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THE INFLUENCE OF THE SURFACE LAYER STRUCTURE IN DISC BRAKE PADS ON THEIR TRIBOLOGICAL PROPERTIES

WPŁYW STRUKTURY WARSTWY WIERZCHNIEJ OKŁADZIN CIERNYCH HAMULCÓW TARCZOWYCH NA ICH WŁAŚCIWOŚCI TRIBOLOGICZNE

Key words:

disc brakes, brake pads, friction layer, coefficient of friction, wear, topography, chemical constitution

Słowa kluczowe:

tarcze hamulcowe, okładziny cierne, powierzchnia tarcia, współczynnik tarcia, zużycie

Abstract

The article presents the results of the stand tribological investigation and microscopic observations of brake pad materials for automotive disc brakes. The reasons for the scatter of the friction coefficient value are analysed. The results of the brake pads' friction surface topography observations and chemical constitution are presented. The investigations were carried out with scanning electron microscopy SEM and energy dispersive X-ray spectroscopy EDS. The

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point, line, and surface analysis of friction layer were done. The average contents of the chemical elements on the friction surface are presented. The heterogeneous nature of the structure on the friction layer was observed. The analysis has shown that brake pads with a compact structure of friction layer and large quantity components (10 components with more than 1% content each) had a smaller scatter of the coefficient of friction value in relation to the materials with a loose structure and less quantity components. The next part of the article presents the structure and geometric parameter products of the wear of the friction material. The problem concerning the quantity limitation of the wear particles entering the environment as dust was discussed.

INTRODUCTION

Brake pad properties have an essential meaning in the automotive brake system and an influence on the effectiveness of braking. Requirements for these elements concern the value and stability of the coefficient of friction as well as the durability of the friction linings. The characteristics of the coefficient of friction in the function of unit pressure, the relative speed of the friction pair, and temperature as well as the step of the wetting of the brake disc and pads all have special significance **[L. 1, 2, 3]**. The tribological investigation has shown considerably differences in the value and course of the coefficient of friction, depending on temperature and time of braking for materials from various producers of brake pads **[L. 6]**. The reasons for these differences can be explained by the analysis of the topography and distribution of the components in brake linings.

Investigations of topography, chemical properties, and the wear of the friction layer of pads and discs are carried out by many research and industrial centres **[L. 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]**. The necessity of the investigation in this domain results from new regulations **[L. 14]**, from growth of the energy and power of braking, and from ecological demands **[L. 4, 10, 11, 15, 16, 17]**. The investigation in these domains has special meaning because of the influence of the friction pairs working parameters (speed, unit pressure, temperature) on the stability of the brake mechanism. It is also essential because of the possibility of foreseeing the friction characteristics of frictional materials **[L. 18, 19]**. The composition of frictional materials changes from the prohibition of the use asbestos, the gradually elimination of the heavy metals, up to the elimination of copper, which is one of the important components of brake pads. Wear products (small particles – dust) enter the atmosphere over the road and on the shoulders. The increase of the pollutions in the air is harmful for the people and environment. For example, the ecological regulations limit copper and the copper alloys contents in brake pads to 20% (mass) present, to 5% by 2021, and to 0.5% by 2025 year **[L. 11]**. Leading companies are already now introducing into the market disc pads without copper or with minimum contents **[L. 11]**. The presented results of investigations paid attention to this component in brake linings.

An essential problem is the reduction of the quality of wear products (dust) formed during the frictional process. It is connected with the reduction of the wear of friction materials in the function of the change in brake energy measured as heat. The estimation shows that an average passenger car emits into the atmosphere about 60 – 80 g of dust on a 10 000 km course.[1] The granulation and composition of the dust from friction materials were analysed **[L. 16]**.

EXPERIMENTAL PROCEDURE

The frictional tests were carried out on a pin-on-disc type stand. The vertical stress on the pad pin was realized by a hydraulic servo, in order to approach the conditions of loading acting in car braking system. The measuring paths were the loading force-measuring path (strain gauge sensor HBM), the friction force path (strain gauge sensor HBM), the hydraulic pressure (strain gauge sensor HBM P8AP), the temperature path (optical pyrometer SIR 10), and the rotational speed of the brake disc, using an amplifier Spider 8 HBM. The data was written to an Excel program. A block diagram of the test stand is presented in **Fig. 1**.

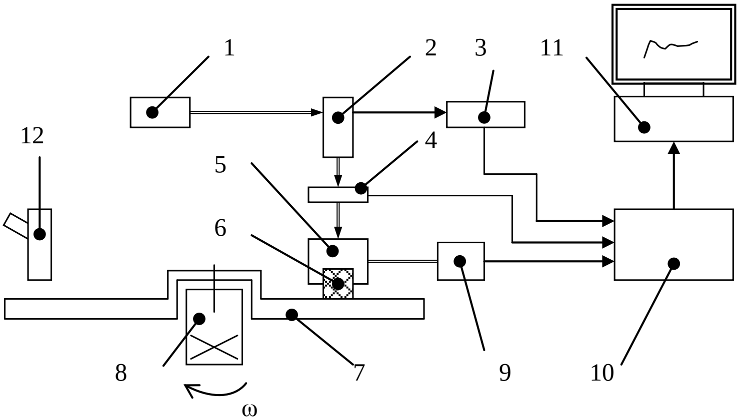

Fig. 1. Scheme of the stand for tribological tests type pin-on-disc: 1 – hydraulic pump, 2 – hydraulic servo, 3 – hydraulic pressure sensor, 4 – force sensor, 5 – pin holder, 6 – tested pin (friction material), 7 – brake disc, 8 – drive of the disc, 9 – friction force sensor, 10 – amplifier, 11 – computer with program for calibration and data registration, and 12 – optical pyrometer

Rys. 1. Schemat stanowiska do badań tribologicznych pary ciernej tarcza hamulcowa – okładzina cierna: 1 – pompa hamulcowa, 2 – siłownik hydrauliczny, 3 – przetwornik (czujnik) ciśnienia, 4 – tensometryczny przetwornik siły docisku próbki, 5 – uchwyt próbki, 6 – badana próbka, 7 – tarcza hamulcowa, 8 – napęd tarczy hamulcowej, 9 – tensometryczny przetwornik siły tarcia, 10 – przetwornik analogowo-cyfrowy ze wzmacniaczem (HBM Spider 8), 11 – komputer rejestrujący, 12 – pirometr do pomiaru temperatury w strefie tarcia

[1] According to **[L. 16]**, the average vehicle emits about 0.5 kg of dust per year from brake system.

Friction pairs under tests consist of samples of brake pads and cast iron brake discs. The material of the samples came from four producers and had various compositions and structures. The successive materials were designated I, II, III, and IV. The sectors of the samples had dimensions of 0.01m x 0.01m. The discs were made with cast iron Zl 20. The friction surface of the discs were ground to a roughness of R_a = 0,25 μm. The tests started with a running-in period of the new pad pin and disc, and then the collaboration of that pair after the running-in period. Conditions of the tests were close to the conditions in an automotive brake system in the range of speed and unit pressure during gentle and normal brakes. The range of the rotational speed of the brake disc was 26.2rd/s (250 rev/min.), 52.3rd/s (500 rev/min.), and 87.2rd/s (833 rev/min.). It corresponds to the vehicle linear speed of about 30 km/h, 60 km/h, and 100 km/h. The average length of the friction force arm was 0.092 m. The unit pressure between the working surfaces of the friction pair was 32 daN/cm^2, 42.5 daN/cm^2, and 53 daN/cm^2. The range of the temperature of the brake disc surface was from 20°C (ambient temperature) to about 120°C. This corresponds to the average temperatures of braking in the urban traffic conditions.

The 5 samples of each material (four materials from four producers) were tested. It made it possible to estimate the scatter of the friction coefficient. Ten cycles of braking for each sample were tested. After the tests, microscopic SEM examinations and spectroscopy EDS IXRF investigations were performed.

THE RESULTS OF TESTING OF THE FRICTION COEFFICIENT OF THE BRAKE LININGS

The courses of the coefficient of friction for each material, for a unit pressure of p = 53 daN/cm^2 and a rotational speed 52,3 rd/s (500 rev/min.) as a second polynomials are presented in **Fig. 2**. The Pearson correlation coefficient was higher than 0.9 for all characteristics. The intervals of the variation of the coefficient of friction values are shown. **Table 1** presents the average values of the coefficient of friction, the standard deviation form average values, and the ratio the standard deviation to average value. The investigations have shown the considerable differences in the values and the time course of the coefficient of friction for tested materials. The scatter of the friction coefficient values was significant – in the range of 0.4 to 0.54. During a single test, the coefficient of friction increased from 5% (material IV) to 40% (material III). The conditions of tests corresponded to conditions of braking during normal and long lasting road braking.

In the first 20 seconds of the tests, the temperature continuously increased to about 120°C on the disc. It was the temperature corresponding to the changes performed during braking in urban traffic. Friction heat has an influence on the friction layer but changes in temperature do no cause the destruction of the friction components (phenolic resins) at this point. Stress and wear of elements have changed the friction layer texture from a primary plateau to a secondary plateau **[L. 1, 13]**. This could cause increase of the coefficient of friction.

Table 1. Average values of the coefficient of friction in the friction pairs under test conditions and standard deviations

Tabela 1. Średnie wartości współczynnika tarcia okładzin w okresie 5–20 s czasu trwania próby oraz odchylenia standardowe

Material (manufacturer)	Average value of the coefficient of friction μ_{av}	Standard deviation $S(\mu)$	$S(\mu)/\mu_{av}$ [%]
I	0.54	0.005 – 0.02	0.9 – 3.7
II	0.55	0.01 – 0.02	1.8 – 3.6
III	0.53	0.02 – 0.03	3.8– 5.7
IV	0.39	0.005 – 0.01	1.3 – 2.6

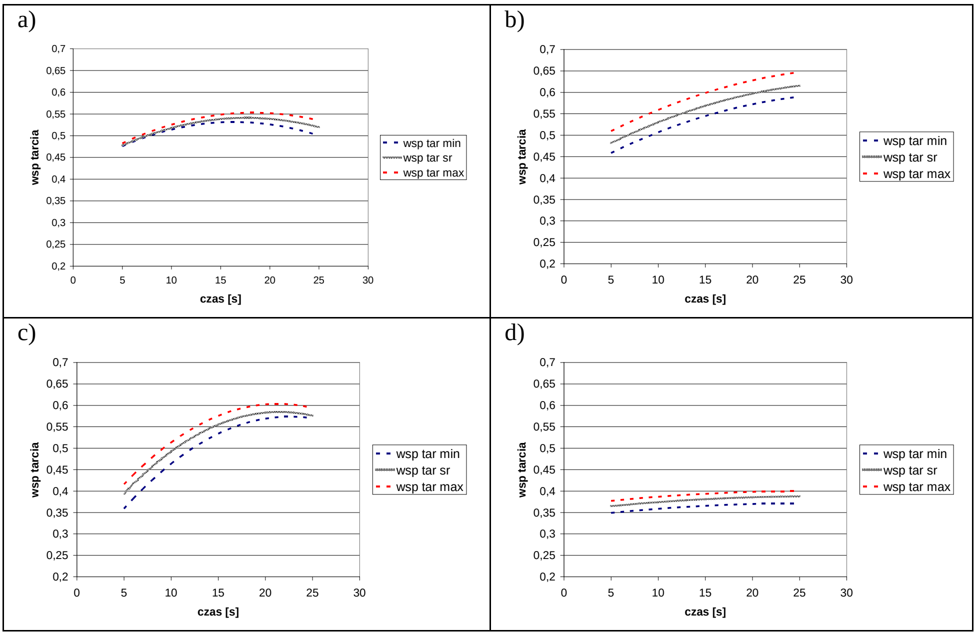

Fig. 2. Course of the average coefficient of friction and variation interval, *p* = 530 N/cm^2, *n* = 52.3 rd/s = 500 rev/min, (a) material (manufacturer) I, (b) material II, (c) material III, and (d) material IV

Rys. 2. Przebieg i zakres zmienności współczynnika tarcia okładzin w trakcie pojedynczego hamowania, *p* = 530 N/cm^2, *n* = 500 obr./min = 52,3 rd/s, a) materiał nr I, b) materiał nr II, c) materiał nr III, d) materiał nr IV

The investigation has confirmed that, during braking, the wear products are put on the surface of the brake disc **[L. 18]**. The structure of disc surface obtains a circumferential–bending form in the macro scale. The adhesion between wear products from pad to disc surface increases together with temperature between friction surfaces. This process influences the increase of disc roughness. Authors **[L. 18]** conclude that the intensity of pad wear can depend on the braking distance and friction work during braking.

STUDY OF SURFACE TOPOGRAPHY AND CHEMICAL COMPOSITION

The analyses of surface topography and the composition of the surface layer of the brake pad material (the contents of particular elements) were conducted. The appearance of the surface of the studied brake lining pads is presented in **Figure 3**. In the photographs of the samples friction layer, one can see distinct

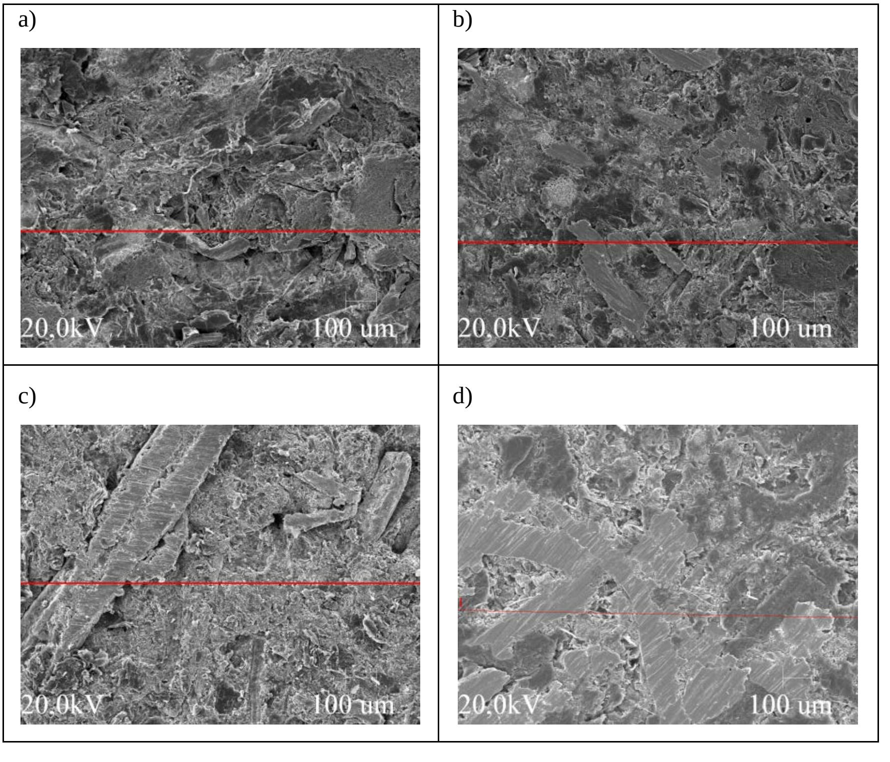

Fig. 3. Images of friction layer of the brake lining pads obtained using scanning electron microscopy (SEM); a) material I; b) material II; c) material III; and, d) material IV

Rys. 3. Obraz powierzchni ciernej nakładki hamulcowej uzyskany na mikroskopie scanningowym; a) materiał nr I; b) materiał nr II; c) materiał nr III; d) materiał nr IV differences in the granulation and arrangement of particular ingredients of the friction material, the level of compacting, cohesivity, and the concision of structure, differences in the amount of craters and their layout, and differences in the quantity and layout of the steel fibres dissipating heat from the surface. The material no IV had the most uniform structure.

In the Energy-Dispersive X-Ray Spectroscopy analysis, one could ascertain the diversity of the chemical composition of this material: 10 elements with the contents of more than 1%. The quantity and the size of iron fibres was considerably lower in the brake lining samples from material IV than in the samples of the remaining materials. The samples of material IV are characterized by the lowest range of the friction coefficient in the function of temperature in relation to the remaining ones. One can also ascertain a better temperature stabilization of the friction coefficient (its lower changeability with temperature). However, the friction coefficient of these brake linings is about 0.15 lower than the friction coefficient of the samples of the remaining materials, and it has the smaller range of values in the function of braking time in relation to the remaining producers.

Micro X-Ray analyses using Energy-Dispersive X-Ray Spectroscopy of the averaged chemical composition of the elements in the analysed area of 1300μm x1000μm of the samples surface were also conducted. The percentage of particular elements in the studied materials is presented in **Tables 2** to **5**.

THE RESULTS ANALYSIS

The study was conducted for the range of temperatures of the disc brake within 20 – 120°C, which corresponded to the conditions of normal braking in urban traffic. In these conditions, one can notice the creation of a surface layer, which consists of two structures: the "primary plateau" on the lining surface and "secondary plateau" **[L. 1, 13]**. The primary plateau is created from the surfaces built from elements of metal fibres and hard coarse-grained particles. Among these surfaces, there are areas gradually filling up with the products of wear and tiny debris. The areas of the secondary plateau gradually come in contact with the disc brake. The proportions of the surface of the primary and secondary plateau change dynamically in the next braking and also in the time of a single braking. These changes have an influence on the value of the friction coefficient.

The confrontation of the structure of the friction layer of the studied materials (**Figure 3**) and the characteristics of the friction coefficient (**Figure 2**) indicates that the larger surface the primary plateau occupies and the more evenly it is arranged, the more quickly the friction coefficient value stabilizes itself. This process is of vital significance in the period of vehicle operation after the replacement of brake lining pads and is felt as a gradually increasing efficiency of braking the vehicle.

However, the explanation of the causes of differences in the value of friction coefficient of the studied brake linings requires additional analyses. The current results indicate that the linings with a smaller surface of primary plateau in relation to the secondary one reached a higher friction coefficient.

The presented model of creating a friction layer refers to slight temperatures on the friction surface (up to about 170°C), i.e. those in which studies were conducted. For these temperatures, thermal degradation of phenolic resins does not yet occur.

The photographs, showed in the **Figures 4** to **7**, depict the exemplary distribution of the chemical elements observed in the surface layer of the studied sample. Only the distributions of the elements are presented, the percentage of which is relatively the biggest, and at the same time they have the strongest influence on the value of the friction coefficient and heat dissipation from the zone of contact. One can notice that, in the samples of the next producers, the amount of elements with the contents exceeding 1% was increasing. Carbon dominates in each sample, which has a decisive influence on the value and stabilization of the friction coefficient as well as iron as an ingredient of steel chips, which aim at heat dissipation. In the brake lining pad made of the material IV, copper occurs (4.6%), included in brass, which aims at heat dissipation. At higher temperatures, it can lower the friction coefficient, but at the same time it prevents micro-vibration and the nosiness of the work of the brake lining pads. In the brake linings of the materials I and II, there is an ingredient of barite ($BaSO_4$). According to the literature, this compound occurs in the brake linings with slightly increasing characteristics of friction coefficient in relation to increases in temperature. Such characteristics were ascertained just for the brake linings of materials I and II.

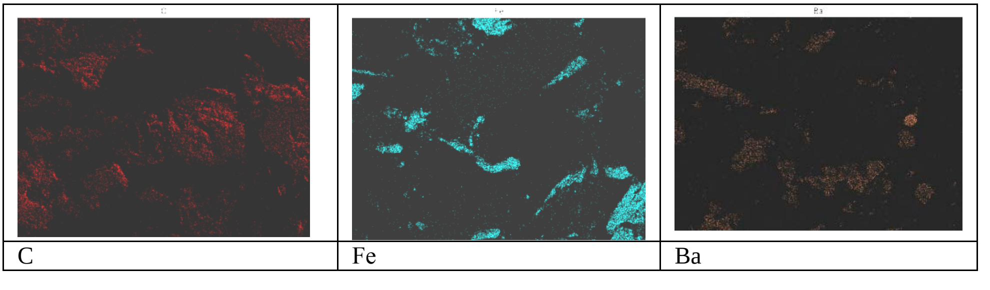

Fig. 4. The arrangement of chosen elements on the friction layer of the brake pad lining; material I

Rys. 4. Rozkład wybranych pierwiastków na powierzchni ciernej nakładki hamulcowej; materiał I

Table 2. The average contents of the chemical elements in the surface layer of friction brake pad lining; material I

Tabela 2. Średnia zawartość pierwiastków w warstwie wierzchniej nakładki ciernej; materiał I

Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	Units
C	Ka	52.89	2.655	60.667	wt.%
O	Ka	10.22	1.167	9.117	wt.%
F	Ka	0.00	0.000	0.000	wt.%
Mg	Ka	4.14	0.743	0.295	wt.%
Al	Ka	11.05	1.214	0.661	wt.%
Si	Ka	13.25	1.329	0.690	wt.%
K	Ka	1.71	0.477	0.099	wt.%
Ca	Ka	5.99	0.893	0.359	wt.%
Fe	Ka	79.76	3.261	8.284	wt.%
Zn	Ka	3.05	0.638	0.637	wt.%
Ba	La	20.56	1.656	3.934	wt.%
Au	La	16.71	1.492	15.256	wt.%
				100.000	wt.%

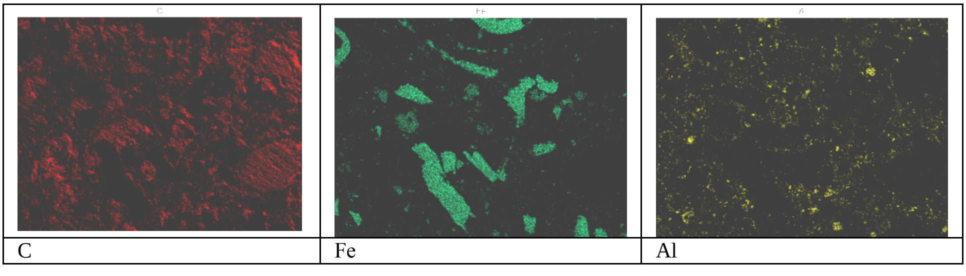

Fig. 5. The arrangement of chosen elements on the friction layer of the brake pad lining; material II

Rys. 5. Rozkład wybranych pierwiastków na powierzchni ciernej nakładki hamulcowej; materiał II

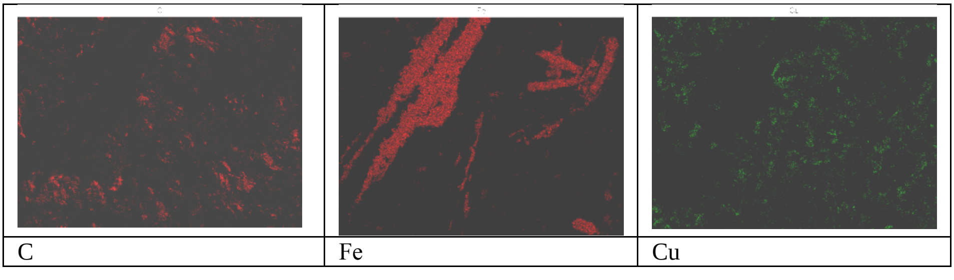

Fig. 6. The arrangement of chosen elements on the friction layer of the brake pad lining; material III

Rys. 6. Rozkład wybranych pierwiastków na powierzchni ciernej nakładki hamulcowej; materiał III

Table 3. The average contents of the elements in the surface layer of the friction brake pad lining; material II

Tabela 3. Średnia zawartość pierwiastków w warstwie wierzchniej nakładki ciernej; materiał II

Elt.	Line	Intensity (c/s)	Error 2-sig	Coc	Units
C	Ka	131,07	4,180	70,472	wt.%
O	Ka	22,26	1,723	12,487	wt.%
Na	Ka	8,77	1,081	0,422	wt.%
Mg	Ka	7,36	0,990	0,237	wt.%
Al	Ka	61,54	2,864	1,647	wt.%
Si	Ka	76,25	3,188	1,812	wt.%
S	Ka	45,70	2,468	1,113	wt.%
Ca	Ka	57,00	2,757	1,516	wt.%
Fe	Ka	118,18	3,969	5,915	wt.%
Ba	La	18,73	1,580	1,643	wt.%
Au	La	6,04	0,897	2,735	wt.%
				100,000	wt.%

Table 4. The average contents of the elements in the surface layer of the friction brake pad lining; material III

Tabela 4. Średnia zawartość pierwiastków w warstwie wierzchniej nakładki ciernej; materiał III

Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	Units
C	Ka	62.90	2.896	54.187	wt.%
O	Ka	40.52	2.324	18.502	wt.%
Na	Ka	37.52	2.236	2.229	wt.%
Mg	Ka	49.07	2.558	2.000	wt.%
Al	Ka	41.00	2.338	1.385	wt.%
Si	Ka	61.66	2.867	1.776	wt.%
S	Ka	86.45	3.395	2.446	wt.%
Ca	Ka	10.35	1.175	0.308	wt.%
Cr	Ka	14.04	1.368	0.575	wt.%
Fe	Ka	112.10	3.866	5.977	wt.%
Cu	Ka	49.91	2.580	4.576	wt.%
Zn	Ka	4.09	0.739	0.455	wt.%
Sb	La	26.09	1.865	2.291	wt.%
Au	La	6.68	0.944	3.292	wt.%
				100.000	wt.%

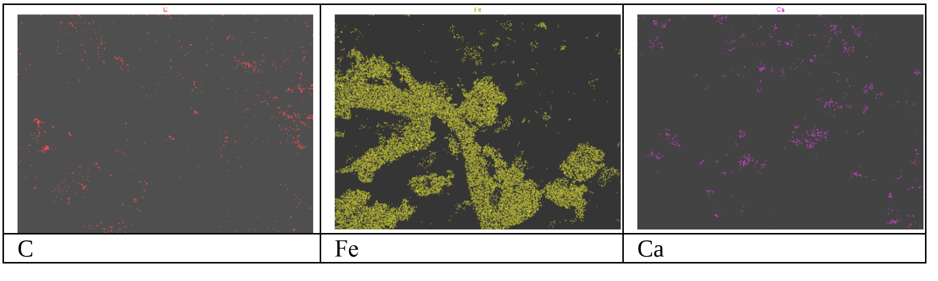

Fig. 7. The arrangement of chosen elements on the friction layer of the brake pad lining; material IV

Rys. 7. Rozkład wybranych pierwiastków na powierzchni ciernej nakładki hamulcowej; materiał IV

Table 5. The average contents of the elements in the surface layer of the friction brake pad lining; material IV

Tabela 5. Średnia zawartość pierwiastków w warstwie wierzchniej nakładki ciernej; materiał IV

Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	Units
C	Ka	46.20	2.482	62.918	wt.%
O	Ka	9.70	1.137	12.924	wt.%
Al	Ka	4.99	0.816	0.413	wt.%
Ca	Ka	45.67	2.468	3.086	wt.%
Fe	Ka	154.75	4.542	20.542	wt.%
Cu	Ka	0.51	0.261	0.117	wt.%
				100.000	wt.%

THE ANALYSIS OF THE PRODUCT OF BRAKE PAD LINING WEAR IN THE ECOLOGICAL ASPECT

The analysis of the structure of the products of the wear of the brake pads lining of the disc brake mechanism, carried out on the example of the studied samples of material III, showed a decisive variety in terms of the size and shape of individual particles of debris (**Figure 8**). They had various forms: irregular, sharp-edged, ball shaped, oval, and porous. They were the particles with the size from several to several dozen micrometres, and among them were larger elements with the size of more than 100 µm. Fragments glued with particles of micron size occurred. Small amount of fragments with filamentous and needle-like appearances were also found. Such particles are dangerous for health, since they may remain in the respiratory system, as well as asbestos fibres. Such a composition of dust results directly from the structure of the studied brake pad lining. One should state that the study of the interaction of these particles on the environment, including the human organism, should jointly include an analysis of chemical composition and geometrical parameters of the particles.

The restrictions in the use of copper in the brake pad linings result from its negative interaction on the environment. Some moss species absorb copper compounds particularly intensively, which leads to their decay. The contents of copper in the studied friction brake pad linings were found in a broad range: from below 1% to more than 4%. One can notice its uneven arrangement in the brake pad lining of material III and its more even layout in the brake pad lining of material IV. The contents of the remaining heavy metals, such as zinc and antimony, were minimal.

The present developmental tendencies in arranging brake pad lining material are the search for new, environmentally friendly fillers to replace those currently applied, and the elimination of copper and the remaining heavy metals **[L. 10, 15, 18]**. The researches show the possibility of replacing copper with TG

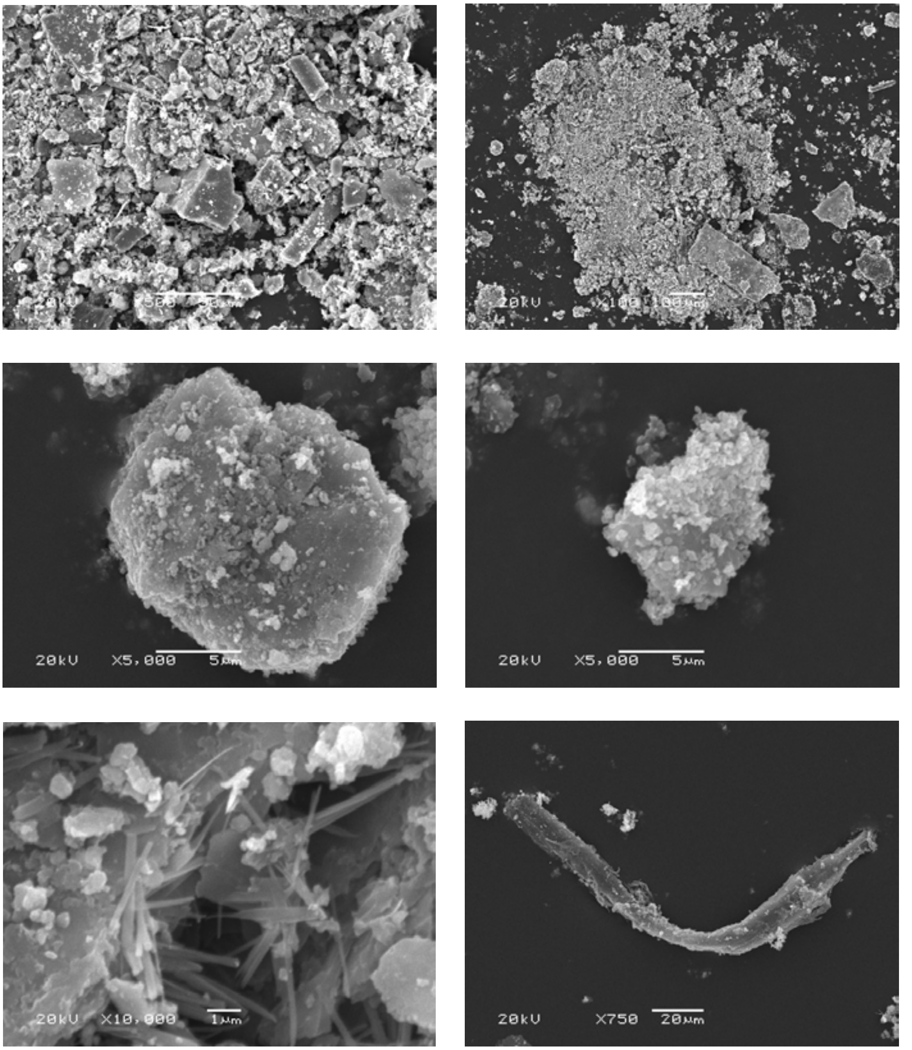

Fig. 8. The products of the wear debris of brake pad lining material collected after the brake test

Rys. 8. Produkty zużycia materiału ciernego nakładki zebrane po testach

graphite due to its good thermal conductivity. The restriction of the amount of dust that is the products of wear is the second developmental direction due to environmental considerations. The dust containing a large amount of iron becomes deposited on the wheel rims making the rims less attractive. The restriction of this phenomenon can be achieved by using the materials produced in NAO technology with low contents of metals, below 10% **[L. 18]**. Steel fibres, mainly responsible for the adherence of the dust to wheel rims are replaced by aramid fibres. One of the means of diminishing the amount of dust, i.e. the decrease of the wear of linings, is changing the shape of the lining surface so that it can facilitate the creation of an additional layer, which is a "third body" taking part in the friction process **[L. 17]**. The products of wear are again taken into the area of the contact of the friction surfaces, creating the shape of a wedge, diminishes the amount that gets outside the friction couple. The effect of these changes is a slightly lower friction coefficient and the necessity of the application of larger unit pressures, in order to obtain the required braking torque.

CONCLUSIONS

1. The research presented a broad range of the values of the friction coefficient of the studied friction materials, in the range 0.39 to 0.54. During a single braking, the friction coefficient increased by 5 to 40%.
2. The smallest changes in the friction coefficient occurred for the brake pad linings from material IV. That material was characterized by the most homogenous structure. In the Energy-Dispersive X-Ray Spectroscopy analysis, this was reflected by the variety of chemical composition: 10 chemical elements with the contents of more than 1%.
3. The brake linings with increasing characteristics in the friction coefficient in relation to temperature contained barite ($BaSO_4$).
4. The studied friction brake pad linings of the disc brake mechanism fulfil currently obliging ecological requirements. They do not contain asbestos, the contents of heavy metals are minimal, and the content of copper is less than currently regulated ranges.
5. The application of NAO technology constitutes the tendency in the production of friction brake pad linings of disc brake mechanisms in which the contents of metals (particularly steel fibres) is restricted. This decreases the amount of the dust deposited on the vehicle's wheel rims.
6. The brake pad linings using the effect of a "third body" are introduced. It limits wear; therefore, it restricts the amount of dust polluting the environment.

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Streszczenie

W artykule przedstawiono wyniki stanowiskowych badań tribologicznych oraz obserwacji mikroskopowych materiału ciernego samochodowych okładzin hamulców tarczowych. Ocenie poddano rozrzuty w wartości współczynnika tarcia pary ciernej hamulca tarczowego, które ujawniają się zarówno w badaniach kolejnych próbek materiału tego samego producenta, jak i pomiędzy okładzinami ciernymi różnych producentów. Przedstawiono wyniki badań topografii powierzchni oraz składu chemicznego okładzin. Badania wykonano z zastosowaniem mikroskopu scanningowego SEM. Do analizy mikrorentgenowskiej stosowano analizator EDS IXRF System. Przedstawiono wyniki analizy spektrometrycznej składu chemicznego okładzin. Wykonano analizy punktowe, liniowe i powierzchniowe. Zaprezentowano średnie zawartości pierwiastków w analizowanym obszarze powierzchni tarcia. Wykazano bardzo dużą niejednorodność struktury oraz chemiczną w poszczególnych strefach badanych powierzchni. Stwierdzono, że okładziny o zwartej strukturze powierzchni i dużej różnorodności składu chemicznego (10 składników o zawartości ponad 1% każdy) charakteryzują się mniejszym rozrzutem wartości współczynnika tarcia zarówno w funkcji temperatury, jak i czasu hamowania w stosunku do materiałów o bardziej luźnej strukturze. Przedstawiono strukturę i parametry geometryczne produktów zużycia okładzin oraz problem ograniczania ilości tych produktów wydostających się do środowiska w postaci pyłów.