Journal of Sustainable Development of Transport and Logistics
journal home page: https://jsdtl.sciview.net

Holenko, K., Dykha O., Babak, O., & Posonskiy, S. (2023). Friction heating and stress-strain state of ventilated disc brakes. *Journal of Sustainable Development of Transport and Logistics, 8*(1), 43-52. doi:10.14254/jsdtl.2023.8-1.3.

Scientific Platform
ISSN 2520-2979

Friction heating and stress-strain state of ventilated disc brakes

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OPEN ACCESS

Article history:

Received: December 22, 2022
1st Revision: January 20, 2023
Accepted: February 19, 2023

DOI:
10.14254/jsdtl.2023.8-1.3

Abstract: This paper describes the study of ventilated car disc brakes stress-strain conditions and friction under the pressure using the ANSYS environment. Such influencing factors are taken into account in the course of research as angular speed value, the pressure of the pads on the disk, the nature of the load application, convection, thermal expansion, etc. Computer modelling of the stress field and the transient thermal field in the area of contact between the pads and the disk is provided by the method of sequential thermostructural communication of the intermediate states of the brake model directly in the ANSYS Coupled Field Transient environment. Besides, the ANSYS calculations were also performed based on the primitive assembly model of two steel blocks (the discrepancy was less than 3%) to determine the identity of the theoretical knowledge about the heating of bodies as a result of the work to overcome frictional forces. Finally, a high level of calculation results convergence by analytical formulas and computer modelling was established. Since this approach justified itself, its principles were taken as a basis in the calculations of ventilated disc brakes of cars, which significantly facilitates their application, knowing the area of the active part of the disc (the rest of the boundary conditions are typical and correspond to the normal operating modes of the vehicle).

Keywords: brake discs, thermal load, stress-strain state, safety, stress, heat flow

1. Introduction

Significant technical developments in the field of heat and mass transfer in such sciences as tribology or thermodynamics, which developed over several decades thanks to scientific progress, gave impetus to the branches of nuclear energy, aviation, automotive, etc. When designing relevant units and aggregates, such as disc brakes of vehicles, a significant role plays in modelling problems related to the phenomenon of thermal or mechanical energy transfer through friction pair contacts. Such modelling

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simulations are relevant when selecting optimal options for braking systems for existing vehicles depending on their class, type and operating conditions, as well as when designing new models of cars, buses, etc. In both cases, the boundary conditions of the calculation are set, which are as close as possible to the real operating environment: the angular speed of rotor rotation, the time of applying the pressure to the brake pads and the nature of its application, the material of the brake pads, the convection of the medium, etc.

As we know, brakes are a unit that creates a frictional resistance to move a system element (rotor) to stop further movement; that is, it is a mechanism used to reduce the speed or stop the movement cycle of the vehicle (Abhang & Bhaskar, 2014; Balasubramanyam, 2014). The task of the current publication is to study the above-mentioned factor of influence on strength indicators (von Mises stress) and temperature of brake components and the whole unit in general. In order to confirm the closeness of theoretical knowledge about the heating of bodies due to the work of overcoming frictional forces and ANSYS calculations, a primitive system of two steel blocks subjected to friction as a result of interaction was additionally modelled. Understanding the basic principles of heating caused by friction, like the convection influence, surface area or applied pressure plays a valuable role. At the same time, we aim to move to more complex research cases, primarily operating with solid-models of real ventilated brakes installed in automobiles. Thus, the presented publication provides an opportunity to get acquainted with the frictional processes step by step for maximal efficiency.

2. Literature review

The influence of the ventilation holes disc surface location on the appearance of micro-cracks should be read in work (Kang, Jung, Hong & Park, 2018) - the authors present the results of tests when braking from a speed of 100 km/h. The research presented in work is based on the analysis of the braking system behaviour under friction conditions at constant pressure, which increases Mises stresses and temperature in the corresponding critical areas. So, for example, in work (Hugar & Kadabadi, 2017), when analysing the stresses of the two-wheeler disc in Bajaj 220cc, the stress values were in the range of 20-30 MPa, and the temperature exceeded 120 °C, and for some models - 230 °C. Long-term use of the brake in a car causes it to heat up during braking (temperature limits reach almost 300 °C) (Jaenudin, Jamari & Tauviqirrahman, 2017, January), so the disc and pads undergo thermal expansion due to high temperature (Santosh, Harish & Sudhakar, 2017), that's why providing discs with ventilation holes to enhance convection plays a crucial role (Satope, Bote & Rawool, 2017). Brake-disc holes and slit shape design to improve heat dissipation performance and structural stability were investigated in work (Park, Lee, Kim & Kim, 2022), and the topic of convective heat transfer characteristics on an outside surface of vehicle brake disc was risen in (Zhang, et al., 2017). The majority of brake model analytical calculations are based on the finite element method (Umale & Varma, 2016).

Atypical research on brakes is presented in the paper (Nakatsuji, Okubo, Fujii, Sasada & Noguchi, 2002), which analysed the nature of cracks that appeared around small holes in the flange of one-piece brake discs, observed under overload conditions – rather rare research type. Such local tests of disc strength are a practical application for laboratories for physic-chemical analysis of material properties, hence the complete resource and possibility of brake operation. A publication (Belhocine, & Ghazaly, 2015) can also be attributed to the study of material properties, where in fact the noise generation of the brake sheet uses the finite element method.

It makes sense to get acquainted with the most recent publications, like the investigation of thermo-mechanical behaviour in brake disc-pad couple using the finite element method (Ay & Demä, 2022) and modern materials used in brakes development, like nano-composite (Sivaprakasam, Abebe, Čep & Elangovan, 2022). We should admit that most publications are dedicated to the automotive branch, though it's possible to meet more exotic research cases of other transport kinds, like the performance optimisation of the disc brake system of electric Two-wheeler using the Taguchi approach (Thakre, Shahare & Awari, 2022) or thermomechanical characterisation of high-speed train braking materials (Mann, Magnier, Brunel, Dufrénoy, Henrion & Guillet-Revol, 2021).

3. Friction influence on the heating of a simplified model

Before starting practical studies, familiarising yourself with the theoretical foundations of heating and heat exchange processes is advisable. Simple heat exchange includes:

- thermal conductivity – the process of heat transfer by structural particles of a substance (heating of a disc rotor and pads, heating of a conductor, dryer, etc.);

- convection – the process of heat transfer by flows of the substance itself in space from an area with one temperature to an area with another. A distinction is made between natural and forced convection or laminar and turbulent (natural - heating of liquid, the air in the room, formation of clouds; forced - mixing of liquid (with a stirrer, spoon, pump, etc.).

- radiative or radiant heat exchange – the heat transfer process by electromagnetic waves (solar radiation).

We will operate with the concepts of heat conduction and convection in the framework of this work. The temperature field *t(x,y,z,τ)* is a set of instantaneous temperature values in space. The increase in temperature in the direction normal to the isothermal surface is characterised by the ratio of the temperature change Δt between the selected isotherms to the distance between them along the normal Δn. The limit of this ratio when Δn approaches zero is called the temperature gradient ($grad\ t$):

$$\lim_{\Delta n \to \infty} \frac{\Delta t}{\Delta n} \cdot \overrightarrow{n_0} = \frac{\partial t}{\partial n} \cdot \overrightarrow{n_0} = grad(t) \qquad (1)$$

where: $\overrightarrow{n_0}$ - unitary vector directed along the normal in the direction of temperature increase; $\partial t/\partial n$ - a derivative of the temperature in the direction of the normal.

The relationship between the heat flux density $\vec{q}$ and the temperature gradient $\vec{\nabla} t$ is expressed by the Fourier law:

$$\vec{q} = -\lambda \vec{\nabla} t = -\lambda \frac{\partial t}{\partial n} \overrightarrow{n_0} \qquad (2)$$

where: λ - thermal conductivity coefficient (heat flow density at a temperature gradient equal to unity. It characterises the ability of a substance to conduct heat).

The law of heat conservation for elementary volume:

$$\delta Q_{\tau 1} + \delta Q_{\tau 2} = \delta Q_{\tau 3} \qquad (3)$$

where: $\delta Q_{\tau 1}$ - the amount of heat entering the elementary volume by thermal conduction over time $d\tau$; $\delta Q_{\tau 2}$ - the amount of heat released during the time $d\tau$ due to internal sources; $\delta Q_{\tau 3}$ - enthalpy change in elementary volume over time $d\tau$. Below we will give an example of the heating of two steel bodies as a result of work to overcome frictional forces, so it is important to understand the physical parameters of steel:

$$\lambda, \rho, c = const \qquad (4)$$

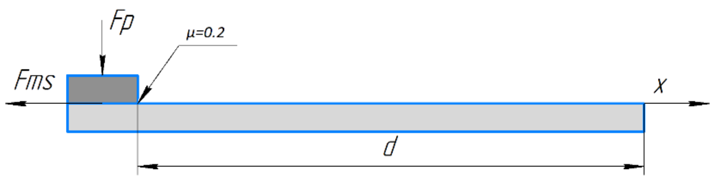
where: ρ – density, kg/m^3; c - specific heat capacity, J/kg·°C

Then the law of heat conservation for an elementary volume will take the form:

$$q_v + div\lambda \vec{\nabla} t = \rho c \frac{dt}{d\tau} \qquad (5)$$

By understanding the basics of heat transfer processes, we will move on to determining the identity of theoretical knowledge about the heating of bodies as a result of performing work to overcome frictional forces and ANSYS Coupled Field Transient calculations. A simplified assembly model of two steel blocks will be used in our research (Figure 1).

Figure 1: Simplified friction model



The model consists of two steel elements: a base and a block sliding along it, passing a distance *d* equal to 1 m. A constant pressure of 1 MPa acting on an area of 0.01 m^2 creates a force F_p, is applied to the upper surface of the block. Friction coefficient μ =0.2. For understanding: the boundary conditions include the symmetry parameter of the contact pair with respect to friction, so the symmetry of heat transfer between bodies is considered. Let's calculate the heating value of the bar as a result of the friction force F_{ms}:

$$\Delta T = {}^{F_{ms}\,d}/_{mc} = {}^{F_p \mu\, d}/_{mc} = {}^{2000 \cdot 1}/_{3.125 \cdot 434} = 1.48\,°C \qquad (6)$$

where: m – mass of the block, 3.125 kg; c - specific heat capacity of the material (Structural Steel), 434 J/kg·°C.

We compare the obtained results with the analysis of the model in the ANSYS Coupled Field Transient environment, pre-simulated in SolidWorks: 1.48 °C – theoretical calculation and 1.52 °C – computer simulation (Figure 2). This convergence of results (within 3%) allows judging the practical feasibility of using the computer calculation method in ANSYS.

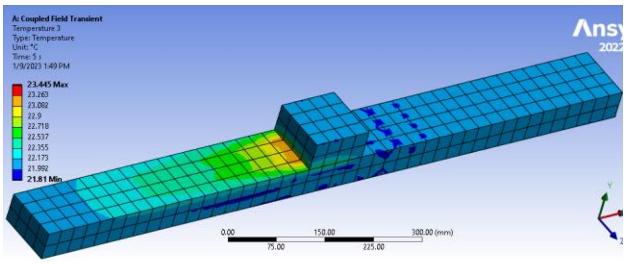
How does convection affect the final results of our simplified problem? The coefficient of heat transfer by convection numerically characterises the heat flow dissipated or absorbed by a unit surface of a solid body, with a temperature difference between the solid body and the coolant of one Kelvin. The unit of measurement of the heat transfer coefficient is W/(m^{2}K). The basic relationship for heat transfer by convection is the formula:

$$q = h \cdot A \cdot (T_a - T_b) \qquad (7)$$

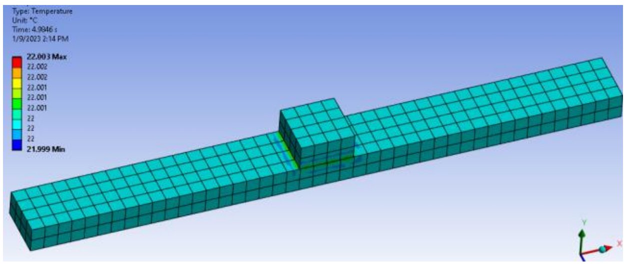
where: q - heat transferred per unit of time; h - heat transfer coefficient; A - speed of fluid movement; T_a - object surface temperature; T_b - environment temperature.

We compare the results obtained for our model with consideration of convection (5 W/(m^{2}K)), and without it - we will analyse the temperature changes in the intermediate states of the model (Figure 2).

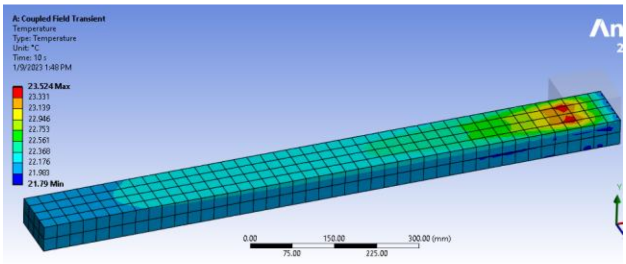
Figure 2: Temperature map of simplified friction model with and without convection



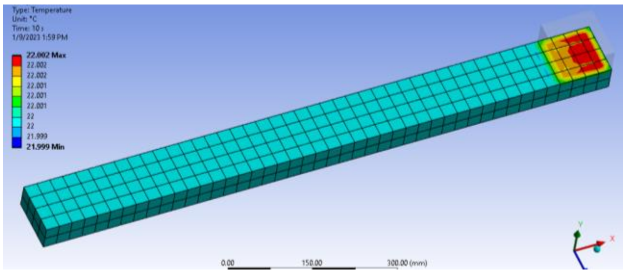
t = 5 s; q = 0 W/(m^{2}K); T_{max} = 23.38 $°C$



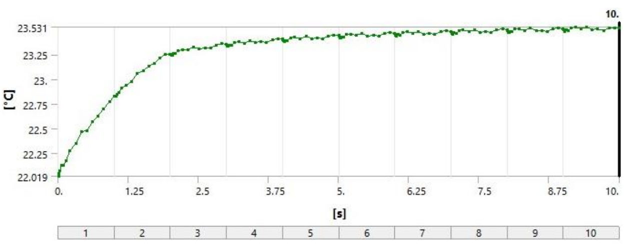
t = 5 s; q = 5 W/(m^{2}K); T_{max} = 22.005 $°C$



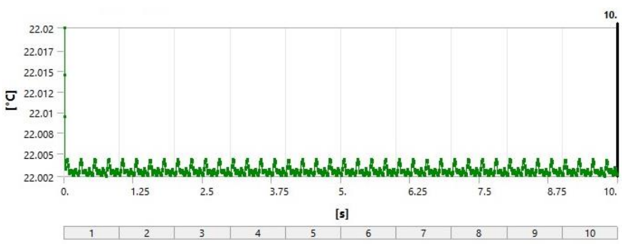
t = 10 s; q = 0 W/(m^{2}K); T_{max} = 23.53 $°C$



t = 10 s; q = 5 W/(m^{2}K); T_{max} = 22.005 $°C$



Temperature graph: q = 0 W/(m^{2}K)



Temperature graph: q = 5 W/(m^{2}K)

It follows from the temperature graphs that even minimal convection, equal to 5 W/(m²K), which corresponds to stagnant air without active movements of air masses, significantly affects the heating of the model elements:

- in the case of 0 W/(m²K) (no convection), the temperature rises from 22°C to 23.53°C within 10 s. The graph has a non-linear character with rapid growth in the first 2 s;

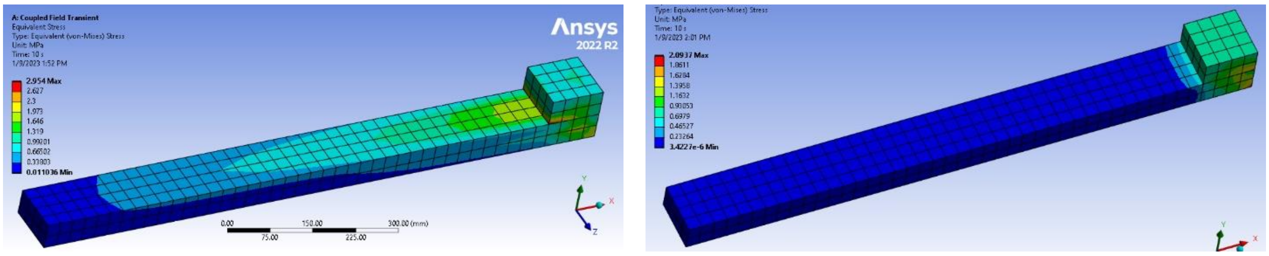
- in the case of 5 W/(m²K), the temperature drops at the very first moment of the movement of the block from 22.02 °C to 20.02 °C, which is explained by the minimal movement of air masses by the block itself, which causes cooling.

How does convection affect stress in the model? The Ansys Workbench environment stress determination is based on the following foundation: the equivalent stresses are related to the principal stresses by the equation:

$$\sigma_e = \left[\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}\right]^{1/2} \tag{8}$$

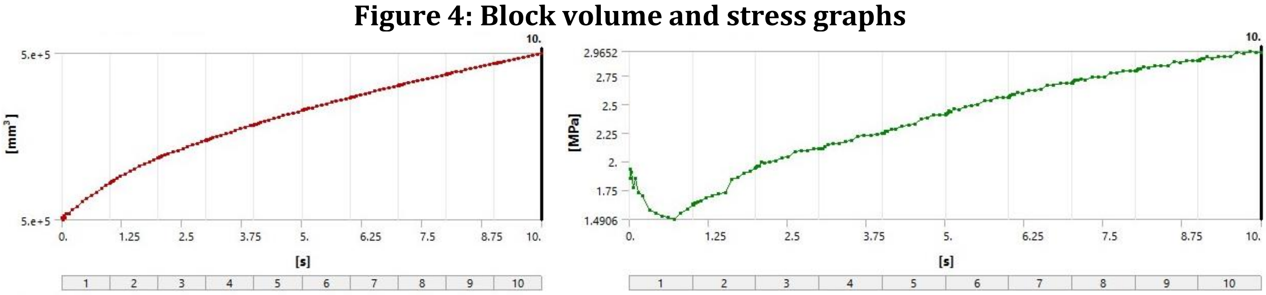
where: σ_1, σ_2, σ_3 – main stresses. Based on the values of the main stresses, an estimate of the strength of the material at the investigated point of the deformed solid body is given. Equivalent stresses, also known as "von Mises stresses" (denoted as "Equivalent (von Mises)" in Ansys Workbench), are often used in projects because they allow any arbitrary three-dimensional stress state to be represented as a single positive stress value. So, the stress of the model without convection was 2.95 MPa, with convection - 2.09 MPa (Figure 3). Such results are related to the phenomenon of thermal expansion due to the transformation of the kinetic energy of the block movement into thermal energy, which leads to an increase in the volume of the model and the penetration of its components (block and base). This process is visually confirmed by graphs of volume growth and block stresses, which have a similar character (Figure 4).

Figure 3: Stresses of the simplified friction model with and without convection



t = 10 s; q = 0 W/(m²K); σ=2.95 МПа t = 10 s; q = 5 W/(m²K); σ=2.09 МПа

Figure 4: Block volume and stress graphs



Block volume growth Mises stress of the block

Thermal expansion can be described by the following properties relevant to the behaviour of solid bodies:

- thermal coefficient of volumetric expansion (measured in inverse Kelvin degrees K⁻¹):

$$\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial t}\right) \tag{9}$$

If the volume expansion coefficient changes significantly with temperature, then the equations must be integrated:

$$\frac{\Delta V}{V} = \int_{T_0}^{T_0+50} \alpha(T)dT \tag{10}$$

- thermal expansion of the area of a solid body:

$$\Delta S = 2\alpha S_1 \Delta t \, , \tag{11}$$

where: T_0 - initial temperature; ΔS – area change (for example, brake pads or disc); S_1 – starting area; Δt – temperature change.

4. Friction research of ventilated car disc brakes

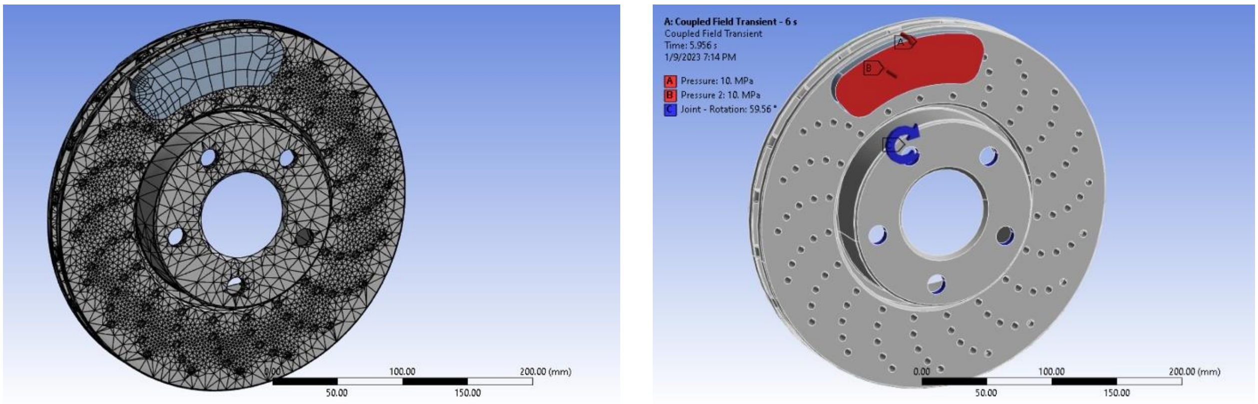
The disc brake is a system consisting of a brake disc (rotor), brake pads and callipers actuated by a hydraulic cylinder. The brake disc rotates with the wheel, and the pads mounted on the brake callipers grip it to stop or slow the wheel. Brake pads generate heat through friction, converting kinetic energy into heat to reduce the vehicle's kinetic energy. Understanding the theoretical part of the heating process of the simplified model allows us to move on to a more complex case - the solid model of ventilated disc brakes. Our goal is to form a relatively simple and effective applied methodology for analysing the behaviour of pads with a rotor by the method of sequential thermostructural coupling of the intermediate states of the brake model directly in the ANSYS Coupled Field Transient environment.

The model consists of 83023 finite elements and 143802 nodes; material – Structural Steel. The total calculation time on the equipment of 2 Intel Xeon physical processors (24 cores in total), RAM 48 Gb, and NVIDIA GeForce 4Gb video was 4 h 56 m. Boundary conditions include (Table 1):

Table 1: Boundary conditions for the thermal calculation of a car disc brake

	Meaning	Unit
Pressure on pad #1	10	MPa
Pressure on pad #2	10	MPa
Rotation angle	60	°
Temperature	22	°C
Experiment duration	6	s
Increment step	0.1	s
Friction coefficient	0.2	-

Figure 5: Calculation model of brakes in ANSYS Coupled Field Transient environment



FEA model of the disc with pads — Boundary conditions of the research

Boundary conditions should be pre-calculated for the practical use of the given technique. Therefore, the angular velocity should be initially determined (set in the Ansys environment):

$$\omega = {}^{v}/_{R_t} \tag{12}$$

where: v – initial speed of the car, m/s; R_t – wheel radius of the car, m.

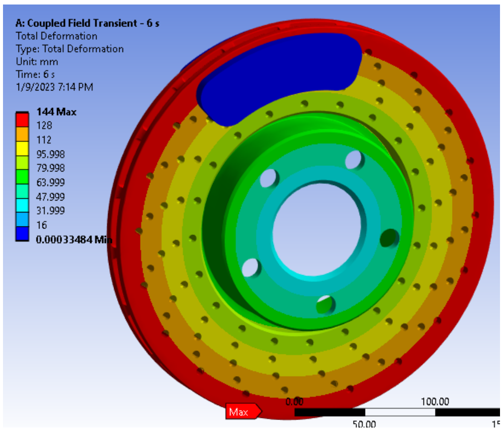
The value of the pressing force F_d can be found as follows:

$$F_d = \frac{k\cdot(M\frac{v^2}{2})}{2\frac{r}{R}(vt-\frac{1}{2}\left(\frac{v}{t}\right)t^2)} \tag{13}$$

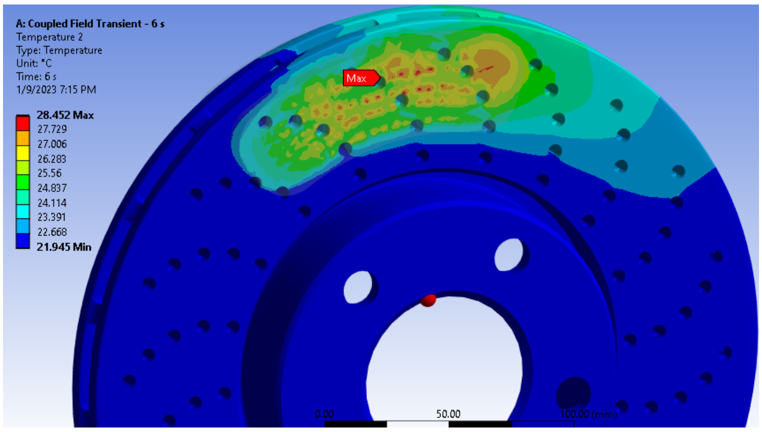
where: k - load factor – 0.3 in most cases; M – mass of the car, kg; t – stop time, s; r – brake disc radius, m; R – wheel radius, m.

Now, having the magnitude of the compressive force F_d, it's possible to calculate the pressure P, knowing the area of the pad.

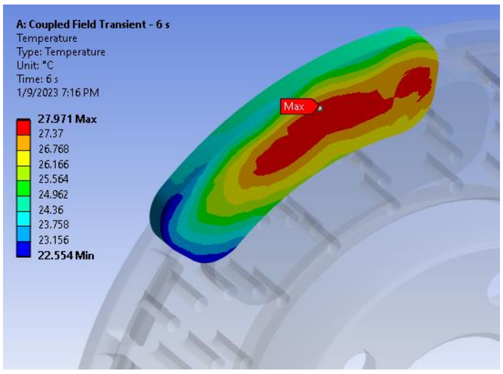
Figure 6: Results of the stress-strain and thermal state of disc brakes



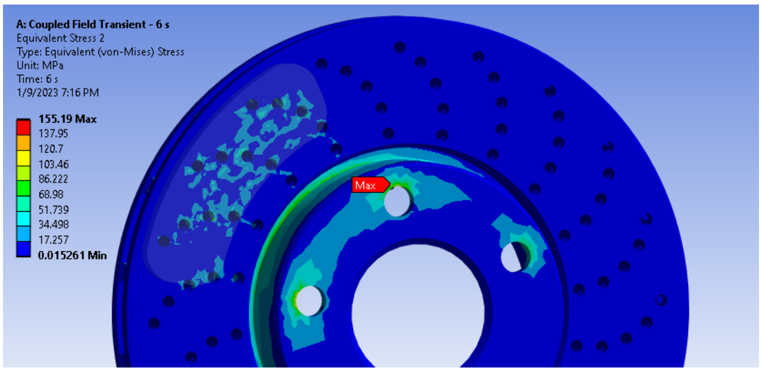
Disc deformation



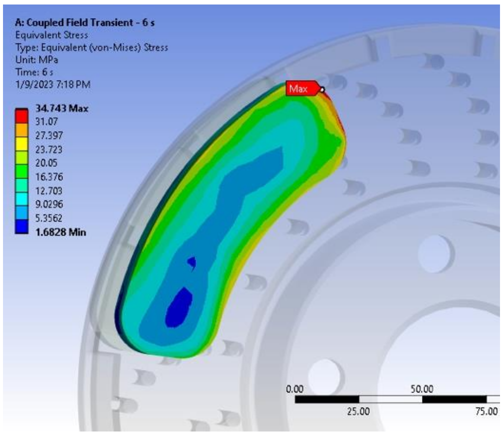
Disc temperature map



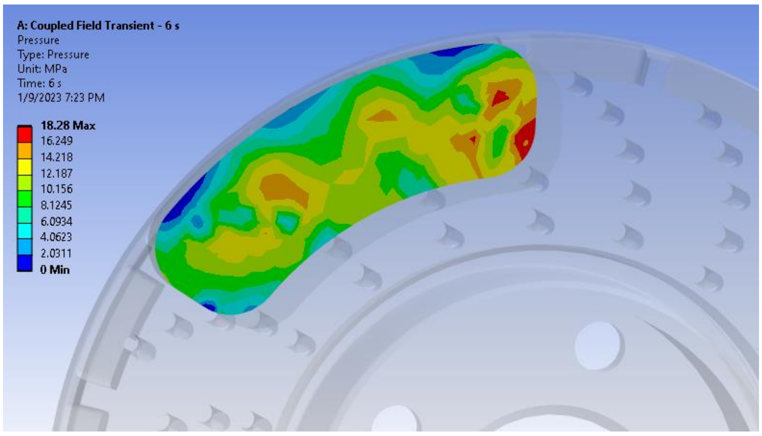
Brake pad temperature



Disc (rotor) equivalent stress (von Mises)



Brake pad temperature stress

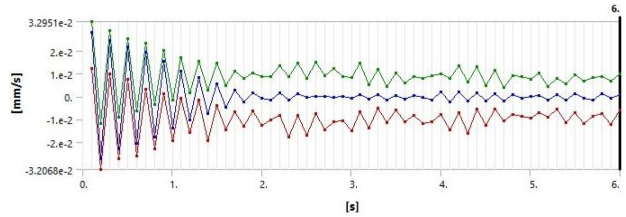


Pad surface pressure

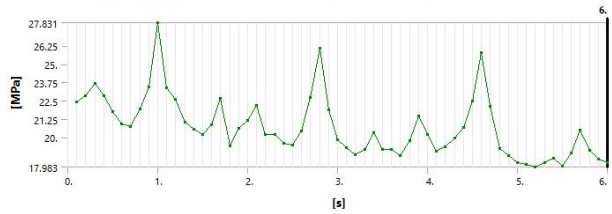
The presented results (Figure 6) allow us to judge thermal loads, locations of increased pressure (18.28 MPa) and stresses (34.7 MPa) on the pads surface (wear zones); make sure that the central part of the pad is the most thermally loaded (29.9 °C); trace the heat spot on the disk as a result of the friction of the pad on it (28.45°C); to find the amount of stress in the bolt holes (155.19 MPa). The last parameter of the found out max stress is essential from the strength point of view – the rotor with mounted holes for bolt fastening has to correspond using yield strength from one side and stay thermal resistant – from another. Therefore, modern disc brakes consist of assembled parts, like the frictional disc part of ceramics and the hub of durable steel. The number of holes increases from 3 in the case of slow city/golf cars to 6 for the supercars with massive torque on the wheels. Trucks might have 10 or even more bolts to mount the disc on the hub and reduce the specific load.

To observe the parameters of the pads during the experiment, it is recommended to refer to the corresponding graphs:

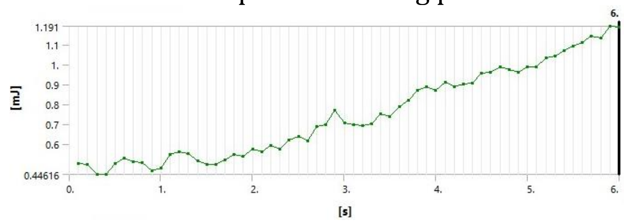
Figure 7: Graphs of the behavior of brake pads during the experiment



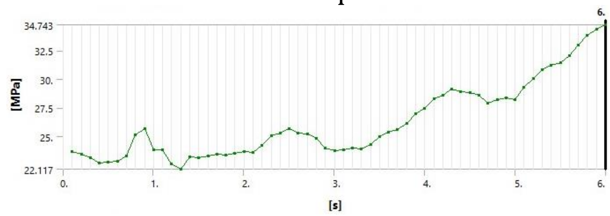
Linear speed of moving pads



Pressure on the pad surface



Pad strain energy



Pad von Mises stress

5. Conclusions

The given studies of the stress-strain state and thermal behaviour of ventilated disc brakes using ANSYS Coupled Field Transient are of a practical nature when designing new vehicles with the appropriate selection of the optimal brake configuration for them. The presented method of formation of boundary conditions with pressure and angular speed of the rotor rotation due to the mass of the car, its linear speed, the diameter of the wheels and braking time allows modulating one's own configurations of disks, ventilation holes in them, to select materials and shape of pads, etc.

Based on a simplified friction pair model (block and base), the effect of convection on the cooling of the model was established, and the identity of theoretical heating definition and computer calculations using FEA modelling was verified (error < 3%). The amount of convection strongly affects the obtained model temperature values, and in the case of car wheel rim ventilation, it suggests that cooling should not be excessive because the brakes will not show optimal characteristics at low temperatures.

The given episode of disk rotation can be extended throughout the experiment to cover a longer duration. The task of our research was to form an accessible analytical research methodology that could interest engineers or scientists to expand and adapt it to their own needs. This can be especially useful for tuning companies, who are often involved in improving the factory car's parameters, installing larger diameter rotors, ceramic and other modern materials brakes with an increased number of callipers and additional ventilation holes on the bumper and wings of cars (Sivaprakasam, P., Abebe, E., Čep, R., & Elangovan, M., 2022).

Acknowledgments

The authors would like to acknowledge that this work is part of the Department of Tribology, Automobiles and Materials Science research. Khmelnytskyi National University. All Figures, tables, and equations listed in this paper will be included in the final report after this study.

Author contributions

All authors reviewed the results and approved the final version of the manuscript.

Declaration statements

The authors report no potential conflict of interest.

Citation information

Holenko, K., Dykha O., Babak, O., & Posonskiy, S. (2023). Friction heating and stress-strain state of ventilated disc brakes. *Journal of Sustainable Development of Transport and Logistics, 8*(1), 43-52. doi:10.14254/jsdtl.2023.8-1.3

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