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RESEARCH

Investigation of the Penetration and Temperature of the Friction Pair Under Different Working Conditions

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A B S T R A C T

The phenomenon of vehicle braking is very complex, because during the braking process, the heat will be generated on the braking disc and the braking pads. This will cause the penetration in the contacting surfaces. In this research paper, three-dimensional model is developed and validated using finite element technique. It was used ANSYS/Workbench 14.5 software, Transient Structural module to achieve the numerical analysis. During the stopping process, the high temperatures appeared on the braking pads, where the temperature exceeded 150 ℃ when applied pressure is 0.9 MPa. While, when the applied pressure is 1.1 MPa the temperature on the contact surface is exceeded 180 ℃ after just 1.3 s. The important conclusion based on the results is the most significant factors on the distribution and magnitude of temperature that appear on the contact surfaces are applied pressure and the penetration. Besides that, it was found, that the penetration in high measure depends on the temperature, which proves the value of the coherence, which is almost equal to 1.

1. INTRODUCTION

The phenomena of friction and wear appear when the movement exists between two bodies that are in contact. Where the friction is one of the most influential factors in the braking process, which influences on the vehicle stopping process. It is desirable that the value of the friction is as great as possible in order to reduce the stopping distance/time [1]. Besides that, it is desirable that the sliding speed be as smaller as possible, because it has negative influence on the braking performances [2]. Owing to the sliding, the great amount of heat will be generated in the very short time, which can cause thermal deformations of the braking parts, which further have negative influence on the pressure distribution [3].

The value of the applied pressure in the braking installation will have direct effect on the value of the friction coefficient, as well as on the frictional heat generation on the contact surfaces. Consequently, this thermal effect will reduce the friction coefficient, which leads to reducing the braking torque as well [5].

The rate of brakes wear depends on the followings [5]:

- Vehicle weight (heavier vehicles with larger brake pads have higher brake wear).
- Traffic conditions (stop and go traffic increases brake using/wear).

The wear is a very complex mechanism, and besides working regime (friction coefficient value, sliding speed, pressure, contact surface temperature) to which are exposed two bodies, in the contact [6]. Also, the material characteristics have a significant influence on the wear rate. Brake wear can be caused by material failure mechanism such as adhesive wear, abrasive wear, surface fatigue and corrosion [7,8]. Where the characteristics of materials (steel and friction) affected by wear under such conditions.

There are many researches that investigated the rate of wear using different type of material for the disc, such as cast iron and Al MMC materials. It was found that the disc made from Al MMC materials has higher resistance to wear [9, 10], while the friction coefficient for this disc is higher with 20%. This which directly affect the improvement of the braking performances. However, by increasing of the normal load, the wear will be increased, while the coefficient of friction will be decreased [11]. With temperatures increasing (over than 500 °C), the friction coefficient drops significantly [12]. Which means that is necessary to choose the optimal braking disc according to the certain working conditions, to obtain the good braking performances [1].

The undesirable phenomenon of wear is the formation of the third body, more accurate accumulation of the wear products. During the braking process, it will have formation of primary and secondary unevenness as shown in Fig. 1. These are responsible for the performances of braking system. The primary unevenness appears because of the hard fibers of the braking pads, which have less tendency to wear [14]. These fibers are scratching disc, and leaving behind it cracks on the contact surface of the disc. While material from the disc accumulates on the contact surface of the braking pad, which represent secondary unevenness (so it's called third body). By the reduction of the applied pressure during the braking, it can be started to peel off in flakes [15]. The wear is responsible for the negative effect on the performance of the braking system, as well as for the malfunction. Also, the wear is responsible for the noise and vibrations formation, which are appearing during the braking process [16]. There are other researchers investigated in this area but, where they focused on the protection of environment. Their results showed that the wear of the brakes has a great measured influence on the particle emission [17,18]. The size of the particles is directly connected with the potential health problems of all living beings [19].

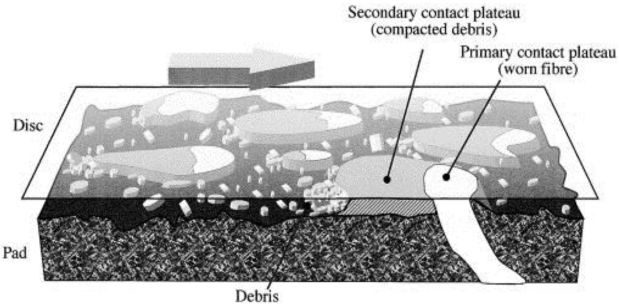


Fig. 1. The contact surface of the braking pad [14].

The high friction between the contacting surfaces that appears during the braking process, cause to grow the surface temperatures of the friction pair dramatically. While the temperature will be affected further the thermal stresses and wear. Owing to non-uniform distribution of the contact pressure, the temperature will be not uniform distributed over the contact surfaces of braking disc and pads as well [20]. The magnitude and distribution of the temperatures are influenced directly by the thermo-physical properties of materials [21,22]. Also, the shapes of the contact surfaces of the braking pad have the influence on the value of the temperature generated in the friction pair [23]. When reduce of the contact surfaces area, the temperature will be raised. Besides the materials, the shape of the braking pad, and the construction of the disc itself have an influence on the value of the generated temperature. In the research of the Belhocine and Bouchetara [24], it was performed analysis of two braking discs, where the first one was the disc with full cross section, while the other one was vented disc. Under the same boundary conditions, the vented disc was cooler at the end of the braking process. How today, in most cases are used vented discs, the temperature on the contact surface is higher, while the temperature on the ribs is much lower. This occurred due to the conduction in disc and high convection in ribs [25]. Of course, the shape of the ribs plays very important role in cooling operation of the vented braking disc [26]. However, in case of consistent braking, the temperature at the end of process will achieve value over 800 °C [27]. So, in such conditions of exploitation, the braking characteristics will fade.

The measurement of the magnitude and distribution of the temperature on the contact surfaces is very complex and expensive, due to the complex interaction among the effecting factors. However, it can be calculated the values of temperatures numerically with an acceptable degree of errors. Aleksendrić et al. showed that the difference between the experimental and numerical results was not exceeded 3.14 % [28]. So, the results that were obtained by numerical analysis are accurate and acceptable.

The aim of the paper is to investigate deeply the penetration phenomenon in the contact surfaces, with respect to the temperature of the friction pair, during the braking process. It was applied the numerical analysis (finite element method) to find the solution of the contact problem. It was used ANSYS software 14.5, module Transient Structural, to achieve the numerical tasks. The results show that the influence of the temperature on the penetration in the contact surfaces of the brake system.

2. THE MODELING OF BRAKING SYSTEM

The braking system consists of many parts, starting from command device (braking pedal), parts which are serving for braking force transfer, till working parts (friction pair, braking disc and braking pads). In this paper, it will be investigated only the main parts that are responsible of the braking process. These main parts are the braking disc and braking pads. Because these parts are exposed to high temperatures and pressures, therefore it's necessary to be results very reliable during the entire braking process. Besides the steering system, the safety of all traffic participants depends also on the braking system.

The analysis will be performed using the three dimensional model of the braking disc and pads, as shown in Fig. 2. In this study, it was assumed that the materials are homogenous and isotropic, where the braking pads are made from friction material. The constructive dimensions and material characteristics are given in Table 1.

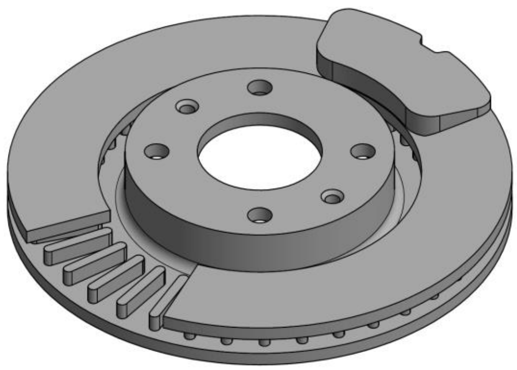


Fig. 2. Three dimensional model of the friction pair.

Table 1. Thermo-mechanical properties and design characteristics of the brake disc and brake pad.

Parameters	**Values**	
Inner disc radius, m	0.0667	
Outer disc radius, m	0.13285	
Disc height, m	34.3	
Disc thickness, mm	0.0221	
Thickness of the disc braking plate, m	0.0068	
Thickness of the air gap, m	0.0083	
Thickness of braking pads, m	0.012	
Material properties	**Disc (cast iron)**	**Pad (frictional material)**
Density, kg/m³	7100	2300
Elastic modulus, GPa	118	20
Poisson ratio, -	0.32	0.3
Thermal conductivity, W/m·°C	53.3	3
Specific heat, J/kg·°C	490	1200
Thermal expansions, 1/°C	$10.85 \cdot 10^{-6}$	$10 \cdot 10^{-6}$

3. THE WORKING CONDITIONS OF THE BRAKING SYSTEM

It this analysis, it is considered that the passenger car is moving on the dry asphalt. Where the starting speed is 120 km/h, which corresponds to the wheel angular speed 107.26 rad/s. Table 2 lists the working parameters such as braking time, friction coefficient that appears in the friction pair, as well as the other parameters, which are important for vehicle stopping and for defining the boundary conditions.

Table 2. The boundary conditions of braking process [29-31].

Name	Value
The speed before braking, rad/s	107.26
The speed at the end of braking, rad/s	0
Friction coefficient in friction pair, -	0.336
Grip coefficient, -	0.7
Drag coefficient, -	0.3
Air density, kg/m³	1.225
Frontal surface of the vehicle, m²	2.01
Vehicle mass, kg	1126
Influence of inertial masses, -	1
Acting pressure of braking pads on the braking disc, MPa	0.9 1.1
Stopping distance, m	80.99
Braking time, s	4.77

It is considered the case, when a vehicle moves on the straight road, without the influence of the wind. This paper will be showed the values of penetration and temperature for two different cases, when the values of applied pressure are 0.9 MPa and 1.1 MPa (Table 2).

4. THE COUPLED THERMAL-STRUCTURAL PROBLEM IN BRAKING SYSTEM

In order to perform the coupled analysis (thermal-structural), it should be used a suitable element type, that allow to study the thermal and structural behaviors of the brake system. The flowchart of the developed numerical approach of the thermal-structural problem is shown in Fig. 3.

In order to simulate real exploitation conditions, the Transient Structural module will be used. It was used ANSYS 14.5 software to achieve the analysis. The applied module allows the disc rotation simulation, while pads are acting on it with pressure, which in this case is constant. The starting angular speed is 107.26 rad/s, and final one is 0 rad/s. Angular speed is defined by the motion low, as following,

$$v = 107.26 - 22.486 \cdot t \quad (1)$$

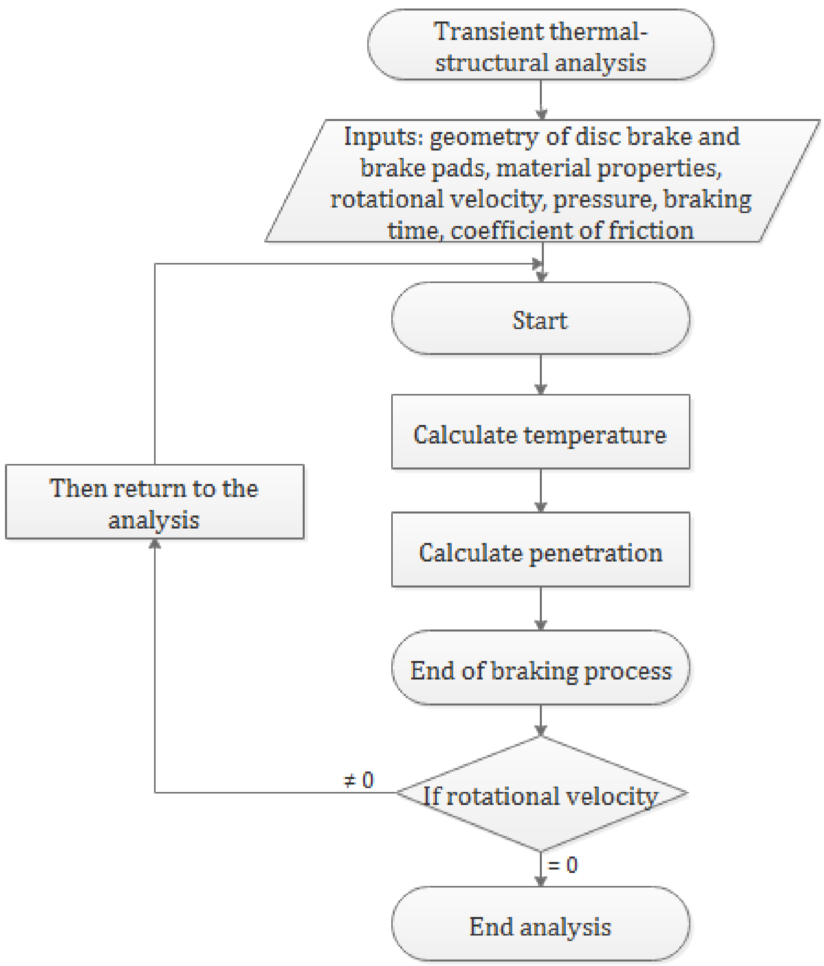


Fig. 3. Flowchart of the developed numerical approach for thermal-structural problem.

In difference from many researches that investigated in this area, the proposed approach of simulation is closest to the real braking process. This allows better understanding of the interaction of factors in the braking process on the results (temperature and penetration). So far researches are based on application of convection and heat flux, in order to cause the friction pair heating. This will lead that the values of temperature are constant on the entire surface of braking elements, what in reality is not possible. Because of the constant rotation of the braking disc, which cause its constant cooling. Also, the obtained values of temperature shown in some researches [32], will cause the start of melting of the braking disc, which is made from cast iron. Every heating over 30% of the melting temperature, will cause permanent deformations (plastic deformations) of the braking disc, thermal cracks on the braking disc and appearing of hotspots [33]. The melting temperature of the cast iron is around 1260 °C, so the braking disc shouldn't heat over 378 °C.

The shape of the element is tetrahedral (Fig. 4), and the type of selected element is SOLID227 [34]. It was achieved the mesh sensitivity to find the optimum mesh from the computational accuracy point of view. It was used several mesh sizes to achieve the numerical analysis of brake system, which starting with coarse mesh and increasing the number of elements until reach the results to stability. Where, it was found the number of elements and nodes of the frictional pair as shown in Table 3.

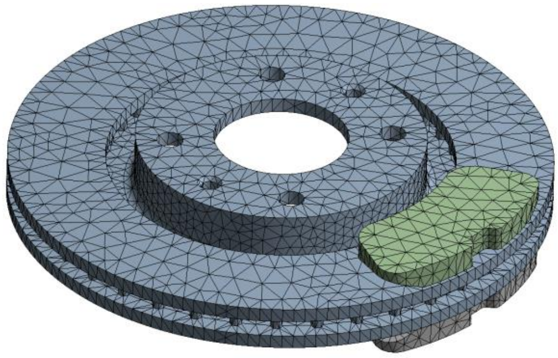


Fig. 4. Finite elements mesh.

Table 3. Number of elements and nodes in the friction pair .

	Disc	Pad	
		Inside	Outside
Number of nodes	38938	1684	840
Number of elements	21096	1660	824

The target surfaces are surfaces of the brake disc and the contact surfaces are surfaces of the brake pads. The selected elements for contact and target surfaces are CONTA174 and TARGE170, respectively. These elements have degrees of freedom in all three directions, as well as temperature. The algorithm which used in the contact problem is the Augmented Lagrange [35].

5. FRICTION HEAT GENERATION ON THE BRAKING SYSTEM

When movement exists between two bodies that are in contact, the sliding occurs. It was mentioned earlier, that the undesirable phenomena of the friction is heat generation. The total amount of generated heat due to friction, is described as [36,37].

$$Q_{total} = \mu \cdot p \cdot V \tag{2}$$

Where μ is coefficient of friction, p contact pressure and V sliding velocity.

Where the total amount of friction by one part is generated on the braking pad (Q_d), and by other part is generated on the braking disc (Q_p), represented as followings [36,37].

$$Q_d = \frac{T_p - T_d}{r_d + r_p} p + \frac{r_p}{r_d + r_p} Q_{total} \tag{3}$$

$$Q_p = \frac{T_d - T_p}{r_p + r_d} p + \frac{r_d}{r_p + r_d} Q_{total} \tag{4}$$

Where Q is heat, T is temperature, r is thermal contact resistance constant, and subscript d and p denoting disc brake and brake pad, respectively.

6. RESULTS AND DISCUSSIONS

Mostly brake systems operate under extreme load conditions, where the automotive designers should be taking these critical conditions in the design process to obtain a successful system. This meaning that the brake system is reliable during the entire duty cycle. The results in this section will highlight the variations of the penetration and temperature that appeared on the brake pads during the braking operation under different applied pressures.

Penetration physically represents the entrance of one body to another one. During the braking process, the existing interaction between the braking disc and pads will cause the penetration phenomenon. Penetration will cause resistance to the disc rotation, which influence on the heat generation in braking system. Also, penetration in some way is connected to the wear. Penetration represents a very important parameter, which should be considered during analysis of the braking process.

During the braking process, the temperature increased dramatically, as seen in Table 4. When the applied pressure of the braking pads on the braking pads is 1.1 MPa. The maximum values of temperature are appeared on the inner braking pad occurred after 1.397 s, while on the outer braking pad occurred after 1.338 s. The maximum temperature first appeared on the outer pad, which is the consequence of the umbrella effect [38,39].

The most important point is the safety of all traffic participants, where it can be noticed that there is no thermal effect through the thickness of the system where the temperature almost constant and not affected significantly by the frictional heat generated. It was found that temperatures for the inner and outer pads are not exceeded 40.248 °C and 40.958 °C, respectively.

Under these circumstances, there is no heating effect on the braking fluid, which is considered a very good point, because the heating of the braking fluid can cause dropping of the braking pedal.

The highest values for penetration appeared in the case of the highest temperature. Two values of applied pressures are assumed, which are 0.9 MPa and 1.1 MPa. In both cases, the maximum values of penetration are found in the inner braking pad, while the maximum values of temperatures are found in the outer braking pad.

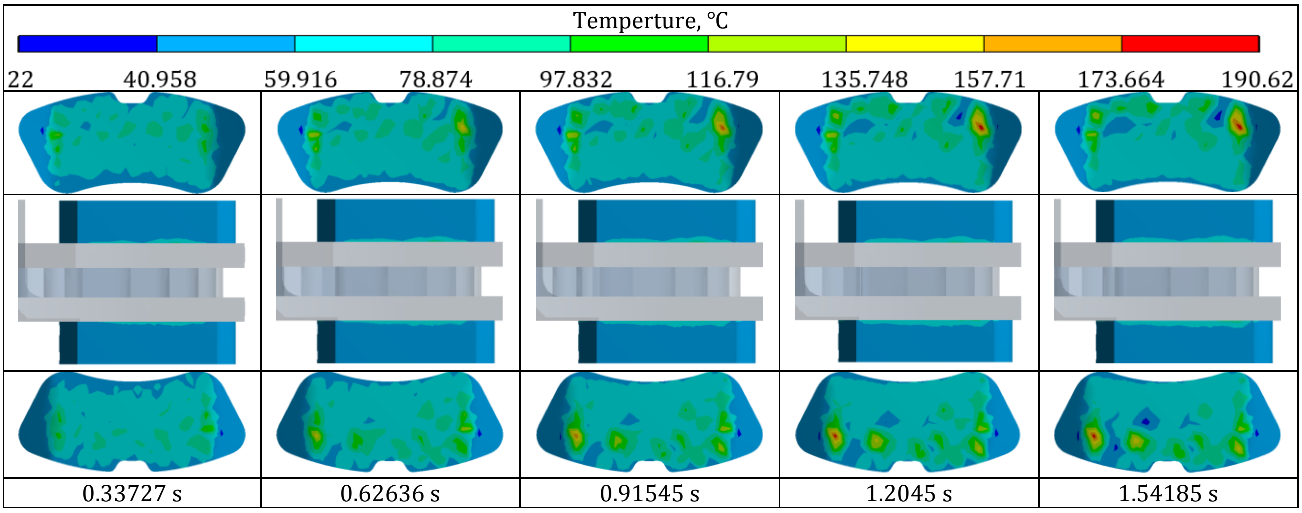
At the beginning of the braking operation, the temperature is equal to the environment surrounding temperature which is 22 °C. Later on, the temperature grown with barking time until reach the maximum value at the end of the process as shown in Table 4.

When applied pressure is 0.9 MPa, it was found that the maximum values of temperature on the inner and outer braking pads are 156.36 °C and 159.95 °C that occurred after 1.382 s and 1.331 s (Fig. 5), respectively.

It can be seen that the penetration and temperature have approximately the same behavior during the braking process, except the peak point for temperature that occurred at a different time from the penetration.

In the case, when the applied the highest pressure (1.1 MPa), the obtained values of the penetration and temperature are shown in Fig. 6. The maximum value of temperature that appeared on the inner braking pad is found 186.23 °C after 1.397 s as shown in Fig. 5. Where this value of maximum temperature is considered the peak point that occurred during the whole braking process and after that the pad starts to cool.

Table 4. The temperature field of the outer and inner braking pad the acting pressure 1.1 MPa.



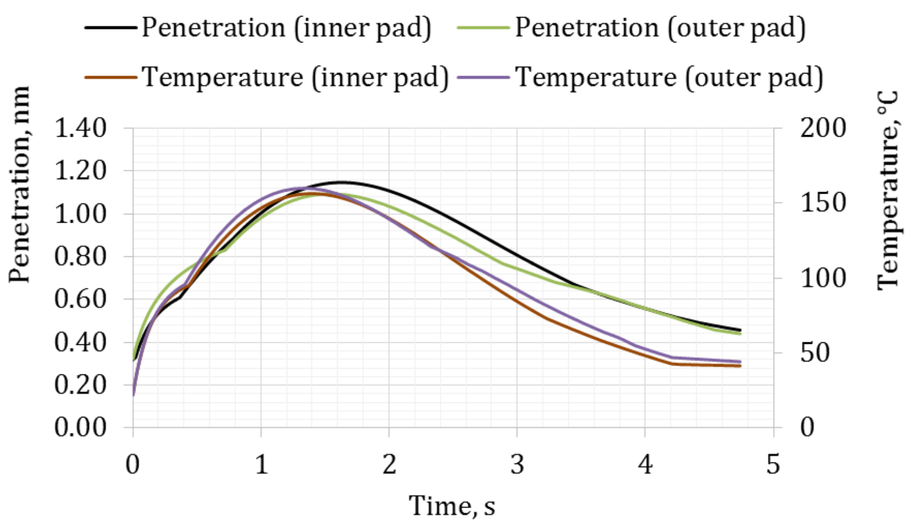


Fig. 5. Diagram representation of the penetration and temperature for inner and outer brake pad, when the acting pressure is 0.9 MPa in the function of time.

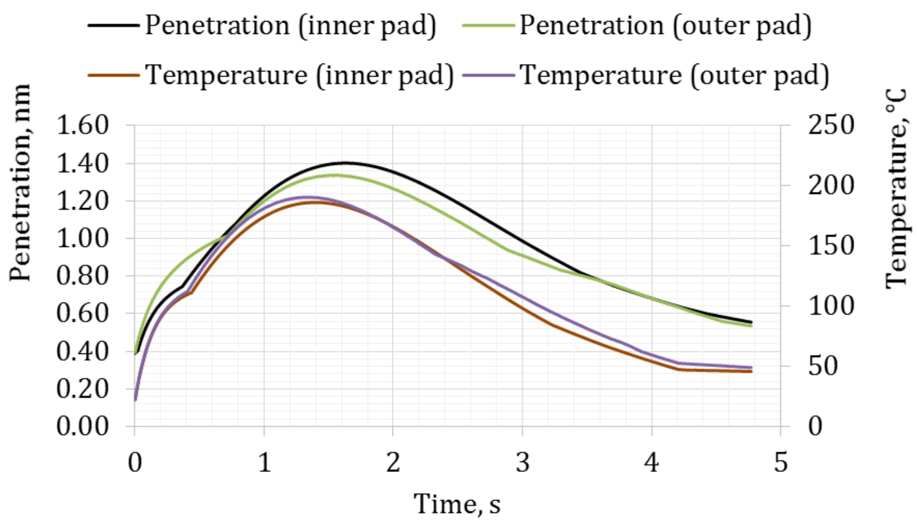


Fig. 6. Diagram representation of the penetration and temperature for inner and outer brake pad, when the acting pressure is 1.1 MPa in the function of time.

Figure 6 represents the variation of penetration and temperature as a function of time for the outer braking pad when applied pressure is 1.1 MPa. It was found that the maximum value of temperature occurred after 1.338 s. After that, the temperature started to decrease, because the angular speed decreases too. So the braking disc has more time for cooling. Or in other words, the disc that was in contact with the braking pad, in the next moment is free to rotate, and nothing is acting on it. This occurred in the inner and outer pads when the applied pressure was 0.9 MPa.

In the next moment, when this part of the disc started in contact with pads, it was found that the level of temperatures in the braking disc is lower than those in the pads. This occurred due to the high thermal capacity of the disc compared with the lower thermal capacity of the pads. It was found that the obtained results in this research paper are compatible with the results of other researchers that used different approaches to obtain the solution of the thermal problem in the brake system [20]. So, as a result of this, the most amount of heat generated dissipated to the surrounding environment.

The influence of the temperature on the penetration is shown in Fig. 7. Where the value of the coherence is between 0.96 and 0.97, more accurate it is very close to be equal 1. It can be noticed that the temperature has a great influence on the penetration.

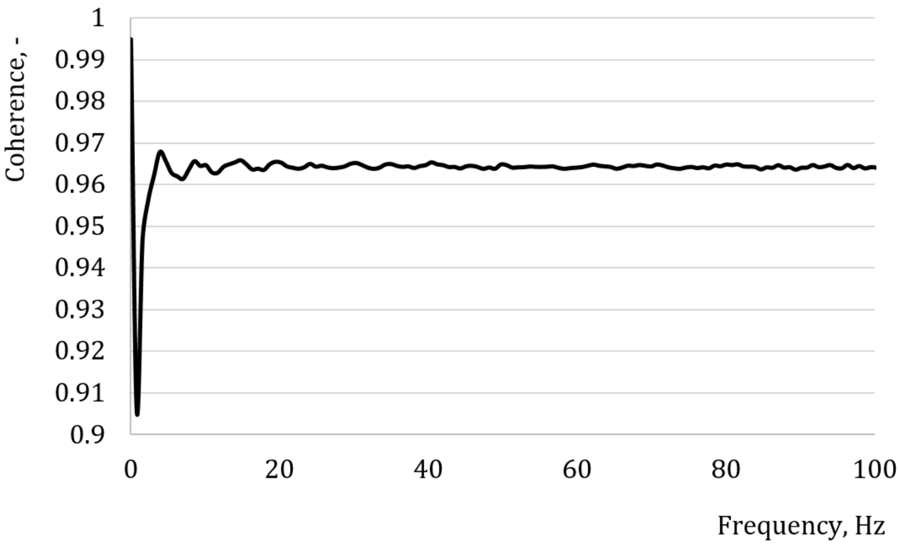


Fig. 7. Coherence between penetration and temperature for outer braking pad when the acting pressure is 1.1 MPa.

Based on the results of Fig. 6, it can be proved the solid relationship between the variation of penetration and temperature during the braking period. Where, both have approximately the same behaviors.

It was found also, that the final surface temperature at the end of the braking process was higher than the initial temperature. In case when the applied pressures are 0.9 MPa and 1.1 MPa, the final temperatures are found to be 40 °C and 50 °C, respectively (Figs. 5 and 6). According to obtained results, it was found that the brake pads need more time to cool.

7. CONCLUSIONS AND REMARKS

In this study, it was investigated the influence of the applied pressure in the brake system on the frictional heat generated and penetration of braking pads. It was applied two different values of pressures, to study the behaviors of the temperature and penetration during the braking process.

It was found that the temperature of the friction pads grown to peak value after approximately 1.3 s. However, when the stopping process is started, and there is no movement of the vehicle on the downhill, the braking was constant and the temperature of the friction pair decreased after 1.4 s.

The safety of other participants in traffic is not disturbed, because the temperature of the braking pad was not so high (under 40 °C). Where this level of temperature is insufficient to case the heating of the braking fluid, that dropping of the braking pedal. Besides that, the period of stopping process is very short (t = 4.77 s), which means that is a very short period for braking pads to generate high level of temperatures. Therefore, the braking performances will be not disturbed. Also, the high thermal capacity of the brake disc is considered the main advantage in the brake system design to dissipate the most amount of heat generated to the surrounding environment.

On the other hand, the final temperatures of the braking pads were not returning to the initial temperature, but one part of the generated heat stays on their contact surface. The results of this kind of studies can be used to analysis of vehicle emergency stopping, in some critical situations. In the case of consistent braking, in some cases the temperature of the friction pair can quickly exceeding 800 °C [27]. Where under such circumstances the fade will be appeared and this will be affected negatively the braking performances and this will lead to the traffic accident in some cases.

This research paper is considered to be the first step and will be followed by other researches that will study this problem and go into more depth with it. It can be studied the penetration and temperature when vehicle is moving on the downhill and where constant braking during the entire braking process exist. Also, it is very interesting to investigate, how temperature will change in the case of consistent braking till stopping with starts speed of the vehicle 120 km/h. There is another significant point which is the effect of friction materials on the environment and organisms [40]. In future research, the negative impact of brake pad particles on the environment on one hand and on living organisms on the other hand will be examined.

Acknowledgement

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