Article citation info:
Chłopek Z, Suchocka K, Zawistowski A. Comparative examination of disc brake friction pairs with brake pads of different types in respect of their tribological properties. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2016; 72(2): 15-28, http://dx.doi.org/10.14669/AM.VOL72.ART1

COMPARATIVE EXAMINATION OF DISC BRAKE FRICTION PAIRS WITH BRAKE PADS OF DIFFERENT TYPES IN RESPECT OF THEIR TRIBOLOGICAL PROPERTIES

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Summary

Results of the examination of disc brake friction pairs with conventional and ceramic brake pads have been presented. The friction pairs were examined in respect of the wear of their elements as well as the dust emission related to the friction pair wear. The empirical tests were carried out on a test stand designed for the testing of friction characteristics of brake linings and brake pads. The immission[4] of specific size fractions of the particulate matter was measured with the use of a dust monitor. Moreover, friction surface temperature was measured with the use of a camera. The tests were carried out in three series (one series run during the bedding-in process and two series of tests run on the pairs having been bedded-in), with the test cycles consisting of intermittent braking, where the interruptions were controlled by various factors, e.g. the friction surface temperature. The wear of the friction pair with ceramic brake pads was found to be lower than that of the pair with conventional pads and the relative difference was almost 40% and somewhat more than 25% when defined by the friction pair thickness and mass, respectively. In the dust dispersed in the ambient air in the measuring room, the PM1 particulate matter fraction (of the equivalent particle size being below 1 μm) was found to predominate. The particulate matter immission was found to be much lower (by about 50%) for the ceramic pads compared with the conventional pads. The temperature of the friction pair was not considerably affected by the type of the brake pads used. In general terms, it was ascertained that the use of ceramic pads resulted in a measurable improvement in the tribological properties of the disc brake friction pair.

Keywords: disc brakes, ceramic materials, tribological properties, particulate matter immission

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4 „Immission" is the concentration of a pollutant dispersed in the atmospheric air, measured at a height of 1.5 m above the Earth's surface [5, 6]

1. Introduction

An important source of the dust emitted from tribological pairs in motor vehicles is the brake system. It is estimated that an average motor vehicle annually consumes about 0.5 kg friction material from the brake system [4]. With respect to the danger posed by dust to the human health and the environment, it is advisable to undertake all the possible actions that would make it possible to reduce the emission of particulate matter from brake systems. One of the possible improvement directions is the application of innovative materials, engineering designs, and technologies [3, 7, 9, 13-15]. The solutions of this kind include the use of ceramic materials for the construction of disc brake pads.

Dusts pose serious danger to the human health and the environment. It was as long ago as in 1524 when Georgius Agricola wrote in his work "De re metalica" about the harmful impact of dust on the human health [1].

According to EN 481, the term "dust" is defined as the dispersed phase in a two-phase system consisting of solid body, i.e. small solid particles, suspended in gaseous dispersion medium, i.e. air.

In general, the shape of dust particles is not spherical. Therefore, a specific convention must be adopted to define the particle size. There are many different criteria of determining the equivalent particle dimensions. Usually, the method of determining the equivalent particle size is defined by applicable regulations [2, 4-6, 11], e.g. EN 481 or ISO 7708. Depending on the conventional dust particle size, the following dust categories are defined:

- TSP (total suspended particles), with equivalent particle size below 300 μm;
- fine-grained dust, consisting of particles of equivalent size below 75 μm, which settle out under their own weight but may remain suspended for some time;
- fine dust PM10, with equivalent particle size below 10 μm;
- fine dust PM2.5, with equivalent particle size below 2.5 μm;
- dust PM1, with equivalent particle size below 1 μm;
- nanoparticles, with equivalent particle size below 100 nm [11].

The particulate matter PM10 is the dust that can go through a size-selective inlet, defined in the reference method for the sampling and examination of PM10 (see EN 12341), with a 50% efficiency cut-off at an aerodynamic diameter (AED) of the particle of up to 10 μm. The particulate matter PM2.5 is the dust that can go through a size-selective inlet, defined in the reference method for the sampling and examination of PM2.5 (see EN 14907), with a 50% efficiency cut-off at an aerodynamic diameter (AED) of the particle of up to 2.5 μm. Similar definitions are applicable to other particle size fractions, e.g. PM1.

According to standard EN 481 [16], two dust fractions are defined:

- Inhalable fraction (that can be breathed into the nose or mouth);
- Thoracic fraction (that can penetrate to the bronchioles).

The inhalable fraction consists of particles with equivalent sizes smaller than 100 μm. Particles with dimensions bigger than 30 μm are arrested in the upper part of the respiratory tract (nose, mouth, throat, and larynx) and then excreted with mucus. The middle parts of the respiratory tract (trachea, bronchi, and bronchioles) are reached by the thoracic fraction, the particle size of which does not exceed 20 μm. These particles may accumulate in the upper and middle parts of the respiratory tract. The gas-exchange regions (alveoli) are reached by the particles whose dimensions are smaller than 7 μm. The particles with dimensions smaller than 2.5 μm penetrate to, and accumulate in, even the deepest lung regions. The dust particles soluble in body fluids penetrate directly into the blood.

The particulate matter PM10, especially the PM2.5 fraction, causes various respiratory diseases such as asthma or chronic bronchitis, leads to deterioration in the function of lungs, and even can contribute to premature death. There are many publications univocally confirming that the air pollution with dusts is a factor aggravating the symptoms of chronic obstructive pulmonary disease (COPD) [12].

The dusts considered particularly harmful to the human health include those that contain particles with heavy metal compounds (especially arsenic, lead, cadmium, nickel, and mercury), with many of them having mutagenic or carcinogenic properties. Extremely toxic are also the particles containing heavy cyclic hydrocarbons, which are carcinogenic compounds [5, 6].

2. Object and purpose of the tests

The empirical tests were carried out on disc brake friction pairs where the brake disc was made of cast iron and the brake pads used were of two different types:

- conventional, denoted by "N";
- ceramic, denoted by "C".

Individual disc pads were identified according to their position in relation to the brake disc: those directly pressed by the hydraulic piston were assigned letter "T" ("back"); letter "P" ("front") was assigned to those viewed when facing the front side of the test stand.

The following parameters were constant for both disc brake friction pairs:

- calliper type;
- brake disc dimensions;
- effective radius of the brake disc.

The tests were carried out to compare disc brake friction pairs provided with conventional and ceramic brake pads in respect of their tribological properties, thermal load on the friction pair, and ecological impact in the form of immission of particulate matter in the measuring room, the particulate matter being emitted from the friction pairs.

The tests were carried out on a Krauss 2, model RWS75A, brake lining and brake pad tester, PIMOT equipment ID code AB 738, in test conditions as specified below:

- Hydraulic system pressure – 0.86 MPa;
- Disc brake speed – 660 min^{-1};
- Cooling airflow rate – 10 dm^3/s.

The test scope included:
- measurements of the friction surface temperature with the use of a Flir Systems thermal imaging camera, model FLIR-T62101;
- measurements of the immissions of specific size fractions of the particulate matter emitted from friction pairs, carried out in the measuring room;
- measurements of friction pair mass and thickness in order to evaluate the friction pair wear.

The immissions of specific size fractions of the particulate matter referred to as TSP, PM10, PM2.5, and PM1 were measured with the use of a TSI DustTrak DRX Aerosol Monitor, model 8533/8534.

The tests on the Krauss machine consisted of successive braking cycles, where the 5 s braking period was followed by a brake release period of 10 s. When the temperature at the measuring point of the test stand reached a level of 250 °C, the cyclic braking was interrupted for the system to be cooled to a temperature of 100 °C and then the test was resumed. The tests were carried out in three series, i.e. one series run during the bedding-in process and two series of tests, run immediately one after the other, on the pairs having been bedded-in.

The friction surface temperature was recorded at 15 s time intervals and the immissions of specific particulate matter size fractions were recorded at 5 s time intervals.

The curves having been recorded were subjected to digital processing in order to eliminate gross errors and to reduce the proportion of high-frequency noise in the signals used for the analysis. The gross errors were identified by analysing the current values of the variance of measurement results; such errors were corrected by linear interpolation of the measurement results. To reduce the proportion of high-frequency noise in the signals to be analysed, the signals were subjected to low-pass filtration with the use of second-order non-recurrent filters.

3. Results of empirical testing of disc brake friction pairs

Example time histories of the immissions of specific particulate matter size fractions in the measuring room and of the friction surface temperature have been presented in Figs. 1-4.

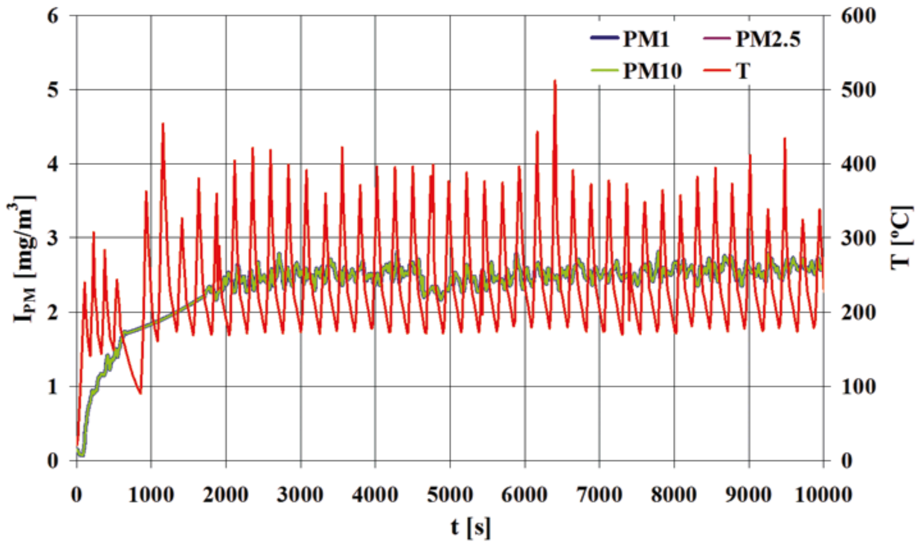

Fig. 1. Time histories of the immissions of specific particulate matter size fractions (I_{PM}) in the measuring room and of the friction surface temperature (T) for the friction pair with conventional brake pads (the first series of measurements)

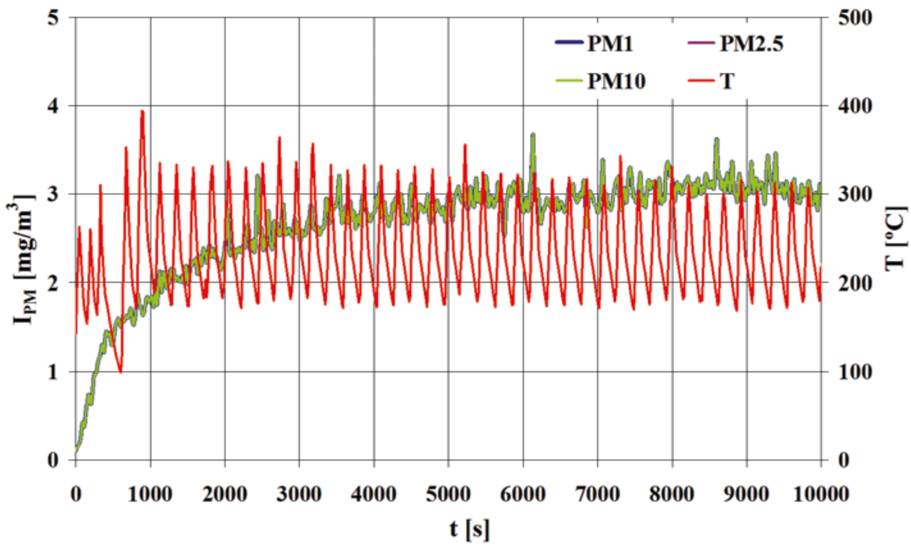

Fig. 2. Time histories of the immissions of specific particulate matter size fractions (I_{PM}) in the measuring room and of the friction surface temperature (T) for the friction pair with conventional brake pads (the second series of measurements)

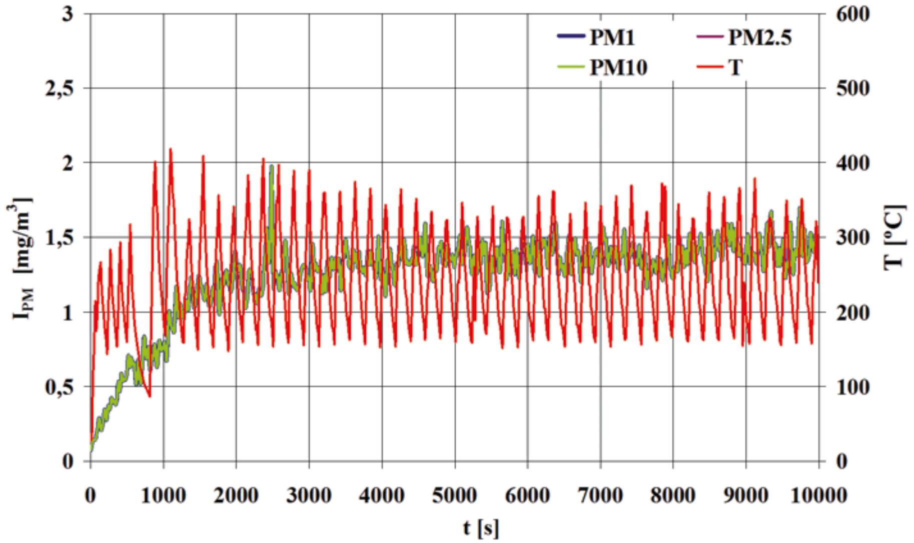

Fig. 3. Time histories of the immissions of specific particulate matter size fractions (I_{PM}) in the measuring room and of the friction surface temperature (T) for the friction pair with ceramic brake pads (the first series of measurements)

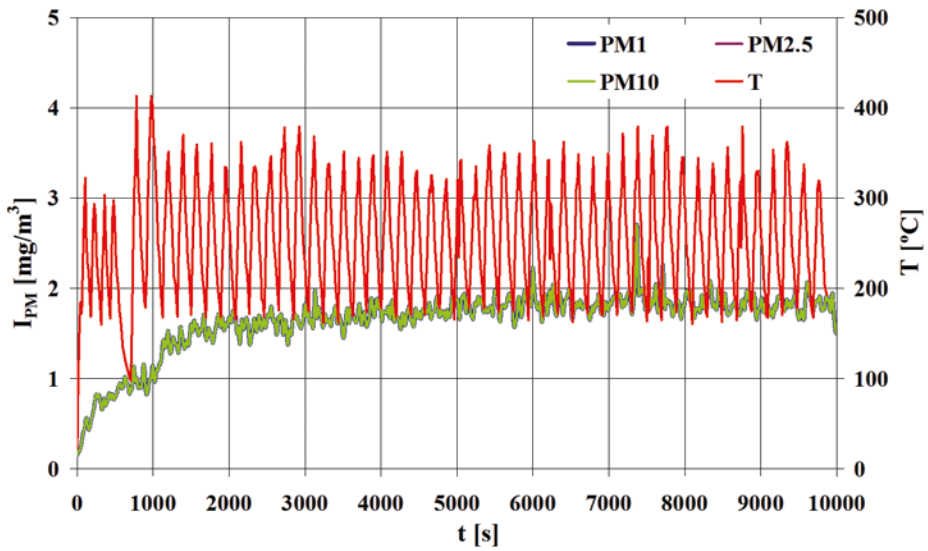

Fig. 4. Time histories of the immissions of specific particulate matter size fractions (I_{PM}) in the measuring room and of the friction surface temperature (T) for the friction pair with ceramic brake pads (the second series of measurements)

It can be clearly seen in Figs. 1-4 that the PM1 fraction, i.e. very fine dust with equivalent particle size below 1 μm, predominated in the particulate matter emitted from the disc brake friction pairs, which is consistent with the information available from the literature [4]. The time histories of the PM10, PM2.5, and PM1 dust concentration were almost identical; therefore, only one curve can be seen in the graphs plotted in the resolution available because the curves representing the immission of individual dust fractions overlap with each other.

Figs. 5 and 6 present a comparison between the time histories of the TSP dust immission recorded for the friction pairs with conventional and ceramic brake pads. The temperature vs. time curves plotted for the friction surface of the brake disc for the same friction pairs have been compared with each other in Figs. 7 and 8.

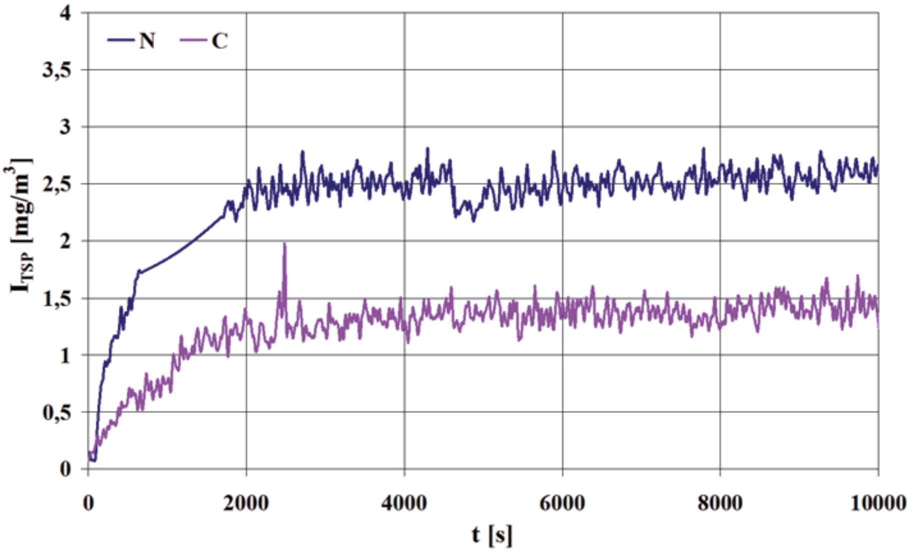

Fig. 5. Comparison between time histories of the TSP dust immission (I_{TSP}) recorded for the friction pairs with conventional and ceramic brake pads (the first series of measurements)

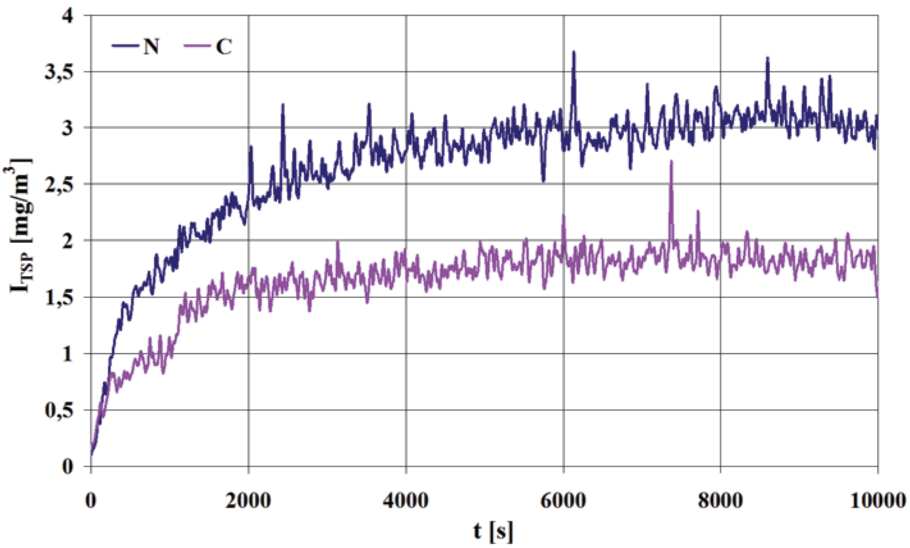

Fig. 6. Comparison between time histories of the TSP dust immission (I_{TSP}) recorded for the friction pairs with conventional and ceramic brake pads (the second series of measurements)

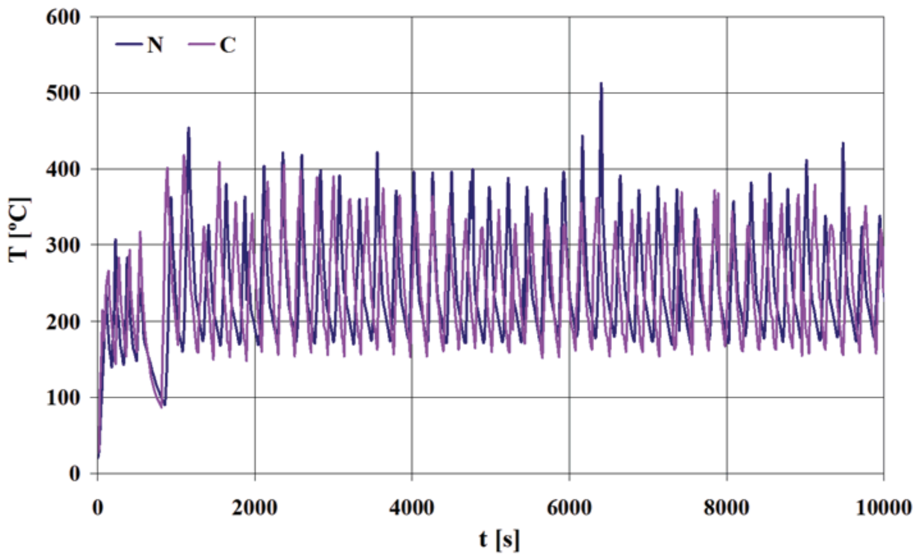

Fig. 7. Comparison between the temperature (T) vs. time (t) curves plotted for the brake disc's friction surface for the friction pairs with conventional and ceramic brake pads (the first series of measurements)

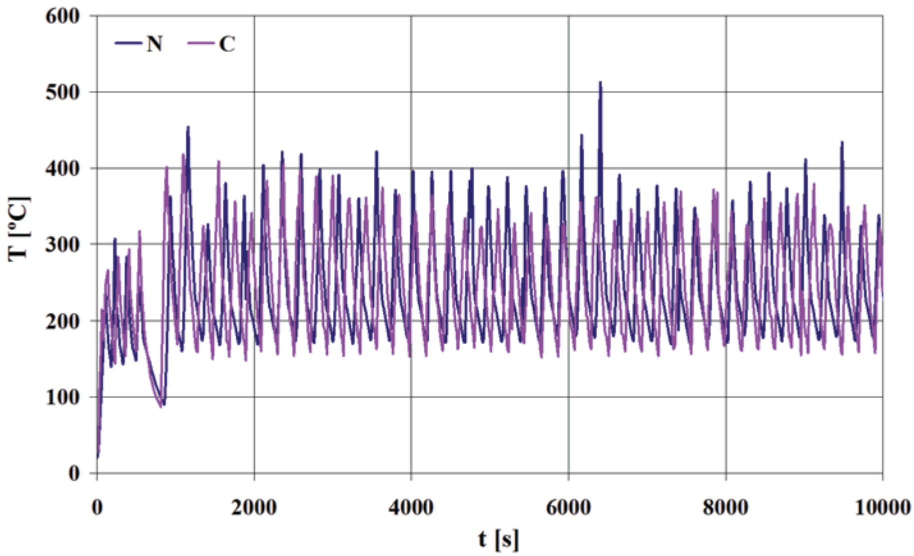

Fig. 8. Comparison between the temperature (T) vs. time (t) curves plotted for the brake disc's friction surface for the friction pairs with conventional and ceramic brake pads (the second series of measurements)

It can be easily noticed that the TSP dust immission was definitely lower for the friction pairs with ceramic brake pads; as regards the friction surface temperatures recorded for both types of the brake pads, the temperature vs. time curves were similar to each other.

Fig. 9 shows, as an example, the correlational interdependence between the TSP dust immission in the measuring room and the temperature of the brake disc's friction surface for the friction pair with conventional brake pads in the second series of measurements.

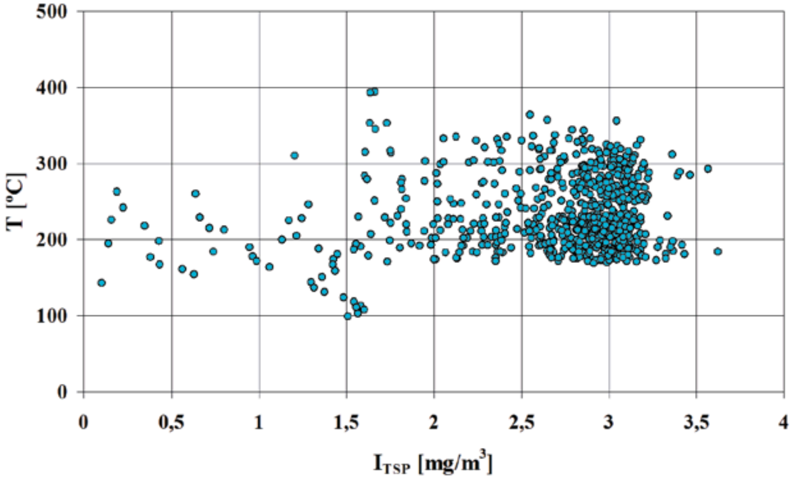

Fig. 9. Correlational interdependence between the TSP dust immission in the measuring room (I_{TSP}) and the temperature (T) of the brake disc's friction surface for the friction pair with conventional brake pads in the third series of measurements

The correlation between the sets under investigation was evaluated with the use of the Pearson linear correlation theory as well as the Spearman rank correlation, Kruskal gamma correlation, and Kendall tau correlation theories [8, 16].

The values of the coefficients of correlation between the sets under investigation are within the range 0.093-0.145 (Fig. 10).

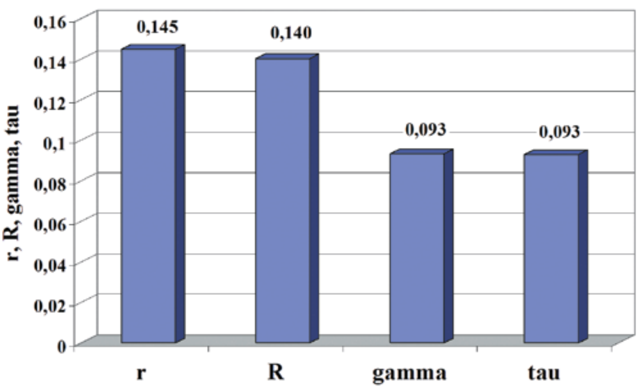

Fig. 10. Coefficients of Pearson, Spearman, Kruskal gamma, and Kendall tau correlation (r, R, γ, and τ, respectively) between the TSP dust immission in the measuring room (I_{TSP}) and the temperature (T) of the brake disc's friction surface for the friction pair with conventional brake pads in the third series of measurements

Although the values of the coefficients of correlation are relatively low, the probability that the hypothesis of absence of correlation will not be rejected is very low, too: for the Pearson linear correlation, it is lower than 0.005; for the Spearman rank correlation, it is lower than 0.000068; and for the Kruskal gamma correlation and Kendall tau correlation, it is lower than 0.000083. These very low values of the probability that the hypothesis of absence of correlation will not be rejected result from high cardinality of the sets under the correlational analysis [8, 16] (the cardinality of each of the sets exceeded 800). Therefore, a conclusion may be formulated that the sets of the TSP dust immissions in the measuring room and the temperatures of the brake disc's friction surface are interdependent, in accordance with the correlational analysis results.

Table 1 shows results of measurements of material wear in the experimental tests (during the bedding-in process and the other two test series) on the friction pairs with conventional brake pads. Results of similar measurements carried out for the friction pairs with ceramic brake pads have been given in Table 2. Individual disc pads were identified according to their position in relation to the brake disc: those directly pressed by the hydraulic piston were assigned letter "T" ("back"); letter "P" ("front") was assigned to those viewed when facing the front side of the test stand.

Table 1. Results of measurements of the friction pair wear: conventional pads

	Friction pair thickness [mm]		Friction pair thickness loss [mm]	Friction pair mass [g]		Friction pair mass loss [g]
	Before test	After test		Before test	After test	
Pad T	12.05	11.13	0.92	300.062	291.599	8.463
Pad F	12.41	11.43	0.98	305.585	291.920	13.665
Both pads	24.46	22.56	1.9	605.647	583.519	22.128

Table 2. Results of measurements of the friction pair wear: ceramic pads

	Friction pair thickness [mm]		Friction pair thickness loss [mm]	Friction pair mass [g]		Friction pair mass loss [g]
	Before test	After test		Before test	After test	
Pad T	11.93	11.36	0.57	294.679	288.762	5.917
Pad F	12.02	11.43	0.59	294.524	284.016	10.508
Both pads	23.95	22.79	1.16	589.203	572.778	16.425

In graphical form, the reduction in mass of the friction pairs with conventional and ceramic brake pads has been presented in Fig. 11. The reduction in thickness of the same friction pairs has been shown in Fig. 12.

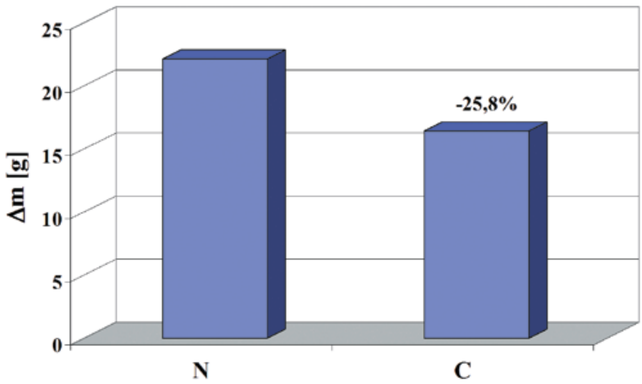

Fig. 11. A reduction in mass of the friction pairs with conventional (N) and ceramic (C) brake pads

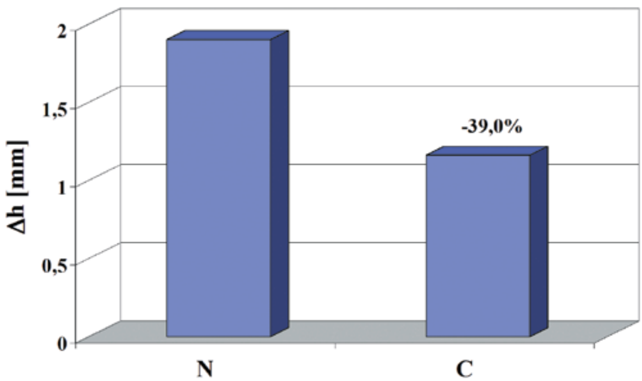

Fig. 12. A reduction in thickness of the friction pairs with conventional (N) and ceramic (C) brake pads

The difference in the measures of wear of elements of the disc brake friction pairs, recorded as a result obtained from the tests carried out, is very distinct. In relation to the reduction in mass of the friction pair with conventional brake pads, the corresponding reduction in the case of ceramic pads was lower by more than 25%. In terms of friction pair thickness, this difference in the friction pair wear reached a level of 39%.

4. Recapitulation

The results of testing disc brake friction pairs with conventional and ceramic brake pads are unequivocal. The examination of the total wear of a friction pair, evaluated on the grounds of measurements of friction pair masses and thicknesses, indicates a significant difference in the tribological properties of elements of the friction pairs under examination. The differences in the wear measures were significant: thanks to the use of ceramic brake pads in place of pads of the conventional type, the loss of mass of the friction pair was reduced by more than 25% and the loss of thickness of the friction pair was reduced by 39%.

The lower emission of particulate matter from the friction pairs provided with ceramic brake pads resulted in a significant reduction in the particulate matter immission in the measuring room during the tests on the friction pair with ceramic brake pads. The relative difference in the particulate matter immission was of the order of 50% when ceramic brake pads were used.

As one of the outputs of the tests carried out, the distribution of specific size fractions in the particulate matter emitted from friction pairs was determined. In its overwhelming majority, this particulate matter consisted of dust with equivalent particle size below 1 μm, which is extremely harmful for human health.

In spite of a big difference in the particulate matter emission from friction pairs with conventional and ceramic disc pads, no major differences were revealed in time histories of the temperature of brake disc friction surface, which indicates that there was no considerable difference in the power of the heat generated by friction.

The results of the experiments carried out unequivocally show the benefits that can be gained from the use of ceramic brake pads in the brake disc friction pair.

The full text of the article is available in Polish online on the website http://archiwummotoryzacji.pl.

Tekst artykułu w polskiej wersji językowej dostępny jest na stronie http://archiwummotoryzacji.pl.

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