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ASSESSMENT OF THE INFLUENCE OF THE COEFFICIENT OF FRICTION ON THE TEMPERATURE DISTRIBUTION OF A DISC BRAKE DURING THE BRAKING PROCESS

OCENA WPŁYWU WSPÓŁCZYNNIKA TARCIA NA ROZKŁAD TEMPERATURY TARCZY HAMULCOWEJ PODCZAS HAMOWANIA

Key words: braking, thermal processes, finite element method.

Abstract Brake assemblies are key mechanisms in the aspect of safe and reliable operation of devices and machines. Due to intense thermal processes that occur during braking, the brakes are exposed to an accelerated wear. The article assesses the impact of tribological cooperation conditions between the caliper and the disc of a disc brake on the temperature of a disc. The variable value in the simulations was the coefficient of friction between the cooperating surfaces. A direct effect of the increase of the analysed parameter on the enhancement of brake elements' temperature was found. At the same time, a similar nature of thermal processes was observed for all values of the friction coefficient taken into account.

Słowa kluczowe: hamowanie, procesy cieplne, metoda elementów skończonych.

Streszczenie Zespoły hamulców są kluczowymi mechanizmami w aspekcie bezpiecznej i niezawodnej pracy urządzeń oraz maszyn. Z uwagi na intensywne procesy cieplne zachodzące podczas hamowania hamulce narażone są na przyspieszone zużywanie. W artykule dokonano oceny wpływu warunków współpracy tribologicznej pomiędzy zaciskiem a tarczą hamulca tarczowego na rozkład temperatury tarczy. Wielkością zmienną w symulacjach była wartość współczynnika tarcia pomiędzy współpracującymi powierzchniami. Stwierdzono bezpośredni wpływ wzrostu analizowanego parametru na zwiększenie temperatury elementów hamulca. Jednocześnie zaobserwowano zbliżony charakter przebiegu procesów cieplnych dla wszystkich wartości współczynnika tarcia uwzględnionych w symulacjach.

INTRODUCTION

Disc brakes, apart from mechanical interactions, are exposed to the influence of intensive thermal processes. Therefore, for operational reliability, it is necessary to ensure that their elements are resistant to the influence of high temperatures (up to 800ºC) **[L. 1]**. The release of significant amounts of heat threatens the brake's *thermal stability*. One of the most effective structural variants that reduce the risk of this adverse phenomenon is the usage of ventilated discs. In this solution, the disc is divided into two smaller ones, which results in a larger heat dissipation area. The air flow between the discs is also increased, which further reduces the temperature and eventually decreases the intensity of thermal processes **[L. 2, 3]**. Differences in the construction of both analysed disc shapes are shown in **Fig. 1**.

In **[L. 4–7]** the authors evaluated the impact of the used material and the brake disc construction variant on the operation of the brakes. It has been shown that, apart from the influence on the temperature, the utilization of a ventilated disc reduces the stress level in the assessed structure. This is due to the appearance of an additional surface that strengthens the disc. Furthermore, it was found that, due to the more intense heating of cast iron and steel discs, it is preferable to use aluminium alloys for this element. This is the result of several times greater thermal conductivity and specific heat value of

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aluminium alloys compared to the other listed materials. With this in mind and considering the unit weight which is nearly three times lower, aluminium alloys are more favourable materials for brake discs, as excessive heating of braking systems can cause a number of phenomena that significantly reduce operating reliability, such as the following **[L. 5, 8, 9]**:

- Additional vibrations;
- Formation of microcracks;
- Deformations within discs; and,
- The rise of the unit pressure value, which further increases the level of heat and results in intensification of this adverse effect. This is due to the formation of thermoelastic deformations that locally change the values of the friction coefficient.

On the other hand, aluminium alloys have significantly lower strength compared to steel and cast iron, which reduces the possibility of using these materials for brake discs.

Other key factors for the course of brake wear are surface hardness and surface condition **[L. 10, 11]**.

Fig. 1. Model of the disc brake with pads: normal and ventilated discs [L. 1]
Rys. 1. Model tarczy hamulcowej wraz z zaciskami: tarcza normalna i wentylowana **[L. 1]**

AIM OF THE ANALYSES

The article supplements the earlier work of the authors **[L. 6, 7]** in which the influence of geometrical features of the disc and the material from which it was made on the course of its heating process was verified. The purpose of this work was to analyse the impact of the combination of the friction on the values and temperature distribution of ventilated disc brakes. The friction coefficient between the disc and the calipers (in the range of 0.25–0.45) was assumed as the variable parameter, the other input data did not change throughout the simulations. The selected coefficient of friction reflected the values used in real car brakes (among others **[L. 12]**). It was analysed to what extent increasing the coefficient of friction does not generate a temperature level close to the permissible one. It also assessed whether the qualitative distribution of the disc temperature changes as the friction conditions in the brake vary.

For the purpose of the work, quantitative and qualitative analyses in the scope of temperature were made. The comparisons included the following:

- Values of temperature within the disc,
- Temperature distribution within the disc, and
- The course of temperature changes during braking.

Due to the narrow framework of this article, the analyses did not assess the effectiveness of the braking process. It was assumed that, for all selected values of the friction coefficient, the braking distance of the vehicle does not exceed the permissible values. The only criterion taken into account during the analyses was the course of thermal processes, detailing the previously mentioned aspects.

The implementation of the goal of work is to be the basis for providing a safer braking process in terms of the temperature of the brake disc. This will be possible by selecting more favourable conditions for the friction of the brake pair and the resulting elimination of overheating of the discs, among others, in the local aspect.

RESEARCH METHOD

The course of thermal processes during braking of a SUV from 180 km/h to complete standstill during 7 s (emergency braking) was analysed **[L. 6, 7]**. Simulations were carried out using the finite element method. As in the previous publications of the authors, due to the construction of the braking assembly, solid finite elements, mainly cubic, were used in the analyses. Tetrahedral elements were adopted in areas with less regular geometry. Minimizing the number of tetrahedral elements was caused by the greater inaccuracy of the simulation results carried out using them **[L. 13, 14]**.

The material data used in the calculations is summarized in **Table 1**.

Table 1. Material data included in the analyses
Tabela 1. Dane materiałowe przyjęte do analiz

Parameter	Disc	Caliper
Density [kg/m^3]	7800	1450
Young modulus [GPa]	209	1.4
Poisson's ratio [-]	0.29	0.24
Thermal expansion [m/mK]	1.26e-5	1.1e-5
Thermal conductivity [W/mK]	48	1.1
Specific heat [J/kgK]	452	1200

In order to analyse the temperature distribution within the disc, 3 points **(Fig. 2)** were placed in the radial direction, with the number of the point increasing as the distance from the centre of the disc increased. The selection of points was carried out in the same way as in the past publication of the authors **[L. 7]**, enabling the supplementation of previously obtained results.

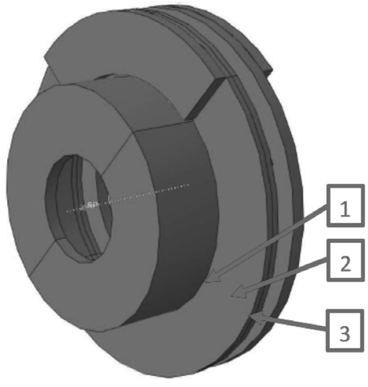

Fig. 2. Model of the disc used in simulations. Points for which temperature level was analysed are marked

Rys. 2. Zastosowany w symulacjach model tarczy hamulcowej z zaciskami. Oznaczono punkty, dla których analizowano wartości temperatury

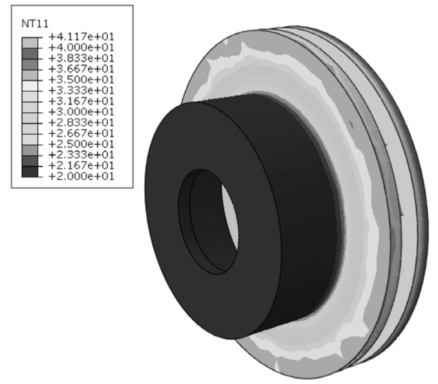

Fig. 3. Distribution of temperature within the disc after the process of braking for a coefficient of friction μ = 0.3

Rys. 3. Rozkład temperatury tarczy po hamowaniu dla współczynnika tarcia μ = 0,3

SIMULATION RESULTS

After carrying out the simulation for all of the analysed cases, the temperature distribution of the disc was obtained during the braking process and after its completion. Examples are shown in **Fig. 3 and Fig. 4**.

A characteristic for all obtained results is the temperature distribution of the disc in a layered form in the radial direction. The temperature changes gradually as the distance from the centre of the disc changes. This relationship does not apply to the entire disc, but only to the parts cooperating with the calipers, i.e. within the friction surfaces. In the rest of the area, significantly less heat is emitted, which causes the temperature to be much lower (even several dozen times). It was observed that, for smaller values of the coefficient of friction, the temperature increases with the distance from the central part of the disc **(Fig. 3)**. The inverse relationship occurs when the coefficient of friction takes higher values, i.e. a higher disc temperature occurs closer to the central area **(Fig. 4)**.

Based on the analyses of the temperature time course of selected disc points **(Figs. 5–8)**, it can be stated that this regularity occurs throughout the entire braking process, regardless of the value of the input variable (friction coefficient).

Further assessment of the obtained charts leads to the conclusion that, for each analysed value of the coefficient of friction between the calipers and the disc, the temperature rises to a certain time, after which it decreases. For smaller values of m, the maximum temperature occurs in the initial braking phase **(Fig. 5)**, while with a higher coefficient of friction, the temperature of the disc begins to decrease in the second half of the tested process **(Figs. 6–8)**.

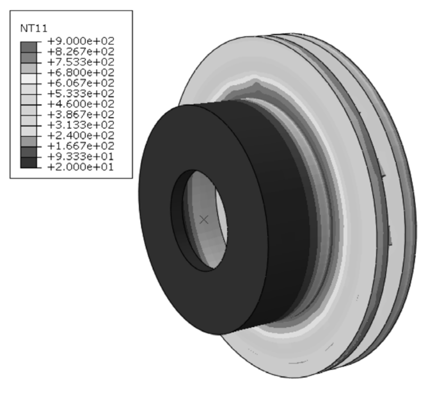

Fig. 4. Distribution of temperature within the disc after the process of braking for a coefficient of friction μ = 0.45

Rys. 4. Rozkład temperatury tarczy po hamowaniu dla współczynnika tarcia μ = 0,45

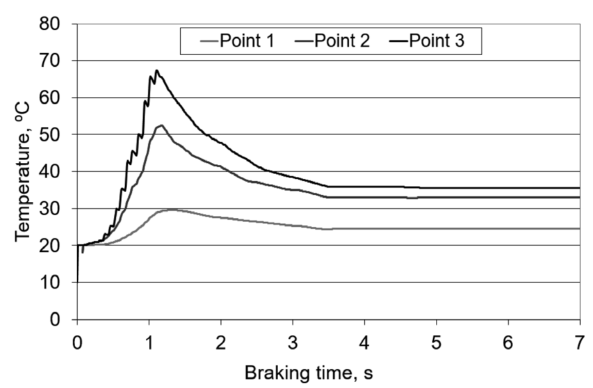

Fig. 5. Course of temperature changes on the surface of an analysed disc for a coefficient of friction μ = 0.3

Rys. 5. Przebieg zmian temperatury na powierzchni badanej tarczy dla współczynnika tarcia μ = 0,3

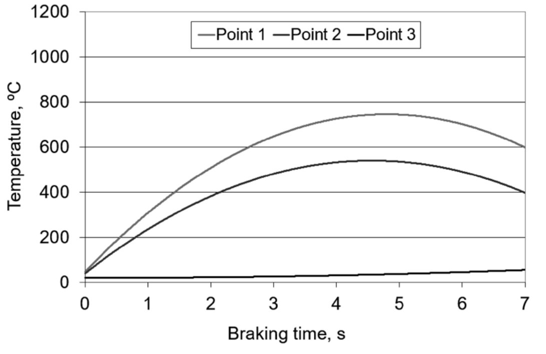

Fig. 6. Course of temperature changes on the surface of an analysed disc for a coefficient of friction μ = 0.35

Rys. 6. Przebieg zmian temperatury na powierzchni badanej tarczy dla współczynnika tarcia μ = 0,35

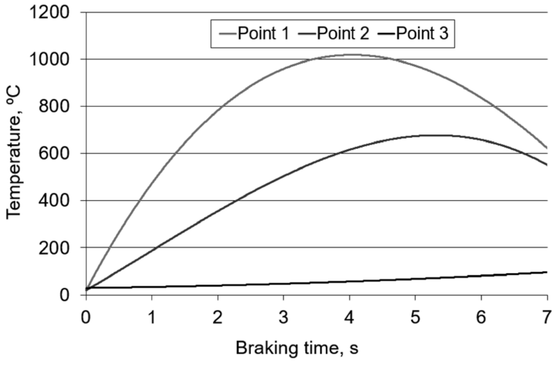

Fig. 7. Course of temperature changes on the surface of an analysed disc for a coefficient of friction μ = 0.4

Rys. 7. Przebieg zmian temperatury na powierzchni badanej tarczy dla współczynnika tarcia μ = 0,4

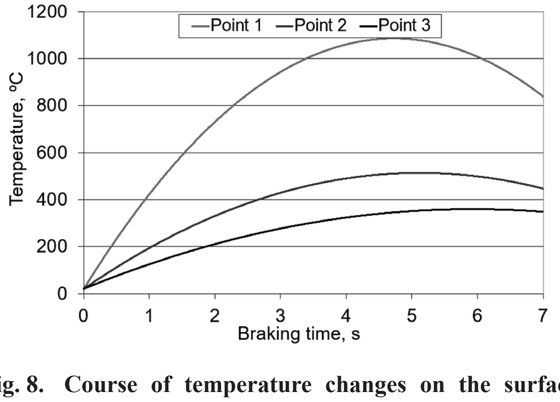

Fig. 8. Course of temperature changes on the surface of an analysed disc for a coefficient of friction μ = 0.45

Rys. 8. Przebieg zmian temperatury na powierzchni badanej tarczy dla współczynnika tarcia μ = 0,45

Maximum temperature values in the selected points of the disc for all of the friction coefficients taken into account are shown in **Fig. 9**.

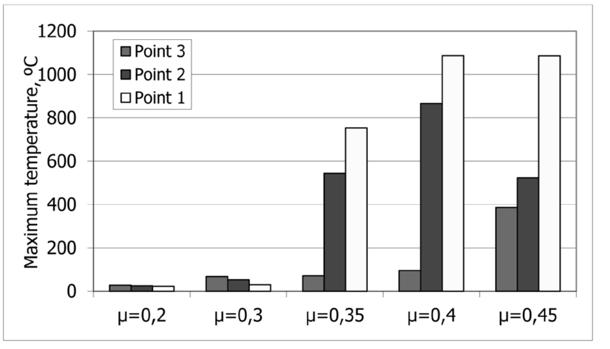

Fig. 9. Comparison of maximal values of disc temperature for all analysed cases

Rys. 9. Zestawienie maksymalnych wartości temperatury tarczy dla wszystkich analizowanych przypadków

Based on the analyses of the results of the simulations, the following relationships were observed:

- For all analysed values of the coefficient of friction, the maximum temperature occurred before the end of braking. For lower values of μ, the highest temperature appeared in the initial braking stage, and, for higher values of this factor, it occurred in the final stage. A possible cause of this phenomenon is generation of larger amounts of heat when braking from a higher initial speed. The decrease in disc temperature at the end of braking was observed for all cases, and it can be justified by the dispersion of part of the heat released at the end of the braking process and by a smaller increase in this type of energy.
- A rise of the friction coefficient resulted in an increase in disc temperature during braking, with values between μ = 0.25 and μ = 0.3, μ = 0.35 and μ = 0.4, μ = 0.4 and μ = 0, 45, respectively. These changes were gradual. The largest increase in temperature occurred when the friction coefficient changed between μ = 0.3 and μ = 0.35. The reason may be the exceeding of the limit amount of heat released, i.e. one at which the thermal processes in the brake disc intensify. The authors plan to identify this phenomenon in the future.
- For μ = 0.3, the temperature was distributed most evenly in relation to the radius of the disc (difference up to 40ºC). At the same time, the temperature of the disc increases in a radial direction as it moves away from its centre.
- In the range of μ = 0.35 – 0.45, the temperature of the disc in the radial direction varies significantly, even up to 1000ºC. At the same time, the temperature of the disc decreases in the radial direction as it moves away from its centre.
- From μ = 0.4, the temperature during braking exceeds the permissible level indicated in the literature (800ºC).

Values of friction coefficient higher than these assumed in the analyses are obtained in special-purpose vehicles, such as rally cars; however, such brakes are characterized by faster wear, including both the disc and calipers.

CONCLUSIONS

The used caliper-brake disc friction pair combinations allow the selection of different friction coefficient values. For the steel disc analysed in the article, obtaining $\mu = 0.4$ may lead to the loss of brake thermal stability, which prevents further safe and reliable operation of the brakes. This means that, in emergency braking conditions for the vehicle parameters adopted in the simulations, the value of the friction coefficient should be lower than $\mu = 0.4$. At the friction coefficients of $\mu = 0.2$ and $\mu = 0.3$, the amount of heat generated is relatively small, which guarantees a thermally safe braking process.

It should be emphasized that the only criterion taken into account in this analyses is the course of thermal processes, as indicated in the beginning of the article.

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