sciendo

DOI 10.2478/ama-2019-0025 acta mechanica et automatica, vol.13 no.3 (2019)

COMMON METHODS IN ANALYSING THE TRIBOLOGICAL PROPERTIES OF BRAKE PADS AND DISCS – A REVIEW

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received 10 May, revised 28 September 2019, accepted 30 September 2019

Abstract: Disc brakes in passenger cars are extremely important due to safety concerns. Their operational quality largely rests on the conditions of contact between the working elements, which mainly consists offlat and dry sliding. The tribological phenomena thatoccur during braking are, unfortunately, extremely complex and difficult to recreate in laboratory settings. Many scientific institutes conduct research to improve our understanding of these phenomena. The results they present make it possible to continuously simplify the procedures for selecting friction materials and reducing the costs of identifying the properties of new products. This article analyses the methods commonly used by researchers. It also presents different set-ups of research stations, as well as the advantages and drawbacks of each method.

Key words: Ball-cratering, pin-on-disc, inertia dynamometer, FE method, brakes

1. INTRODUCTION

The brakes are the most important components of any vehicle as they are responsible for reducing its speed or stopping it completely. This is particularly important in hazardous situations in which the proper action of the braking system may save the health and lives of many road users. The issue is deepened by a continuing tendency to increase the power and torque generated by contemporary automobile engines, which directly corresponds to higher commuting speeds (Szpica, 2015a). This motivates many researchers to conduct studies aimed at improving our understanding of the complicated phenomena, which occur during braking.

Automobiles today primarily use disc brakes. The friction pair in this solution comprises in the brake disc and brake pads (Fig. 1).

Fig. 1. Disc brake friction pair: 1 – brakepads
2 – correspondingbrake disc

During braking, as the pad is pressed against the disc, friction occurs, which transforms kinetic energy into heat. Part of the heat initiates chemical reactions, which may transform or degrade some of the components of the brake pad (such as resin) (Česnavičius et al., 2016; Kilikevičius et al., 2016). Most of the remaining energy, in the form of heat, is then released into the atmosphere (Blau and McLaughilin, 2003; Borawski, 2016). A wide range of research, mainly simulations, is being conducted in order to determine the amount of energy involved in the process, as well as its displacement among different parts of the system (Adamowicz, 2016; Yevtushenko and Grześ, 2015b). This is mainly because the design of the braking system makes direct measurements considerably difficult.

The process of braking is largely affected by the tribological properties of discs and pads. The former are commonly made from grey cast iron, as it is characterised by good thermal conductivity and anti-vibration capacity (Maluf et al., 2007). Newest disc solutions, especially in sports cars, utilise composite materials based on ceramics (Schmidt et al., 1999). Matters are different for brake pads. Their structure is far more complicated. Brake pad makers use approximately 2000 different materials (Blau, 2001), which have various effects on the final product. An average brake pad is made from 10 to 20 different substances. Selecting the right composition for the brake pad and predicting its impact on the final products is a difficult task. It requires prototypes and tremendous amounts of research and abundant experience (Nagesh et al., 2014). The decision must also take into account the intended use of the brake pad, and their operating conditions. The final properties of the brake pad are also shaped by production technology, which is usually the best kept trade secret of every manufacturer. Effective production technology may improve the tribological properties of the brake pad by 100% (Nicholson, 1995; Patel and Jain, 2014).

2. CLASSIFICATION OF RESEARCH METHODS

Contemporary technological advancement makes it possible to use various research techniques in many different ways producing more or less accurate results (Walliman, 2010). Also, every method consumes certain costs and time necessary to conduct the tests (Dundulis et al., 2012; Mieczkowski, 2019). In terms of passenger cars and their parts and components, based on the above mentioned criteria, the main types of research consist of(Axén et al., 2001; Sikder, 2014):

- road tests – thetest involves a vehicle in its entirety (which is why the test is expensive, time-consuming, and difficult to perform) moving in a natural setting, producing the best quality results;
- bench tests – slightly less expensive, but also involving a complete vehicle. The research conditions are set artificially by, for example, regulating temperature, humidity, or air flow;
- complete component tests – the test involves a single component of the car in a controller, repeatable setting (such engine tests in a dynamometer);
- parts tests – focusing on selected properties of individual parts, such as the brake disc or pad;
- model tests – a process aimed at fast and inexpensive research, for example, for comparative purposes; model tests are used when there is no possibility of testing a complete part, or when the research is restricted by cost or time limitations, or requires a fully controllable test setting.

The friction elements in brakes are susceptible to different types of wear. The most common type of wear is abrasion, the deterioration of the surface layer of friction elements moving against each other (Varinauskas et al., 2013). The loss of the pad's material is caused by separation of particles due to scratching, micro grinding, and the formation of grooves (Zmitrowicz, 2006). This type of wear is the main focus of this work. The most important criterion for categorising the research methods used in determining the abrasive wear parameters is the macrogeometry of the contact between the sample and the counter-sample. This is an important design feature in equipment used in measuring the coefficient of friction and wear rate.The following solutions are most common (Bhushan, 2002; Hoehn et al., 2008; Hussein, 2015):

a) point contact (ball-disc, Fig. 2a), used in ball-cratering
b) line contact (cylinder-disc, Fig. 2b), used in pin-on-disc,
c) surface contact (surface to surface, Fig. 2c), used in inertia testbeds.

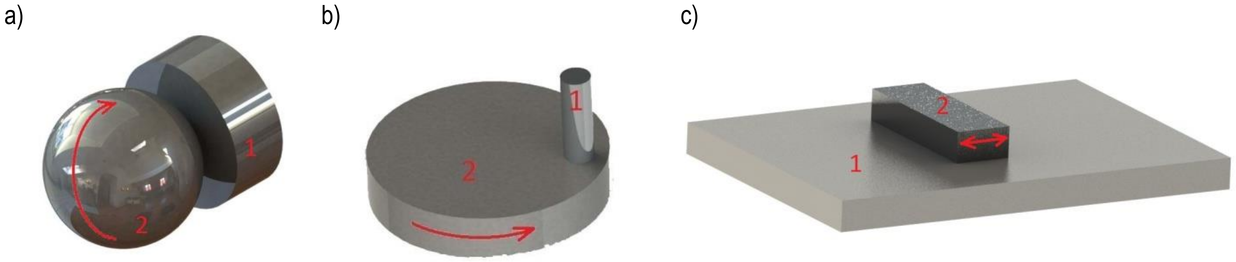

Fig. 2. Commonly used macrogeometric friction pair contact sites: a– point contact, b– line contact, c– surface contact, 1– stationary element, 2– moving element

Finding the appropriate test method is difficult. Each method presented above makes it possible to measure the force of friction (or the coefficient of friction) and the wear rate. Different types of contact, however, produce significantly varying results, which are also far from reality (Adachi and Hutchings, 2003 and 2005). The issue is partially solved by standardising the test samples and conditions (Dumbleton, 1981). Still, a decent knowledge of tribometers is necessary to select the most appropriate measuring system. It is also necessary to fully analyse the actual process to be recreated in the test station. This allows for a proper representation of the necessary real-life conditions, as only then does test make sense (Stachowiak et al., 2004).

The main aim of the article is review and comparison of friction materials' test methods.

3. RESEARCH METHODS AND THEIR MAIN FEATURES

Ball-cratering is a test thatthe friction pair consists of in a cylindrical sample (1" in diameter, 10 mm high) and ball (also 1" diameter) (Osuch-Słomka, 2012). The method was designed to study micro-wear of ceramic coatings, but as the conducted research demonstrates – it may be successfully applied to other industries for testing metals and non-metals (Priyana and Hariharan, 2014; Mergler and Huis't Veld, 2003; Bello and Wood, 2005). This is made possible by the numerous advantages of this method, including a decent result reproducibility and short time of individual tests. Depending on the researchers' requirements, it is possible to run the test with a lubricating or cooling agent, or any other liquid occurring in natural conditions (Cozza, 2014).

Many companies manufacture work stations for ball-cratering, with all sharing certain elements. Fig. 3 presents a diagram of a ball-cratering station, a T-20 model made in Poland. This equipment places the sample (1) in the holder of a vertical arm on a rotating lever and its weight is equated by a counterweight (7) placed on the other side of the horizontal lever arm. The other side of the lever has a scale for placing the load (5) in order to press the sample against the counter-sample. The lengths of the arms of the rotating levers are equal, meaning that the downforce is equal to the set pressure of weights on the scale. The counter-sample is mounted on a shaft of an electrical motor (8) (with regulated speed). The strain gauge (4) located above the sample holder makes it possible to monitor the force of friction directly during the test.

The rotating ball grinds against the sample. Its vertical position allows the removed material to drop freely, preventing it from interfering with the test (Cozza et al., 2009). The friction creates a crater, which is measured in two dimensions to determine a mean diameter, and then to determine the abrasive wear rate coefficient (K_c) using the Archard equation (Osuch-Słomka, 2011) (Fig. 4 presents examples of craters and methods for measuring the diameter). The station measures friction in real-time, making it possible to easily calculate the coefficient of friction for the pair.

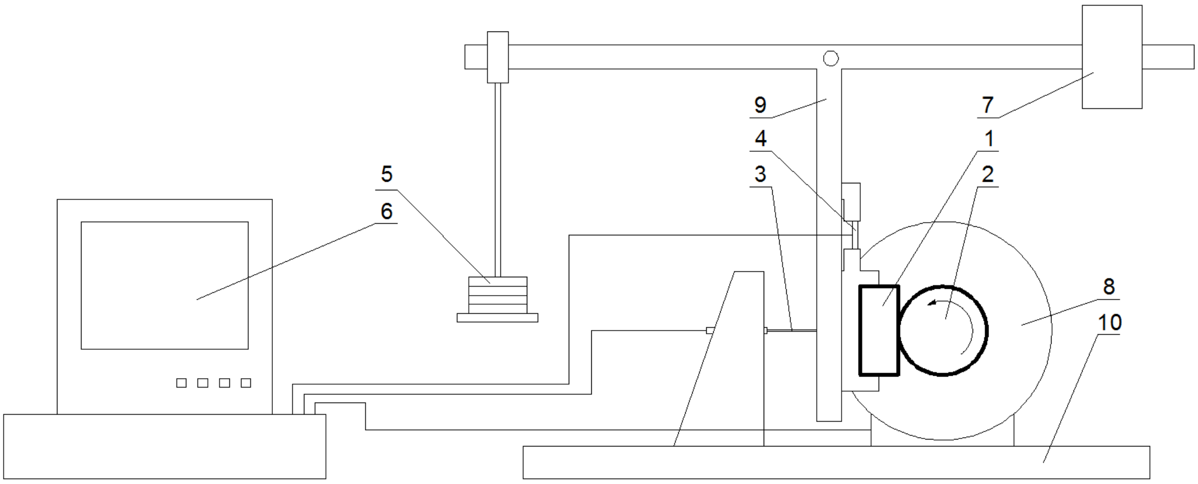

Fig. 3. T-20 test station diagram: 1 – sample, 2 – counter-sample (ball), 3 – displacement sensor, 4 – strain gauge for measuring friction, 5 – weights, 6 – computer, 7 – counterweight, 8 – electrical motor, 9 – rotary arm, 10 – base

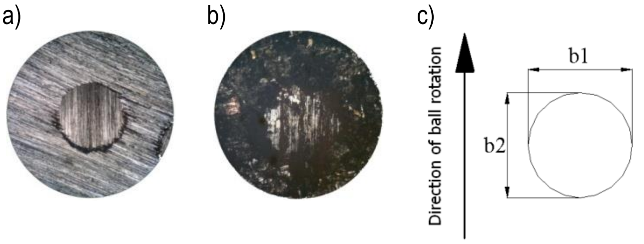

Fig. 4. Craters formed during tests on: a– brake disc, b– brake pad, c– diameter measurement method

Unfortunately, the structure of a brake pad and the actual nature of the contact between the pad and the disc (Eriksson et al., 2002; Bouchetara and Belhocine, 2014) make the ball-cratering test not the best-suited method in the discussed example. Point contact produces the risk of studying not the tribological properties of a complete brake pad, but rather focusing on the properties of one of the pad's many components. That is why every test could yield different results. Some researchers suggest applying unusual methods, such as using rubber balls (counter sample) and pressing the two test samples against the ball (Fildes et al., 2012) or submerging the friction pair in an abrasive slurry (Shipway and Hogg, 2007). Although it was demonstrated that these methods improve the reproducibility of results, this type of tests do not reflect the actual operating conditions of the braking pair and have no application in their research. The crux in obtaining quality test results may lie in planning the experiment properly. This, unfortunately, is very time consuming (Szpica, 2016, 2018, Mieczkowski, 2017). Although many experiment planning methods have been developed, the one most frequently used for these types of measurements is the Taguchi method for process optimisation (Gee et al., 2003; Osuch-Słomka et al., 2013). This method makes it possible to determine the boundary conditions for a specific experiment, that is, the load, speed, and friction distance. The operation, coupled with an appropriately high number of samples, produces correct results corresponding to actual conditions.

Tab. 1. Main advantagesand disadvantages of Ball-cratering

Advantages	– good reproducibility of results – short time of individual experiments – tests can be performed in the presence of, for example, lubricating agents – low costs of experiments
Disadvantages	– necessity of using additional equipment to measure the craters – complicated experiment planning process – point contact between the friction pair, which in the case of brake pads requires the performance of numerous tests – the type of contact does not reflect the actual operating conditions of brakes – no possibility of observing the complex mechanisms of braking

Pin-on-disc is a test that studies friction and wear in sliding conditions. It is used for recreating the linear contact macrogeometry of the sample and counter-sample. The method may be applied in tests on dry fiction and with the use of lubricants (Kaleli, 2016; Nuraliza et al., 2016). With the use of an environmental chamber, the experiments can be conducted in the presence of various gasses or changing humidity (Tamboli and Sheth, 2008). The pin-on-disc method makes it possible to determine the average coefficient of friction between a friction pair, and evaluating the wear rate of the friction surfaces. The first parameter is measured directly during the experiment as a function of time or number of disc rotations, while the second parameter is determined on the basis of the change (loss) of weight of the sample. The necessary data is obtained by weighing the sample before and after the test. Of course, the sample has to be carefully cleaned before weighing using products like acetone or washing benzene. Otherwise the results may be seriously flawed (Li et al., 2016; ASTM G99-17, 2017; Ramesh et al., 2015; Nair et al., 2009).

In most stations, the disc revolves on a vertical surface (Fig.5a), although there are instruments in which the disc is placed vertically (Kucera and Prsan, 2008) (Fig. 5b). Due to similarities to a disc brake, the stations with a vertical rotation axis are well suited for testing brake discs and pads. As with ball-cratering, placing disc horizontally makes the pin slide on loose sample fragments torn away during the experiment. That is why, the same material may yield different end results in several experiments (Trzos, 2010). Despite all this, this setting of the pin-on-disc method is frequently used in testing samples of brake pads (Surojo et al., 2015; Gopal et al., 1994; Elakhame et al., 2017; Sugözü and Dağhan, 2016; Nosko et al., 2017).

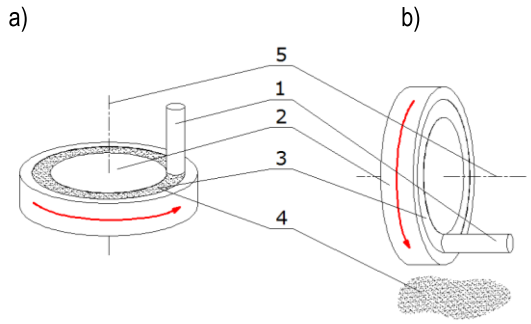

Fig. 5. Different pin and disc settings: a– vertical disc rotation axis, b– horizontal disc rotation axis, 1– pin, 2– disc, 3– sign of wear, 4– fragments loosened during abrasive wear, 5– disc rotation axis

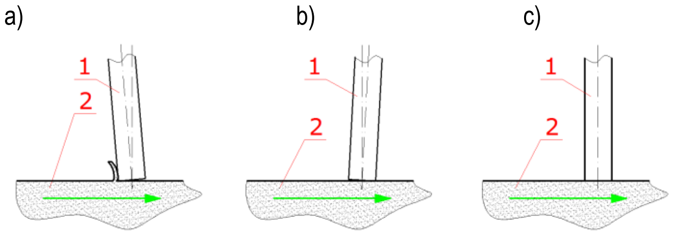

Fig. 6. Friction pair operation in the pin-on-disc method: a– positive pin pitch resulting in grinding, b– negative pin pitch resulting in sliding against the sample surface, c– correct contact, 1– stationary pin, 2– spinning disc

It is essential to position the pin correctly against the disc (at a right angle - Fig. 6c). Even slight variation may interfere with the experiment, as it is easy to grind the surface of the sample (Fig. 6a), or slide against it (fig. 6b) (Blau, 2014; Pauschitz et al., 2005). The problem may be avoided by preparing the pin properly. One way to do it is to set up the station and initially cover the contact surface with sanding paper. The disc then rotates until the contact surface with the pin is evened out. Any possible irregularities become levelled, providing correct contact between the friction pair (Uyyuru et al., 2007). Another solution is to use pins without a flat tip, such as ball-ended pins, or using balls instead of pins (using the ball-on-disc method) (Li et al., 2013). These methods differ greatly from the real-life contact between disc and pad, and therefore, are not recommended for testing the working elements of braking systems.

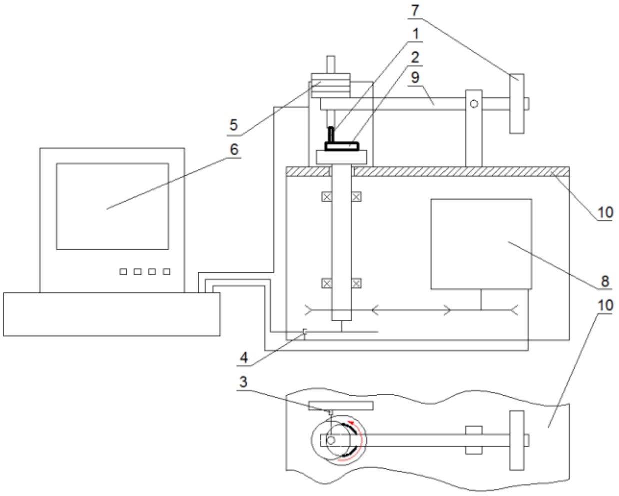

Fig. 7. Pin-on-disc test station diagram: 1 – stationary pin, 2 – spinning disc, 3 – strain gauge for measuring friction, 4 – rpm sensor, 5 – load, 6 – computer, 7 – counterweight, 8 – electrical motor, 9 – rotary arm, 10 – body

Figure 7 presents a diagram of a T-11 pin-on-disc test station made in Poland. The stations may differ slightly among manufacturers, general operating principle remains the same. The pin (1) is placed on a lever (9) preventing it from moving. The lever is fastened to the body of the station, but may rotate (10). The body holds an electrical motor (8), which uses a gear to spin the shaft with an rpm sensor (4). The second element of the friction pair, the disc (2), is attached to the shaft. Due to friction, the lever (9) tilts and deforms the strain gauge (3), which registers the friction. Some stations have the strain gage installed directly on the rotary arm (9). Appropriate downforce is provided by weights (5) placed directly above the pin. Rotation speed is regulated manually or using the computer (6), which also records the experiment. If necessary, the station can be furnished with an infrared sensor (e.g., thermo-vision camera (Zdravecká et al., 2013; Rowe et al, 2013) or a thermocouple with a probe located in the pin (Dwivedi, 2002) for temperature monitoring.

Tab. 2. Main advantages and disadvantages of pin-on-disc

Advantages	– contact geometry of friction pair close to the actual cooperation between brake disc and pad – tests can be carried out in the presence of, for example, lubricating agents – low cost – short time of experiment
Disadvantages	– additional equipment required for measuring loss of mass – in the case of horizontal rotation axis, the fragmented material remains on the friction surface, impairing test results – the pin must be placed very carefully against the disc – no possibility of observing the complex mechanisms of braking

Inertia dynamometry used for testing the working components of braking systems, the discs and pads. Thanks to their special designs, a complete disc and two pads can be installed in the station (in a factory made calliper, from a specific car model). This is a test method allowing macrogeometry tests in surface-to-surface settings (Hagino et al., 2016). Thanks to the measurements made in a setting closely resembling real (road) conditions, this is the best method presented so far, as it allows obtaining real results (Telang et al., 2016), and is cheaper and less time-consuming than road tests with an entire vehicle (Sarkar and Hirani, 2015). That is why this method is commonly used in the development of new friction materials for brake systems (Tsang et al., 1985). Extensive procedures were developed to determine the course and boundary conditions of experiments in order to standardise testing. Unfortunately, they only take into account emergency situations and do not reflect the every-day of a brake system (Min-Soo, 2011; Grochowicz et al., 2014; Czaban and Szpica, 2013). Recreating the changing conditions of braking is also an issue. There have been attempts at using sufficiently powerful motors with adjustable speed, but this brought about the problem with measurement accuracy (Wu et al., 2009).

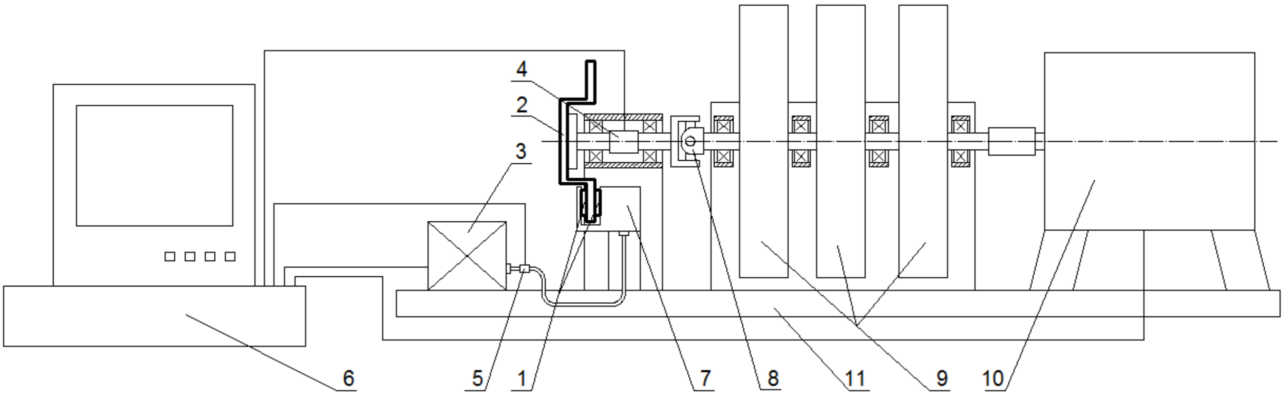

Fig. 8. Diagram of an inertia dynamometry station: 1– brake pads, 2– brake disc, 3– hydraulic piston, 4– torque and speed monitor, 5– pressure sensor, 6 – computer, 7 – brake calliper, 8 – cardan joint, 9 – rotational mass, 10 – electric motor, 11 – base

Figure 8 presents a diagram of a typical test station. Here, the disc (2) is attached to the hub. Rotation is provided via the electric motor (10), which also propels the rotational mass (9). Depending on the manufacturer and intended use, the station may be equipped with one or more rotational masses. These serve as energy accumulators stimulating the inertia of a vehicle during braking. Depending on the properties of the simulated vehicle, the mass is adjusted by adding or removing weights (Min-Soo et al., 2010). The speed can also be adjusted in order to simulate different braking scenarios. When the desired speed is reached, the motor is disconnected and the measurement begins. Braking is provided by the calliper (7) to which the brake pads are attached (1). The calliper is powered by a hydraulic pump (3). Pressure is monitored throughout the experiment (5), which can be used for calculating the normal force in the friction pair. The braking torque is measured by the torque sensor (4) located on the shaft connecting the disc hub and rotational mass. Everything is controlled by a computer (6), which also records the course of the experiment. Similar to the pin-on-disc method, the station can be furnished with temperature measuring sensors. Usually,thisfunction is performed usinga thermal camera, sometimes – using a thermocouple (Balotin and Neis, 2010). Sometimes inertia stations are used to study the chemical compounds released to the environment during brake pad wear. Clearly, this type of testing requires additional instruments such as a sealed body, fan forcing air movement, and set of filters for air exhausted from the test station during the experiment (Matejka et al., 2017).

Tab. 3. Main advantages and disadvantages of inertia dynamometers

Advantages	– thanks to the possibility of testing complete sets of discs and pads, this method best reflects the real conditions of braking – allows (to a degree) testing of complex processes recreating the braking process, such as change of contact pressure throughout the experiment
Disadvantages	– the method is standardised, accounting for only extreme situations – recreating complicated, changing conditions of braking is problematic – significant cost purchasing or building the test station, resulting in high total cost of research in comparison to the methods described above – lack of linear regulation of rotational mass – the mass is increased by adding weights with a specified mass, therefore, the change is non-gradual

Simulations of braking systems or their components are currently a very popular research method. Their popularity stems from low costs in comparison to the other tests, as the only requirement is a computer with some specific software. Unfortunately, while the other methods do not require precise knowledge of phenomena occurring in the studied process, in simulations, this is a necessity(Mieczkowski et al., 2007; Szpica, 2015b). Without detailed knowledge of the phenomena and their relationships, all described mathematically, and without abundant material data (such as density, thermal conductivity, heat capacity, etc.), it is impossible to conduct a simulation, and even the smallest error may flaw the end results (Borawski, 2018; Yevtushenko, 2014). It is also difficult to simulate the workmanship imperfections or the heterogeneous structure of the brake pad material, resulting from sintering. Still, many researchers conduct simulations not only for brake discs and pads, but also in terms of other brake components such as valves (Kamiński and Kulikowski, 2017), hoses (Kaminski, 2017), pumps (Geromel, 2014), and complete braking systems (Khot and Borah, 2015), or even entire engines (Puławski and Szpica, 2015).

An interesting alternative to simulations is constructing mathematical models and using them to simulate the test stations described above. These models are most commonly used for the pin-on-disc method. One of the biggest advantage of such an approach is the possibility of verifying the results obtained in the model against a real working station. Authors of such models claim that upon a successful verification, the model can completely replace experiments conducted on the test station, which significantly reduces the time of research and lowers the cost to a minimum. Additionally, such models provide the possibility of examining values, which are either difficult or impossible to measure on a real test station, such as pressure distribution on the contact surface between the friction pair (Chmiel, 2008; Perez et al., 2011; Yan et al., 2002; Abdullah and Schlattmann, 2016). This methodology can be used successfully in the development of new brake pad compositions.

There is a large group of researchers analysing temperature distribution in the working elements of brakes using FEM. This type of research is important because conventional measurements are extremely difficult or quite impossible in some cases (e.g., in the friction pair). Using a computer, researchers are able to determine exactly how the temperature is distributed both in the disc and in the brake pad (Adamowicz, 2017; Grzes, 2017; Talati and Jalalifar, 2009), and they can also change the starting conditions of the test, such as the car’s speed during braking, or the clamping force between the friction surfaces (Yevtushenko et al., 2017; Yevtushenko and Grześ, 2015a; Yevtushenko and Grześ, 2016). Unfortunately, due to the reasons described earlier, the results of simulations are difficult to verify experimentally. Some researchers tried using thermal cameras, yet the specificity of the disc surface may yield some measurement disturbances (Richard, 2004).

Computer software using FEM make it possible to evaluate the tension both on the surface of the studied pair, as well as underneath. Since this tension is generated by expanding materials, the obtained results are in a way an expansion on simulation thermal tests (Dakhil et al., 2014; Belhocine and Bouchetara, 2014). It is also possible to measure the distribution of pressure along the contact surface of the friction pair, or the abrasive wear rate of a brake pad. These models, however, require expanding the virtual environment with pistons, and even full callipers in some cases, and involve certain simplifications, like assuming that the disc is a rigid structure thatdoes not wear (Abubakar et al., 2006; Rashid and Strömberg, 2013; Abebaw, 2015; Söderberg and Andersson, 2009).

Tab. 4. Main advantages and disadvantages of simulations

Advantages	– lowest cost of all of the research methods presented here – no specialist instruments required – full control over test conditions (such as ambient temperature, pressure, friction pair sliding speed) – extensive universality making it possible to test practically any element and any phenomenon, provided that it be described mathematically
Disadvantages	– requires knowledge of advanced mathematics, thermodynamics, physics, and chemistry – necessary simplifications deteriorate the reflection of reality – in some cases, lack of result verification, as the tested parameter is unmeasurable or difficult to measure

4. SAMPLE RESEARCH RESULTS

In order to check how the methods described above work in the friction material testing process, ball-cratering, pin-on-disc and computer simulation tests were performed. As a test object, brand new brake pads of a popular passenger car were used. Samples of various sizes were cut from the pads to fit into the laboratory stands. Grey cast iron was used as a counter-sample. The laboratory tests were carried out at air humidity of35% and ambient temperature of 21°C. These parameters were measured using a MT886 hygrometer and a type K thermocouple connected to a Velleman DEM106 sensor.

Ball-cratering: As already mentioned, in this method, it is important to properly plan the experiment. For this purpose, the method described in previous publications was used (Borawski, 2016; Borawski and Tarasiuk, 2018). The input parameters of the experiment thus determined are: load: 0.6N, distance: 150 m, speed of rotation: 150 rpm; therefore, total time of the experiment was 752s. The recording of the friction force value (Ft) carried out during the experiment (Fig. 9) allowed the determination of the friction coefficient, which equals 0.41.

In addition, measuring the size of craters allowed the calculation of the coefficient of abrasive wear rate from the Archard's equation:

$$K_c = \pi \frac{b^4}{64RSQ} \tag{1}$$

where b is the arithmetic mean of the measurements of the crater diameter in the direction of sphere rotation and in the perpendicular direction, R- radius of the counter-sample, S- friction distance, Q- load. In the considered method, the Kc coefficient value is 4.138·10-13 mNm-3.

Pin-on-disc: In this study, a T-11 stand was used. The parameters for the experiment were as follows: velocity v = 1 m/s, path S = 1000 m, touch diameter d=18 mm, and load Q = 5 kg; so, the total time of the experiment was 1000 s. The parameter recorded during the tests, as in the previous experiment, was the value of friction force (Fig. 10). It was used to calculate the coefficient of friction of cooperating materials. The calculation result revealed a friction coefficient of 0.38.

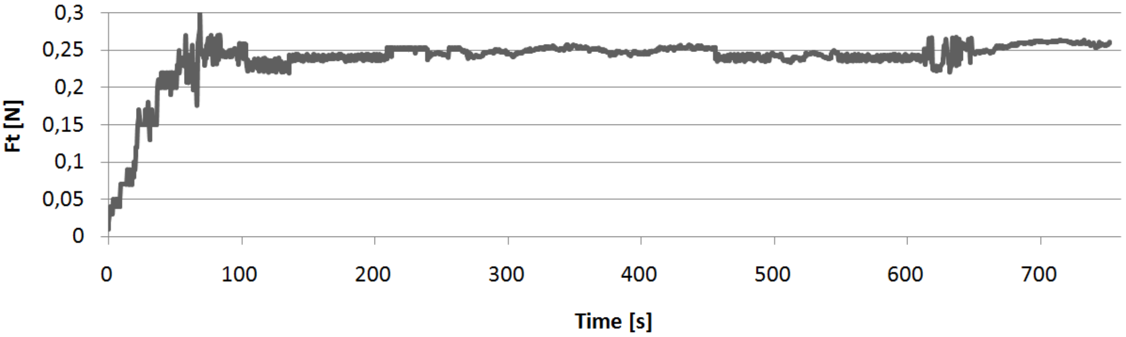

Fig. 9. Example time profile of the friction force obtained during ball-cratering test

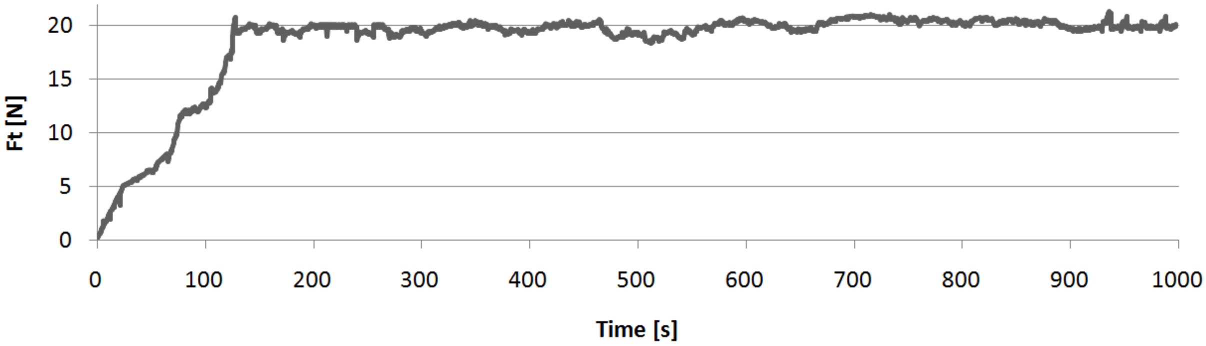

Fig. 10. Example time profile of the friction force obtained during pin-on-disc test

In addition, the sample was weighed before and immediately after testing. Before that it was thoroughly cleaned. The weight loss was 0.69896 g, while the volume loss was $2.4525 \cdot 10^{-5}$ m^3. These quantities allowed to determine the coefficient of abrasive wear rate. The Archard's equation was used to calculate the $K_c$value, but in a slightly different form:

$$K_c = \frac{S \cdot Q \cdot g}{V} \quad (2)$$

where: *V* - volume of wear material [m^3], *g* - gravitational acceleration. The obtained result is $K_c = 3.917 \cdot 10^{-13}$ mNm^{-3}.

Simulation tests: In the simulation, the previously developed mathematical model was used (Borawski, 2018a; Borawski 2018b). It was assumed that a vehicle with a mass of 1500 kg (with tires 205/55/R16) will be braked from an initial speed of 90 km/h. The result of braking is a complete stop of the vehicle. It was also assumed that the tire coefficient of friction to the road is 1.0, which gives a constant delay of 9.81 m/s2. The coefficient of friction of the pad against the disc was assumed averaged from the values obtained in the tests described above, i.e. 0.395. The ambient air temperature was set to be 27°C. In addition to the above, the following assumptions were made:

- invariability of friction coefficients,
- constant and equal contact pressure for both pads,
- homogeneity of the pad material and contact with the entire surface,
- constant braking delay,
- no influence of external factors (e.g., road unevenness, air resistance).

The properties of friction materials necessary to perform the simulation were experimentally determined and summarized in Tab. 5.

Simulation tests were carried out using FEM. The model with the mesh (which consisted of about 6,200 elements, mostly of triangular shape, which gave nearly 32,000 degrees of freedom) is shown in Fig. 11.

The results of the tests were the temperature profiles of the disc and the pads. Temperature was gauged attwo points: in the geometrical centre of the braking pad at 0.2 mm from its surface (Fig. 12) and at 0.2 mm from the surface of the disc at the opposite side, after turning it by 180 ° (Fig.13).

Tab. 5. Material properties of the sample and counter sample.

	Sample	Counter sample
Thermal conductivity	150 [W/(m*K)]	47 [W/(m*K)]
Density	2860 [kg/m^3]	7870 [kg/m^3]
Heat capacity at constant pressure	1050 [J/(kg*K)]	498 [J/(kg*K)]

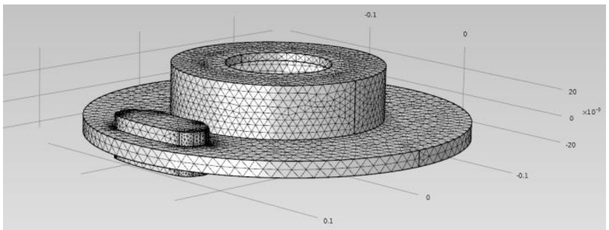

Fig. 11. A simplified model of the disc and pads with the mesh applied

In addition, the research showed that during braking under the conditions assumed above 73801 W of thermal energy will be produced.

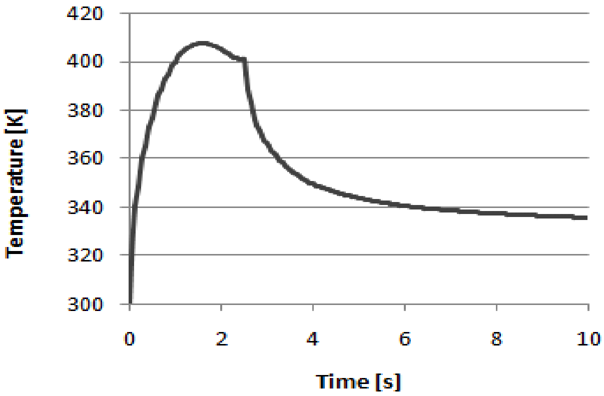

Fig.12. Brake pad temperature

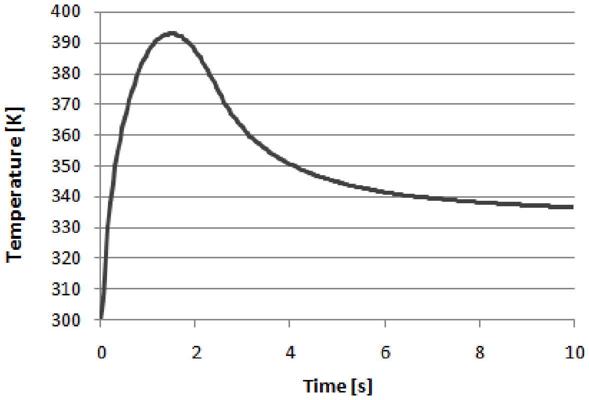

Fig.13. Brake disc temperature

Analysing the obtained results, the statement can be risked that with proper planning, ball-cratering and pin-on-disc methods can be used interchangeably. Simulation tests in turn can be treated as their development, allowing to examine parameters that are very difficult or impossible to measure.

5. CONCLUSIONS

The process of vehicle braking is very complex. The high temperatures thataccompany it may lead to various tribochemical reactions, including oxidation of metallic components (Polajnar et al., 2017), formation of new alloys (Matejka Et al., 2011), or even thermal degradation of the brake pad binder. Damaged resin (the most common brake pad binder) causes the contact layer of the brake pad to become brittle (Placha et al., 2017; Cai et al., 2015). This results in radical changes in the material's tribological properties. Unfortunately, these conditions are not easily recreated, making laboratory tests or simulations of brake pads troublesome. Moreover, in real-life settings, there is always surface contact between the friction materials. This is because the contact surface undergoes elastic or even plastic deformation, which is not always reflected in experimental settings. Development of a research method thattakes into account the disturbances occurring in road conditions (such as wheel rotation speed change corresponding the varying tire rigidity (Kulikowski and Szpica, 2014) and building a suitable test station would likely involve costs and difficulties, which could not be borne by most institutions. That is why, many researchers must compromise and choose a method thattakes into account certain simplifications in their experiments, making their test results, to a greater or lesser degree, flawed.

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Acknowledgements: The research has been carried out within work no. MB/WM/4/2017, financed from funds used for the development of young scientists and doctoral students.