Polish Society of Composite Materials
Polskie Towarzystwo Materiałów Kompozytowych

17: 2 (2017) 84-89

COMPOSITES THEORY AND PRACTICE

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Received (Otrzymano) 28.05.2017

TRIBOTECHNICAL PROPERTIES OF SINTERED BRONZE-BASED COMPOSITES REINFORCED WITH Al-BASED HARD PARTICULATES

This paper describes the changes in the tribotechnical properties of CuSn10 sintered bronze and MMCs based on this bronze reinforced with ultrafine composite Al-based powders. It was observed that the presence of hard particulates in the MMCs leads to a decrease in the friction coefficient and, particularly, wear rate. The presence of Al-based particulates in the MMC reduces the wear rate considerably. It decreases in the direction of FeAl → NiAl → Ti-Al-Cr particulates and for the best MMC composition the gain is about 20 times. In the MMC wear process, micro-craters are formed on the contact surface and it is the principal reason for the decrease in the wear rate.

Keywords: **metal-matrix composites (MMCs), surface analysis, friction, wear behavior**

WŁAŚCIWOŚCI TRIBOTECHNICZNE KOMPOZYTÓW NA BAZIE BRĄZU SPIEKANEGO UMOCNIONYCH TWARDYMI CZĄSTKAMI NA BAZIE Al

W pracy zbadano zmiany właściwości tribotechnicznych spiekanego brązu CuSn10 oraz kompozytów metalowych na bazie tego brązy umocnionego twardymi cząstkami proszków na bazie aluminium: FeAl, NiAl oraz Ti-46Al-8Cr. Obecność w kompozycie twardych cząstek na bazie Al prowadzi do zmniejszenia współczynnika tarcia i intensywności zużycia. Temperatury w strefie styku są stabilne, maksymalne temperatury zaobserwowano w warunkach wzrastającego obciążenia. Intensywność zużycia zmniejsza się w kierunku FeAl → NiAl → Ti-Al-Cr cząstek i dla kompozytu o najlepszym składzie przewaga sięga 20 razy. Zasadniczą przyczyną zmniejszenia intensywności zużycia są mikrokratery powstające na powierzchniach styku.

Słowa kluczowe: **kompozyty metalowe, analiza powierzchni, tarcie, zużycie**

INTRODUCTION

Powder metallurgy (P/M) materials are extensively used nowadays because of their low cost and no or minimum need for metalworking processes. In addition, these materials have unique properties that cannot be obtained by standard melting-casting processes.

Copper-based P/M materials are widely used in industry equally with iron and steel, and aluminum-based P/M materials. They are used for self-lubricating bearings and as friction materials, in brushes, filters, structural parts, electrical parts, etc. P/M bronzes typically originate as premixes consisting of elemental copper and tin powders with some technological additives. It is known that copper and lead, which have limited solubility in each other, are difficult to alloy by conventional ingot metallurgy. P/M bronze parts are frequently selected for structural applications because of the corrosion and wear resistance of bronze. Nevertheless, their low hardness and strength, as well as poor wear resistance limit their usage [1].

The properties of sintered bronzes can be improved with the incorporation of reinforcing particulates by developing bronze-based metal matrix composites (MMC). The use of various particulates to reinforce the material has been investigated in numerous publications. Carbides, borides and metal oxides are most widely used for reinforcement due to their high hardness and wear properties, particularly TiC [2], WC [3], SiC [4], TiB_2 [5], ZrC [6], Al_2O_3 [7].

On the other hand, reinforcements with different intermetallic particulates have also been investigated. Intermetallics are of interest because of their varied chemical composition and variety of their physical and mechanical properties. In [8], hardening of an Al-based material with Ni_3Al intermetallic particles was studied. It was found that Ni_3A1 intermetallic particles act as load-bearing elements due to strong bonding between these particles and the Al matrix. The P/M method is successful in processing these wear-resistant AMCs for tribological applications. In [9], the wear behavior of aluminum MMCs reinforced with different nickel aluminides was investigated. It was concluded that reinforcing aluminum alloys with intermetallics greatly increases the wear behavior by the order of two-three times compared to the base alloy. In [10], the friction and wear behavior of Cu-Fe_3Al P/M composites in dry sliding is described. It was found that the friction coefficients for these composites were independent of the contact pressure and the sliding speed variation. With an increasing volume fraction of Fe_3Al particles, the wear resistance of the composites increased at lower contact pressures but not at higher contact pressures, and the coefficients of friction decreased slightly. The wear rate of Cu-Fe_3Al composites decreased with an increase in sliding speed.

The laminar copper-intermetallic composite structure and properties are examined in [11]. Cu_4Ti, Cu_2Ti and CuTi particles were used to reinforce copper. The results showed that the hardness of the intermetallic layers in the composites is significantly higher than the hardness of the copper layers and the wear resistance of the composites increases with an increase in the thickness of the intermetallic layers and is similar to that of CuSn8 bronze. The formation and examination of the structure and properties of sintered copper matrix composites containing aluminum-ferric intermetallic phases is described in [12]. Two kinds of additives were used: AlFe particles and $AlFe_3+\alpha$ (a solid solution of aluminium and copper in iron) particles. It was found that composites containing the AlFe phase have high electrical conductivity and also a high microhardness. Intermetallic $AlFe_3+\alpha$ phases have a lower average microhardness in comparison with AlFe. On the other hand, their advantage is a diffusion joint between the particles and the matrix. The results of investigations of the properties and wear behaviors of (Ni_3Al)p reinforced Cu matrix composites were presented in [13]. The experiments showed that the density and electrical conductivity of the composites decrease with an increasing particle fraction. The composites have lower compression yield strengths in comparison with unreinforced sintered copper. The friction coefficient of Cu increased with an increasing sliding speed, whereas the friction coefficient of the composites decreased with an increase in the sliding speed and the values of friction coefficients for the composites increased in comparison with sintered copper. The wear resistance of the investigated composites considerably improved with an addition of Ni_3Al and grew with an increasing Ni_3Al fraction. With the addition of Ni_3Al to copper, the direct copper-counterface contact was reduced, which resulted in an increase in wear resistance.

In this paper, the tribotechnical properties of sintered bronze-based composites reinforced with a micro quantity of different Al-based particulates are studied.

EXPERIMENTAL PROCEDURE

Commercial powders of copper with an average particle size of 25 μm and tin with an average particle size of 20 μm were used to produce the sintered bronze CuSn10 base. It is known that alloying copper with tin enhances the operational properties by improving the embeddability, conformability and seizure resistance [14, 15].

Hard Al-based particulates (aluminides) were obtained by the mechanically activated self-propagating high-temperature synthesis method and their sizes were 3 μm.

The mixture of Cu+10 wt.% Sn and Cu+10 wt.% Sn+(0.2, or 0.5, or 1 wt.%) aluminide components was prepared in a"drunken barrel" mixer for 0.5 h. The samples were pressed with a hydraulic press to a relative density of 85÷88% and sintered in the atmosphere of endothermic gas at 780÷800°C.

The microstructures of cross sections of the specimens were examined using an MEF-3 optical microscope. The cross sections were etched in a 3% solution of ferric chloride in ethanol. The surface textures were analyzed using scanning electron microscopes JEOL JSM-5600LV and MIRA.

The tribotechnical tests were performed in conditions of concentrated and distributed contact. The concentrated contact tests were carried out using an Amsler A-135 tester at the sliding speed of 0.45 m/s. The tests were performed with stable loads of 500 N and 1000 N and with an incremental load in the range 300÷1000 N. The incremental load was applied with a step increase of 100 N every 5 min. The samples were made of MMC and the counter-bodies (rollers) were made of 41Cr4 EN 10083-1:2006 steel in the hardened state, with a hardness of 45÷50 HRC. The test time was 1 hour. L-AN 68 machine oil with the flow rate of 30 drops per minute was used as the lubricant. The values of the momentary coefficients of friction were calculated from the measured values. The temperature in the friction and wear zones were controlled as well. The temperatures were measured with a thermocouple. The magnitude of the segmental wear of the samples was registered using an optical microscope with an accuracy of 0.005 mm.

Distributed contact tests were carried out using a pin-on-disc MT-2 tester [16]. The rotating counter-bodies were made of AISI 1045 steel and had a hardness of 42÷45 HRC. They were in contact with the flat surfaces of three pin samples 10 mm in diameter. The tests were carried out at the sliding speed of 7 m/s in two stages. In the first stage, the average coefficients of friction were determined under a load increasing from 10 N until seizure occurred. In the second stage, the wear rates were determined under a stable load equal to 50 N and test time of 1 h. I-20 industrial oil was used as the lubricant with the flow rate of 8÷10 drops per minute. The magnitude of linear wear was registered using an optimeter with an accuracy of 0.001 mm.

RESULTS

The results of the SEM and X-ray diffraction analyses of the intermetallic powders are shown in Figure 1. The X-ray diffraction analysis of the FeAl/15%Al_2O_3 powder showed that the particulates consist of FeAl intermetalloid and Al_2O_3 inclusions in the amount of 13÷15%, as well as a small amount of Fe_2Al_5 intermetalloid and α-Fe phase (Fig. 1a). The NiAl/15%Al_2O_3 powder consists of NiAl intermetalloid with Al_2O_3 inclusions (Fig. 1b). The Ti-46Al-8Cr particulates consist of a γ-TiAl compound as the matrix in which Ti_3Al and $AlCr_2$ double intermetalloids and $Al_{0.67}Cr_{0.08}Ti_{0.25}$ triple intermetalloids are located (Fig. 1c).

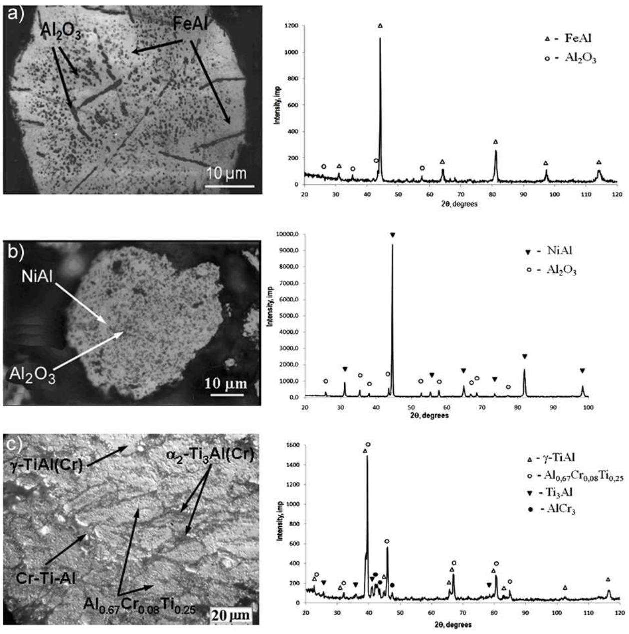


Fig. 1. Structures and compositions of reinforcing compounds: a) FeAl, b) NiAl and c) Ti-46Al-8Cr

Rys. 1. Struktury i składy związków umacniających: a) FeAl, b) NiAl oraz c) Ti-46Al-8Cr

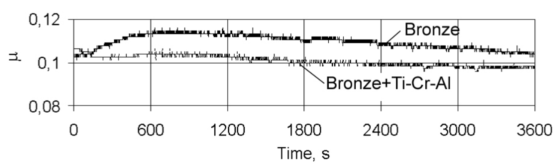
The CuSn10 sintered bronze has the structure of Sn in a Cu solid solution of varying concentration with α+δ eutectoid inclusions, twin crystals and a certain amount of pores. After introducing all the tested intermetallic compositions, significant refinement of the structure was observed as a result of increasing the recrystallization centers and delaying secondary recrystallization. In the material with NiAl intermetalloid additives, there is a local alloying nickel-copper matrix, and a decrease in porosity and minimal content of α+δ-eutectoid are observed in comparison with the materials with additives of FeAl and Ti-Cr-Al intermetalloids. The reinforcing particulate sizes are considerably smaller in comparison with the pores. They are located uniformly in the material body and have a rounded shape. The values of and changes in momentary coefficients of friction in conditions of concentrated contact for the samples made of the investigated materials are shown in Table 1. It can be seen that the material composition affects the friction coefficient differently, depending on the load value and stability.

The sintered bronze friction coefficient increases when the load is increased, whereas the composites containing FeAl and NiAl compounds are characterized by a decrease in the friction coefficient with an increasing load. The presence of complex Ti-Cr-Al particulates in the material provides stability of the coefficient of friction. The coefficient depends very much on the dynamics of the load. It grows under an increasing load more than 1.5 times for sintered bronze and 1.1÷÷1.2 times for MMCs. The influence of the amount of reinforcing additives is insignificant.

It should be noted that the friction coefficients decrease depending on the time of friction in some cases. This is due to an increase in the contact area resulting from increasing sample wear and reducing normal pressure in the friction zone as well as better running-in of MMCs.

TABLE 1. **Friction coefficients depending on loading conditions**
TABELA 1. **Współczynniki tarcia w zależności od warunków obciążenia**

CuSn10	0.5% FeAl	1% FeAl	0.5%% NiAl	1% NiAl	0.5% Ti-8Cr-46Al	1% Ti-8Cr-46Al
Stable load 500 N						
0.068	0.050	0.103	-	0.080	0.056	0.085
Stable load 1000 N						
0.073	-	0.106	0.100	0.243	-	0.100
Incremental load						
0.180	0.114	-	0.113	-	0.093	-



Friction coefficients depending on time of friction

The studies of the tribotechnical properties of sintered tin bronze with the addition of intermetallic compounds at a high sliding speed in conditions of distributed contact show that the minimum friction coefficient and maximum critical seizure pressure are obtained with the introduction of 0.5% composite FeAl powder, namely 0.012÷0.015 (Fig. 2). The coefficient of friction and critical seizure pressure for CuSn10 sintered bronze without additives are equal to 0.03÷0.035 and 2.7 MPa, with the addition of NiAl and Ti-8Cr-46Al they are close in value and equal 0.015÷0.022 and 5.6÷÷5.8 MPa.

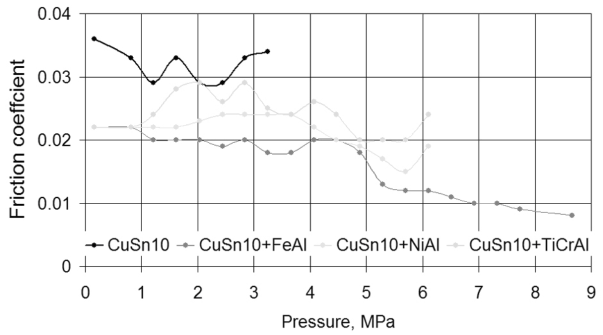


Fig. 2. Friction coefficients depending on pressure in distributed loading conditions

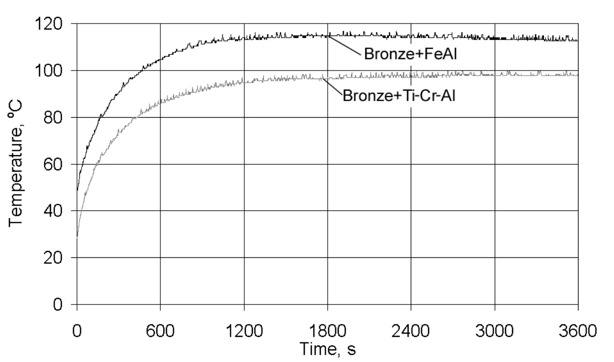
Rys. 2. Współczynniki tarcia w zależności od ciśnienia w warunkach obciążenia dystrybuowanego

The values of and changes in temperatures of friction for the samples made of the investigated materials are shown in Table 2. The temperature of sintered bronze can reach about 160°C. In all the cases the temperatures are higher in comparison with MMCs and the difference reaches 20%. When the load increases twofold, the friction temperature grows about 1.7 times. The temperatures of MMCs are almost the same. Under incremental loading conditions the friction temperature is about twice higher s in comparison with stable load conditions. The influence of the amount of reinforcing additives is insignificant.

TABLE 2. **Friction temperatures depending on loading conditions**

TABELA 2. **Temperatury tarcia w zależności od warunków obciążenia**

CuSn10	0.5% FeAl	1% FeAl	0.5%% NiAl	1% NiAl	0.5% Ti-8Cr-46Al	1% Ti-8Cr-46Al
Stable load 500 N						
56	49	71	-	59	63	62
Stable load 1000 N						
98	-	113	106	124	-	97
Incremental load						
152	117	-	114	-	96	-



Temperatures subject to time of friction

The wear rates of the friction surfaces of the tested materials depend on their composition and loading conditions as shown in Table 3. The wear rates increase significantly for incremental loading conditions in comparison with stable loading. Increasing the mass content of NiAl and the Ti-Cr-Al compound hardly affects the MMCs wear rate, but in the case of FeAl particulates the wear rate increases considerably. Increasing the load value twofold hardly affects the wear rates. Generally, the wear rate decreases when aluminum compounds are present in the composite in the direction FeAl→NiAl→Ti-Cr-Al, wherein there is an almost 20-fold difference between the best composite and bronze.

TABLE 3. **Wear rate [mm^3/km] depending on loading conditions**

TABELA 3. **Intensywności zużycia [mm^3/km] w zależności od warunków obciążenia**

CuSn10	0.5% FeAl	1% FeAl	0.5%% NiAl	1% NiAl	0.5% Ti-8Cr-46Al	1% Ti-8Cr-46Al
Stable load 500 N						
0.304	0.663	1.974	-	0.045	0.054	0.058
Stable load 1000 N						
2.540	-	2.066	0.532	0.500	-	0.060
Incremental load						
5.18	1.750	-	0.533	-	0.137	-

Similar changes were also observed in MMCs under distributed loading (Fig. 3). The tests realized under these conditions revealed that increasing the content of hard particulates decreases the wear rate. The wear resistance increases in the direction NiAl → FeAl → TiCrAl compound and reaches about a 3.5 times difference for the best MMC composition. However, the wear mechanism varies considerably.

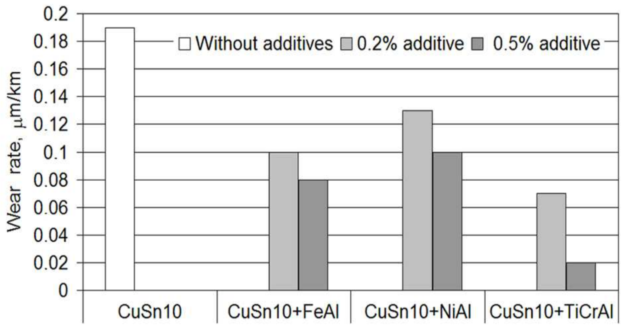


Fig. 3. Wear rates of tested materials depending on additive content under distributed loading

Rys. 3. Intensywności zużycia materiałów badanych w zależności od zawartości dodatków przy obciążeniu dystrybuowanym

Interconnected micro-craters along with traces of abrasive wear were observed on the friction surfaces (Fig. 4). The intensity of micro-crater formation increases in the direction FeAl →NiAl→TiCrAl compound. In our opinion, a specific contact, typical of materials containing hard microparticulates, is observed in this case. These microparticulates in the process of wear are concentrated at the hardened steel-composite interfaces, forming load-bearing type elements. A similar effect was described in [8, 16 and 17].

Due to this effect, as well as to the guaranteed presence of oil on the friction surfaces, the wear rate of the composites is reduced significantly. This is indirectly confirmed by the previously described tests on the influence of the additive contents and the load level on the wear rate. Analysis of the wear surfaces of the counter-bodies under concentrated contact conditions identified abrasive wear in the form of scratches arranged in the direction of the sliding speed and adhesive interaction (mass transfer) of the friction bodies: the material of the samples was transferred to the surface of the steel rollers. The mass transfer for MMC was stable and independent of the friction conditions. For sintered bronze under continuous incremental loading, considerable intensification of copper and tin transfer was observed. The copper and tin particles are located in accordance with the sliding speed direction.

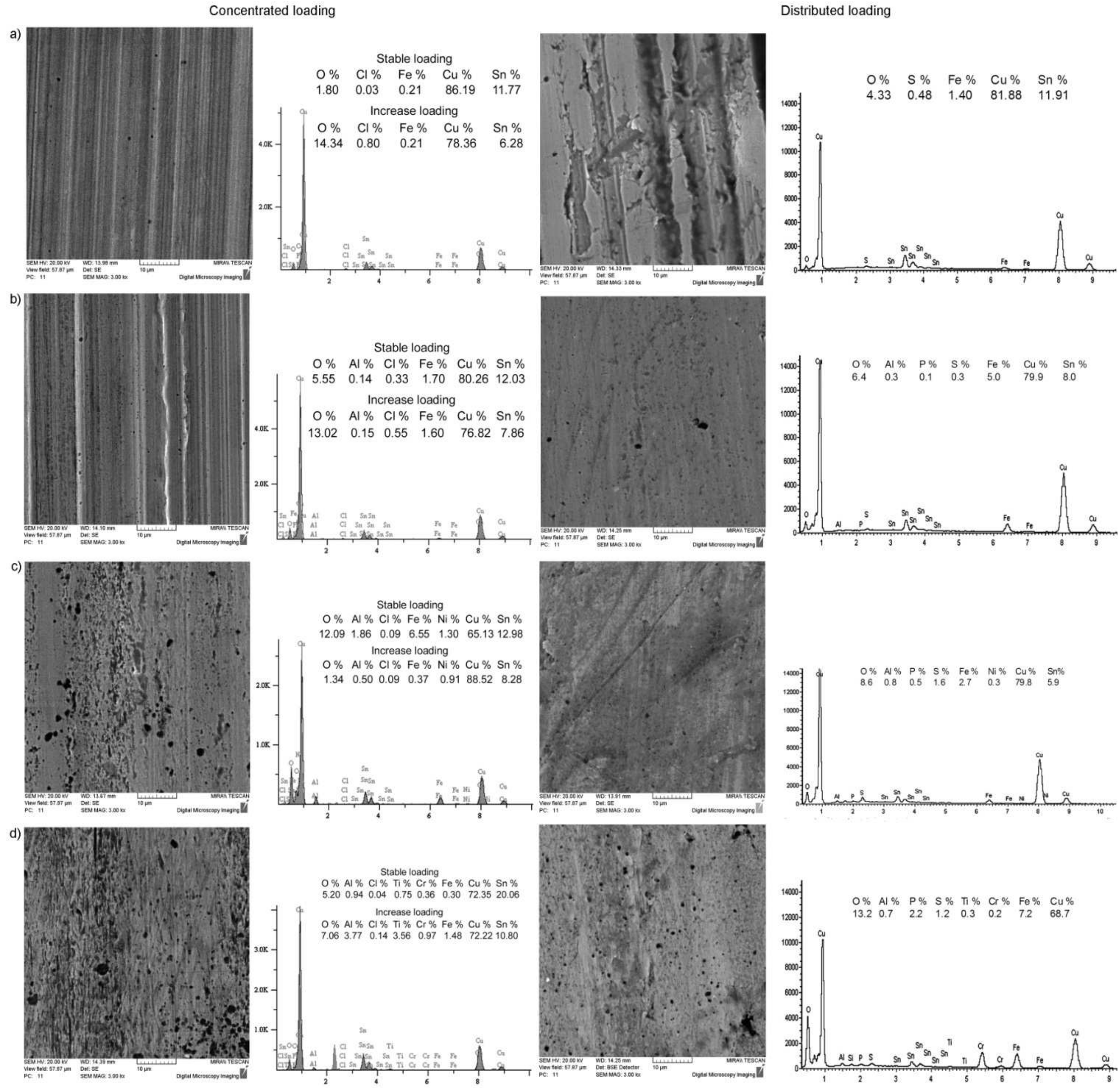


Fig. 4. Results of SEM analysis of samples after friction cycle: a) CuSn10, b) CuSn10+FeAl, c) CuSn10+NiAl and d) CuSn10+TiCrAl

Rys. 4. Wyniki analizy SEM próbek po cyklu tarcia: a) CuSn10, b) CuSn10+FeAl, c) CuSn10+NiAl oraz d) CuSn10+TiCrAl

CONCLUSIONS

The following conclusions can be drawn from the present investigation. The momentary coefficient of friction of the sintered MMC-41Cr4 hardened steel pairs depends on the friction conditions and, as a rule it is lower in comparison with sintered bronze under stable loading and concentrated contact conditions. When the loading is increased, differences in the friction coefficients are observed and the CuSn10-NiAl composite is the best. Under distributed contact, the friction coefficient values are less significant and decrease in the direction CuSn10 → CuSn10 + FeAl → CuSn10 + + NiAl→ CuSn10 + Ti-46Al-8Cr composites. The best is the CuSn10+FeAl MMC with the coefficient of friction equal to 0.012÷0.015. The presence of Al-based particulates in the MMC reduces the wear rate considerably. It decreases in the direction FeAl → NiAl → Ti-8Cr-46Al compound and the gain is about 20 times for the best MMC composition. In the MMC wear process, micro-craters are formed on the contact surface and it is the principal reason for the decrease in the wear rate.

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