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INFLUENCE OF BICYCLE BRAKE SYSTEM ON USERS SAFETY

WPŁYW UKŁADU HAMULCOWEGO ROWERU NA BEZPIECZEŃSTWO UŻYTKOWNIKÓW

Key words: bicycle brake, pad, disc, braking force, wear, braking efficiency.

Abstract In many big cities, for example, Silesia Conurbation, in order to limit the negative results of automotive vehicles operation, toll bicycle rental stations have been actuated. Their users are incidental persons. Therefore, the safety of a traffic participant on bicycle ways and on areas with bicycle traffic depends on the sufficiency of braking systems. In the bicycle industry, there are many of types of brake systems from mechanical to hydraulic. A common part of the brake systems is a friction contact. In this paper, the results of tribological examination of materials used for bicycle brakes have been presented. Tribological investigation (coefficient of friction, wear rate) of classic (the oldest) rubber pad/AW-6061 alloy wheel band, composite with thermoplastic matrix/steel and AW-6061 alloy wheel band as well as friction composite with duroplastic matrix/steel brake disc contacts have been conducted. Microscopic observations of examined materials surfaces have been done and the wear mechanisms have been explained. A preliminary estimation of the influence of used materials on the safety of a traffic participant has been done.

Słowa kluczowe: hamulec rowerowy, klocek, tarcza, siła hamowania, zużycie, skuteczność hamowania.

Streszczenie W wielu dużych miastach, np. Konurbacji Śląskiej, w celu ograniczenia negatywnych skutków eksploatacji pojazdów samochodowych wprowadzono samoobsługowe, odpłatne wypożyczalnie rowerów. Ich użytkownikami są przypadkowe osoby. Dlatego bezpieczeństwo uczestników ruchu na ścieżkach rowerowych i w miejscach ruchu rowerów zależy m.in. od skuteczności hamowania układów hamulcowych. W przemyśle rowerowym istnieje wiele odmian układów hamulcowych od mechanicznych po hydrauliczne. Częścią wspólną wszystkich rozwiązań jest skojarzenie cierne. W artykule przedstawiono wyniki badań skojarzeń materiałów stosowanych na hamulce rowerowe. Wykonano badania tribologiczne (współczynnik tarcia, zużycie) klasycznych (najstarszych) skojarzeń guma/obręcz ze stopu aluminium, kompozyt z osnową termoplastu/stal i obręcz ze stopu aluminium oraz kompozyt cierny z osnową duroplastu/stalowa tarcza hamulcowa. Wykonano badania mikroskopowe powierzchni badanych materiałów i wyjaśniono różnice w mechanizmach zużywania. Dokonano wstępnej oceny wpływu stosowanych materiałów na bezpieczeństwo uczestników ruchu.

INTRODUCTION

Since the invention of the vehicle, countless models of motor vehicles of various brands around the world have been developed, tested, and put into operation. Vehicles with gasoline, diesel, and gas engines are in use. Due to economics and ecology, there were various trends. At the beginning of the 21st century, the number of vehicles powered by internal combustion engines and emissions emitted by them in the form of exhaust gases, noise, and wear products reached values that prompted people to pro-ecological activities. Eco- and electromobility have become fashionable concepts. The most visible effect of this is the attempt to switch to vehicles powered by electric motors. Analyses prepared and published are incomplete, because they do not take into account many factors, such as environmental pollution by the power industry producing electricity, how to dispose of millions of used batteries, the resources and price of lithium (significantly increased demand for the production of low-density composites and lithium-ion batteries) and catastrophic conditions of its production in the countries

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of South America (from 1 ton of dusting salt, 5 kg of pure lithium are obtained), urban infrastructure unsuitable for a huge number of vehicles, e.g., in the Upper Silesia Conurbation.

Bearing in mind the communication difficulties in the city centre, in Katowice, since 2015, an alternative bicycle transport called "City by Bike" has been launched, i.e. a system of self-service, paid bike rentals. In the first year, there were 3 bike rental stations, in 2016, there were already 11 of them, and in 2017, there were already 35 stations, in which 20 thousand users rented bikes 103 620 times [**L. 1**]. Moving by bicycle in Silesia finds more and more residents' support, as evidenced by the declaration of construction of the next 11 rental stations within the civic budget.

Similarly to Katowice, it is in Gliwice, Tychy, Pszczyna, and other regions of Poland. In Warsaw, there have been 205 rental stations open since 2012, out of which 7,915,552 bicycles were rented in 2012–2016 [**L. 2**]. A rental station for 12 bikes takes a place sufficient to park one car. In cities such as Katowice, there are not enough spaces for parking, which is why cycling to the centre can help solve the problem of communication and improve the environment.

Rented bikes are used by random people with diverse driving skills, which are why one should take care of the safety of the drivers of the bike and other road users, including passers-by near the bicycle paths. Beside to city rental, there are tourist bike rentals; in addition, there are numerous bicycles for individual owners.

The basic factor determining the safety of bicycle users is the braking performance, which depends on friction force determining the braking distance. The friction force depends on the value of the coefficient of friction and the pressure force of the brake elements. In older types of bikes, rubber was used for brake pads and composites with thermoplastic matrix in newer types. The latest solutions use small-size blocks of composites with a matrix of thermosetting resins with fillers, including metal ones.

Taking into account the growing number of bicycles in city traffic, in sport and recreation, there are a few Polish-language [**L. 3**] and English-language [**L. 4–6**] publications devoted to bicycle brakes and they are examining [**L. 6**] and launching a new specialty: Eco- and Electromobility in Transport at the Faculty of Transport Silesian University of Technology, which has started research on the impact of bicycle braking systems on the safety of road users. Students from the Scientific Circle participate in the research. This article is devoted to the impact of materials used to produce bicycle braking systems on the braking performance and the durability of bicycle brakes, which co-decide on the safety of driving.

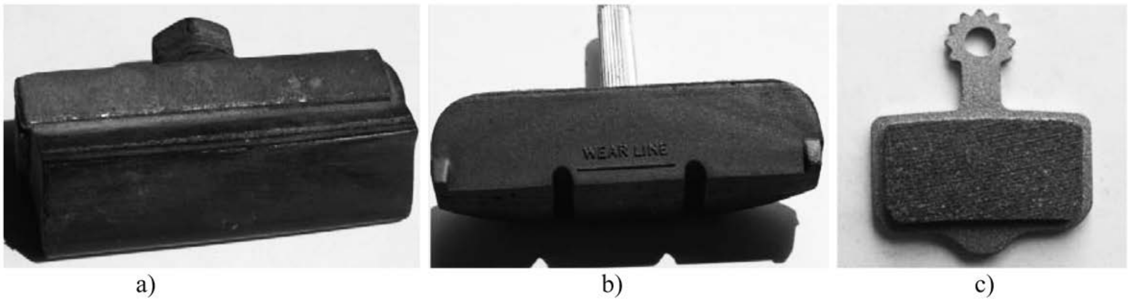

a) b) c)

Fig. 1. Bicycle brake pads made of rubber (a), composite with thermoplastic matrix (b) and composite with thermosetting matrix

Rys. 1. Klocki hamulców rowerowych wykonane z: a) gumy, b) kompozytu z osnową termoplastyczną, c) kompozytu z osnową żywicy termoutwardzalnej

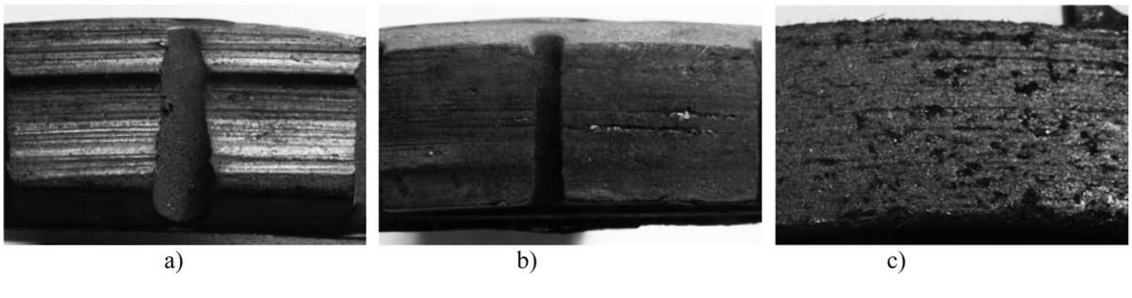

a) b) c)

Fig. 2. Surfaces after friction of rubber pad (a), composite with thermoplastic matrix (b) and composite with thermosetting matrix

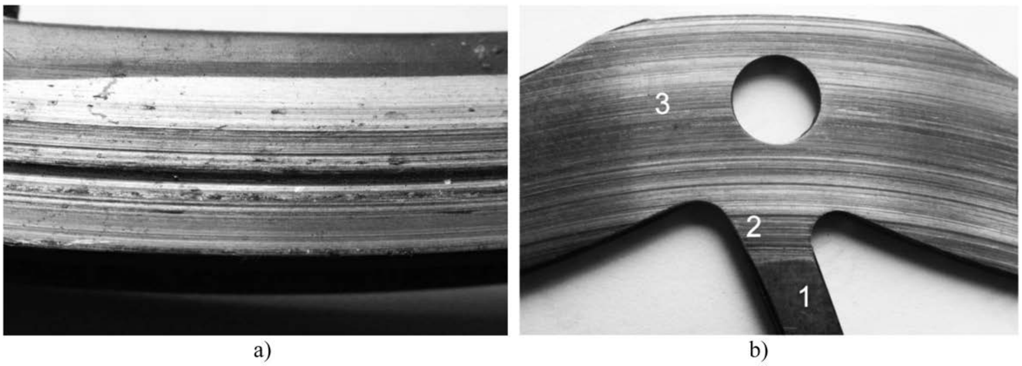
Rys. 2. Powierzchnie po tarciu klocka gumowego (a), kompozytowego z osnową termoplastyczną (b) i kompozytowego z osnową termoutwardzalną

MATERIALS USED FOR TESTING

On the basis of an overview of available solutions of braking systems currently used by bicycle manufacturers, three friction materials groups were selected for testing, i.e. rubber (used in older types of block brakes), a composite with a thermoplastic matrix (currently used), and a composite friction material with a thermosetting resin matrix. Counter samples were made of steel used for bicycle brake discs and aluminium alloy (AW-6061) used for bicycle wheel rims. Brake pads made of rubber and thermoplastic composite (**Fig. 1**) are used in tourist bicycles, sometimes urban (often drum brakes), and composite ones with a thermosetting resin matrix are used for performance bicycle riding.

TRIBOLOGICAL TESTS

Before laboratory tests, in order to determine the mechanisms of wear of friction elements of bicycle brakes, macroscopic tests were carried out. Selected examples are shown in **Figures 2** and **3**.



a) b)

Fig. 3. Surfaces of wheel band (a) and brake disc after rubbing: 1 – part without friction, 2 – part of rib being in contact with pad, 3 – correct friction area

Rys. 3. Powierzchnie robocze obręczy koła (a) i tarczy hamulcowej (b) po tarciu: 1 – fragment niebiorący udziału w tarciu, 2 – fragment ożebrowania, po którym trze klocek, 3 – obszar poprawnej współpracy

Tribological tests were carried out on the T-01M tester (**Fig. 4**), in which the sample was cut from friction materials cubes with a working surface area of 1 cm^2, and counter-samples were made of steel and aluminium alloy. The cubes were fixed in the holder. A view of samples and counter samples is presented in **Figure 5**. During the rubbing, friction forces were measured and recorded using a force transducer (0.5 accuracy class) and wear of rubbing elements using a laboratory scale with an inaccuracy of 0.2 mg. The tests were carried out in the following conditions: relative velocity v = 0.0073 m/s, unit pressure p = 0.2 MPa, friction distance s = 22.5 m, number of repetitions n = 5. These conditions correspond to the beginning of single braking with a bicycle running at a speed of 20 km/h. The results of macroscopic examinations of selected brake friction elements are shown in **Figures 2** and **3**. The results of tribological tests are presented in **Table 1**. The dependence of the friction coefficient on the braking time in contact with rubber and thermosetting composite is shown in **Figure 6**, and with a composite with a thermoplastic matrix in **Figure 7**.

Table 1. Results of tribological tests

Tabela 1. Wyniki badań tribologicznych

Contact	Friction coefficient μ	Wear, Δm, mg			
		of block	$\sigma_{\Delta m}$**)	of disc	$\sigma_{\Delta m}$
Rubber/AW-6061	0.63–0.42*)	0.48	1.11	2.72	2.96
Guma/stal	0.23–0.44	0.44	0.43	0.2	0.12
Thermopl. matrix composite/AW-6061	0.56–0.52	2.6	1.59	0.22	0.016
Thermopl. matrix composite/steel	0.86–0.36	0.93	0.53	0.05	0.056
Thermoset. matrix composite/steel	0.37–0.48	0.65	0.72	0.2	0.23
Thermoset. matrix composite/AW-6061	0.56–0.61	3.4	1.18	7.2	7.9

*) value at the beginning and the end of examination,

**) $\sigma_{\Delta m}$ – standard deviation for average wear of 3 samples.

Fig. 4. Friction contact of T-01M tester: 1 – sample, 2 – sample holder, 3 – countersample, 4 – friction force gauge

Rys. 4. Węzeł tarcia testera T-01M: 1 – próbka, 2 – uchwyt próbki, 3 – przeciwpróbka, 4 – tensometryczny przetwornik siły tarcia

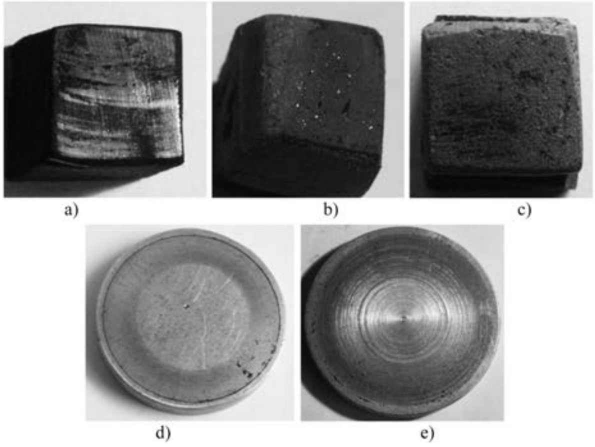
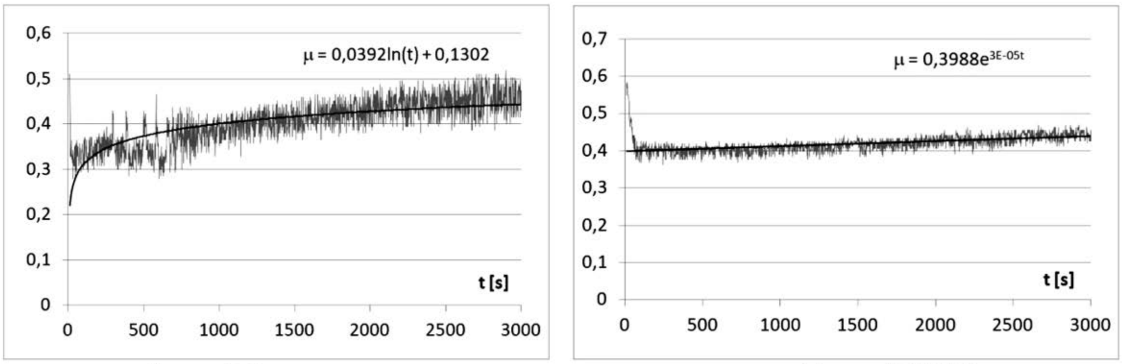


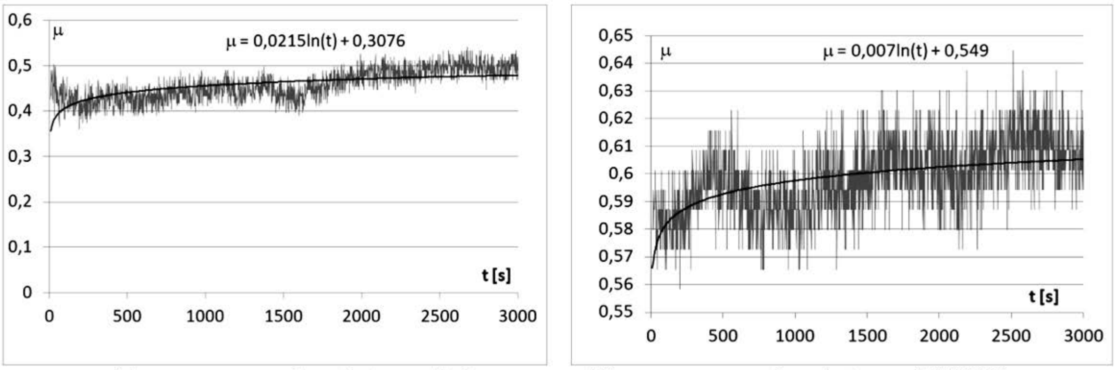
Fig. 5. Samples made of rubber (a), thermoplastic matrix composite (b), thermosetting matrix composite (c) and countersamples made of AW-6061 alloy (d)) and steel (e) after friction

Rys. 5. Próbki z klocka gumowego (a), kompozytowego z osnową termoplastyczną (b) i kompozytowego z osnową z żywicy termoutwardzalnej (d) oraz przeciwpróbki ze stopu AW-6061 (d) i stali (e) po tarciu



a) guma/stal

b) guma/AW 6061



c) komp. z osnową duroplastyczną/stal

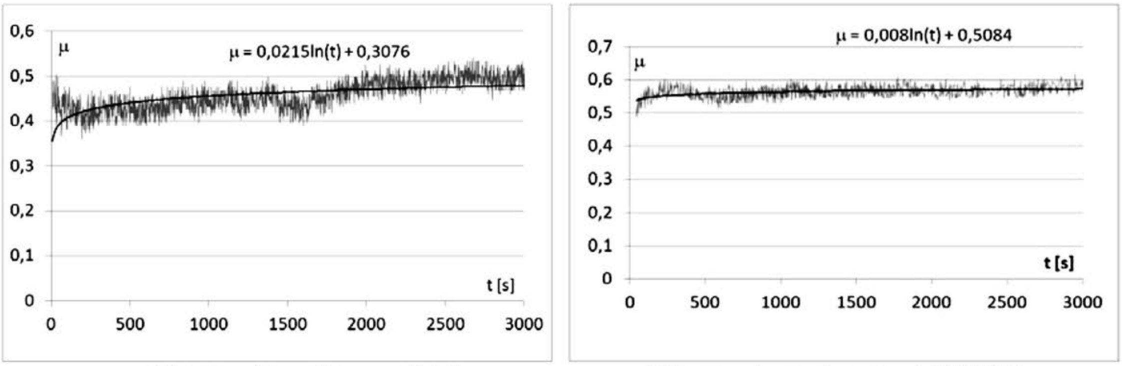
d) komp. z osnową duroplastyczną/AW 6061

Fig. 6. Friction coefficient (μ) vs. braking time (t) of rubber (a, b) and thermosetting (c, d) pads

Rys. 6. Zależność współczynnika tarcia (μ) od czasu hamowania (t) klocków gumowych (a, b) i termoutwardzalnych (c, d)

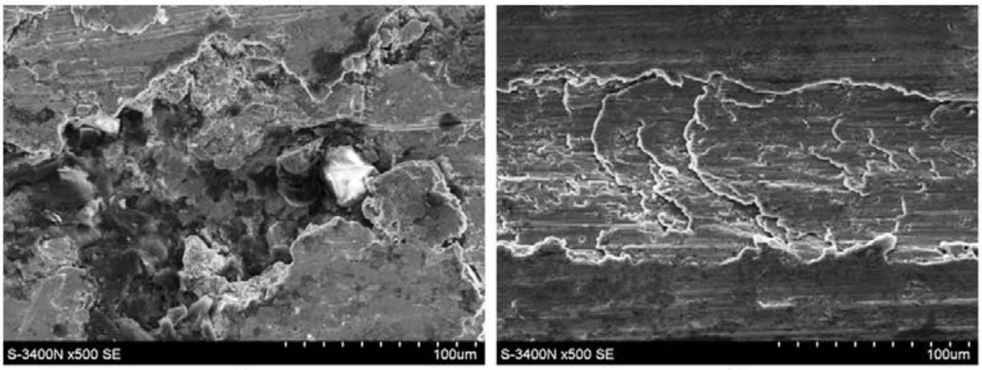
MICROSCOPIC EXAMINATION

In order to explain the differences in the mechanisms of the wear of the materials examined, microscope examinations (SEM) were made on the surface of pad and friction discs. A view of the surface of the rubber block after rubbing against the AW 6061 alloy disk is shown in **Figure 8**, and the block of thermosetting resin after rubbing against the steel disc is shown on **Figure 9**.



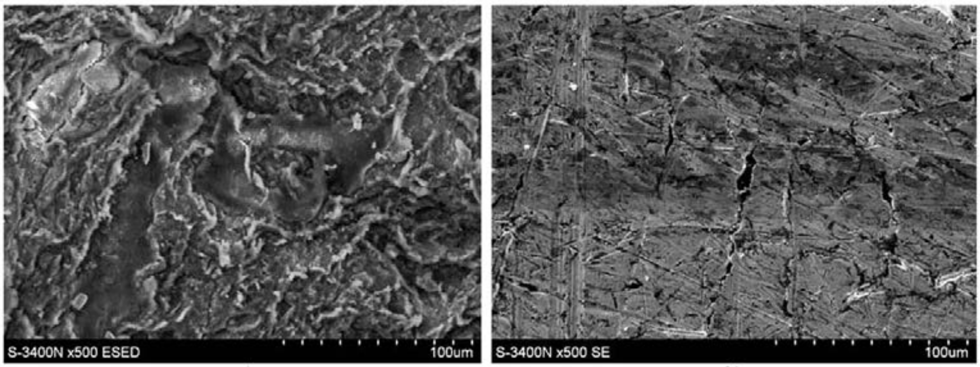
a) komp. z termopl. osnową/ stal b) komp. z termopl. osnową/ AW-6061

Fig. 7. Friction coefficient (μ) vs. braking time (t) for thermoplastic pad against steel (a) and AW60-61 (b)
Rys. 7. Zależność współczynnika tarcia (μ) od czasu hamowania (t) dla klocków termoplastycznych podczas tarcia ze stalą (a) i AW-6061 (b)



a) b)

Fig. 8. Surfaces of rubber pad (a) and AW-6061 alloy disc (b) after friction
Rys. 8. Powierzchnie po tarciu gumowego klocka hamulcowego (a) i tarczy z AW-6061 (b)



a) b)

Fig. 9. Surface of thermosetting composite brake pad (a) and steel disc (b) after friction
Rys. 9. Powierzchnie po tarciu termoutwardzalnego klocka hamulcowego (a) i stalowej tarczy (b)

DISCUSSION OF RESULTS

From the macro photographs shown in **Figures 2** and **3**, it can be concluded that, during the rubbing of the rubber pads and the thermoplastic composite against the aluminium wheel rim, there is abrasive wear of the block (**Figs. 2a** and **2b**) and rim (lengthwise scratches in **Fig. 3a**). It even results in the negative projection of the shape of the rim on the block (**Fig. 2a**) and the inclusion of rim wear products in the block material (**Figs. 2b**). The composite block of a thermosetting resin also is abrasively worn (**Fig. 2c**) and thermal degradation of the resin takes place. The steel disc rubbing against the block undergoes an even abrasive wear (Area 3 in **Fig. 3b**). It can also be seen that the width of the block or its assembly was not correct, because the block rubbed against the ribbing of the disc (Area 2 in **Fig. 3b**). Such contact may threaten to inhibit the block and cause its damage, which could cause the loss of control over the bike, which jeopardizes safety.

The rubbing a rubber block (**Fig. 5a**) vs. an AW-6061 alloy disc (**Fig. 5d**) is dominated by abrasive wear accompanied by a slight delamination of the rubber (**Fig. 8a**). The friction forces cause local delamination of the second type (adhesive). As a result of the heat generated by the friction and the low thermal conductivity of the rubber, there is local plastification and the replacement of aluminium alloy along the direction of the block's movement (**Fig. 8b**). During bench tests, the degree of the coverage of the cube and disk was larger (10 mm cube length and 94.2 mm friction circumference) than the brake pad and wheel rim (300 mm and 2100 wheel circumference); therefore, the friction heat dissipation is slower and the adhesive wear effect is bigger.

During the rubbing of a composite block of a thermosetting resin against a steel disk, abrasive wear prevails and there is a slight thermal destruction of the resin (**Fig. 8a**) caused by the frictional heat. On the steel disk, a sliding film is created from the wear products of the block (darker places in the middle of **Fig. 9b**). As a result of abrasive wear, polishing of fragments of contact surfaces occurs.

The analysis of the results contained in **Table 1** and friction coefficient diagrams shows that the frictional resistance in the rubber/steel contact (**Fig. 6a**) and a composite with the duroplastic/steel matrix (**Fig. 6c**) are similar. The coefficient of friction in the rubber/AW-6061 contact at the beginning of rubbing is the highest (0.6, **Fig. 6b**), and at the end of the rubbing the lowest is (0.44). This is due to the presence of natural aluminium oxide on the surface of the disc made of AW-6061 alloy. The oxide thickness is a few nanometres, which is why it is removed after several seconds of friction.

An attempt to use a thermosetting matrix composite for rubbing against the AW-6061 alloy showed that the friction force is the highest (0.56–0.61), but the wear of the disk (7.2 mg) and block (3.4 mg) are too big. When using such a brake in a bicycle, this would result in a quick wear of the wheel rim. This would increase the play between the pad and the rim and would weaken the rim resulting in its damage and the safety of road users menacing.

Noteworthy is the high wear of friction material made of composite on a thermoplastic matrix rubbing against AW-6061 (2.6 mg) and the steel (0.93) disc. This may result from a thermoplastic matrix that becomes plastic under the influence of frictional heat. Important information for the user is the lower value of the coefficient of friction of the brake with a rubber block (0.23) for several dozen seconds from the beginning of braking, which has an impact on safety.

A disturbing phenomenon is the large dispersion of the mass losses of friction material and discs, which may indicate a lack of homogeneity in the chemical composition of the materials for the brake pads. Confirmation of this requires a qualitative analysis. The discs made of the AW 6061 alloy and steel used for brake discs were turned from rolled rods of known chemical composition.

Considering the significant differences in friction radius of the rim brake (350 mm) and disc brake (80 mm) and the similar values of friction coefficients, it can be concluded that almost four times more pressure force is required to maintain similar values of braking forces in a disc brake. This requires different mechanisms of clamping the pads to discs.

SUMMARY

A very large number of tour and performance bicycles owned by individual users and numerous self-service rental stations create logistical problems with the control of their condition and possible servicing. From the point of view of the safety of road users on bicycle lanes and in the city, the condition of braking systems is important. Therefore, the determination, in the laboratory, of the intensity of wear of brake system components in conditions simulating driving, e.g., urban, can be helpful in choosing the friction contacts appropriate for urban driving and in determining the time of their safe use.

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