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PHYSICOCHEMICAL ASPECTS OF THE WORK OF PASSENGER CAR BRAKE LININGS. PART I: THE EFFECT OF FRICTIONAL ADDITIVES

FIZYKOCHEMICZNE ASPEKTY PRACY OKŁADZIN HAMULCOWYCH SAMOCHODÓW OSOBOWYCH. CZ. I: WPŁYW DODATKÓW CIERNYCH

Key words: brake linings, abrasives, third body, surface, friction and wear, acoustic effects.

Abstract: The paper presents the influence of various systems of abrasive additives which determine the performance of the friction materials of brake pads. A friction material was used for the tests, in which the base recipe was modified with various types of abrasive additives: 1. "low steel" – of low steel content, containing aluminium and chromium oxides; 2. "hybrid" – containing in addition to abrasive components from the low steel family, abrasive components such as zirconium silicate, magnesium oxide or iron oxides, which are characteristic of the family of asbestos-free organic materials (NAO); and 3. "mild hybrid" – containing abrasive components found in the friction materials of the NAO family, on the formation and structure of the so-called third body on the surface of the brake disc as a result of braking. High-resolution scanning electron microscopy with an X-ray analyser (SEM-EDS) equipped with a focus ion beam (FIB) was used to study film thickness, morphology, and chemical composition. The results of the physicochemical analysis of the third body were correlated with the results of tribological tests on a brake dynamometer adapted to the measurements of acoustic signals (NVH – noise, vibration and harshness). The tests were carried out in accordance with the SAE-J2522 procedure, commonly known as AK-Master. The obtained results confirm the important role played by the so-called third body, formed on the surface of the brake disc for safety (COF), durability (wear of friction elements) and the acoustic spectrum accompanying braking.

Słowa kluczowe: okładziny hamulcowe, dodatki cierne, trzecie ciało, powierzchnia, tarcie i zużycie, efekty akustyczne.

Streszczenie: W pracy przedstawiono wpływ różnych układów dodatków abrazyjnych, które decydują o wydajności materiałów ciernych klocków hamulcowych. Do badań zastosowano materiał cierny, w którym modyfikowano recepturę bazową rożnego rodzaju dodatkami abrazyjnymi: 1. o małej zawartości stali (z ang. *low steel*) – zawierających w swoim składzie tlenki aluminium i chromu; 2. hybrydowe (z ang. *hybrid*) – zawierających oprócz składników abrazyjnych z rodziny low steel takie składniki abrazyjne jak krzemian cyrkonu, tlenek magnezu czy tlenki żelaza, które są charakterystyczne dla rodziny bezazbestowych materiałów organicznych – w skrócie NAO (z ang. *non-asbestos organic*); oraz 3. tzw. łagodne hybrydy (*z ang.* mild hybrid) – zawierające składniki abrazyjne, które występują w materiałach ciernych z rodziny NAO, na tworzenie się i strukturę tzw. trzeciego ciała na powierzchni tarczy hamulcowej w wyniku hamowania. W badaniach grubości filmu, jego morfologii i składu chemicznego wykorzystano wysokorozdzielczą skaningową mikroskopię elektronową z analizatorem rentgenowskim (SEM-EDS) i układem zogniskowanej wiązki jonów (FIB). Wyniki analizy fizykochemicznej trzeciego ciała poddano korelacji z wynikami badań tribologicznych na dynamometrze hamulcowym, przystosowanym do pomiarów sygnałów akustycznych NVH (z ang. *noise*, *vibration and harshness*). Badania prowadzono zgodnie z procedurą SAE-J2522, znaną powszechnie pod nazwą AK-Master. Uzyskane wyniki potwierdzają istotną rolę, jaką odgrywa tzw. trzecie ciało, powstające na powierzchni tarczy hamulcowej na bezpieczeństwo (COF), trwałość (zużyciem elementów ciernych) oraz widmo akustyczne towarzyszące hamowaniu.

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INTRODUCTION

Today's braking systems must be characterised by much greater efficiency due to the much greater power generated by the drive systems and the weight of motor vehicles, including those powered by an electric motor. In addition, there are higher expectations related to driving comfort (NVH, noise, vibration and harshness). The main ingredients for the production of brake pads friction plates are fillers, friction components and solid lubricants of natural or synthetic origin.

The role of abrasives in the performance of brake linings

The components used in producing friction materials can be divided into five main groups: reinforcing fibres, resin binder, fillers, lubricants and abrasives **[L. 1]**. However, it should be remembered that some components fulfil various functions in the friction composite and may be classified into more than one group.

Abrasive components in the friction materials of brake pads play an important role in terms of stopping distance, disc life and the tendency to generate noise **[L. 2–5]**. Inorganic particles of relatively high hardness, such as zircon, quartz, aluminium, magnesium, zirconium, chromium or iron oxides, zeolites and silicon carbide, used as an abrasive in brake lining friction materials, “renew” the sliding surface by eliminating components subject to pyrolytic degradation in frictional contact **[L. 6]**. The selection of abrasive components depends on their hardness, size, shape, fracture toughness, wear resistance and “aggressiveness” towards the brake disc **[L. 2, 7]**.

Yang and Kim investigated the synergism of action of abrasive particles with solid lubricant on the example of zircon and antimony sulphide **[L. 8]**. They found that abrasive particles remove a third body layer (TBL) from the brake disc surface, increasing torque variation during braking. The fine abrasive particles partially removed the TBL and caused friction instability, while the coarse particles provided better friction stability, even though causing very high wear to a brake disc. A similar effect was noted in the research on creak groan in the friction material from the low steel family containing zirconium **[L. 9]**, quartz **[L. 10]** or zircon particles **[L. 11]**. The research subject was also the influence of the size on friction and wear of non-steel friction materials. The braking performance and the wear rate of the brake discs also depend on the fracture toughness of the abrasive particles **[L. 12]**. The cracking of silicon carbide particles in the friction material from the semi-metallic family on the friction surface describes the behaviour of the fragmented grains during braking **[L. 13]**. It was found that the SiC solids provided a stable COF but were also responsible for high brake disc wear. Kim and co-workers investigated the frictional characteristics of four friction materials containing various abrasive components: SiC, $ZrSiO_4$, SiO_2 or MgO, determining friction characteristics for single particles, multiple particles, and brake pads with the same abrasive components **[L. 14]**. In light of the obtained results, the COF dropped in sequence $SiC>ZrSiO_4>SiO_2>MgO$, regardless of the load.

Mechanism of third body formation

Godet suggested that wear particle compaction after braking should play a major role in third body formation between the lining and the brake disc **[L. 15]**. Jacobson et al. **[L. 16–18]** pointed out that friction layers are discontinuous, comprising primary and secondary contact patches protruding from the surface. According to Steffens, the rupture of the contact patches can be considered a source of frictional vibrations accompanying braking **[L. 19]**. An increase in the load on the system can lead to the continuous destruction and reconstruction of contact points and changes in the structure and properties of the third body **[L. 20]** and the evolution of the coefficient of friction during transient states **[L. 21]**. Despite numerous papers devoted to brake friction materials, describing phenomena accompanying braking **[L. 22–29]**, neither structure nor role of the third body has been unambiguously resolved. Early research by Osterle et al. **[L. 20, 22]** showed the formation of nanocrystalline oxide phases with composition dependent on the composition of the friction lining material. Third body layers were comprehensively analysed using XPS by Wirth et al. **[L. 30]** and by Osterle et al. **[L. 31]** using novel methods of cross-sectional layer characterisation and comparing the findings with the situation at the friction lining surface. Recently, the correlation between friction and the structures found on the pads’ surfaces was discussed by Neis et al. **[L. 32]**.

Information on the role of abrasive components in a brake lining friction material and their influence on the brake performance is limited due to the difficulties in analysing the behaviour of abrasive components in the multi-phase friction composite on the friction surface and the utilitarian nature of such knowledge **[L. 14]**. The behaviour of abrasive particles on a microscopic scale is believed to be the leading cause of the noise, and vibration accompanying braking is one of the main barriers to optimising the performance of commercial friction lining materials.

The research on model brake lining materials has nothing to do with the behaviour of the actual materials **[L. 33]**. The paper presents unique studies of the influence of friction additives on the performance of actual brake lining materials from the point of view of the composition and morphology of the third body. The tribological tests and acoustic analysis results were interpreted based on these observations.

MATERIALS

Brake linings

The studies were carried out on the examples of breaking linings representing: 1. "low steel" materials – containing aluminium and chromium oxides, 2. "hybrid" materials – containing, in addition to low steel components, friction components such as zirconium silicate, magnesium oxide or iron oxides, and 3. "mild hybrid" materials – containing friction components that occur in the friction materials of the "hybrid" family, and are not present in the materials of the "low steel" family. Due to the influence of other components on the effect of friction additives, mainly lubricant additives, the tests were carried out on brake linings with the same base composition, containing the specification of abrasive additives, which is presented in **Table 1**.

Table 1. Frame composition [vol. %] of the tested brake linings, detailing abrasive additives

Tabela 1. Skład ramowy [% obj.] badanych okładzin hamulcowych z wyszczególnieniem dodatków abrazyjnych

Material / Composition	Low steel	Hybrid	Mild hybrid
Organic fibres	96.5	96.8	96.5
Metallic fibres			
Mineral fibres			
Resin			
Fillers			
Carbons			
Other lubricants			
Aluminium oxide	1.5	0.7	–
Chromite	2	–	–
Magnesium oxide	–	1	–
Iron oxide	–	1.5	1.5
Zirconium silicate	–	–	2

Brake disc

The research used a highly carburised TRW DF 2804 cast iron disc (TRW, USA). Samples for microscopic examinations of the friction trace, with dimensions of 20 x 20 x 10 mm, were cut from the brake disc with the use of a CNC machine-milling, applying a carbide milling cutter.

EXPERIMENTAL

SEM-EDS analysis

The surface of the friction trace on the brake discs and exposed cross-sections prepared using a focused beam of Ga^+ ions (FIB) were subjected to microstructure imaging studies using scanning electron microscopy (SEM), and their elemental composition analysis, using the Energy Dispersive X-ray Spectroscopy (EDS) method. The tests were carried out using a Helios 5 UX scanning electron microscope (ThermoFisher Scientific, USA), equipped with a FIB (Phoenix column) and an EDS system (EDAX Octane Elite Plus). The surface imaging of the samples was carried out with a 2–3 keV electron beam using a TLD detector („Through-The-Lens Detector") for secondary electrons (SE) for imaging in topographic contrast and MD („Mirror Detector") of backscattered electrons (BSE) for imaging in compositional contrast. Elemental composition analysis (EDS) was performed at the energy of 20 keV.

The samples' cross-sections were prepared using the FIB-SEM technique based on gradual sputtering of the sample material while scanning the sample surface with a Ga^+ ion beam (in energy 2–20 keV and current 41 pA–40 nA range). Before FIB sectioning, a Pt protective layer was deposited to the surface of the sample to protect the surface structures present in the sample from the unwanted sputtering during preparation and enhance the SEM imaging of structures on the cross-section surface. The workflow of the preparation process is shown in **Fig. 1**.

During the preparation process, it was possible to collect SEM images as well as images generated by an ion beam.

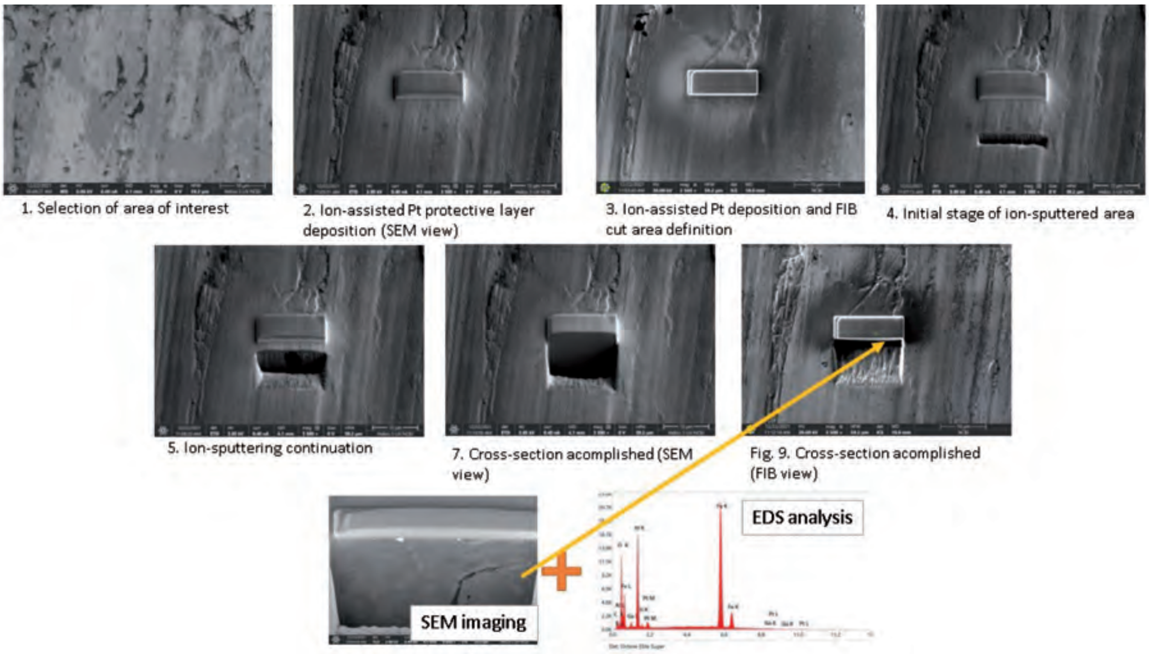
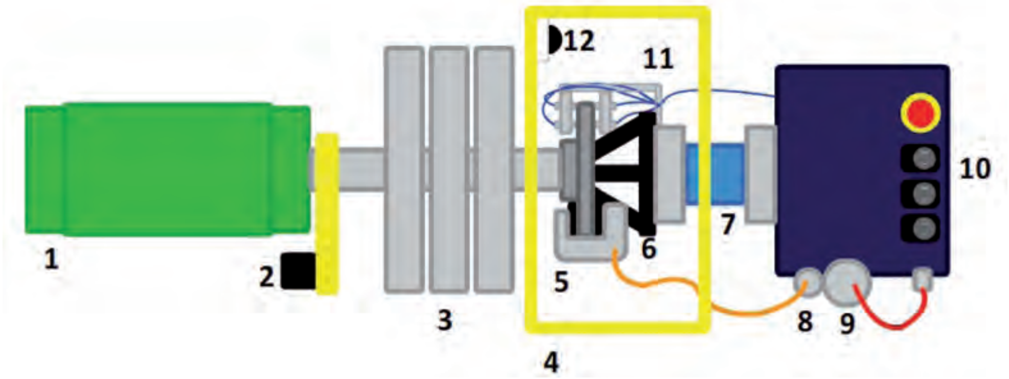

1. Selection of area of interest
2. Ion-assisted Pt protective layer deposition (SEM view)
3. Ion-assisted Pt deposition and FIB cut area definition
4. Initial stage of ion-sputtered area
5. Ion-sputtering continuation
7. Cross-section acomplished (SEM view)
Fig. 9. Cross-section acomplished (FIB view)

Fig. 1. The focused ion beam (FIB) cross-sectioning workflow
Rys. 1. Etapy procesu preparatyki przekrojów przy wykorzystaniu wiązki jonów (FIB)

Performance analysis

The SAE-J2522 "AK-Master" test procedure was used during experimental research. This procedure is the main and the most versatile tool for comparing friction materials, enabling the determination of the following parameters:

1. Green efficiency – an evaluation of braking efficiency of brand-new pads immediately after installation and necessary braking system adjustment;
2. Performance in relation to speed – a test measuring the change in braking efficiency related to speed from 40 km/h to 210 km/h for various values of pressure in the braking system;
3. Fading resistance – a measure of the impact of temperature rise on braking efficiency;
4. Recovery of the coefficient of friction – an evaluation of the capability to increase and



1 – DC drive motor, 2 – rotational speed transducer, 3 – inertia flywheels, 4 – acoustically insulated brake enclosure, 5 – test object (brake disc – brake pad), 6 – brake dyno fixture, 7 – torque transducer, 8 – pressure sensor, 9 – brake fluid flow sensor, 10 – measurement tailstock, 11 – disc thickness variation measurement system (DTV), 12 – HD camera
1 – silnik napędowy prądu stałego, 2 – przetwornik prędkości obrotowej, 3 – bezwładnościowe koła zamachowe, 4 – izolowana akustycznie obudowa hamulca, 5 – para testowy (tarcza hamulcowa – klocek hamulcowy),
6 – osprzęt hamulcowy, 7 – przetwornik momentu obrotowego, 8 – czujnik ciśnienia, 9 – czujnik przepływu płynu hamulcowego, 10 – tablica pomiarowa, 11 – system pomiaru zmienności grubości dysku (DTV), 12 – kamera HD

Fig. 2. Scheme of the inertia brake testing station LINK Model 3000
Rys. 2. Schemat bezwładnościowej stacji testowania hamulców LINK Model 3000

stabilisation of the coefficient of friction after braking affected by fading;

5. Stability of the coefficient of friction – a determination of the coefficient of friction change at various temperature, pressure and speed levels.

The braking tests were carried out using a performance inertia brake dynamometer M3000 (LINK Engineering Company, USA), adapted to measure NVH (Noise-Vibration-Harshness) acoustic signals – **Figure 2**.

The instrument enabling testing at actual scale is a complete brake from one vehicle wheel. It is equipped with a 186 kW drive engine, three flywheels with a total weight of 1,164 kg, a sound-insulated brake enclosure, a measuring tailstock with a mounted torque meter and a hydraulic brake actuation system. The construction of the station frame ensures effective vibration damping and does not transfer vibration to the ground. Acquisition of test parameters is carried out via a rotational speed sensor, brake disc and pad temperature sensors, control and recording pressure sensors, brake fluid flow sensor, high-resolution optical camera, disc thickness variation system (DTV) and NVH system, allowing measurement of noise and vibration emitted by the brake under test.

The brake enclosure (test chamber – 4), made of corrosion-resistant materials, creates an appropriate test environment by maintaining a constant temperature and controlling the cooling airflow and temperature. In addition, its interior is covered with acoustic material, whose task is to isolate the tested object from external noise, which creates the right conditions for acoustic measurements by reducing the intensity of the background noise – **Figure 3**.

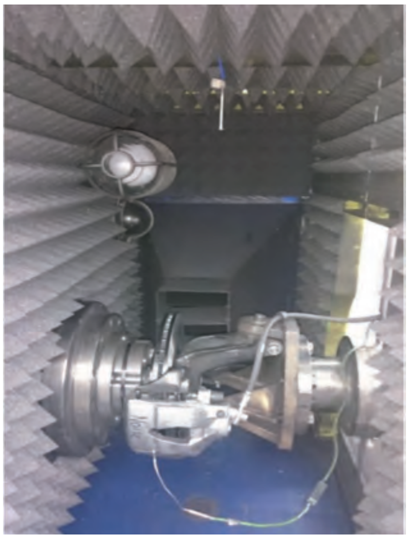


Fig. 3. The interior of the brake enclosure is adapted for acoustic tests

Rys. 3. Widok wnętrza komory pomiarowej, przystosowanej do badań akustycznych

The dynamometer is equipped with an NVH multi-channel measuring system and 1st class PCB Piezotronics measuring microphone, allowing accurate recording of noise emitted by a pair of brake pads – disc (brake). The system records the frequency, intensity and duration of each noise peak emitted by the brake under test. Signals are recorded in real time, which allows the recording and analysis of individual acoustic spectra.

The brake system used for dynamometer testing was the front brake of VW Golf MK IV (WVA 23130), using a ventilated disc and inertia of 65 kgm^2. After each ISO 2522 – AK Master test, the value of the brake pads and the disc's linear and weight abrasive wear was determined. Each brake pad and each disc were weighed before and after the test and measured at four (disc) or 8 points on the outside and inside (brake pads) – **Figure 4**, and the obtained values were averaged.

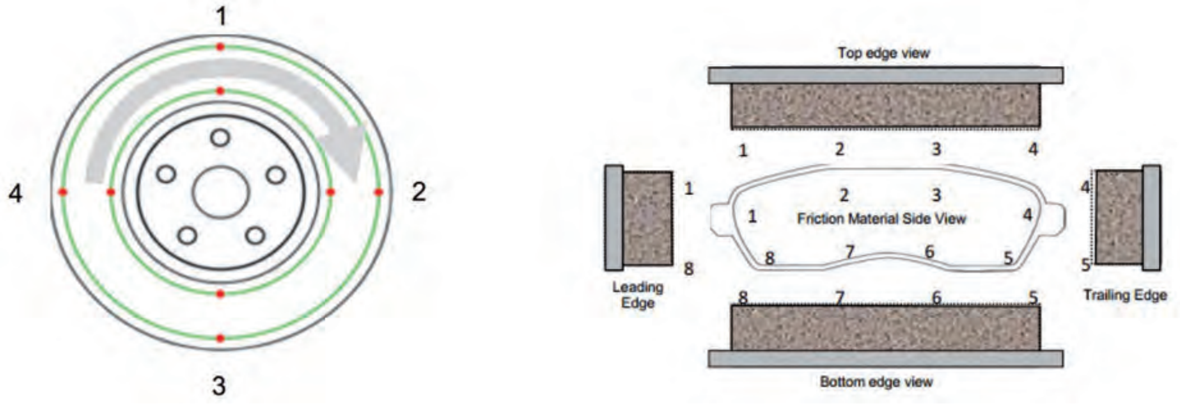


Fig. 4. Disc and brake pads measurement points

Rys. 4. Punkty pomiarowe na tarczy i klockach hamulcowych

RESULTS AND DISCUSSION

The third body layer (TBL) formation is the result of the continuous interaction of the friction material and the brake disc surface during braking. The layer created in this way, with a different composition and properties than the material of the disc or brake pad, separates the elements of the friction pair. The research was limited to the influence of some abrasive components characteristic of three families of friction materials on the TBL formed on the surface of the brake disc and the broadly understood performance of the friction material.

Third body composition

The formation of TBL, its initiation, growth and degradation is responsible for the course of the friction coefficient and possible vibrations, which are the cause of undesirable noises.

Brake discs made of grey cast iron, after machining by turning or grinding, have a grooved surface with a clear contrast, revealing numerous scratches, losses and impurities. EDS analysis carried out on the surface of the brake disc sample before the braking test showed the presence of such elements as C, O, Cr, Si, S, Ti, Mn and Fe. SEM imaging on the surface of their cross-sections prepared by the FIB technique revealed the presence of discontinuous layers of an irregular thickness (0.2–1.2 µm) located at a meaningful depth of several micrometres below the surface of the tested fragment of the target. The SE images also show a grain size difference above and below the carbon layer. The presence of fine oval grains in the area from the disc surface to the carbon layer and longitudinal grains extending parallel to each other in the area below the carbon layer is characteristic of the severe plastic deformation that occurred while grinding the surface of the brake disc.

After the braking tests in the surface areas of the samples studied in the topographic contrast, one can see numerous scratches and cracks forming textures composed of layers of wear particles originating from both friction pair elements – **Figure 5**.

Plateaus and depressions shielding the brake disc surface, formed by the compaction of wear products as a result of their fragmentation and chemical reactions between this mixed material and the atmosphere, are called first body material (FBM). Apart from the top of the FBM, a mechanically mixed layer (MML) was created, containing loosely tied particles of wear

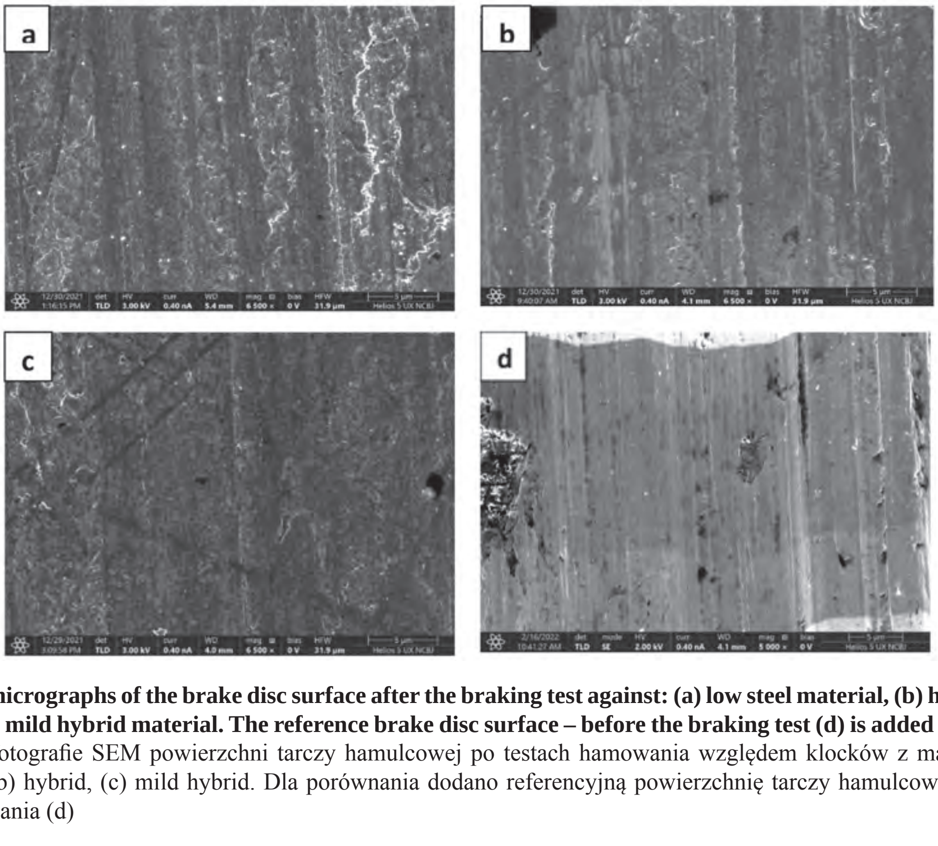


Fig. 5. SEM micrographs of the brake disc surface after the braking test against: (a) low steel material, (b) hybrid material, and (c) mild hybrid material. The reference brake disc surface – before the braking test (d) is added for comparison

Rys. 5. Mikrofotografie SEM powierzchni tarczy hamulcowej po testach hamowania względem klocków z materiału: (a) low steel, (b) hybrid, (c) mild hybrid. Dla porównania dodano referencyjną powierzchnię tarczy hamulcowej przed testami hamowania (d) products from the surface layer of both elements of the friction pair called mechanically mixed layer (MML). While the material of the tested brake disc is the same, i.e., grey cast iron, the composition of the friction linings was different. This explains why the composition and microstructure of the wear products that make up the TBL are different – **Figure 6**.

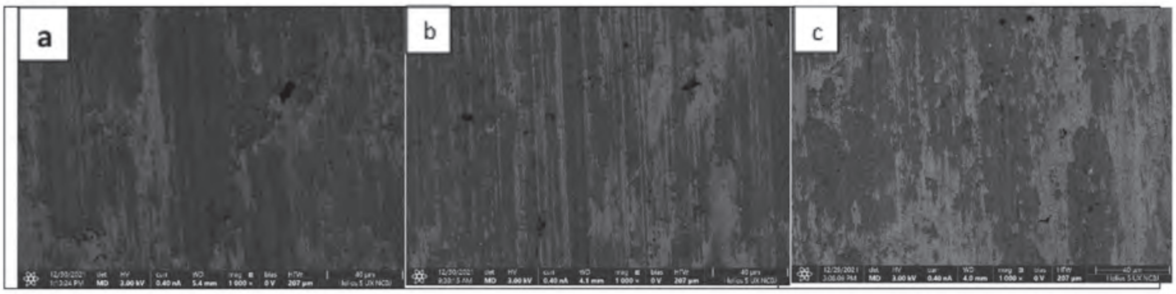


Fig. 6. SEM compositional contrast BSE images of the brake disc surface after the braking tests against: (a) low steel material, (b) hybrid material, and (c) mild hybrid material

Rys. 6. Obrazy SEM w kontraście kompozycyjnym (BSE) powierzchni tarczy hamulcowej po testach hamowania względem klocków hamulcowych z materiałów: (a) low steel, (b) hybrid, (c) mild hybrid

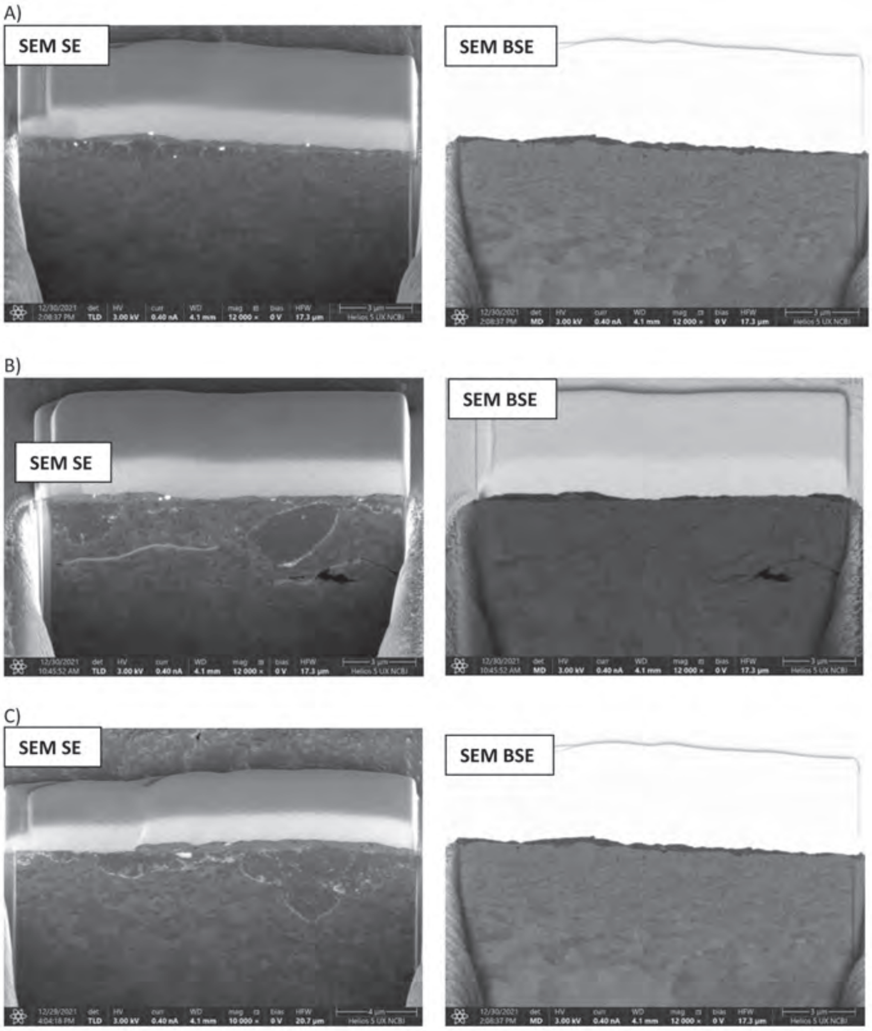


Fig. 7. SEM (SE and BSE) micrographs of the cross-sections of the tribofilm formed on the brake disc surface after braking test against the brake pads: A) low steel, B) hybrid, C) mild hybrid

Rys. 7. Analiza SEM przekroju tribofilmu powstałego na powierzchni tarczy hamulcowej po próbie hamowania względem okładzin hamulcowych: A) low steel, B) hybrid, C) mild hybrid

The layer formed by the wear products – the so-called third body layer (TBL), represents characteristic trails of various shapes, depending on the friction material of the used lining. Braking of friction linings made of low steel material leaves thin deposited layers on the surface of the brake disc, which form discontinuous, wide trails – **Figure 6a**. In the case of hybrid linings, these trails take the form of thin, discontinuous trails – **Figure 6b**, while mild hybrid linings have the shape of discontinuous, torn trails – **Figure 6c**.

Depending on the type and amount of abrasives in the brake pad material, the morphology and chemical composition of TBL differs for each of the tested samples. SEM BSE imaging analyses of the cross-sections of the TBL layers created as a result of braking reveal that, regardless of the type of brake pad material, they all consist of clearly formed upper and lower layers, which differ in thickness – **Figure 7** and elemental composition – **Table 2**. The images also show the submicron size of Al_2O_3 abrasive particles embedded in the FBM layer, shielding a brake disc.

The outermost layer of the third body layer – MML, which is not directly bonded to the surface of the brake disc, consists mainly of mixed wear products of the friction pair elements. The detected elements can come from both the disc and the brake pad material. The other elements listed in **Table 2** come from the brake pad wear products. Some of them, like Zr, can only be attributed to abrasives; others: S and Sb, only to lubricants. The first body material (FBM) layer contains elements that occur not only in the abrasive system. Elements such as Mg or Al can come from both abrasive additives and mineral fibres, which are part of the base formula of brake pads. It seems likely that some abrasive additives, like Al_2O_3 or chromite, have a greater tendency to form a thicker third body layer (TBL) than others, whereas softer magnesium and iron oxides or zirconium silicate on the other way round. In their case, TBL is less developed (**Figure 6**) and thinner (**Figure 7**), but their FBM layer becomes thick with visibly embedded microparticles of Al_2O_3, which eventually stabilises friction at a lower, but still accepted coefficient of friction (COF) value. Big particles of hard abrasives embedded in FBM, probably together with Sb lubricant, shield a brake disc. Very hard abrasives like Al_2O_3 but of submicron size cause high wear of the brake disc in the case of low steel lining material, forming a thicker MML, which is frequently renewed. Depending on the combination of hard/soft (magnesium and iron oxide) abrasive components, the friction base material may promote the initiation and stabilisation of both parts constituting TBL. The third body layer's thickness, composition and morphology can be correlated with the results of the dynamometer tests.

Table 2. EDS results analysis of TBL
Tabela 2. Rezultaty analizy EDS trzeciego ciała (TBL)

A) inner layer (deformed) – first body material (FBM)
A) warstwa wewnętrzna (zdeformowana) – FBM

Material	Elemental composition										
Low steel	Fe	O	C	Si	Cr	Mn	Ti	Ba	Mg	Ca	S	Al
Hybrid	Fe	O	C	Si	Cr	Mn	Ti	Ba	Mg	Ca		Al
Mild hybrid	Fe	O	C	Si	Cr	Mn	Ti	Ba	Mg	Ca	S	Al

B) outer layer – mechanically mixed layer (MML)
B) warstwa zewnętrzna (MML)

Material	Elemental composition										
Low steel	Fe	O	C	Si	Cr	Mn	Ti		Ca	S	Sb	
Hybrid	Fe	O	C	Si	Cr	Mn	Ti	Ba			Sb	
Mild hybrid	Fe	O	C	Si	Cr	Mn	Ti				Sb	Zr

Performance analysis

The performance of the brake and the phenomena occurring in the area of contact between the pad and the brake disc are both physical, thermomechanical and chemical in nature. Kinetic energy is converted into heat, plastic deformation, chemical reactions, and wear debris **[L. 16]**. As a result, the friction coefficient and the wear of the friction pair are changed. Detailed test results of brake linings made of the friction materials studied, performed according to ISO SAE J2522 (AK Master), are included in Annexes 1–3. **Figure 8** compares the efficiency performance of three friction materials tested (AK-Master test).

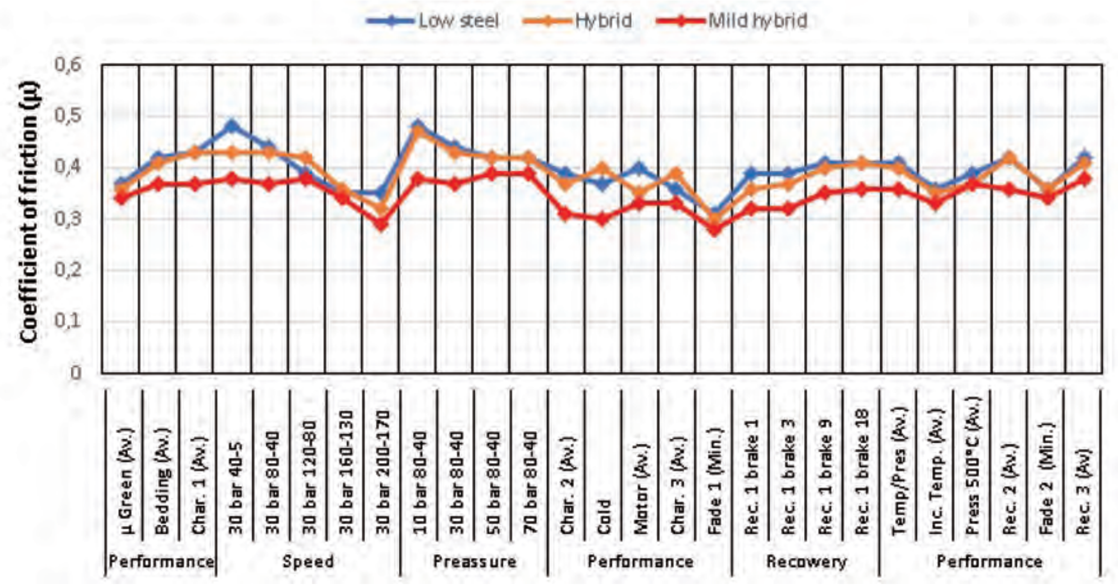


Fig. 8. ISO SAE J2522 – AK Master efficiency comparison for the friction materials tested
Rys. 8. ISO SAE J2522 AK Master – podsumowanie wydajności badanych materiałów ciernych

Much higher COF values characterise friction materials from the low steel and hybrid family compared to the material of the mild-hybrid family – **Table 3**.

Table 3. ISO SAE J2522 – AK Master COF comparison for the friction materials tested
Tabela 3. ISO SAE J2522 AK Master – wartości współczynnika tarcia badanych materiałów ciernych

COF / Material	Nominal	Fade	Minimum	Maximum
Low steel	0.40	0.34	0.31	0.48
Hybrid	0.40	0.34	0.30	0.43
Mild hybrid	0.34	0.32	0.28	0.38

Better stability of COF for mild hybrid material can be explained by thicker, homogeneous FBM of TBL and very thin fragments of discontinuous outer MML. The composition of abrasive additives characteristic of the low-steel formula is responsible for the permanent refreshing of thick, continuous MML, which on the one side provides the highest COF, but on the other hand, the friction is unstable, making the wear of the brake disc increased – **Table 4**.

Table 4. Wear of the friction pair elements after ISO SAE J2522 – AK Master test
Tabela 4. Zużycie elementów pary ciernej po teście ISO SAE J2522 – AK Master

Linear wear [µm] / Material	Brake pad	Brake disc
Low steel	10.4	7.6
Hybrid	9.7	6.0
Mild hybrid	9.3	1.6

A dynamic equilibrium between the MML destruction and restitution taking place can be reasonably assumed regarding the friction level. "Refreshing" of MML is responsible for the highest difference between the minimum and maximum COF values for the low steel family material compared to the hybrid or especially the mild hybrid material. It follows that the friction material of the mild hybrid family has clearly lower COF but exhibits the most stable friction, which can also be due to the presence of zirconium silicate in TBL, acting synergistically with Sb_2O_3 **[L. 34]**. This translates into the amount of abrasive wear of the friction pair elements, particularly noticeable in relation to the brake disc. Friction linings made of mild hybrid material are definitely less "aggressive" in relation to the brake disc than linings made of low-steel and hybrid materials. Wear is also directly related to noise, as proposed by Lee et al. **[L. 35]**. The noise accompanied by braking of the brake linings materials studied during AK Master tests is characterised (NVH) in **Figure 9**.

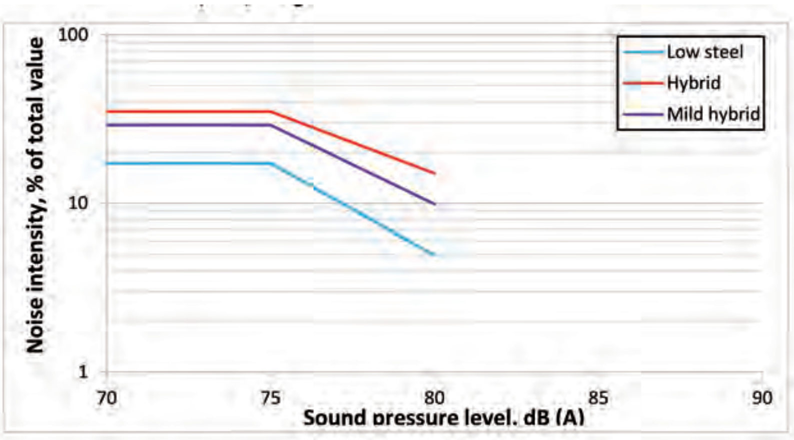


Fig. 9. Noise-Vibration-Harshness (NVH) analysis of the brake lining materials tested
Rys. 9. Analiza hałasu-wibracji-twardości (NVH) badanych materiałów okładzin hamulcowych

None of the tested materials generates noise with an intensity above 80 dB. Again, hybrid and mild hybrid friction materials differ significantly from low-steel ones. It seems likely that the reason is the greater wear of the disc cooperating with the brake pad materials from the low steel and hybrid families compared to the mild hybrid, causing frequent renewing of the TBL. The hardness of the abrasives plays a significant role in this case. The abrasive systems used include hard friction materials such as aluminium oxide, quartz, silicon carbide or zirconium silicate (7–9 on the Mosh scale) and mild ones such as chromium oxide, pyrite, magnetite or magnesium oxide (5–6 on the Mosh scale). The friction particles during dry skid significantly contributed to the efficiency of the brake performance and the wear of both the pads and the brake disc. It is influenced by several factors, such as the ratio of the fraction of hard to soft abrasive particles, their size and shape, as well as the interactions between the abrasive grains and the material of the brake pad and TBL. The applied system of friction components in the material from the low steel family probably acted on the abrasive mechanism of the hard Al_2O_3 (9 on the Mohs scale) and the polishing action of the milder chromite (5.5 on the Mohs scale) abrasive particles, which resulted in greater wear of the brake disc. Thus, the system provided a thick and continuous layer of TBL, favourable in terms of noise and vibration (NVH) reduction. The percentage of squeaking brakes for this material would be the smallest and amounted to 17%, whereas linings made of the hybrid family material had the highest percentage of squeaking brakes, which was 35%. In these linings, apart from Al_2O_3, magnesium and iron oxides were used, which did not have the same polishing ability as chromite. This resulted in greater changes in the structure of the TBL, which showed less tendency to produce MML, which was thinner and discontinuous. The lower abrasive wear of the disc and the lower coefficient of friction can be attributed to the "shielding" of the disc material by its microrough surface, while reducing the contact surface of the friction pair elements. The system of friction components in the mild hybrid material no longer contained hard Al_2O_3 particles but only slightly softer zirconium silicate (7 on the Mohs scale), which was definitely less “aggressive” in relation to the brake disk. As in the case of the material from the hybrid family, a thick and continuous MML layer (as in the case of the low steel material) did not develop, resulting in a 29% percentage of squeaking brakes, despite the development of the FBM layer **[L. 34]** with a high tendency to “shield” the brake disc.

SUMMARY

1. Friction additives for brake pads significantly affect the composition and structure of the TBL. Finding a balance between the abrasives and the rest of the components is essential during the recipe optimisation process. Only their proper selection can ensure optimal performance and driving comfort during braking.
2. The selection of friction components has a significant impact on the particles of soft components, i.e., metal sulfides or their oxidation products, which mix with iron oxides on a submicron scale, creating a tribofilm capable of shielding the surface of the brake disc, as in the case of a mild hybrid material. This effect is much smaller in the case of material from the low steel family, where the wear of the disc is several times higher.
3. Additional clusters of hard particles like Al_2O_3 do not interfere with the smooth sliding effect and vibration increase, provided they are fully embedded in the FBM layer.
4. With the help of friction additives, it is possible to properly create the growth, propagation and restitution of MML, which is responsible for silent braking required by modern brake systems.
5. The friction components significantly influence the plastic deformation of the FBM layer on the brake disc, determining the ability to form MML. An ideal TBL is one that has the ability to screen the brake disc surface and generates an even and stable MML.

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