

RESEARCH ON THE EFFECT OF TEMPERATURE AND SPEED OPERATING MODES ON THE WEAR RESISTANCE OF BRAKE PADS

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Abstract: The study reviews the effect of operating modes on brake pad wear and braking efficiency under different temperature and speed phases. The dynamic changes occurring in the friction pair during braking are described, and the causes of brake pad wear and the factors affecting its magnitude are analyzed. The effects of speed and temperature modes on changes in braking efficiency and wear resistance characteristics of a brake pad were investigated in the laboratory of BCZ “Tribo” LLC using a TecSa TTR2600 dynamometer. Laboratory testing of a 2TP-114 Tp108 R3 brake pad specimen was carried out in accordance with ISO 26866:2009. Evaluation of wear of the 2TP-114 Tp108 R3 brake pad specimen during testing under different temperature and speed conditions showed that as the speed increased from 60 to 100 km/h, mass and linear wear also increased, but this increase was not critical and did not lead to changes in microstructure or destruction of the pad.

Keywords: brake friction pair, efficiency, wear resistance, microstructural changes, friction, thermomechanical effect, tribological properties.

Introduction. The wear process of vehicle brake pads is a nonlinear and non-stationary system that changes over time and is difficult to predict. The sensitivity of the braking mechanism to temperature, pressure, and speed during braking primarily depends on the composition of the braking system components and the proportions between them. Although there are not many variations in the material used to manufacture brake discs, there are many possibilities for selecting and combining materials in brake pad manufacturing. Therefore, manufacturers and scientists continuously create and experiment with different combinations of materials in brake pads to achieve the desired result.

Typically, when studying the influence of various factors on the wear resistance of braking mechanisms, braking efficiency is evaluated during tests and chemical and microstructural changes occurring on the brake pad surface during simulation of the braking process are studied. Thus, Bevz O.V., et al. [2] evaluated the performance of passenger-car brake pads under different operating conditions (speed and temperature). The studies were conducted on a special test bench using the braking assembly of a Hyundai Accent vehicle. Volkov V., et al. [10], using a mixed braking system of a passenger vehicle as an example, evaluated the influence of the stability of braking mechanism characteristics on the braking process. The experimental results showed that under cold and cooled braking mechanisms, the mean value of the friction coefficient and the dispersion of its values are approximately the same. However, at high temperatures they decrease significantly. Yamshynskiy M., et al. [13], based on the assessment of friction element characteristics, proposed an objective function that makes it possible to select the most advantageous design composition of a brake pad for a specific vehicle. According to their research, heat dissipation during braking and optimization of the friction coefficient should tend toward maximum values, while wear of the friction pair, environmental emissions, and cost should tend toward minimum values.

Most foreign studies of the wear resistance of braking mechanisms note the influence of various factors (friction temperature, braking speed, vehicle weight, and operating conditions) on changes in microstructure and the tribological properties of the brake friction pair. Wan Z., et al. [11], as a result of a series of experiments, found that the friction coefficient is inversely proportional to vehicle speed, while showing a mixed trend depending on vehicle mass. Chen F., et al. [4] studied braking and wear trends for PMC/C-SiC and PM-30CrMnSi pads under high-energy braking. The experimental results showed that the PM-C/C-SiC brake pair had better characteristics due to the use of carbon-fiber-containing lubricant, which promotes formation of a dense tribolayer during braking. The main wear mechanisms for the PM-C/C-SiC brake pair were oxidation and delamination wear, whereas the PM-30CrMnSi brake pair was

characterized mainly by adhesive and abrasive wear. Wang S., et al. [12] proposed the CNN-LSTM method (remaining-life prediction based on processing data from multi-object complex systems) for real-time monitoring of brake pad wear thickness, which makes it possible not only to study in detail the spatial characteristics of brake disc speed, brake pressure, brake pair temperature, and other wear-related information, but also to retain current information in the time dimension. Borawski A. [3], investigating the wear resistance of braking mechanisms, proposed a test method based on the Taguchi optimization approach. To determine the friction coefficient and abrasive wear rate, tribological experiments were conducted on a series of brake pad specimens containing copper both in powder and fiber form. The test results showed that replacing aramid fibers with copper did not significantly change the friction coefficient or abrasive wear rate. Lee H., et al. [6] investigated how the grain size of a copper matrix in sintered copper-based composites affects the microstructure and tribological properties of tribolayers formed during sliding friction. The results showed that wear dynamics and composite hardness significantly affect the stability and composition of tribolayers. It was also found that the characteristics of self-lubricating tribolayers play a decisive role in determining the friction coefficient and wear resistance.

The analyzed studies are useful for understanding how various thermomechanical factors affect brake pad wear and contribute to further research aimed at finding more wear-resistant materials and designs to improve the efficiency and durability of braking mechanisms.

The aim of the study was to investigate the effect of different operating modes on brake pad wear and braking efficiency under different temperature and speed phases.

To achieve this aim, the following tasks were set:

- 1) 1) to investigate the dynamic changes occurring in the friction pair during braking;
- 2) 2) to analyze the causes of brake pad wear and the factors affecting it;
- 3) 3) to conduct laboratory tests of a 2TP-114 Tp108 R3 brake pad specimen on a TecSa TTR2600 dynamometer;
- 4) 4) to evaluate the effect of speed and temperature modes on changes in brake pad wear-resistance characteristics.

Materials and Methods. During vehicle braking, a thermomechanical engagement effect occurs at the contact surface of the brake friction pair, resulting in damage to the surface and subsurface layers of the brake disc and pad. This phenomenon occurs in any braking system when, with increasing temperature, the friction coefficient decreases substantially [8], while the brake disc and pads wear. Brake system wear is a complex dynamic process (Fig. 1) in which, as a result of pressing the brake pad against the brake disc (1) and friction between them, a displacement (2) occurs caused by relative sliding of the friction-pair surfaces, which leads to plastic deformation of the contacting materials (frictional load (3)). This, in turn, contributes to a reduction in the thickness of the brake pad and disc, with the latter wearing highly unevenly.

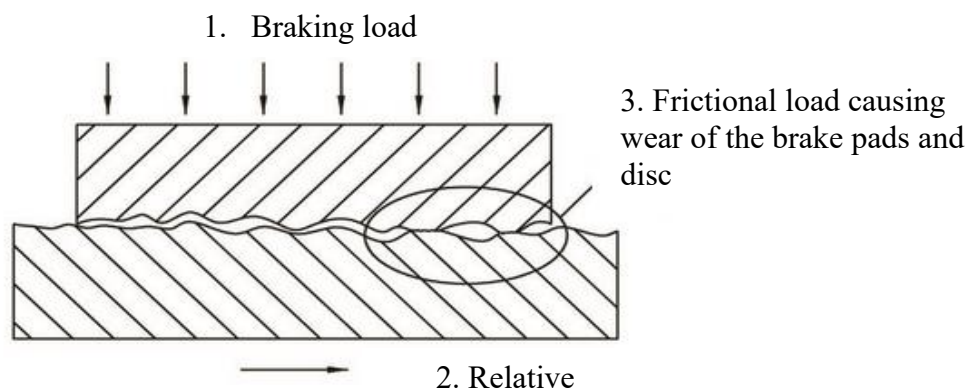


Fig. 1. Scheme of dynamic changes in the friction pair during braking

Source: developed based on [7; 15].

In addition, during braking at high speed and with a heavy vehicle, high temperature develops in the braking mechanism and wear of the frictional contact occurs. Thus, the wear process of a brake pair is the gradual destruction of friction material under the influence of friction, thermal, and mechanical loads arising during braking [14]. Visually, it can be represented as a linear scheme in which each stage is a block describing a process (Fig. 2).

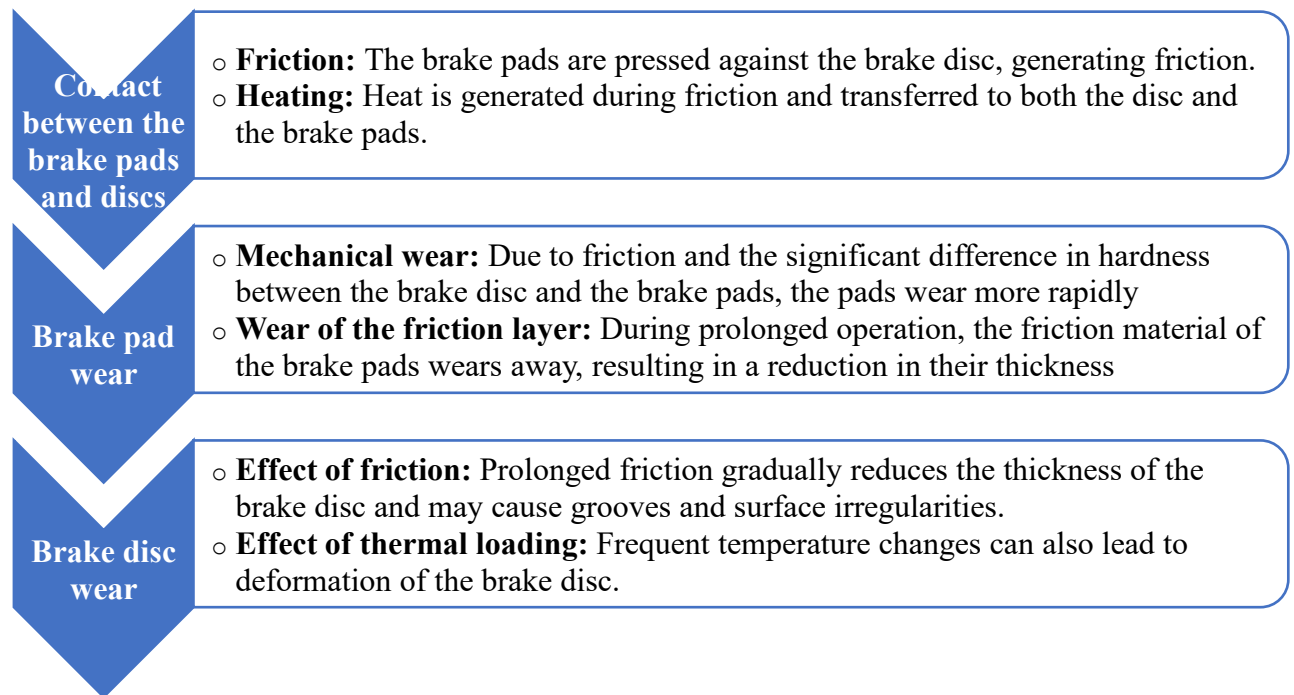


Fig. 2. Brake friction-pair wear process

Source: developed based on [3; 9; 12; 15].

However, brake pad wear is a natural process that occurs during vehicle operation and has objective causes. Therefore, brake pad wear is usually monitored through regular maintenance and replacement as necessary. It can also be predicted and calculated. Thus, Archard introduced the classical wear theory for braking mechanisms [5], in which wear volume (V) for a smooth surface is determined by the formula:

$$V = K \times \frac{P \times L}{H}, \quad (1)$$

where: P – normal force of adhesion at the contact surface;

L – relative sliding distance;

H – hardness of the friction material;

K – dimensionless wear coefficient.

However, under real vehicle operating conditions, the contact surface of the friction pair is rough, so the actual contact area is usually related to the micromorphology of the contact surface [1], in which stress changes depending on the wear depth of each individual unit on it, which in turn contributes to an increase in the degree of wear. Considering that during high-speed braking of a loaded vehicle, friction at the contact pair deteriorates and a large amount of frictional heat is generated, the structure of the friction material (viscosity, hardness, resistance, etc.) also changes. The relationship between temperature and friction-material hardness is as follows:

$$H(T) = H_0 \times e^{-\alpha T}, \quad (2)$$

where: H(T) – material hardness at temperature T;

H₀ – initial material hardness;

α – temperature coefficient depending on material properties;

T – temperature.

Thus, a dependence arises in which the degree of pad wear depends on the hardness of the friction material, while a change in temperature in the contact pair can, in turn, substantially affect the hardness of the friction material. Zhang S., et al. [15] expressed this dependence as:

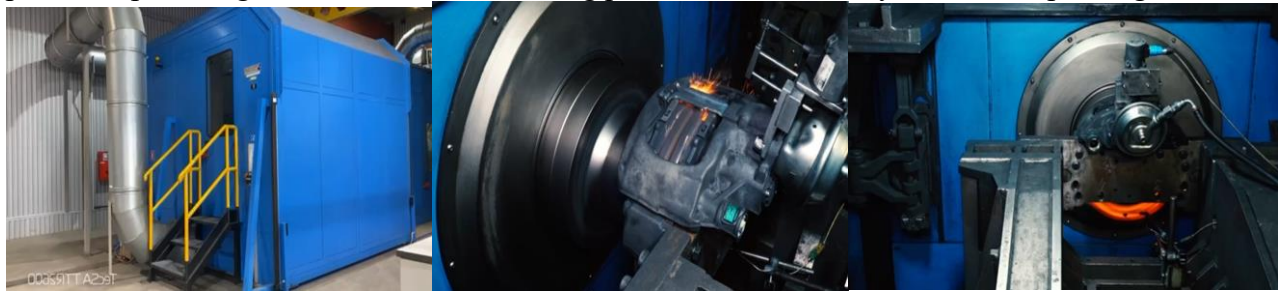
$$H = \text{const} \times \exp\left(\frac{\alpha}{\theta}\right), \quad (3)$$

where: α – constant;

θ – contact temperature.

The dependence of brake pad wear and durability on operating temperature modes can also be verified under laboratory conditions using special equipment. In our case, the characteristics of the brake pad were studied in the laboratory of BCZ “Tribo” LLC on a TecSa TTR2600 dynamometer.

The TecSa TTR2600 dynamometer (Fig. 3) makes it possible to perform a detailed analysis of brake pad wear, providing accurate data for evaluating performance and safety under real operating conditions.



a) general view of the test bench b) mounting of the brake c) test process mechanism

Fig. 3. TecSa TTR2600 dynamometer

Source: BCZ “Tribo” LLC. URL: <https://www.tribo.ua>

Measurement of brake pad wear on the TecSa TTR2600 dynamometer makes it possible to determine how quickly the pads wear during testing and to assess their performance and durability. It should also be noted that during testing all test specimens are subjected to identical conditions, eliminating the influence of human factors (driver condition, driving style, etc.) and vehicle condition (braking-system condition, vehicle load, etc.), thereby providing objective and directly comparable data. One test takes approximately 40 hours, during which the dynamometer records up to 1,000 measurements under different temperature modes and operating conditions.

Results and Discussion. For laboratory testing, a 2TP-114 Tp108 R3 pad specimen is proposed, featuring improved geometry in the form of a tapered edge that damps vibrations and prevents possible destruction of the friction material at the beginning of the working cycle, as well as an additional bedding-in layer that promotes rapid adaptation of the pad to the brake disc (Fig. 4a), and a friction-material composition containing carbon fibers that protect against critical overheating during extreme braking and improve the structural integrity of the pad (Fig. 4b).

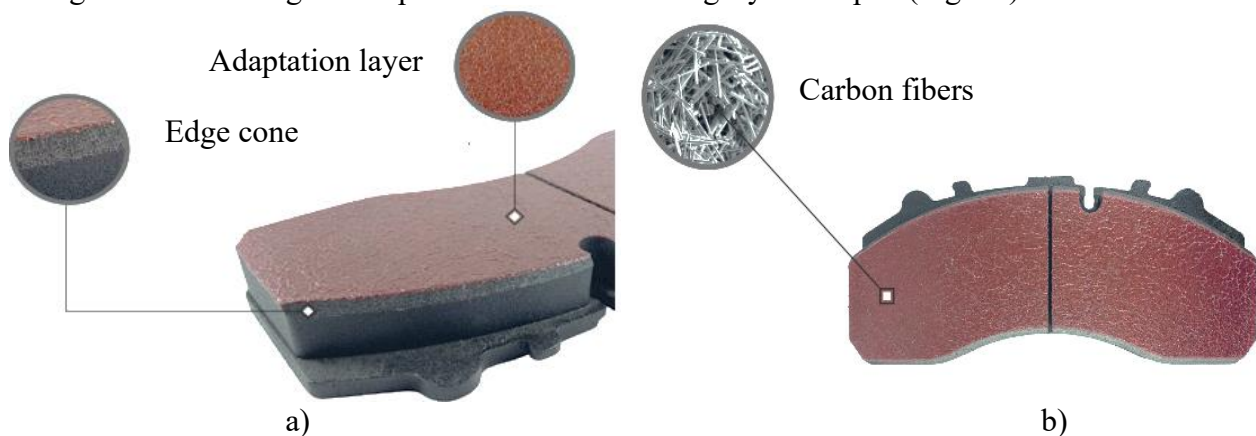


Fig. 4. 2TP-114 Tp108 R3 brake pad

Source: BCZ “Tribo” LLC. URL: <https://www.tribo.ua>

The specimen was tested in accordance with ISO 26866:2009.

The following equipment was used during the tests: Tecsra TTR2600 inertia dynamometer; Radwag APP35/C/1 electronic scales; MK-50 micrometer; VIT-1 hygrometer.

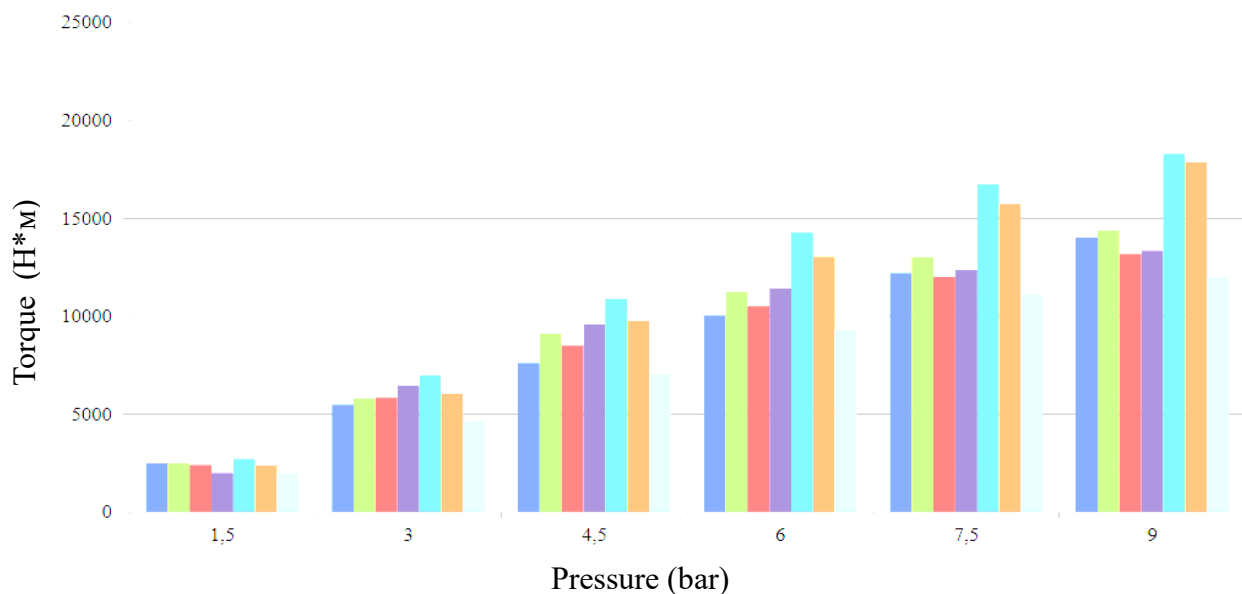
Test conditions and limitations:

1. 1. The brake disc is weighed and measured with a micrometer before and at the end of the test.
2. 2. The brake pads are weighed and measured with a micrometer before the test, before each temperature change in the wear-braking phase, and at the end of the test.
3. 3. The initial temperature (T_p) is specified in the test program; the final temperature does not affect the test program, i.e. under identical initial braking conditions, the final conditions may differ substantially.
4. 4. During the “Wear braking” phases, deceleration of 1.5 m/s^2 is constant. The dynamometer monitors this parameter during braking and continuously increases or decreases the pressure on the pad to maintain the target deceleration of 1.5 m/s^2 .

Test results:

Figure 5 shows braking efficiency after different temperature phases (from 100 to 500°C), where torque (0 to $25,000 \text{ N}\cdot\text{m}$) is the actual indicator of braking efficiency, while pressure (“1.5” – light braking; “9” – brakes fully applied) simulates the force with which the driver presses the brake pedal.

Analysis of braking-efficiency results shows that, with changing temperature and equal forces applied to the brakes, torque remains stable. As the temperature increases to 300°C , braking torque increases, which is associated with oxidation of the sulfides used in pad manufacture. The drop after 500°C compared with the initial phases is insignificant, indicating that the pad can be safely used even at such high temperatures.



Note:

■ – braking with new, newly installed pads;
 ■ – braking in the “bedding-in” mode;
 ■ – braking at 100°C ;
■ – braking at 200°C ;
 ■ – braking at 300°C ;
 ■ – braking at 400°C ;
 ■ – braking at 500°C .

Fig. 5. Braking efficiency results with temperature variation

Source: test protocol for product 2TP-114 Tp108 R3

In Figure 6, each point represents one of 100 accurately simulated braking events in which the test bench maintains a constant pad pressure of 3 bar.

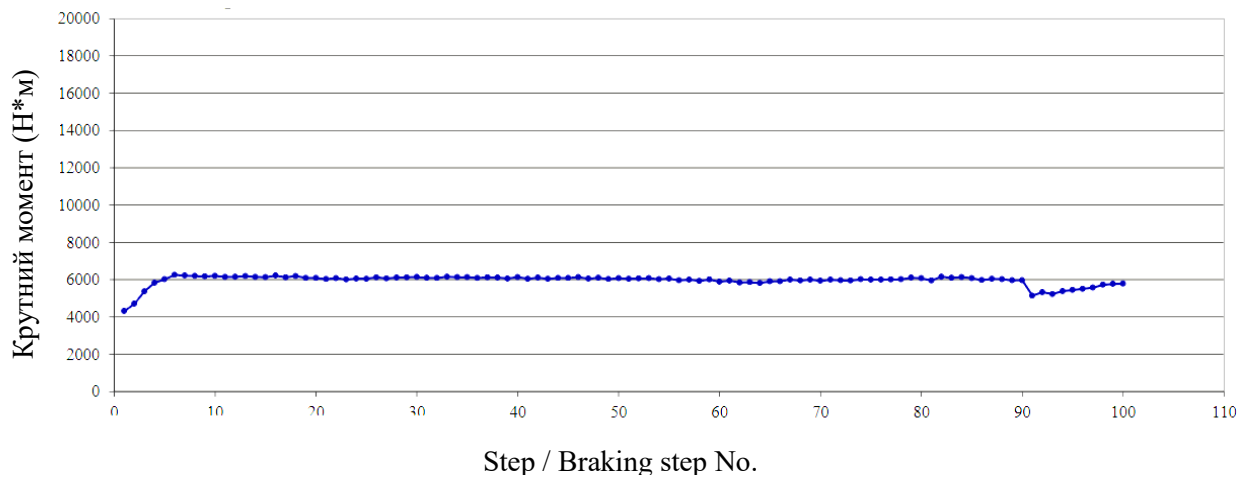


Fig. 6. Bedding-in

Source: test protocol for product 2TP-114 Tp108 R3

Analysis of the results in the bedding-in phase shows that during the first six braking events, braking torque increases and then remains stable (600 N·m) up to the 90th braking event, when a slight decrease in torque occurs. This indicates the importance of properly bedding new pads to the disc when replacing them.

During wear-braking tests, a fixed deceleration of 1.5 m/s² was specified, simulating the same vehicle stopping rate. The more uniform the lines, the better, as this means the driver does not need to change the force applied to the brake pedal and can more easily predict stopping speed.

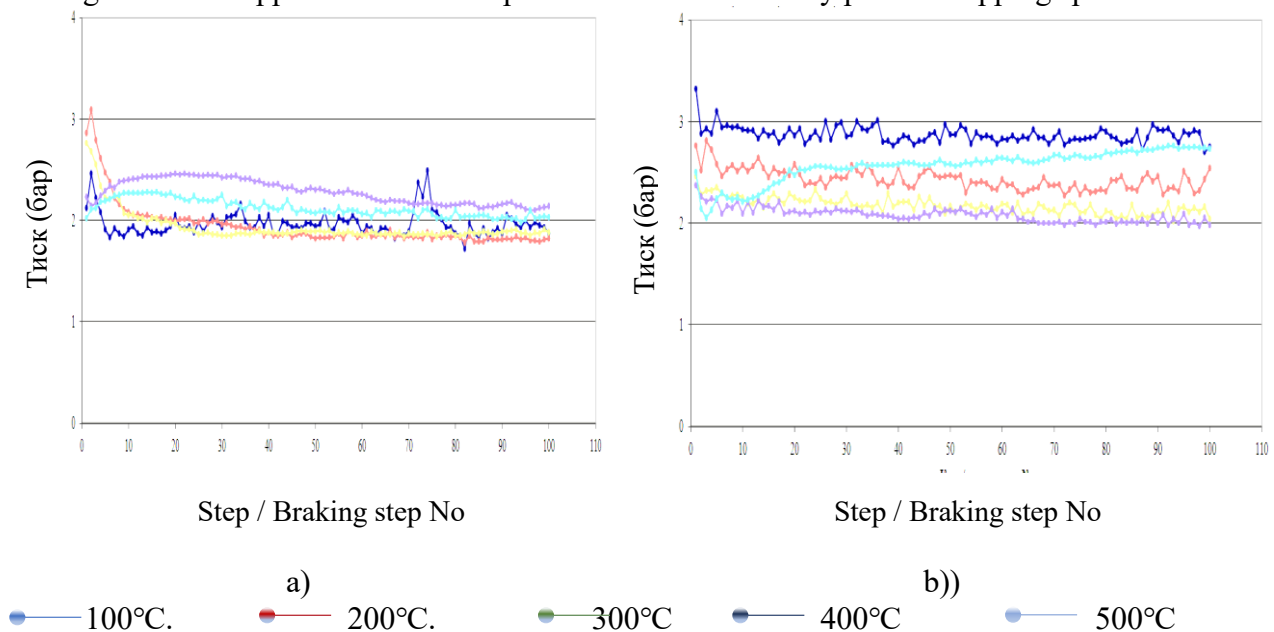


Fig. 7. Wear braking at: a) V=60–10 km/h; b) V=100–50 km/h

Source: test protocol for product 2TP-114 Tp108 R3

Analysis of wear braking results at an initial speed of 60 km/h and a final speed of 10 km/h (Fig. 7a) showed that the specimen demonstrates good and stable results. At different temperatures, different initial pressure peaks are observed (the highest at 100°C, approximately 3.2 bar), with smaller peaks at other temperatures. After several braking steps (approximately after 10), all curves stabilize, and pressure is maintained within 2–2.5 bar. After stabilization (especially after the 70th step), some fluctuations occur at 100°C.

The results of wear braking at an initial speed of 100 km/h and a final speed of 50 km/h (Fig. 7b) show that the brake application force is within 2–3 bar. The increase in speed mainly affected a reduction in braking efficiency at low temperatures (100–200°C) and in the 500°C phase, where

efficiency also gradually decreases. The highest average pressure is observed at 100°C and 500°C (about 3 bar), while the other values remain at approximately 2.2–2.5 bar. The variations in results are not significant, which can also be considered positive.

Table 5. Wear of the brake disc and pad after different temperature phases

Weighing phase			Mass wear (g)			Linear wear (mm)		
Temperature	Initial V km/h	No. of braking events	Pads			Pads		
			Inner	Outer	Average	Inner	Outer	Average
After bedding in	60	100	16,50	16,70	16,60	0,24	0,29	0,26
After 100°C A	60	100	9,70	10,10	9,90	0,21	0,17	0,19
After 100°C B	100	100	34,30	31,80	33,05	0,70	0,60	0,65
After 200°C A	60	100	8,90	13,10	11,00	0,08	0,17	0,13
After 200°C B	100	100	36,20	40,30	38,25	0,64	0,73	0,69
After 300°C A	60	100	6,60	6,40	6,50	0,07	0,09	0,08
After 300°C B	100	100	29,20	28,60	28,90	0,47	0,49	0,48
After 400°C A	60	100	13,50	9,90	11,70	0,07	0,09	0,08
After 400°C B	100	100	61,90	48,60	55,25	0,99	0,81	0,90
After 500°C A	60	100	38,00	29,80	33,90	0,53	0,44	0,49
After 500°C B	100	100	144,90	117,20	131,05	2,55	2,14	2,34
Total wear over the test			399,70	352,50	376,10	6,56	6,04	6,30

A – speed 60 km/h; B – speed 100 km/h

Source: compiled based on test results

As for wear of the friction material of the pad, the results are shown in Table 1 and Fig. 8. The experiment demonstrated an acceptable level of brake pad wear (376.1 g by mass on average and 6.3 mm in linear wear).

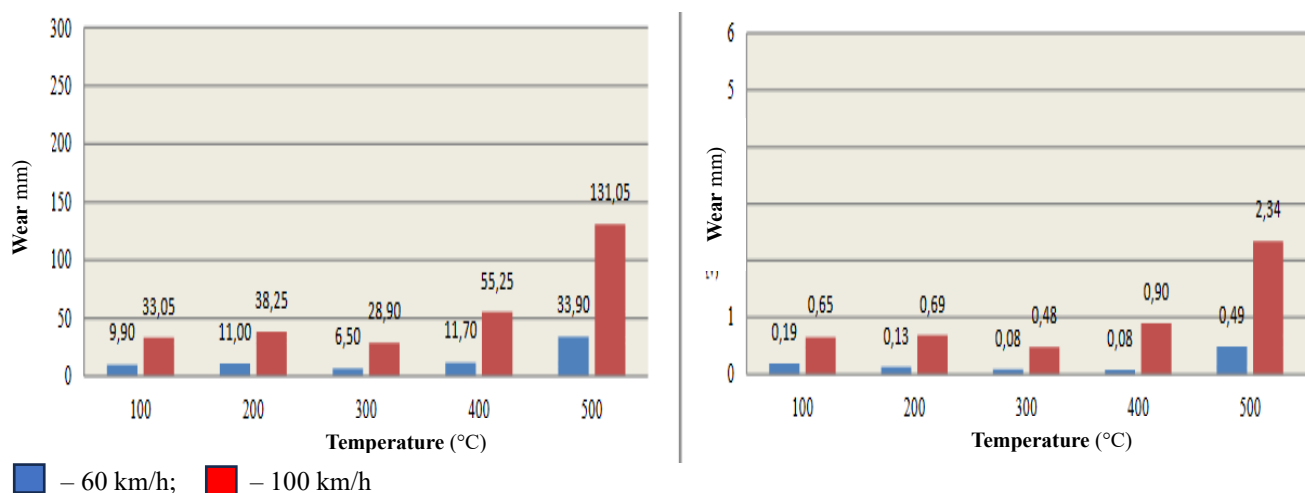


Fig. 8. Comparison of pad wear between speed modes

Source: test protocol for product 2TP-114 Tp108 R3

A more detailed consideration of the wear results for the 2TP-114 Tp108 R3 brake pad specimen during testing under different temperature and speed modes leads to the following main observations:

- mass wear (g): after bedding-in, the average mass wear of the pads is 16.6 g. Trend: pad mass wear increases with increasing temperature. The greatest wear is observed after 500°C at a speed of 100 km/h (131.05 g). A significant jump in wear is observed after increasing the temperature from 400°C to 500°C (from 55.25 g to 131.05 g).

- linear wear (mm): after bedding-in, the average linear wear of the pads is 0.26 mm. Trend: linear wear, as in the previous phase, increases with increasing temperature, but the transition is smoother. After 100°C, the average linear wear of the pads is 0.19 mm. After 500°C at a speed of 100 km/h, linear wear is 2.34 mm. A significant increase in linear wear occurs after 400°C (from an average of 0.90 mm to 2.34 mm after 500°C).

- comparison of inner and outer values: pad wear (inner and outer) shows slight variation, but in some phases, for example after 200°C and 400°C at a speed of 60 km/h, outer wear is substantially greater than inner wear.

- dependence on speed: as speed increases (from 60 to 100 km/h), mass and linear wear also increase. This can be seen by comparing the phases after 100°C at 60 km/h and after 100°C at 100 km/h, where the increase in speed is accompanied by increased wear. However, the increase is not critical and does not lead to loss of braking efficiency or destruction of the pad.

The test results of the 2TP-114 Tp108 R3 brake pad on the TecSa TTR2600 dynamometer can be considered positive. The tests demonstrated high specimen efficiency during braking at both low and high temperatures. Increasing temperature affects both mass and linear wear of the pads. Maximum wear is observed at the highest temperature, 500°C. Increasing speed also increases wear. The most intensive wear occurs at 500°C and a speed of 100 km/h.

Conclusions. The wear process of brake pads has a significant effect on braking efficiency and, consequently, vehicle safety. The main cause of brake pad wear is the gradual destruction of friction material under the influence of friction, thermal, and mechanical loads. During braking, a large amount of heat is released and the brake pad heats to high temperatures, causing thermal stresses in the material. During prolonged or intensive braking, this can lead to thermal degradation of the material, reduced hardness, and accelerated wear.

The study included laboratory testing of a 2TP-114 Tp108 R3 pad specimen, featuring improved geometry in the form of a tapered edge that damps vibrations and prevents possible destruction of the friction material at the beginning of the working cycle, an additional bedding-in layer that promotes rapid adaptation of the pad to the brake disc, and a friction-material composition containing carbon fibers that protect against critical overheating during extreme braking and improve the structural integrity of the pad.

Analysis of braking-efficiency results obtained on the TecSa TTR2600 dynamometer showed that, with changing temperature and equal forces applied to the brakes, torque remains stable. As the temperature increases to 300°C, braking torque increases, which is associated with oxidation of the sulfides used in pad manufacture. The drop after 500°C compared with the initial phases is insignificant, indicating that the pad can be safely used at high temperatures. Increasing braking speeds from 60 to 100 km/h mainly reduced braking efficiency at low temperatures (100–200°C) and in the 500°C phase.

Assessment of wear of the 2TP-114 Tp108 R3 brake pad specimen during testing under different temperature and speed conditions showed that after bedding-in, average mass wear of the pads is 16.6 g and average linear wear is 0.26 mm. Both increase with increasing temperature. The greatest wear is observed after 500°C at a speed of 100 km/h (131.05 g by mass and 2.34 mm linear wear). As speed increases from 60 to 100 km/h, mass and linear wear also increase, but this increase is not critical and does not result in changes in microstructure or destruction of the pad.

Overall, the test results of the 2TP-114 Tp108 R3 brake pad on the TecSa TTR2600 dynamometer can be considered satisfactory. The tests demonstrated sufficiently high specimen efficiency during braking at both low and high temperatures and at different speeds. Further research will focus on comparing the efficiency and wear resistance of the 2TP-114 Tp108 R3 brake pad specimen with analogues manufactured by other producers.

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