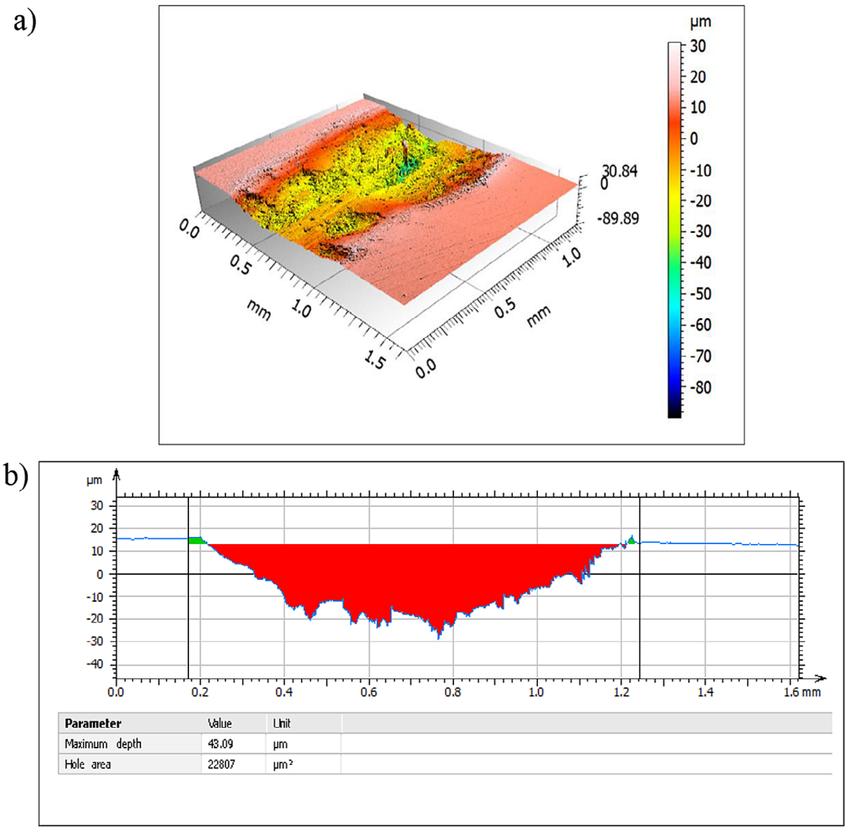


Figure 13. Geometric structure of the surface of the Cu– 2.5% Ti composite after abrasive wear resistance tests: (a) isometric image, (b) surface profile

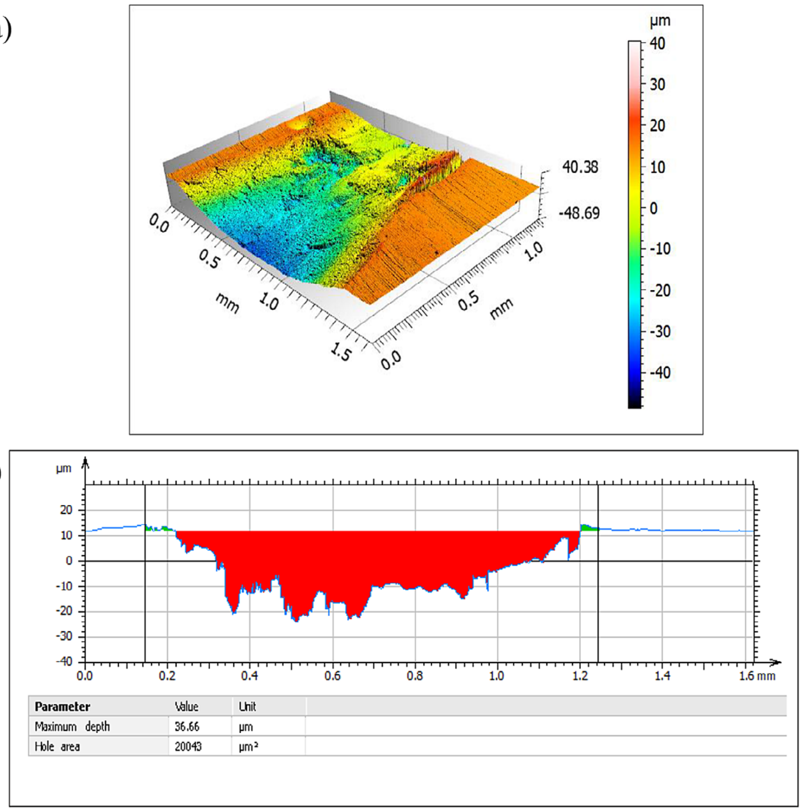


Figure 14. Geometric structure of the surface of the Cu– 5% Ti composite after abrasive wear resistance tests: (a) isometric image, (b) surface profile

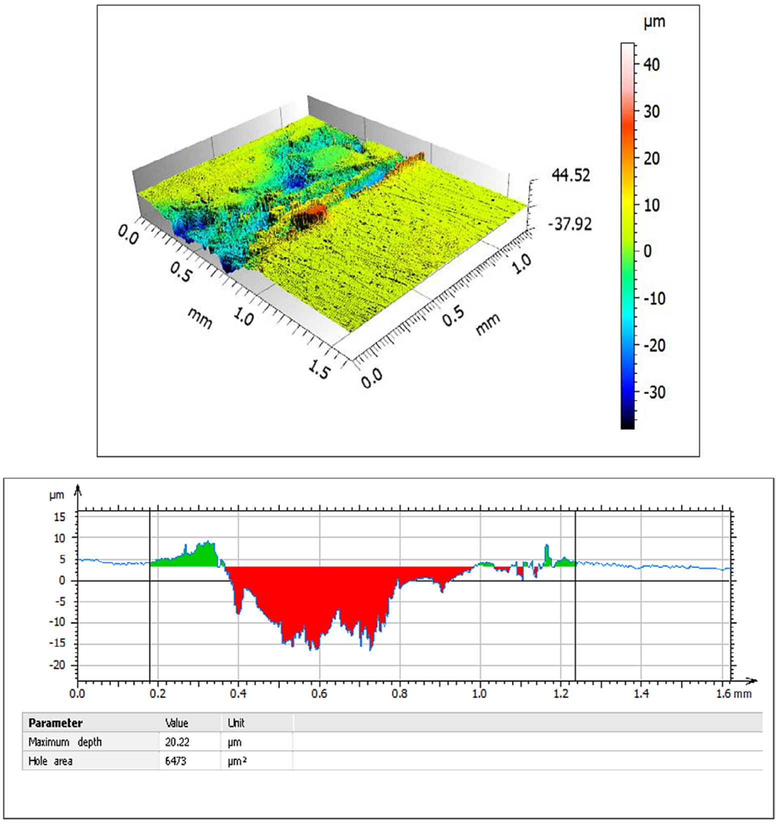
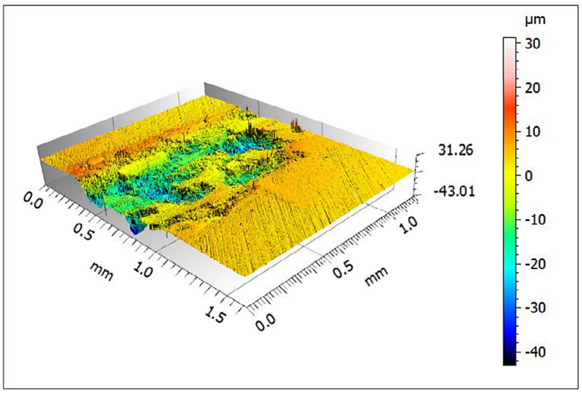
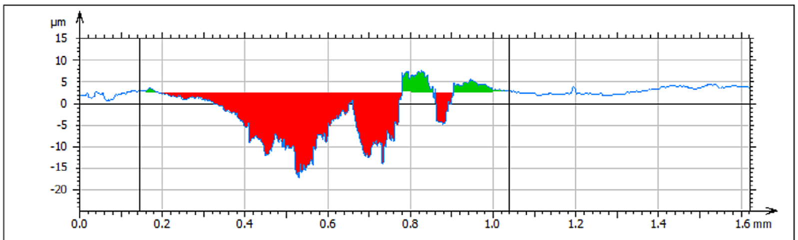


Figure 15. Geometric structure of the surface of the Cu– 7.5% Ti composite after abrasive wear resistance tests: (a) isometric image, (b) surface profile

a)



b)



Parameter	Value	Unit
Maximum depth	20.16	µm
Hole area	5021	µm²

Figure 16. Geometric structure of the surface of the Cu– 10% Ti composite after abrasive wear resistance tests: (a) isometric image, (b) surface profile

Geometric surface structures shown in Figures 13–16 confirm the results obtained during mass loss measurements. With the increase in the content of titanium particles (copper-titanium intermetallic phases) in the copper matrix, abrasive wear decreases. The presented isometric images and surface profiles show very shallow abrasion marks, which indicates high resistance to abrasive wear of the composites. Analyzing the presented surface profiles, it can be seen that the abrasion mark has an irregular shape. This is caused by the presence of copper-titanium intermetallic phases of different sizes.

CONCLUSIONS

The paper presents the results of tests of sintered copper-based composites in which aluminum oxide and titanium were used as strengthening phases. The fabricated composites were subjected to measurements of hardness, density, electrical conductivity, and resistance to abrasive wear. The sinters were also subjected to observations of the microstructure and geometric structure of the surface after tribological tests. The aim of the tests was to obtain a composite with the highest possible electrical conductivity and resistance to abrasive wear. Such a composite can be used in the electrical industry, among others for the production of electric brushes. Currently, the most commonly used material for the production of electric brushes is graphite and copper with the addition of graphite. These elements wear out due to constant contact with a rotating slip ring or commutator of an electric motor. Due to the intensive wear of electric brushes, an attempt to fabrication a composite that is an alternative to the currently used materials was made in this paper.

Analyzing the microstructures of the composites produced, it can be stated that the particles of the strengthening phases are evenly distributed in the copper matrix. Thanks to this, the composites have similar properties throughout their volume. Due to other methods of producing strengthening phase powders, particles of different sizes and shapes are visible in the microstructures. No significant porosity was observed in the microstructures of the Cu-alumina composites. In the case of copper-titanium composites, there is slight porosity in some areas, especially at the boundary of the titanium particles with the copper matrix, which may be related to the Kirkendall effect. Density tests of the composites produced have shown that with the increase in the content of reinforcing particles in the copper matrix, the density decreases. This is due to the fact that both of the applied reinforcing phases are characterized by a density lower than copper. The copper-alumina composite is characterized by a density in the range of 7.42–7.82 g/cm^3, which is about 90% of the relative density. In the case of the copper-titanium composite, the density obtained was in the range of 7.36–7.79 g/cm^3. The decrease in the density of the copper-titanium composite is related to the formation of intermetallic phases with a significantly lower density.

The introduction of titanium and aluminum oxide particles into the copper matrix increased the hardness of the composites. Due to the high hardness of aluminum oxide (9 on the Mohs scale), the hardness of the copper-alumina composites ranged from 46 to 50 HB. The intermetallic phases are characterized by high hardness, which is confirmed by the results of the copper-titanium composite hardness tests. In the presented work, the hardness of the copper-titanium intermetallic phases ranged from 15 to 230 HV0.2. The hardness of these composites ranged from 68 to 92 HB.

The introduction of any alloying additions to copper causes a decrease in electrical conductivity, which was confirmed by the test results. Due to the lack of diffusion connection of alumina particles with the copper matrix, relative electrical conductivity test results were obtained in the range of 28 to 47 MS/m. In copper-titanium composites, titanium atoms do not penetrate deeply into the copper matrix and do not cause a rapid decrease in electrical conductivity. The copper-titanium composites produced in this work were characterized by electrical conductivity in the range of 25–41 MS/m.

Tribological tests of the fabricated composites showed that the introduction of alumina particles did not increase the resistance to abrasive wear. Although the introduction of up to 7.5% of alumina to the copper matrix reduced the wear, the introduction of 10% dramatically increased it. This is a phenomenon that was also observed by other researchers. In the work of Kumar and Singh, the authors obtained a higher resistance to abrasive wear of the composite containing 10% SiC than of the one containing 15%. Similar results were obtained by Li, where the Cu-alumina composite containing 4% of Al_2O_3 had a higher resistance to abrasive wear than the one containing 6% of Al_2O_3. In the case of copper-titanium composites, results were obtained comparable to the results of studies by other authors [13]. With the increase in the content of titanium particles and formed intermetallic phases, the resistance to abrasive wear increases.

Based on the conducted studies, the following conclusions were drawn:

- thorough mixing of powders resulted in even distribution of reinforcing phases in the copper matrix,
- composite manufacturing parameters were selected correctly,
- introduction of reinforcing particles in the form of alumina and titanium resulted in lower density of composites,
- hard particles of alumina and formed intermetallic phases resulted in increased hardness,
- with the increase in the content of reinforcing particles in the copper matrix, the electrical conductivity of composites decreases,
- introduction of alumina particles resulted in lower resistance to abrasive wear despite the friction path being 5 times shorter compared to the copper-titanium composite,
- the shape of particles and the quality of their joint with the matrix are the main factors influencing abrasive wear.

Based on the conducted research, it can be stated that the best combination of properties such as electrical conductivity and resistance to abrasive wear was obtained for the copper-titanium composite. The copper-aluminum oxide composite, despite its high hardness and electrical conductivity, is characterized by low resistance to abrasive wear. Based on the conducted material and tribological tests, it can be stated that the copper-titanium composite can be successfully used in the electrical industry, among others for brushes for electric motors or electrical contacts.

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