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The influence of cross-drilled brake disc geometry on the tribological performances of brake system

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Abstract. In the paper, the results of the estimation of the influence of cross-drilled brake disc geometry on the tribological performances of brake system were discussed. To decelerate a vehicle, kinetic energy of the moving vehicle is transformed into thermal energy by using sliding friction between brake discs and brake pads. Due to the place where it is assembled, brake disc is exposed to the impact of external factors. This results in the sensitivity of torque effectiveness to the water presence on disc surface. Especially, it has a large significance for two-wheel vehicles. That is why, the discs used in such vehicles were chosen for the evaluation. On the test stand, the measurements of the value of friction coefficient of the pair of brake pad and disc were conducted. Two cross-drilled brake discs which differed with geometry were chosen for comparison. The measurement was conducted at various sliding speeds and loads on the surface of disc and brake pad. All the measurements were repeated on dry and wet discs.

1. Introduction

Brake system is a crucial safety equipment for vehicles. Disc brakes have been increasingly adopted in passenger cars for sixty years. Later, they began to be used in motorcycles and subsequently also in bikes. To decelerate a vehicle, kinetic energy of the moving vehicle is transformed into thermal energy by using sliding friction between brake discs and brake pads. Brake system operation has an influence on vehicle stability and steerability [1,2,3]. Especially, it has a large significance for two-wheel vehicles. The vehicles of this type are characterized by sensitivity to effective braking. In general, motorcycles and bikes have separate front and rear braking systems which require operator balancing to achieve effective braking. Bikes and motorcycles do not remain stably upright, for instance, after the onset of excessive front wheel lock and skidding. Possibility of movement control is sensitive to surface conditions such as potholed, wet or oily roads. In addition, bike tyres generally have a reduced road contact patch in comparison to cars. Traction patterns and compounds used for their manufacturing may be suited to a reduced set of road conditions. Motorcycle braking involves rider control tasks which may be substantially more demanding than is the case for cars. The match between operator skill and vehicle properties is of greater relevance to safety in case of a motorcycle and bikes than a car. As usual, the experienced rider made greatest use of the front brake. However, the beginning riders, seemingly for the lack of confidence in control1ing front-wheel braking, made greater use of the rear brake. Due to the place where it is assembled, brake disc is exposed to the impact of external factors. This results in the sensitivity of torque effectiveness to the water presence on disc surface. As it results from the above, brake disc system should be characterized by stable frictional and properties under varying conditions.

The aim of the paper was to compare the influence of water presence on the surface of brake disc on the effectiveness of system operation for two different cross-drilled brake discs geometry.

2. Brake disc system

The difference between braking systems is the mechanism and the components used in the assembly of the system. All of them use frictional materials. A brake pad is normally forced towards the rotating brake disc. Thus will slow down the vehicle and stop the motion. The basic geometry of the brake disc can be differentiated into two main types which is a solid disc brake and ventilated disc brake. The classification is based on their design shape. It can either have ventilated geometry or be without ventilated geometry [4,5]. Solid disc brake is a flat surface not having any notched or grooves at the disc. This design shape had more contact surface area during braking compared to ventilated disc brake. It tends to have more localized thermo-elastic instability on the contact areas. Since solid disc does not have appropriate ventilated hole which can help to dissipate the braking frictional heat to surrounding, some problems appear. The thermo-elastic instability may be the cause of brake fade and pad glazing phenomena [6,7,8]. Ventilated disc brake geometry was widely researched in industry. The properties of the geometry were compared to solid disc brake. The ventilated disc brake is lighter compared to solid one. Another trait is convective heat transfer, also better due to the benefit of its vent hall [9]. Kang and Cho [6] had studied the influence of the disc brake geometry on heat dissipation performance. Their analysis showed that ventilated disc has better braking performance in term of heat dissipation compared to solid disc. Also at smaller speed, ventilated disc can be more controllable. It can provide suitable torque value during braking. There are also researchers that relate the air vent geometry design with aerodynamic cooling. The airflow can increase the braking performance during braking [7]. Apart from that, the shape of cross section plays an important role in the braking performance [8]. Ventilated disc brake got more advantages compare to solid disc. However, it has some disadvantages such as: lower thermal capacity and higher rate of temperature rise when braking is applied repeatedly. In designing and choosing of the ventilated disc, one should also take into consideration its thermal capacity and thermal deformation factor so that it can optimize the brake disc design. During the braking process, friction force on the contact area of the brake pad and brake disc causes wear to the contact area. The wear behaviour influence the coefficient of friction that caused the contact area started to destroy. Design the brake disc geometry must aim at prolonging the disc life cycle. Friction force results from the mechanical action and intermolecular force between the pad and disc rotor friction surfaces. Friction surface is characterized by a large quantity of micro peaks or valleys. The micro peaks are generally called asperities. The mechanical force included the micro peaks and valleys meshed with each other. They lead to deformation, and shearing the asperities. The interaction between the asperities into the dual surface causes ploughing on the friction surfaces [10,11,12]. With regard to complex traffic conditions, vehicles experience a variety of braking modes. During long-time downhill braking and repeated high speed braking, frictional heating may substantially increase the temperature of the friction pair [13,14]. Many studies have shown that such overheating can result in brake deterioration of friction coefficient, increased wear of the brake pad, thermal cracking, judder and squeal of the brake system due to non-uniform thermal deformation of the brake disc [14,15,16,17,18]. Thus, effective cooling of the brake disc is significant in order to ensure brake safety and comfort, especially for contemporary vehicles.

This tribosystem is very complex and variable, and despite a lot of research conducted on it, still incompletely explored and understood.

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3. Experimental procedure

The frictional tests were carried out on the test stand shown in the figure 1. A brake pad, forced towards the rotating brake disc was realized by hydraulic servo, in order to approach the conditions of loading to acting in original brake system. During research the measuring paths were as follows: friction force path - strain gauge sensor of the company Hottinger Baldwin Messtechnik GmbH, temperature path - optical pyrometer; rotational speed of the brake disc. Measurement sensors were connected to an analog-to digital converter also produced by HBM. The courses of friction force obtained during test were recorded on the computer disc. For comparison, two various steel brake discs with the cross-drilled cooling holes were used. The discs differed with the geometry of holes. Both compared discs were shown in figure 2. The measurement of braking torque was conducted at constant rotational speed of brake disc rotor. Before the proper measurement, a series of brakes. The initial phase of the tests corresponded to friction distance equal to 250 meters. In the second part of the measurement, tests as in the first part were repeated. However, during braking water was sprayed on brake disc surface.

Figure 1. The test stand with brake disc rotor

Disc A Disc B

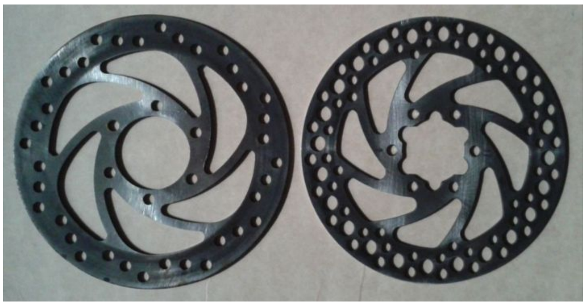
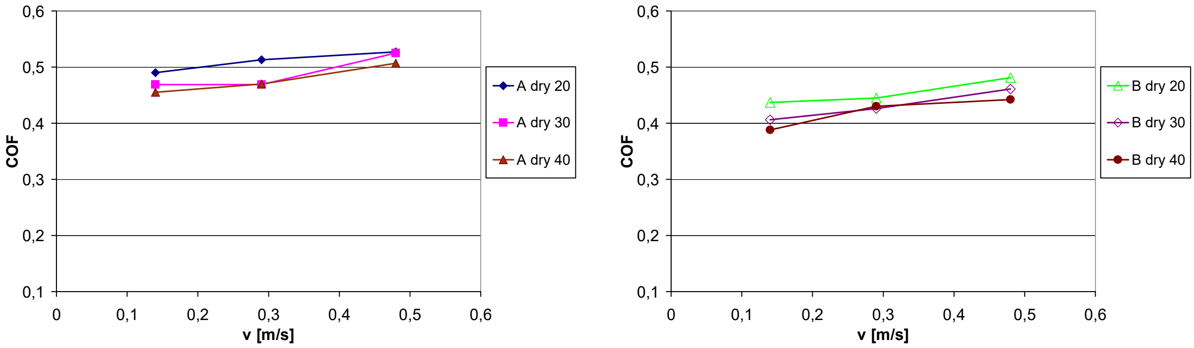


Figure 2. The brake discs used during tests

4. Results of research

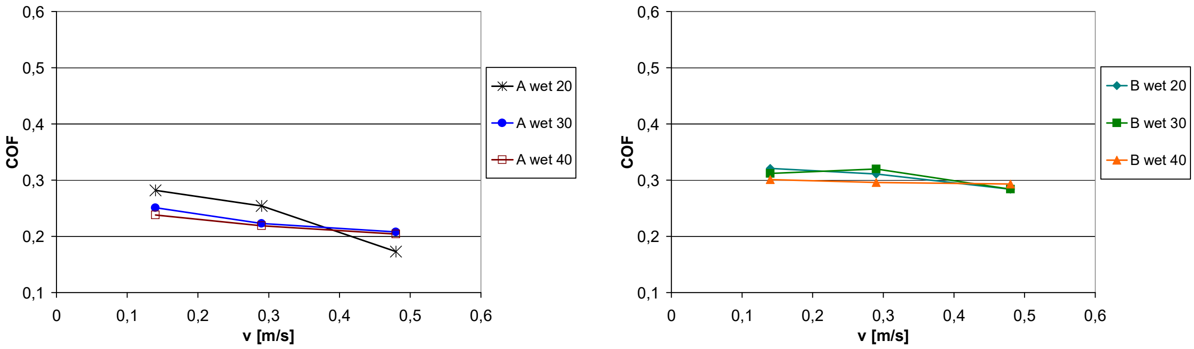
The conducted measurements allowed to estimate the influence of the change of velocity and load of the surface of brake pad and brake disc on friction coefficient during braking. In figure 3, the influence of the sliding speed of the elements on friction coefficient was shown for the compared brake disc geometry. The influence of the speed was shown for three loads on contact surface. As can be observed on the basis of the presented juxtaposition, disc “B” was generally characterized by lower values of friction coefficient.

In figure 4, friction coefficient for wet discs was shown respectively for the same discs as beforehand. In this case, disc “A” was characterized by lower values of friction coefficient. In addition, for the disc “B”, diminishing the value of friction coefficient resulting from the fact that it was wet, was lower than for disc “A”. This means a more stable braking system operation in case of disc “B”. The change of load of the contact surface of the pad and brake disc can cause solely insignificant changes of the value of friction coefficient. In general, in case of dry discs, insignificant increase of friction coefficient can be noticed. It is illustrated with figure 5.Within the range of the studied changes of load on contact surface of brake pad and brake disc, the change of friction coefficient value with the change of the load was very low. In case of wet disc B, the change was practically not observed. The frictional behaviour of brakes is determined by the character of the active surfaces of the disc and pad. The compressive force applied to the brake rotor by the caliper during braking may cause small deflection of the brake rotor that can have an influence on the function of the brake rotor.



a) b)

Figure 3. Friction coefficient vs. sliding speed for various loads on the contact surface of brake pad and disc – respectively for disc „A" and „B" dry discs

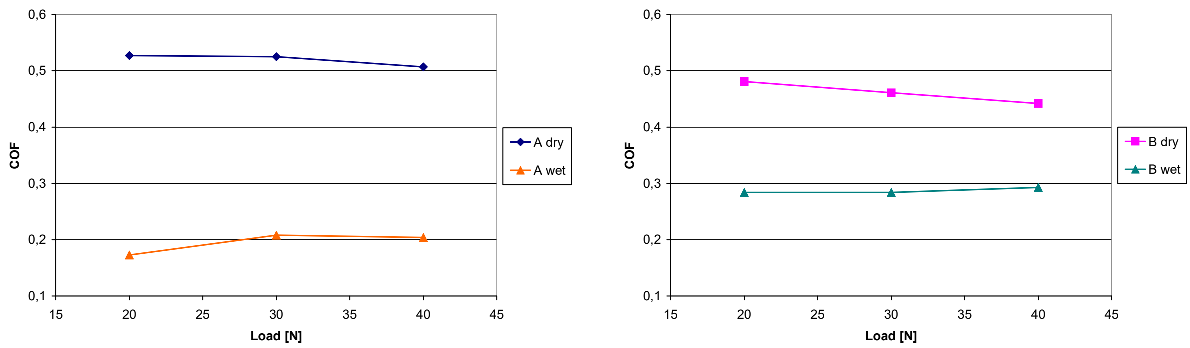


a) b)

Figure 4. Friction coefficient vs. sliding speed for various loads on the contact surface brake pad and disc – respectively for disc „A" and „B" wet discs

Figure 6 shows the influence of the change of disc temperature on the change of the value of friction coefficient for both discs. As can be seen on the presented diagram, the change of the temperature of brake disc has a very strong influence on the value of friction coefficient. The heat generated from contact may cause thermoelastic deformation which will vary the coefficient of friction at brake pad and disc surface. Braking performance can be significantly affected by the temperature rise in the brake rotor. During braking high temperatures may cause brake fade, premature wear, brake thermal cracks.

It was observed that the friction coefficient increased with temperature in the investigated range. The friction coefficient is also related to load and speed. A slight decrease of the friction coefficient with was observed. While applying the brake, brake caliper exerts compressive force on the rotor through the brake pad causing rotor to deflect. At the same braking pressure, the areal braking energy was increased with braking speed being raised. When the braking speed was low, the impact and shear force between asperities in the friction surface were small, so that the asperities could not be easily sheared. With braking speed increasing, the areal braking energy gradually increased. As a result, many asperities created brittle fracture. New asperities and little debris were generated with the original ones rupture. In case when the amount of the asperities increase, the asperities meshing, deforming, shearing, ploughing and braking were raised. The result of this was that the resistance continuously increased and the coefficient of friction increased.



a) b)

Figure 5. Friction coefficient vs. load on the contact surface of brake pad and disc – comparison for dry and wet disc – respectively for disc "A" and "B"

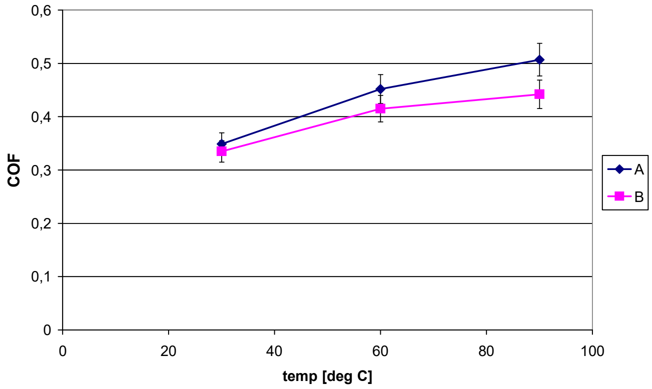


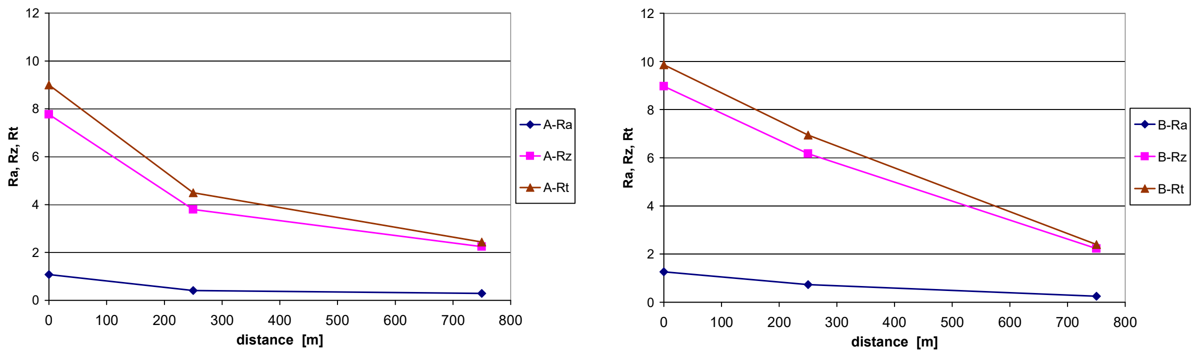
Figure 6. Friction coefficient vs. temperature of the brake disc, for disc „A" and „B"

A lot of phenomena occurring during friction are explained by the presence of so called the third body between pad and brake disc. Particles which are the results of wear and come from the pad and the disc constitute the third body [22]. This layer has a key role in the tribological triplet [23]. The third body separates the first bodies, and transmits the load between them. This body also accommodates the relative velocity. In his paper [24], Eriksson et al. showed that the real contact between brake pads and disc consists of a number of small contact plateaus. The plateaus usually show signs of sliding contact, including a pattern of parallel grooves along the direction of sliding. The creation of the contact plateaus takes place typically where the metal particles come out from the surface, with hardness values considerably higher than the mean hardness of the pad composite. The third body concentrates and compacts around the harder element, enlarging the effective area of the contact plateaus.

The phenomena written above take place during dry friction. When fluid appears on disc surface, it changes significantly friction conditions. Lubricating film may be formed what leads to significant change of friction coefficient. Therefore, after spraying water on the disc surface, almost 40 % decrease of braking torque was recorded.

Figure 7 shows the comparison of the changes of parameters of roughness of the surface of brake discs during operation. Both discs were characterized by very similar parameters of surface roughness.

Using a new brake pad for the first time in its original state, we can observe a higher value of the friction coefficient, followed by a decrease to a lower stable value. This can be explained by the process of development of an actual friction couple contact surface. In this time, a tribological layer is formed which results in stabilization of the friction coefficient value.



a) b)

Figure 7. Changes of the roughness of the surface of brake disc depending on friction distance

5. Conclusions

Brake system is a crucial security equipment for vehicles. To decelerate a vehicle, kinetic energy of the moving vehicle is transformed into thermal energy by using sliding friction between brake discs and brake pads. Brake system operation has an influence on vehicle stability and steerability. Especially, it has a large significance for two-wheel vehicles. The measurements conducted on the test stand allowed to compare tribological characteristics of two brake discs of different geometry. The discs differed with diameter and the arrangement of ventilation holes. The change of operating conditions resulting from the contaminants from the environment reaching the surface of the disc may have a significant influence on the change of friction coefficient and consequently braking effectiveness.

On the basis of the conducted research we can draw particularly the following conclusions:

1. The most significant factor deciding about the value of friction coefficient of the pair of brake pad and disc is the temperature of brake disc. In the evaluated range of variability, it caused the change of friction coefficient up to 15%.
2. Regardless of the geometry of disc with the increase of sliding speed, the increase of the value of friction coefficient was observed. In the range of the change of the speed from 0,1 to 0,5 m/s, the change exceeded 15%.
3. The geometry of brake disc can have a significant influence on preserving effectiveness of braking in case of wet discs. It was ascertained that in such case the differences of values of friction coefficient can reach 30%. Their geometry also decides about the stability of friction coefficient with the changing sliding speed. It is associated with the ability of removing water from the zone of contact of disc and pad.

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