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THE INFLUENCE OF USING CONDITIONS ON TRIBOLOGICAL PROPERTIES OF BRAKE SYSTEMS WITH COMPOSITE DISCS

WPŁYW WARUNKÓW EKSPLOATACJI NA WŁAŚCIWOŚCI TRIBOLOGICZNE UKŁADÓW HAMULCOWYCH Z TARCZAMI KOMPOZYTOWYMI

Key words: brake disc, brake pad, composite material, exposition on oxidation, friction coefficient, wear.

Abstract This paper presents the results of studies on the influence of automotive vehicle parking time on levels of the friction coefficient and wear that influence the braking efficiency of brake systems with composite discs. Discs have been produced of hypereutectic aluminium-silicon alloy (AlSi18NiMgCu) in which the Si precipitates are a reinforcing phase. On the basis of the parking time of a vehicle for a repair, the minimal (τ = 0 h) and maximal (τ = 240 h) time for an exposition on atmospheric factors has been determined, Velocities, unit pressures of brake pad on the disc rotor, and the braking distance are the equivalent of a braking distance of an vehicle with mass of 1300kg running through an built-up area with a velocity of 30 or 50 kmh. On the basis of experiment's results, it has been stated that a car parking time of 48h causes an oxidising of the matrix, which results in a friction coefficient decrease up to 0.18 on the sliding distance of 600–700 m, As a result of the wear of the oxide layer, the friction coefficient acquired a value (>0.3) after about 600–700 m friction distance, which equals 600 rotations of the wheel. A longer parking time (240 h) causes a considerably lower decrease in friction forces, because the oxide layer will be sealed.

Słowa kluczowe: tarcza hamulcowa, klocek hamulcowy, materiał kompozytowy, ekspozycja na utlenianie, współczynnik tarcia, zużycie.

Streszczenie W pracy przedstawiono wyniki badań wpływu czasu postoju pojazdu samochodowego na wartość współczynnika tarcia i zużycia decydujących o skuteczności hamowania układów hamulcowych z kompozytowymi tarczami. Tarcze wykonano z nadeutektycznego stopu aluminium z krzemem (AlSi18NiMgCu), w którym wydzielenia Si stanowią fazę umacniającą. Na podstawie badań czasu postoju pojazdów w oczekiwaniu na naprawę w warsztacie określono minimalny (0 h) i maksymalny (240 h) czas ekspozycji na działanie czynników atmosferycznych. Prędkości, naciski klocka na tarczę i droga tarcia odpowiadają hamowaniu samochodu osobowego o masie do 1300 kg poruszającego się w obszarze zabudowanym z maksymalną prędkością 30 lub 50 km/h. Na podstawie wyników badań stwierdzono, że postój samochodu przez 48 h powoduje utlenianie osnowy, co skutkuje spadkiem współczynnika tarcia do 0,18 na drodze tarcia do 600 m. W wyniku zużywania powstałej warstewki tlenku współczynnik tarcia osiąga wymaganą wartość (>0,3) po około 600–700 m drogi tarcia, co odpowiada ponad 600 obrotom koła. Dłuższy postój (240 h) powoduje znacznie mniejszy spadek sił hamowania, ponieważ warstwa tlenku glinu uszczelnia się.

INTRODUCTION

In Poland and many European Union countries, there are many vehicles, agricultural, construction, and air transport vehicles in use. Each of the technical means of transport during use must be able to control the speed depending on the traffic conditions. The brakes are used to slow down and stop. As for now, friction brakes dominate, which dissipates the kinetic energy of the vehicle as a result of the friction and the wear of particles of friction materials, i.e. pads (claddings) and discs (drums). Consumption products are emitted

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into the environment and some of them get inside the vehicle. The most polluted areas are near junctions and the speed limit signs. Most of the current friction brakes of motor vehicles are equipped with cast-iron brake discs and composite blocks containing resin as a matrix and graphite, ceramics, and metal filings as fillers performing various functions. As a result of each braking of the vehicle with such brakes, solid particles with granulation, depending on the strength of the friction materials and their composition, depending on their chemical composition, enter the environment. The wear products of metal parts of braking systems scattered in the environment are unrecoverable, which is an irreversible loss and reduction of resources of certain elements at the disposal of people.

In order to reduce environmental pollution and material losses, tests are carried out whose task is to obtain brake discs and pads with lower wear and with lower PM_{10} and $PM_{2,5}$ dust emissions. In the European Union, legal regulations are being prepared that "force" car manufacturers and users to reduce emissions of these dusts based on information from on-going research projects (**[L. 1]** Lowbrasys project). The regeneration processes of used brake discs (Rebrake) are becoming more and more important. Reducing the intensity of the wear of discs and brake pads will contribute indirectly to a reduction in the weight of vehicles due to a smaller “supply” of material considering wear and tear.

Currently, several possibilities of limiting the wear of friction elements of braking systems are checked, e.g., volume modification of the chemical composition of discs and blocks, surface modification of discs by coatings, and diffusion of selected elements (nitrocarburizing **[L. 2–3]**), and the use of new engineering materials, e.g., composites based on ceramics and aluminium alloys **[L. 4–5]**.

Currently, automotive vehicles use composite brake discs made of hypoeutectic alloy AC-AlSi9Mg (A359 in the US) with the addition of 20% SiC particles (marking of composite F3S.20S) and near eutectic alloy AC-AlSi12MgNiCu with the addition of 40–60% SiC particles and from the hypereutectic AlSi18MgNiCu alloy. In the first and second material, the SiC particles reinforce the matrix and increase its resistance to wear without impairing the thermal conductivity (λ_{SiC} 100–200 W/(mK)) In the second material, the excess silicon is isolated (solubility of Si in Al at eutectic temperature is 1.65%) and increases wear resistance and does not degrade corrosion resistance. The addition of SiC increases the composites' susceptibility to corrosion due to the cathodic action of SiC relative to the Si solution in Al (α) or the formation of carbide (Al_4C_3) at the boundary of the matrix and reinforcing phase **[L. 6]**.

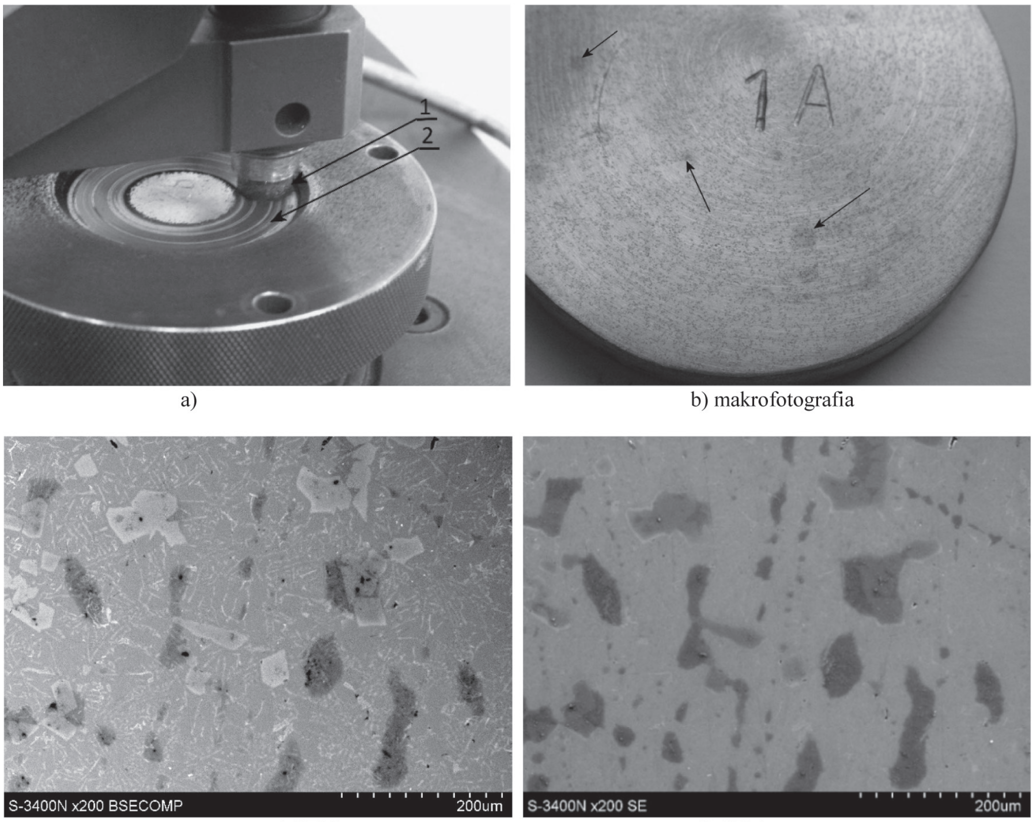
Wear of the composite on a silumin matrix containing from 20% to 40% SiC is several times smaller than that of cast iron. Moreover, the wear of pads rubbing against composite brake discs is smaller than with cast iron discs **[L. 4–7]**. This article is devoted to the impact of the conditions of use of composite brake discs on the effectiveness of braking systems and on environmental pollution.

MATERIALS AND EXPERIMENT CONDITIONS

The research used the AlSi18MgNiCu hypereutectic alloy containing Si primary particles used for the production of commercially available brake discs. The friction partner was a composite brake pad material (F701). Tribological tests were carried out on a pin-on-disc stand, in which the pin (φ = 10 mm) was made of brake pad material, and the disk (φ = 45 mm) was made of a silumin composite.

Test samples were turned from the brake disc (without disturbing the structure of the material) and left to atmospheric air with variable humidity (March, ambient temperature from -5 at night to +5 in the day), without contact with the salty environment of the roadway. The samples were placed in a vertical position (similar to discs in vehicles), without the possibility of water condensate sedimentation. The aim of the research was to check the air impact, and not the corrosive salt solutions used for de-icing the roadway. The view of the brake disc surface after 240 hours of exposure and the friction contact are shown in **Figure 1**.

In order to check the influence of the vehicle's parking time on the coefficient of friction and wear, tribological tests based on a multi-factor, D-optimal plan for three steering factors, i.e. vehicle parking time (exposure of discs to atmospheric agents), relative velocity (v), and the pressure of brake pad on the disc (p). Tests were repeated three times. The boundary conditions, i.e. minimum and maximum values of steering factors, were determined based on the behaviour of the vehicle braking system with a mass of 1300 kg while driving in urban traffic (maximum speed 50 km/h, in some zones 30 km/h). The minimum exposure time (τ) for weather conditions was assumed to be 0 hours, which means that the vehicle braked after earlier use and the surface of the composite disk was not oxidized. The maximum time (τ = 240 h) was taken based on the vehicle's parking in the car workshop. The maximum speed (v = 0.7 m/s) corresponds to the relative speed of the pad to the disc during braking in city traffic, and the minimum (v = 0.1 m/s) corresponds to the speed just before braking. The brake pad pressure on the disc was based on previously measured, by using of the roller dynamometer on the vehicle diagnostic station [**L. 7–8**], braking forces, and friction coefficients. The plan of the experiment and the results of tribological tests are presented in **Table 1**. In order to calculate the regression coefficients describing the tested dependences of the second degree equation, normalization (according to the experimental methodology **[L. 9]**) of steering factors



a) b) makrofotografia

c) SEM d) SEM

Fig. 1. Friction contact of T-01M tester (a) and surface of composite disc after 240 h exposition with visible corrosion centre (b – signet with arrows) and Si precipitate on the matrix (c, d): 1 – frictional material pin, 2 – AlMC disc)

Rys. 1. Węzeł tarcia testera T-01M (a) i powierzchnia tarczy kompozytowej po ekspozycji 240 h z widocznymi ogniskami korozji (b – zaznaczone strzałkami) i wydzielenia Si na tle osnowy (c, d): 1 – trzpień z materiału ciernego, 2 – tarcza z AlMC)

was assigned by assigning the minimum (-1), central (0) values, and maximum (1). The working surfaces of the composite discs were ground with sandpaper 240 to obtain topography similar to the discs after turning. During tribological tests, the friction force was measured using a strain gauge transducer and the weight loss of pins and discs as a function of steering factors. The average square error of the friction force measuring

Table 1. Experiments plan and results of tribological examination of F701 pin/AlMC disc contact

Tabela 1. Plan eksperymentu i wyniki badań tribologicznych skojarzenia trzpień F701/tarcza AlMC

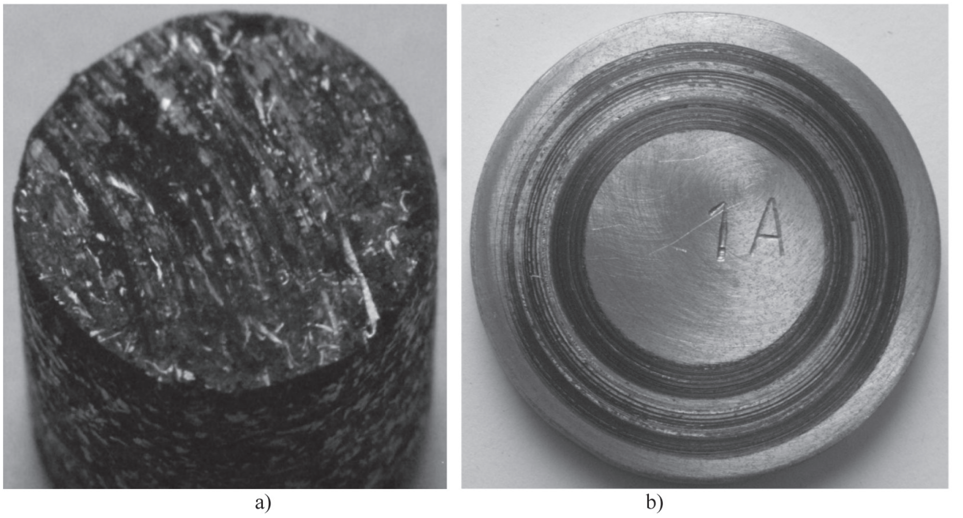
(Countersamples exposed on atmospheric factors acting)

No	Steering factors			Mass loss of AlMC disc Δmd, mg				Mass los of FO701 pin Δmp, mg				Friction coefficient μ	
	v m/s	p MPa	τ_E h	1	2	3	average	1	2	3	average	at start	at finish
1	0.1	0.3	240	2.2	3.9	1.8	2.63	4.4	7.2	3.2	4.93	**0.20**	0.38
2	0.7	0.3	0	0.8	0.7	1.8	1.1	1.7	4.4	1.8	2.63	0.22	0.30
3	0.1	0.7	0	0.2	0.5	1.0	**0.56**	1.1	0.6	3.3	**1.66**	**0.20**	0.30
4	0.7	0.7	240	3.3	3.6	2.7	3.2	6.2	9.4	3.0	6.2	0.24	0.32
5	0.1	0.5	48	7.5	4.5	4.5	5.5	10.1	8.2	6.0	8.1	0.22	**0.42**
6	0.7	0.5	48	12.6	17.2	13.6	**14.46**	8.7	14.8	12.2	**11.9**	**0.32**	0.38
7	0.4	0.3	48	4.2	6.6	1.4	4.1	5.4	7,9	3.0	5.43	0.25	0.36
8	0.4	0.7	48	13.1	18.1	15.6	15.6	9.9	13.6	11.7	11.73	0.28	0.34
9	0.4	0.5	0	0.6	0.7	0.5	0.6	3.2	5.4	2.0	3.53	0.31	0.30
10	0.4	0.5	240	16.2	5.8	2.9	8.3	11.3	12.9	7.7	10.63	0.22	0.36
11	0.4	0.5	48	3.4	3.8	3.6	3.6	5.0	11.4	6.2	7.53	0.22	0.38

path was 3%, and the accuracy of the analytical balance was 0.2 mg. From the surface of the samples after exposure and after tribological tests, macro-photographs and scanning microscopy were performed. Selected results are shown in **Figures 1–3** and **7**.

The dependences of weight losses of the pins and disc and the coefficient of friction at the beginning and the end of friction on pressure and exposure time are described by the second degree polynomials and graphically depicted (**Figs. 5–6**).

The graphs presented are based on the assumption of a central velocity value, i.e. v = 0.4 m/s. This polynomial was developed for steering factors on a normed scale, i.e. the minimum value of the factor was assigned -1, central 0, and the maximum 1. In order to go on a real scale, results should be decoded. The aim of the diagrams is to show the directions of changes of mass pin and disc wear within the area of steering parameters given in the **Table 1**. The results are summarized in **Figures 5–6**. Since the coefficients of friction at the beginning and at the end of the cooperation differed significantly (**Fig. 4**), they were shown in separate diagrams (**Figs. 6a** and **6b**).



a) b)

Fig. 2. Sample (a – pin) and countersample (b – disc) used in tribological experiment
Rys. 2. Powierzchnie robocze próbki (a – trzpień) i przeciwpróbki (b – tarcza) użytych do badań tribologicznych

RESULTS AND DISCUSSION

Figures 1b and **3** show that the Si-precipitates (Si K – **Fig. 3d**) are distributed almost evenly over the entire surface of the brake disc, which ensures the homogeneity of the tribological properties of the contact. The vehicle stops for 48 hours, causing a coefficient of friction decrease to 0.18 from 0.25 for $\tau = 0$ (**Figs. 4a** and **4b**). The reason for this is the formation of a discontinuous layer of porous aluminium oxide. From the photographs of composite discs shown in Figures 1b and 1d after 240 hours of exposure, it appears that hydrated aluminium oxide began to form on the surface of the matrix material (indicated by the arrows in **Fig. 1b**). Moisture absorption causes the oxide pores to partially close **[L. 10]** and a slight decrease in friction forces at the beginning of rubbing (**Fig. 4c**). The thickness of the oxide layer is, however, very small; therefore, it does not exert too much influence on the friction forces, which is confirmed by **Figures 4a** and **4c**.

After exposure for 48 hours, the oxide layer is very thin and porous, which favours the rapid plating of resin wear products from the pad material and the formation of friction reducing film ($\mu = 0.18$ – beginning of graph 4b) for almost 600 m of friction (over 600 brake discs rotations). The film is compact, with breaks at the silicon precipitates (**Figs. 7b, d,** and **e**) and adheres to the surface of the brake disc. This behaviour of the contact of the pad/disc worsens the braking performance. The film produced on the brake disc after 240 hours of exposure is cracked and tends to break around the Si precipitates (**Fig. 7d**), because the adhesion to the sealed oxide is smaller. A part of the wear products of the ceramic components of the pad material and the oxide produced on the brake disc is collected at discontinuities in the film (**Figs. 7b** and **7d**).

During friction, abrasive wear of both the brake pad and disc material prevails, as evidenced by the scratches along the direction of motion in **Figures 2** and **7**, and the powder wear products accumulated on the disc after

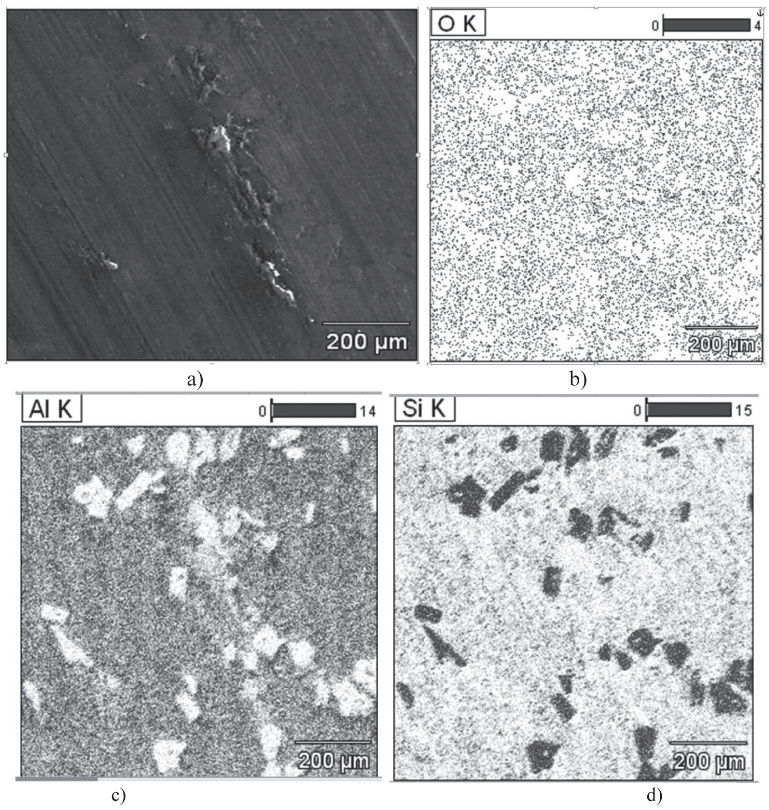


Fig. 3. Elements distribution on surface of composite disc after 240 h exposition

Rys. 3. Powierzchniowy rozkład pierwiastków w tarczy kompozytowej po 240 h ekspozycji

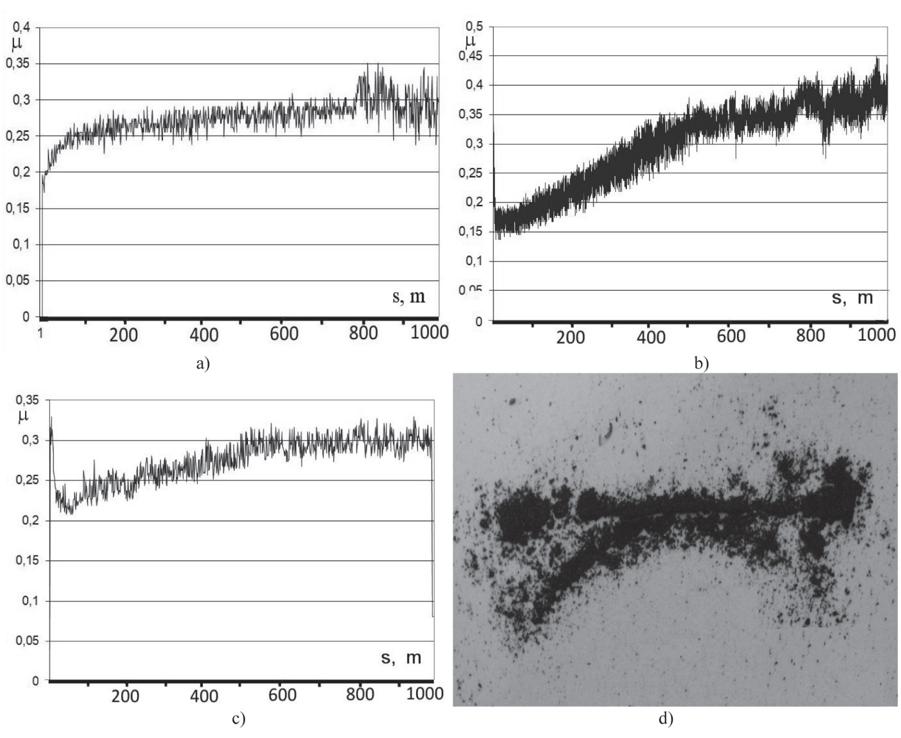
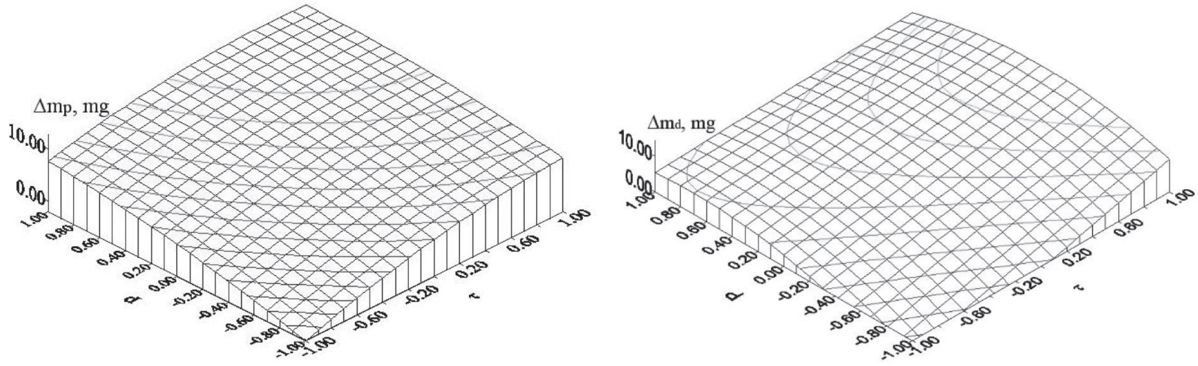


Fig. 4. Friction coefficient vs. sliding distance of disc without (a) after 48 h (b) and 240 h (c) exposition as well as wear debris collected from disc after test (d)

Rys. 4. Współczynnik tarcia w funkcji drogi tarcia tarczy bez ekspozycji (a) po 48 h (b) i 240 h (c) ekspozycji oraz produkty zużycia zsypane z tarczy po badaniach (d) tests (**Fig. 4d**). These products cause dirt on the car rims and environmental pollution. The harder components of the friction material cause micro scratching of the brake disc material, and the very hard silicon releases protruding from the surface of the matrix will cut the friction material of the pad.

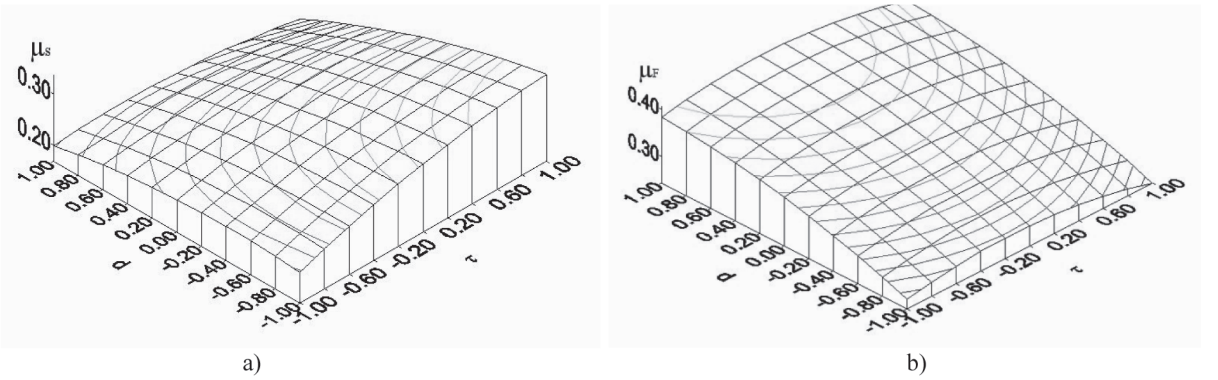
The exposure time has a significant effect on the coefficient of friction at the beginning of rubbing (μ_s – **Fig. 6a**). The vehicle's parking time for 48 hours causes a decrease in the coefficient of friction as a result of the deposition of resin on the surface of the disc (**Fig. 4b**). At the end of the friction, the embedded film from the wear products takes place and the value of the coefficient of friction changes slightly (μ_F – **Fig. 6b**) with the change of the exposure time. This may indicate that the oxide layer has been removed from the surface of the brake disc as a result of friction.

On the basis of **Figure 5**, it can be concluded that the smallest wear of brake pad and brake disc place during rubbing against an nonoxidized disc ($\tau = 0$) with minimal pressure. The vehicle's parking time increases the wear of both the pad and the disc, which is the result of the oxidation of the aluminium matrix of the composite.



a) b)

Fig. 5. Mass lost (Δm) of pin (a) and disc (b) vs. unit pressure (p) and exposition time (τ) for v = 0.4 m/s
Rys. 5. Zależność ubytku masy (Δm) trzpienia (a) i tarczy (b) od nacisku (p) i czasu ekspozycji (τ) dla v = 0,4 m/s



a) b)

Fig. 6. Friction coefficient at the start (a) ant the end (b) of rubbing vs. unit pressure (p) and exposition time (τ) v = 0.4 m/s
Rys. 6. Współczynnik tarcia w funkcji nacisku (p) i czasu ekspozycji (τ) na początku (a) i na końcu (b) współpracy v = 0,4 m/s

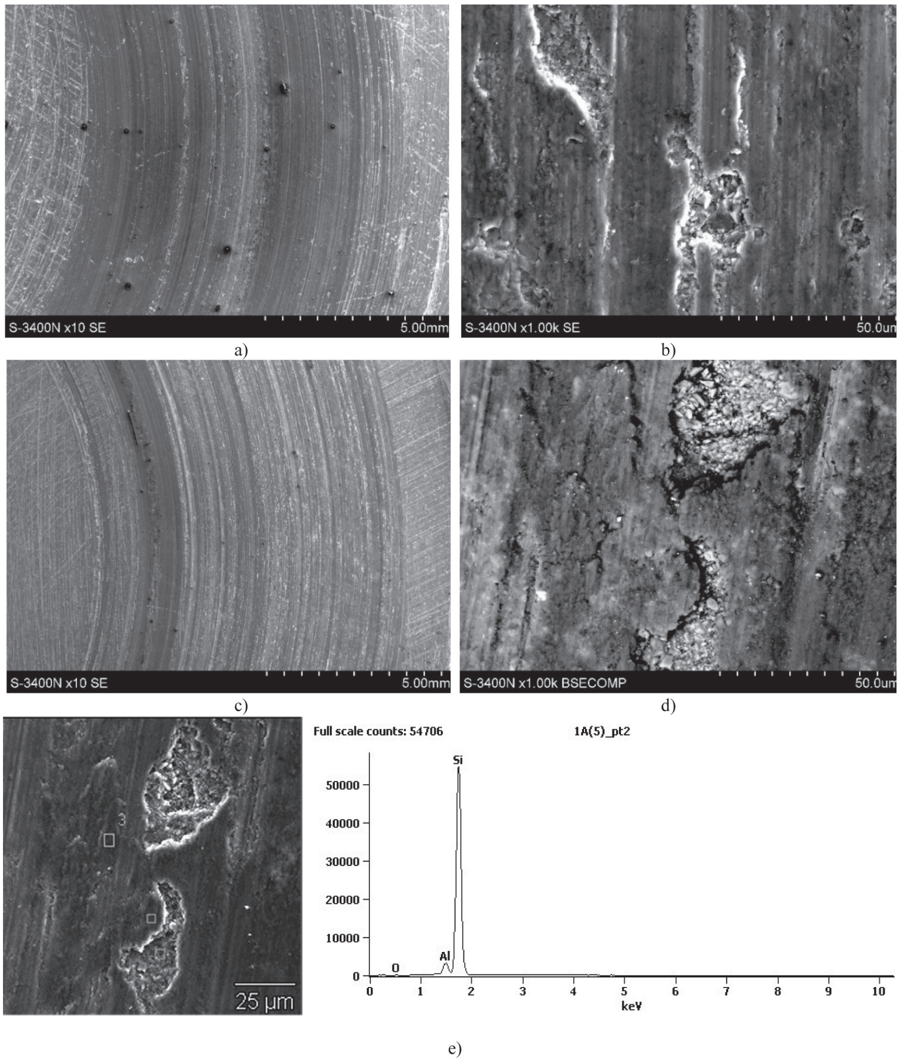


Fig. 7. Surface of disc exposed for 48 h (a, b) and 240 h (c, d) after tribological examination and chemical analyse (e)
Rys. 7. Powierzchnia po badaniach tribologicznych tarcz eksponowanych przez 48 h (a, b) i 240 h (c, d) i analiza składu (e)

CONCLUSIONS

Based on the results of the conducted tests, it can be concluded that the parking time of a car vehicle equipped with brake discs made of composites based on aluminium alloys influences the value of the coefficient of friction and wear. The greatest reduction in the coefficient of friction takes place during the use of the discs after a parking time of 48 hours. The aluminium oxide layer formed on the brake disc is porous, which results in a quick deposition of a sliding film on it with wear products of the resin being a component of the brake pad material. This film reduces the coefficient of friction to 0.18 by almost 600 m of friction distance, which corresponds to 640 rotations of the brake disc with a diameter of 300 mm. The friction of the brake pad against the disc causes wear of oxide layer and an increase to > 0.3 of the coefficient of friction only after 800 meters of friction distance on the testing stand. Extending the braking distance of a vehicle after a 48-hour stoppage will depend on the diameter of the vehicle's wheel and the pad's load on the disc. It should be taken into account by drivers using cars with AlMCs braking disc. The vehicle parking time for 240 hours in the air with variable temperature and humidity causing partial hydration of the resulting oxide causes its sealing, which reduces the adhesion of wear products that reduce friction forces.

REFERENCES

1. A LOW environment impact BRAke SYStem (LOWBRASYS) Horizon 2020 Project No 636592, Brussels 01/09/2015–28/02/2019.
2. Brooke L.: GM aims to double brake rotor service life with new FNC treatment, Automotive Engineering Magazine, Detroit July 21, 2017.
3. Method to increase corrosion resistance in ferritic nitrocarburized treated cast iron substrates US 20110079326 A1.
4. Design and Analysis of Automobile Brake Disc by Using Al/SiC MMC. International Journal of Innovative Research in Science, Engineering and Technology. 6, (3), 2017, pp. 4816–4825.
5. Gulden F., Gramstat S., Stich A., Hoppel W.H., Tetzlaff U.: Properties and Limitation of an Oxide Coated Aluminum Brake Rotor, SAE Flexpaper 05/10/2018.
6. Walczak M., Bieniaś J., Sidor-Walczak J.: Badania korozyjne aluminiowych kompozytów zbrojonych sic wykorzystywanych do produkcji tarcz hamulcowych, Autobusy 6, 2010, pp. 1–7.
7. Posmyk A., Czech R.: Wpływ korozji na eksploatację kompozytowych tarcz hamulcowych, Tribologia 1, 2012, pp. 41–51.
8. Czech R., Posmyk A.: Ocena skuteczności hamowania samochodowych układów hamulcowych na podstawie badań stanowiskowych, Tribologia 2, 2015, pp. 21–29.
9. Polański Z.: Planowanie doświadczeń w technice. PWN, Warszawa 1984.
10. Posmyk A.: Warstwy powierzchniowe aluminiowych tworzyw konstrukcyjnych, Wydawnictwo Politechniki Śląskiej, Gliwice 2010.