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NUMERICAL ANALYZES AND A COMPARATIVE STUDY OF AN AUTOMOTIVE STANDARD BRAKE DISC WITH A DISC DRILLED ALONG THE ARCHIMEDES SPIRAL

ANALIZY NUMERYCZNE ORAZ BADANIE PORÓWNAWCZE SAMOCHODOWEJ STANDARDOWEJ TARCZY HAMULCOWEJ Z TARCZĄ NAWIERCANĄ PO SPIRALI ARCHIMEDESA

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Summary

The article presents the concept of a new friction surface of the brake disc with holes made along the Archimedes spiral. In the brake technology we can meet brake discs with a friction surface that is perforated in a different way. It can be a perforation on the friction surface using holes, cuts, holes and combinations thereof. Despite the many advantages of such disks, the modification of the friction surface increases the wear of the friction material. In the newly designed shield, only one cut

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was made on the disc radius, which was converted into a series of holes arranged in the Archimedes spiral line beginning at the inner radius of the target and ending on the outer radius of the target forming only one scroll. For such a developed concept of friction surface, numerical simulations were carried out referring to a smooth disc without perforation in the scope of determining the temperature rise characteristics as a function of braking time, distribution of reduced stresses and disc deformation. Then, after carrying out a prototype disc with Archimedes spiral drillings there was carried out bench testing of it and of a perforated disk. On this basis, the type of braking at which the drilled disc was characterized by better frictional characteristics against the smooth disc without perforation was determined.

Keywords: brake disc, Archimedes spiral, numerical simulations, bench tests

Streszczenie

W artykule przedstawiono koncepcję nowej powierzchni ciernej tarczy hamulcowej z otworami wykonanymi wzdłuż spiralni Archimedesa. W technice hamulcowej spotyka się tarcze hamulcowe z perforowaną w różny sposób powierzchnią cierną. Może być to perforacją na powierzchni ciernej za pomocą otworów, nacięć, nawierceń oraz ich kombinacji. Mimo wielu zalet takich tarcz, modyfikacja powierzchni ciernej wpływa na wzrost zużycia materiału ciernego. W nowo projektowanej tarczy założono tylko jedno nacięcie wykonane na promieniu tarczy, które zostało zamienione na ciąg otworów ułożonych w linii spirali Archimedesa rozpoczynającej się przy promieniu wewnętrznym tarczy i kończącym się na promieniu zewnętrznym tarczy tworząc tylko jeden zwój. Dla tak opracowanej koncepcji powierzchni ciernej przeprowadzono symulacje numeryczne odniesione do tarczy gładkiej bez perforacji w zakresie wyznaczenia charakterystyki przyrostu temperatury w funkcji czasu hamowania, rozkładu naprężeń zredukowanych oraz odkształceń tarczy. Następnie po wykonaniu prototypowej tarczy z nawierceniami po spirali Archimedesa oraz dla tarczy bez perforacji przeprowadzono porównawcze badania stanowiskowe. Na tej podstawie określono typ hamowań przy których tarcza wiercona charakteryzowała się lepszymi charakterystykami cierno-termicznymi względem tarczy gładkiej bez perforacji.

Słowa kluczowe: tarcza hamulcowa, spirala Archimedesa, symulacje numeryczne, badania stanowiskowe

1. Introduction

By analyzing the available literature about the disc brake system, we can find general information on improving the contact (cooperation) of friction linings with the brake disc. One of the methods of improving the frictional thermal characteristics is the use of drilled and notched discs with standard friction linings. According to the studies contained in [8, 9], cut-off discs in motor vehicles (Figure 1a) affect the effective removal of lining dust from the brake friction pair, which results in renewed brake pads (brake blocks) in subsequent braking. Drilled discs have the best effect on both cleaning of friction linings from wear products as well as degassing of blocks after their annealing at the production stage (phenomenon of fading) and water (aquaplaning phenomenon) [17]. They also limit the phenomenon of local hot spots [4]. However, the holes after drilling through the entire thickness of the friction ring reduce the thermal capacity of the disc, which, with frequent braking and high braking power, can affect their deformation [13, 16]. In addition, holes in the longer service life of brake discs contribute to the formation of thermal cracks (micro cracks) [1, 14] and increase the wear of friction linings. Hence, the compromise is cut and drilled discs in which holes (in the case of only pre-drilled discs) are only up to a certain depth.

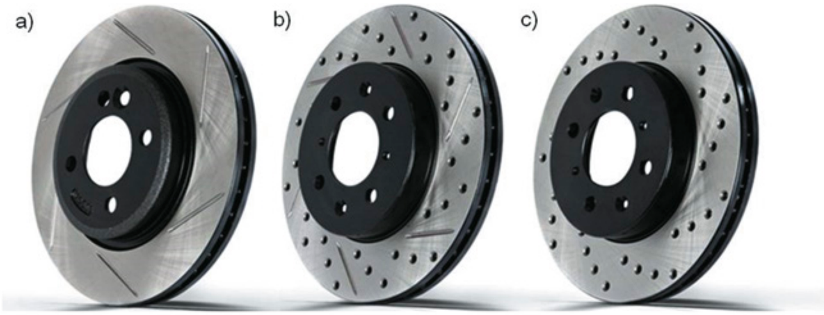


Fig. 1. Ventilated brake discs for motor vehicles: a) cut, b) cut and drilled, c) drilled [7, 8]

The second way to improve the frictional and thermal characteristics is to use brake disc designs made of other materials than cast iron such as steel, baked or carbon fiber discs. The use of floating discs also allows the implementation of large thermal loads that do not cause the increase of stresses leading to disc deformation [15, 16]. Another way to improve the efficiency of the braking system is the use of two and four-piston floating or stationary clamps. However, these solutions are very rarely used in commercial vehicles, only the sporting intended use of cars makes their users convert brake systems to achieve higher braking power and better dissipation of accumulated thermal energy to the environment.

2. The concept of a new brake disc

Based on available literature in the field of disc brake systems, a new friction surface was created with holes arranged along the Archimedes spiral with one turn. This assumption is a compromise both in terms of stabilizing the braking process associated with the constant course of the friction coefficient as a function of braking time and less intensive with other designs of drilled wheels with friction linings. Archimedes spiral in polar coordinates can be written in the following form [6]:

$$R(\varphi) = \frac{(k \cdot \varphi + \Delta k)}{2\pi} \cdot (\varphi + \Delta\varphi) \qquad (1)$$

Where: φ – variable angle expressed in radians,

$R(\varphi)$ – the function of radius dependence on the angle φ,

k – parameter determining the increase in the distance between particular turns of the Archimedes spiral,

Δk – parameter shifting the radius of the function by the given value,

$\Delta\varphi$ – parameter shifting the starting angle of the Archimedes spiral.

The presented solution of the surface of the brake disc with one Archimedes spiral was submitted to the Patent Office of the Republic of Poland in order to obtain patent protection for the invention [5]. Figure 2 shows a diagram and models of the disc with holes arranged in a spiral line.

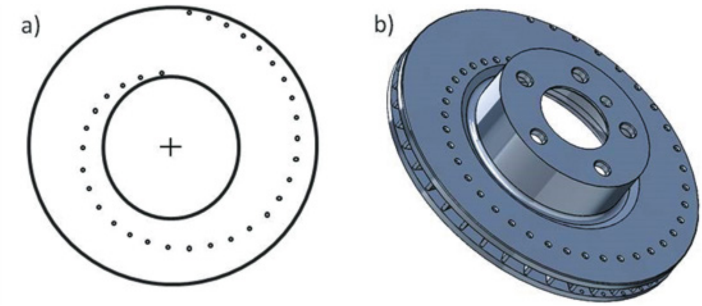


Fig. 2. Brake discs with holes in the Archimedes spiral line with one turn: a) diagram, b) disc model made in the SolidWorks 2016 environment.

3. Boundary conditions of numerical analyzes of brake discs

Before starting numerical analyzes in the scope of determining the temperature distributions, stresses and deformations of brake discs, it was necessary to determine the boundary conditions of the simulation in the SolidWorks 2016 environment. Numerical analyzes were carried out for the case of braking on a flat track with the assumed speed of 160km/h until stopped. Data used for numerical simulations is presented in Table 1.

Table 1. Data for numerical disc brake simulation in a SolidWorks environment

No.	Name	Symbol	Value
1	Vehicle weight (BMW X3 (F25))	M	2270 [kg]
2	The speed of the beginning of braking	v_o	44.4 [m/s]
3	Radius of the brake disc	r_d	0.328 [m]
4	Radius of the car wheel (225 / 60R17)	r_w	0.7018 [m]
5	Braking time	t_z	7 [s]
6	Deceleration rate	a	4 [m/s^2]

In order to calculate the heat flow acting on the disc, first determine the force acting on the brake disc on the basis of [3] with relation (1):

$$F_{DISC} = \frac{0.5 \cdot P \cdot M \cdot v_0^2}{2 \cdot \frac{r_d}{r_w} \cdot \left(v_0 \cdot t_z - 0.5 \cdot a \cdot t_z^2\right)} = \frac{0.5 \cdot 1 \cdot 2270 \cdot 44.4^2}{2 \cdot \frac{0.164}{0.3509} \cdot \left(44.4 \cdot 7 - 0.5 \cdot 3 \cdot 7^2\right)} = 10094.24\,[N] \tag{1}$$

where: P – the ratio of the braking force distribution of the first axle to the second one, P= 1 for braking only the front axle (rear axle unloaded),

M – mass of the vehicle

v_o – braking start speed,

r_d – radius of the brake disc,

r_w – radius of the car wheel,

t_z – braking time,

a – deceleration rate.

Then the heat flow acting on one side of the target in accordance with [3] determines the dependence (2):

$$\dot{Q}(t) = F_{DISC} \cdot v_{DISC}(t) = F_{DISC} \cdot \frac{r_d}{r_w} \cdot (v_0 - a \cdot t) = 209677.4 - 14153(t)[W] \tag{2}$$

Determining the heat flux density is preceded by the calculation of the friction surface of the brake disc with the relation (3):

$$A = \frac{\pi D_z^2}{4} - \frac{\pi d_w^2}{4} = \frac{314 \cdot 0.328^2}{4} - \frac{314 \cdot 0.196^2}{4} = 0.054\left[m^2\right] \tag{3}$$

where: D_z – outer diameter of the brake disc,

d_w – the inner diameter of the friction ring of the brake disc.

The density of the heat flux shows the relationship (4):

$$q = \frac{\dot{Q}(t)}{A} = \frac{209677.4}{0.054} = 3859726\left[\frac{W}{m^2}\right] dla\ t = 0s \tag{4}$$

A heat flux density of 40,000,000 W/m² was assumed for numerical analyzes. However, assuming the value of the coefficient of friction μ = 0.4, from the relation (5) on the basis [3] the force acting on the brake calliper was calculated.

$$F_{CALIPER} = \frac{\dot{F}_{DISC}}{\mu} = \frac{10094.24}{0.4} = 25235.6[N] \tag{5}$$

For the BMW X3 (F25) the diameter of the brake piston is 57mm, while the pressure in the brake system when braking with a delay of 4m/s² does not exceed 60bar. Then the pressure of the brake piston on the block will be in accordance with the relation (6):

$$F_{PISTON} = p \cdot A_t = 6000000 \cdot \frac{\pi \cdot 0.057^2}{4} = 15310.55[N] \tag{6}$$

where: p – brake system pressure,

A_t – surface of the brake piston.

The surface pressure of the lining for the brake disc represents the final relationship (7) on the basis of [3]:

$$p = \frac{F_{PISTON}}{A_{BRAKE} \cdot \mu} = \frac{15310.55}{0.005675 \cdot 0.4} = 6744736[Pa] \approx 6.7[MPa] \tag{7}$$

where: A_{BRAKE} – surface of the brake block, A_{BRAKE}=56.75[cm^2].

Using the dependencies (1) - (7), numerical simulations of the temperature distribution on the brake discs were performed during braking. Figure 3 presents the temperature distribution of the brake discs after the stop braking simulation for selected time moments.

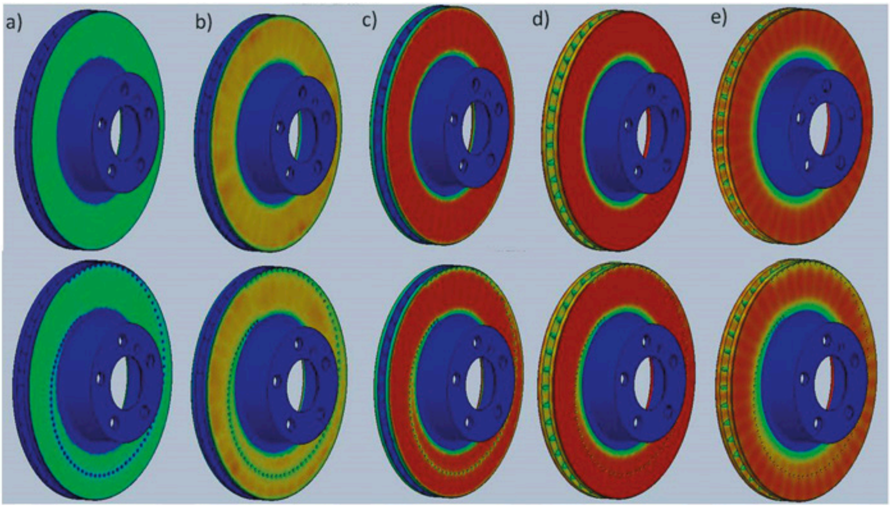


Fig. 3. Distribution of temperature on smooth disc (without perforation of friction surface) and disc with holes made in a spiral line after simulated braking lasting 7 seconds at the moment of time: a) 1s, b) 2s, c) 3s, d) 6s, e) 7s.

For each moment of braking after the simulation, the maximum temperature of the disc was determined. On this basis, a characteristic of the temperature increase of the discs (perforated and smooth) was made during simulated braking lasting 7 seconds (Fig. 4).

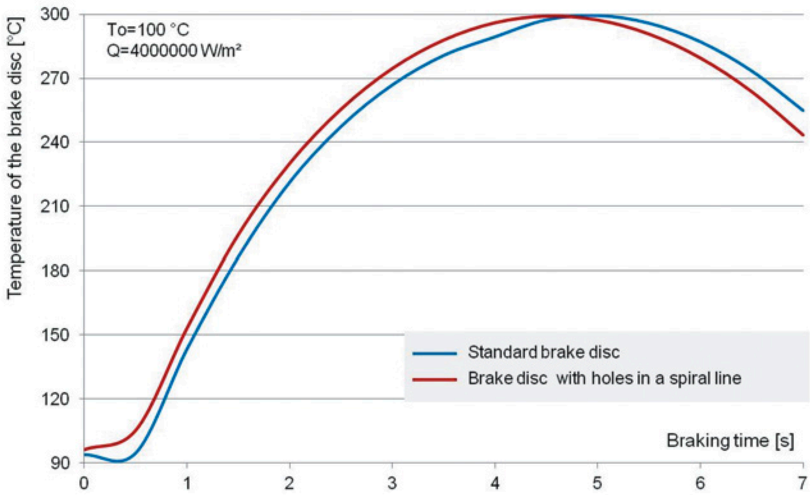


Fig. 4. Distribution of average temperature of brake discs after simulated braking.

When analyzing the graph presented in Figure 4, it is stated that the additional perforation on the disc reduces the temperature of the disc in the last braking phase in relation to the classic disc. Stress distribution analysis was performed for Mises reduced stress, taking into account the heat flux effect on friction rings of brake discs, temperature of other brake disc components and the braking torque on the disc in relation to its axis of symmetry. The braking start temperature was set to simulate at 100°C, while the heat flux as a result of thermal simulations was imported to simulate the stress distribution. The braking torque value, similarly to the braking start temperature value, was determined from the AK Master test card. For stresses simulation, a torque value of 686Nm was assumed as during the simulation of the fading phenomenon. Figures 5a) and 5b) show the view of the brake discs with the Mises reduced stress distribution.

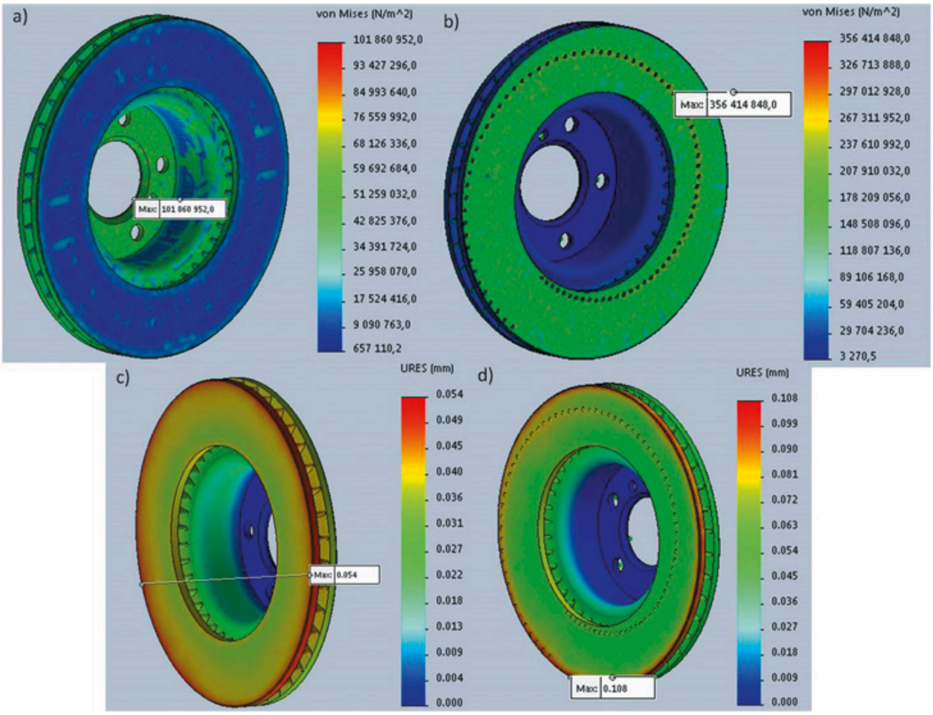


Fig. 5. Numerical analysis of von Mises reduced stresses for a standard disc without perforation, b) with holes in a spiral line and deformations c) for a standard disc, d) with holes in a spiral line

In contrast, Fig. 5c) and 5d) show displacements (deformations) of brake discs after simulation of reduced stresses. In each of the analyzed cases of brake discs, it can be observed that the greatest deformations occur on the outer radius of the second (inner) friction ring, i.e. on the engine side and the stresses in the drilled disc bore holes are three times greater with respect to the smooth plate without perforation. In long-term operation of brake discs drilled within the holes, thermal cracks may occur.

4. Methodology of brake discs testing

The second stage of work on the disc with a new friction surface with holes drilled in the spiral line was station tests. The friction-mechanical tests (where the change of coefficient of friction and disc temperature during braking were registered) were carried out at LUMAG in Budzyń on the inertia test bench for drum brakes and disc brakes of Tecsa TC185-EL car vehicles. The test object was two 24.0128-0254.1 brake discs with ventilating blades. The first classic disc without perforation, the second with Archimedes spiral drills with one coil (Fig. 6b) cooperating with the LUAG sintered friction linings type LU 551.

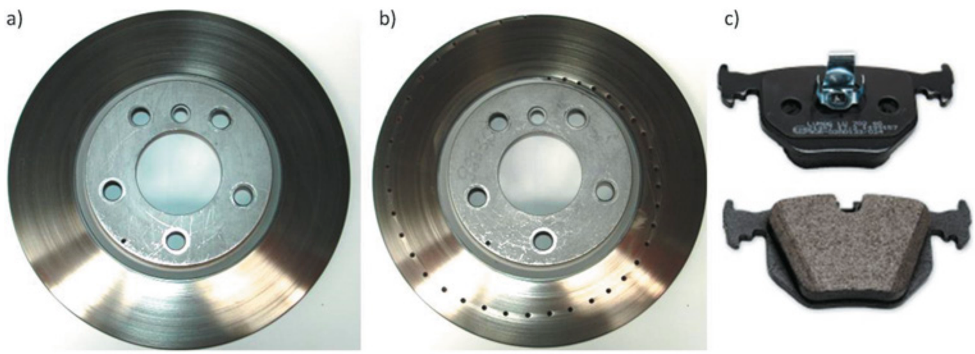


Fig. 6. View of the brake discs used during the test, a) standard disc (smooth), b) disc with holes in the spiral line, c) view of friction linings.

Figure 7 shows the view of the brake station at LUMAG [7, 8].

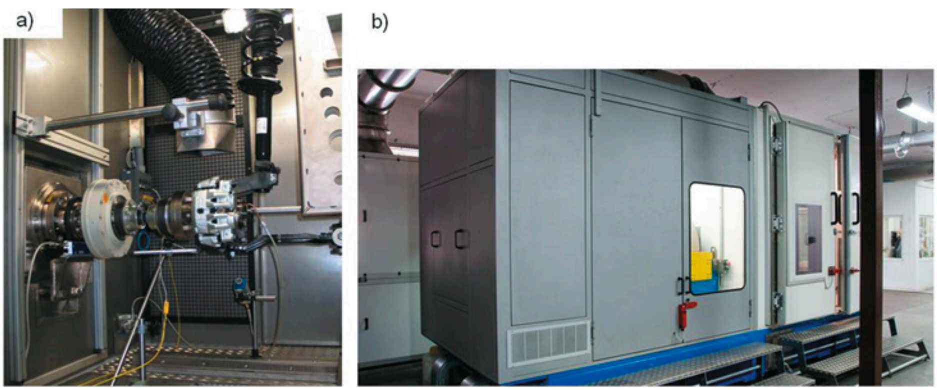


Fig. 7. View of the brake station at LUMAG, a) view of the test section with the calliper of the disc brake mounted, b) view of the driving part of the station with covered rotating masses of different inertia [10, 11].

The AK-Master research program according to SAE J2522 [12] was used for the research. For the mentioned program, braking and stopping in various speeds were performed. The pressure in the brake system in most tests was 30 bar. The temperature measurement of the brake disc was carried out using one thermocouple attached to the brake disc. The brake test was carried out in accordance with the assumptions of the active method described in [2]. Table 2 presents the requirements for individual trials and the conditions for their implementation.

Table 2. Guidelines for conducting the AK-Master test according to SAE J2522 prior to the braking test

No.	Name of the test	Speed in km/h	Pressure in bars	Disc temperature in °C	Number of trials
1	μ Green test	80-30	30	100	30
2	Bedding test	80-30	30	100	60
3	Characteristic value 1	80-30	30	100	6
4.1	Test Speed/Pressure Sensitivity	40-5	10, 20, 30, 40, 50, 60, 69, 79	100	8
4.2	Test Speed/Pressure Sensitivity	80-40	10, 20, 30, 40, 50, 60, 69, 79	100	8
4.3	Test Speed/Pressure Sensitivity	120-80	10, 20, 30, 40, 50, 60, 69, 79	100	8
4.4	Test Speed/Pressure Sensitivity	160-130	10, 20, 30, 40, 50, 60, 69, 79	100	8
4.5	Test Speed/Pressure Sensitivity	180-150	10, 20, 30, 40, 50, 60, 69, 79	100	8
5	Characteristic value 2	80-30	30	100	6
6	Cold Application	40-5	30	40	1
7	Motorway test	100-5	60	40	1
		190-105	60	40	1
8	Characteristic value 3	80-30	30	100	18
9	Fade 1 test	100-3	from 38 to 60	100 without cooling	15
10	Recovery 1 test	80-30	30	100	18
11	Temperature/Pressure Sensivity 100 test	80-30	10, 20, 30, 40, 50, 60, 69, 79	100	8
12.1	Increasing Temperature 500 test	80-30	30	100, 150, 200, 250, 300, 350, 400, 450, 500	9
12.2	Pressure Line 500 test	80-30	10, 20, 30, 40, 50, 60, 69, 80	500	8
13	Recovery 2 test	80-30	30	100	18
14	Fade 2 test	100-3	from 38 to 60	100 without cooling	15
15	Recovery 3 test	80-30	30	100	6

For one cycle of tests (per target) there were 276 brake trials from various speeds, pressure and initial temperature of the brake disc.

5. Brake discs test results

The first two tests of bench tests by SAE J2522 standards in accordance with the guidelines in Table 2 are related to the friction material reaching the brake disc. The first evaluation of the coefficient of friction variation is made after the test of sensitivity to the speed of braking and pressure in the hydraulic system (Test Speed/PressureSensitivity). Figures 8-12 show the frictional and thermal characteristics of the disc brake depending on the speed and pressure in the brake system.

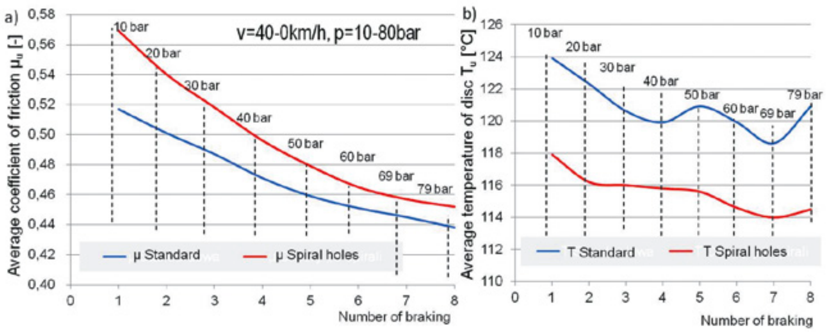


Fig. 8. The course of a) the average coefficient of friction, b) the mean temperature of the disc as a function of subsequent braking (v = 40-0km /h) for the standard disc without perforation and the disc with holes made in a spiral line for the *Speed/PressureSensitivity* test.

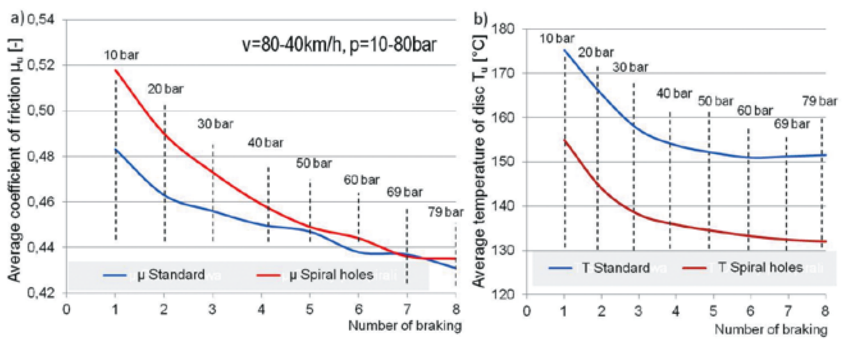


Fig. 9. The course of a) the average coefficient of friction, b) mean temperature of the disc as a function of successive braking (v = 80-40km /h) for standard disc without perforation and disc with holes made in a spiral line for the *Speed/PressureSensitivity* test.

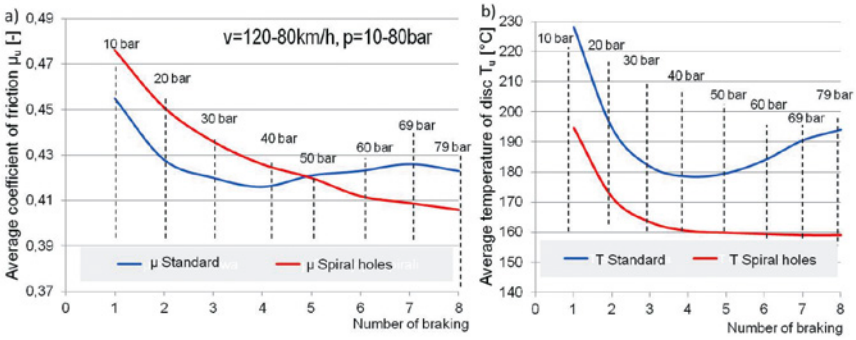


Fig. 10. The course of a) the average coefficient of friction, b) the mean temperature of the disc as a function of successive braking (v = 120-80km/h) for the standard disc without perforation and the disc with holes made in a spiral line for the *Speed/PressureSensitivity* test.

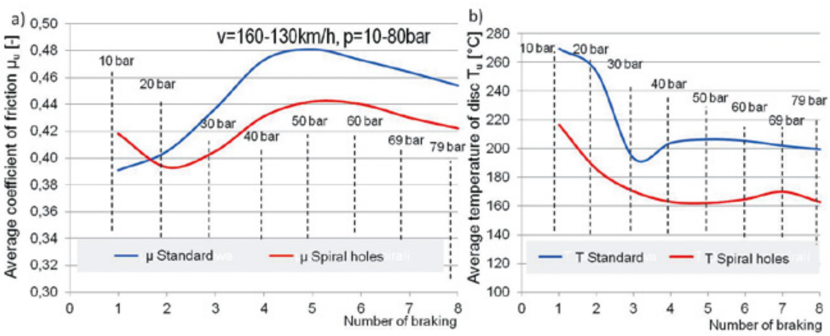


Fig. 11. The course of a) the average coefficient of friction, b) mean temperature of the disc as a function of successive braking (v = 160-130km /h) for standard disc without perforation and disc with holes made in a spiral line for the *Speed/PressureSensitivity* test.

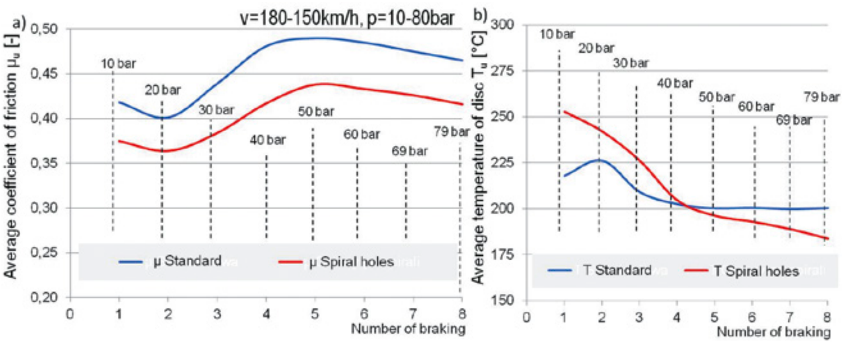
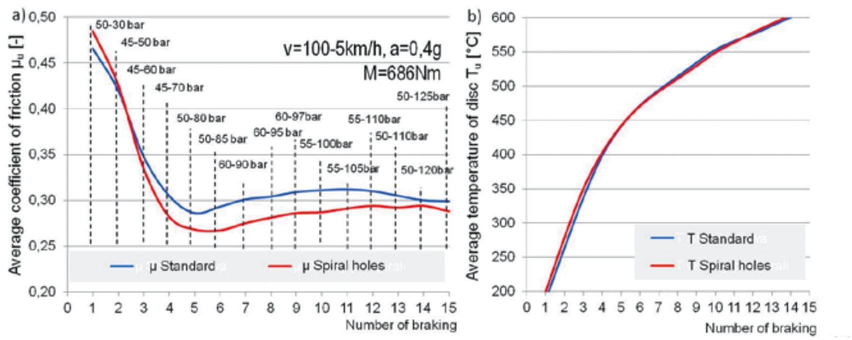


Fig. 12. The course of a) the average coefficient of friction, b) the mean temperature of the disc as a function of successive braking (v = 180-150km/h) for the standard disc without perforation and the disc with holes made in a spiral line for the Speed *Speed/PressureSensitivity* test.

Fade type braking. i.e. fading is performed in 15 repetitions without prior cooling of the disc and with variable pressure. This test maps the braking from a speed of 100 to 5km/h in order to achieve a constant braking deceleration of 0.4g, which results in a non-linear increase of brake pressure during the test. Figure 13 shows the distribution of the average coefficient of friction and temperature from a given braking test.

Increasing Temperature 500°C inhibition is performed in 9 trials with constant pressure for each trial, i.e. 30 bar. An important feature of this test is the measurement in the variable increasing temperature of the discs, i.e. the beginning of braking. The first braking takes place at a disc temperature of 100°C, followed by a further 50 °C more up to 500°C braking start temperature for the last 9th trial. The mentioned test maps the braking from a speed of 80 to 30 km/h. Fig. 14 shows the courses of average coefficient of friction and average temperature for the tested discs, i.e. standard without perforations and with holes in the spiral line.



13. The course of a) the average coefficient of friction, b) mean temperature of the disc as a function of successive braking (v = 180-150km/h) for the standard disc without perforation and the disc with holes made in a spiral line for the *Fading* test.

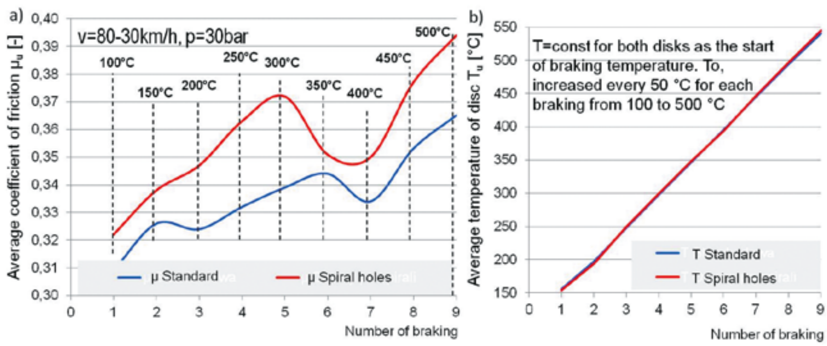


Fig. 14. The course of a) the average coefficient of friction, b) mean temperature of the disc as a function of successive braking (v = 180-150km/h) for standard disc without perforation and disc with holes made in a spiral line for the *IncreasingTemperature* test 500°C.

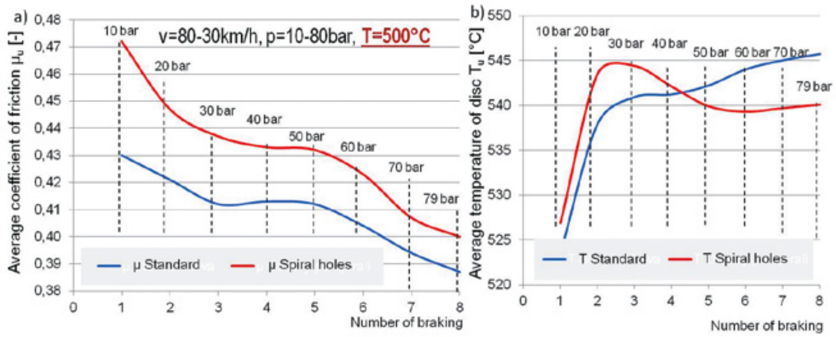


Fig. 15. The course of a) the average coefficient of friction, b) the mean temperature of the disc as a function of successive braking (v = 180-150km/h) for the standard disc without perforation and the disc with holes made in a spiral line for the *Pressure Line* 500 test.

Pressure Line 500°C type braking is performed after the *IncreasingTemperature* 500°C test. The test is carried out in eight replicates with variable pressure for each test. The first test is carried out at a pressure of 10bar, another 20, 30, 40, 50, 60, 70 and 80bar at the 8th test. The mentioned test maps the braking from a speed of 80 to 30 km/h. The initial temperature of the target was 500°C before all tests. Fig. 15 presents a comparison of the average coefficient of friction and the temperature of the dial. Analyzing the diagrams presented in Figures 8-15 it is stated that the additional perforation on the friction surface does not improve all the frictional characteristics of the classic disk. The usefulness of drilled discs is observed in the case of braking from low and medium braking speeds and during braking with high heat load. In addition, wear tests were carried out for the tested wheels.

Table 3. List of final results after AK-Master test according to SAE J2522

No.		Standard smooth disc	Disc with holes in a spiral line
1	Weight usage of friction linings	23g	24g
2	Linear wear of brake discs	0.06mm	0.07mm
3	The average coefficient of friction from all tests	0.399	0.402
4	Total braking distance	89.7m	88.3m
5	Total braking time	1531.2s	1499.4s

Table 3 presents the list of wear elements of the brake friction pair, i.e. friction linings and the brake disc. In addition, the final (average) result from the bench tests was included in the mean factor of all trials, total braking distance and time after 276 braking.

6. Summary

On the basis of numerical analyzes and comparative tests carried out with the AK-Master test according to SAE J2522 of the drill disc in relation to the classic disc, the following conclusions were made:

a) discs drilled in relation to the classic disc without perforation get about 5% higher mean temperature in the first phase of braking, while in the second braking phase the temperature also decreases by about 5%. On the basis of numerical analyzes, a more rapid increase in the average temperature of the perforated disc compared to the classic one is observed, which means that the drilled disc reaches its maximum value faster. However, the maximum temperature of the discs showed about 2% lower disc temperature drilled to the classic disc from the entire simulation time,

b) the perforated disc exhibits nearly three times greater increase in the strains reduced according to Mises in relation to the classic disc only in the area of perforation. In longer operation, this may be the reason for the formation of surface cracks. Further numerical simulations have shown that it is possible to significantly reduce the tension around the holes of the drilled disc using the chamfering of the edge of the hole at the friction surface of the disc,

c) in bench tests, drilled discs do not improve all frictional characteristics in terms of the increase of the average coefficient of friction relative to smooth discs, while they improve the instantaneous coefficient of friction as a function of time and mean temperature of the brake disc,

d) a significant increase in the average coefficient of friction for a disc drilled in the Archimedes spiral line with one turn occurs during braking from low and medium braking speeds. The classic disc without perforation showed a higher or similar level (depending on the pressure) of the mean coefficient of friction during high speed trials from 160 to 180km/h.

e) the fading test showed that the drilled discs do not affect the increase of the coefficient of friction, in the first braking the drilling disc showed a slightly higher average coefficient of friction and in subsequent braking the higher μ_u showed the classic disc,

f) perforated discs show the highest suitability in terms of braking at high thermal load as well as increasing pressure in the braking system, then a significantly higher coefficient of friction in the entire pressure range, i.e. from 10 to 80bar, is observed,

g) the pre-drilled discs show more stable waveforms of instantaneous and average coefficient of friction in relation to the classic disc, which translates into a constant value of the braking deceleration. Standard deviations from the mean value in most braking were almost twice smaller than the standard disc,

h) wear tests on 276 simulated braking showed a slight higher (by 1gram) wear on friction linings cooperating with the disc perforated in the form of holes in the spiral line and wear on the thickness of the perforated disc by 0.01mm in relation to the smooth disc.

i) the disc with holes in the Archimedes spiral line has also passed positively tests on the inertia brake station for rail vehicles, detailed results from these tests are presented in [3].

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References

[1] Kasem H, Brunel J F, Dufrenoy P, Siroux M, Desmet B. Thermal levels and subsurface damage induced by the occurrence of hot spots during high-energy braking. "Wear". 2011; (270): 355-364.

[2] Leszek W. Wybrane zagadnienia metodyczne badań empirycznych. Instytut Technologii Eksploatacji, Radom. 2006: 142-153.

[3] Mackin T J. Thermal cracking in disc brakes, Engineering Failure Analysis 9. (2002): 63–76.

[4] Panier S, Dufrénoy P, Weichert D. An experimental investigation of hot spots in railway disc brakes. "Wear". 2004; 256: 764-773.

[5] Sawczuk W. Tarcza hamulcowa. Application for granting a patent marked with number P.418361 from 16.08.2016.

[6] Sawczuk W. Koncepcja nowej tarczy hamulcowej do pojazdów szynowych. Technika Transportu Szynowego.2016; 12.

[7] Website: http://www.iparts.pl/czesc/tarcza-hamulcowa-ate-24012802541,0-3-24012802541-985783.html

[8] Website: http://www.rgarage.pl/index.php/modyfikacje/brakes/tarcze-wiercone-czy-nacinane8.

[9] Website: http://mojafirma.infor.pl/moto/eksploatacja-auta/uklad-hamulcowy/271667,Co-daja-nawiercane-tarcze-hamulcowe-czy-mozna-je-montowac-w-kazdym-aucie.html

[10] Website: http://lumag.pl/inwestycje-w-urzadzenia-badawcze/

[11] Website: http://motofocus.pl/technika/14036/lumag-inwestuje-w-urzadzenia-badawcze-do-klockow-breck

[12] Website: https://webstore.ansi.org/RecordDetail.aspx?sku=SAE+J+2520-2013+(SAE+J2520-2013)20

[13] Website: http://www.autoexpert.pl/aktualnosci/Te-elementy-najczesciej-sie-psuja-w-naszych-autach,9417,1

[14] Wu S C, Zhang S Q, Xu Z W. Thermal crack growth-based fatigue life prediction due to braking for a high-speed railway brake disc. "International Journal of Fatigue" 87. 2016: 359-369.

[15] Yan H B, Zhang Q C, Lu TJ. Heat transfer enhancement by X-type lattice in ventilated brake disc. "International Journal of Thermal Sciences" 107. 2016: 39-55.

[16] Yan H B, Zhang Q C, Lu T J. An X-type lattice cored ventilated brake disc with enhanced cooling performance. "International Journal of Heat and Mass Transfer" 80. 2015: 458–468.

[17] Yan H B, Feng S S, Yang X H, Lu T J. Role of cross-drilled holes in enhanced cooling of ventilated brake discs. "Applied Thermal Engineering" 91. 2015: 318-333.