Waldemar TUSZYŃSKI*, Michał GIBAŁA**, Andrzej GOSPODARCZYK***,
Stanisław KOZIOŁ****, Krzysztof MATECKI*****, Witold PIEKOSZEWSKI******,
Mariusz SICZEK*******, Marian SZCZEREK********, Jacek WOJUTYŃSKI*********

THE NEW INERTIA DYNAMOMETER FOR FRICTION AND WEAR TESTING OF BRAKE PADS AND BRAKE DISCS

NOWE STANOWISKO BEZWŁADNOŚCIOWE DO BADANIA TARCIA I ZUŻYCIA KLOCKÓW I TARCZ HAMULCOWYCH

Key words:	inertia dynamometer, brake pad, brake disc, friction.
Abstract:	For the sake of driving safety, the right choice of the brake pad friction material and its manufacturing processes to obtain the appropriate tribological properties is a matter of priority for brake pad manufacturers. Determination of the tribological properties is best done in component tests, i.e. in the setup: brake pads – brake disc. At the request of one of the domestic brake pad manufacturers, as part of the POIR project, an inertia dynamometer for testing friction and wear of brake pads and brake discs was developed and manufactured, which was given the symbol T-33. A test methodology was developed based on the "Cold application section" procedure described in SAE J2522:2003. The T-33 inertia dynamometer is designed for testing brake pads and brake discs intended for five vehicles representing the passenger vehicle class and vans. The paper presents the new test stand, test methodology, and results of verification tests of the T-33 dynamometer (interlaboratory comparison tests) performed on the Cinquecento vehicle brake setup.
Słowa kluczowe:	stanowisko bezwładnościowe, klocek hamulcowy, tarcza hamulcowa, tarcie.
Streszczenie:	Ze względu na bezpieczeństwo jazdy właściwy dobór materiałów materiału ciernego klocków hamulcowych oraz procesów jej wytwarzania w celu uzyskania odpowiednich właściwości tribologicznych jest sprawą traktowaną priorytetowo przez producentów klocków hamulcowych. Właściwości te najlepiej wyznaczać w układzie: klocki–tarcza hamulcowa. Na zlecenie jednego z krajowych producentów klocków hamulcowych, w ramach projektu POIR opracowano i wykonano stanowisko bezwładnościowe do badania tarcia i zużycia klocków i tarcz hamulcowych, któremu nadano symbol T-33. Opracowano metodykę badawczą opartą o procedurę „Cold application section", opisaną w normie SAE J2522:2003. Stanowisko bezwładnościowe T-33 przeznaczone jest do badania klocków i tarcz hamulcowych przeznaczonych dla pięciu samochodów, reprezentujących klasę samochodów osobowych i dostawczych. Przedstawiono nowe urządzenie, metodykę badawczą oraz wyniki badań weryfikacyjnych stanowiska T-33 (międzylaboratoryjnych badań porównawczych) wykonanych na zestawie hamulca samochodu Cinquecento.

*   ORCID: 0000-0002-1022-9621. Łukasiewicz Research Network – Institute for Sustainable Technologies, Tribology Department, Pułaskiego 6/10 Street, 26-600 Radom, Poland.

**   ORCID: 0000-0003-0815-4955. Łukasiewicz Research Network – Institute for Sustainable Technologies, Tribology Department, Pułaskiego 6/10 Street, 26-600 Radom, Poland.

*** ORCID: 0000-0002-4537-5389. Łukasiewicz Research Network – Institute for Sustainable Technologies, Control Systems Department, Pułaskiego 6/10 Street, 26-600 Radom, Poland.

**** ORCID: 0000-0001-5773-8098. Łukasiewicz Research Network – Institute for Sustainable Technologies, Prototype Department, Pułaskiego 6/10 Street, 26-600 Radom, Poland.

***** ORCID: 0000-0002-5211-2798. Łukasiewicz Research Network – Institute for Sustainable Technologies, Prototype Department, Pułaskiego 6/10 Street, 26-600 Radom, Poland.

****** ORCID: 0000-0002-4607-4211. Łukasiewicz Research Network – Institute for Sustainable Technologies, Tribology Department, Pułaskiego 6/10 Street, 26-600 Radom, Poland.

******* ORCID: 0000-0002-9060-7994. Łukasiewicz Research Network – Institute for Sustainable Technologies, Prototype Department, Pułaskiego 6/10 Street, 26-600 Radom, Poland.

******** ORCID: 0000-0002-1049-7853. Łukasiewicz Research Network – Institute for Sustainable Technologies, Tribology Department, Pułaskiego 6/10 Street, 26-600 Radom, Poland.

********* ORCID: 0000-0002-6386-2375. Łukasiewicz Research Network – Institute for Sustainable Technologies, Tribology Department, Pułaskiego 6/10 Street, 26-600 Radom, Poland.

INTRODUCTION

There are many parameters that define the quality of friction materials of brake pads [L. 1]. These are, e.g., density, hardness, compressibility, thermal expansion, shear strength, friction, and antiwear properties. They often conflict with each other, e.g., the high hardness of the friction material of the brake pad, giving good resistance to abrasive wear, can cause accelerated, undesirable wear of the brake disc.

Brake pad manufacturers are constantly striving to improve the performance of the friction material from which the brake pads are made. They must also comply with changing laws. Probably the best known was the need to eliminate – from the friction material – asbestos fibres due to their carcinogenicity. In Poland, this order was introduced in 1997 by the act prohibiting the use of asbestos-containing products [L. 2]. All material changes required conducting comprehensive verification tests of physico-mechanical and tribological properties. This was because the elimination of one component required replacement with others, sometimes several, which, in turn, could have a significant impact on the properties of the friction material.

Two approaches are used in current tribological experimental brake pad tests. Part of the research works is performed on model samples (e.g., cylindrical samples) cut from the friction material of the brake pad, rubbing against a disc imitating the brake disc. This approach was used by the authors of the papers [L. 3–8].

Very often, tests are performed in the brake pad-brake disc setup, most often using inertia dynamometers. This approach was employed by the authors of the papers [L. 9–14].

It should also be mentioned that a lot of works are devoted to modelling processes occurring in the brake pad–brake disc setup, which concerns, e.g., the friction process [L. 15].

In relation to experimental research, it is worth quoting the considerations of Habig [L. 16], who analyzed the pros and cons of individual research categories of the "Heinke's tribological test chain", included in DIN 50 322. In this categorization, tests on model samples are in Category VI, while tests performed in the brake pad–brake disc setup are in Category III.

Habig claims that, in the most commonly used tests on model samples, the test parameters are clearly separated and can easily be kept constant, but serious adulteration is possible, e.g., as a result of different heat flow, different tribochemical reactions, different load application methods, and different vibrations of tribosystems. These adulterations disappear as the loading and shape of the tested tribosystem are closer to real conditions.

The experience of the authors of this paper shows that the industry prefers testing on real brake components. Tests on model samples can, in principle, only be used as "screening" tests for various mixtures being selected for brake pad friction material; according to some reports, tests on model samples can be up to one hundred times cheaper than testing original components or assemblies [L. 17].

Due to the above-mentioned industry requirements, as part of the POIR project performed for one of the domestic brake pad manufacturers, the T-33 inertia dynamometer was developed and manufactured, which is the subject of this paper. It was assumed that, compared to existing solutions, the new stand should be of small size for location in an existing laboratory space, should be made within a relatively small budget, and the test methodology should be based on the "Cold application section" procedure of SAE J2522:2003 with the possibility of its development by further standardized test methods.

T-33 INERTIA DYNAMOMETER

The T-33 inertia dynamometer allows testing brake pads and brake discs during braking. It is designed to test brake pads and discs from vehicles with a GVW (gross vehicle weight) range from a light passenger vehicle to a heavy van, at a simulated vehicle speed at time of brake application of 40 km/h. During the tests, at a given brake application, based on many measured parameters, the maximum and average friction coefficient and braking deceleration are automatically calculated. The temperature of the brake pad friction material is also measured at two points, as well as the temperature of the brake disc. All measured values are collected in the dynamometer system memory and transferred to a computer for further data analysis. They are also displayed in real time on the operator's screen. The test is fully automated.

A photograph of the T-33 dynamometer with the raised bonnet of the test chamber is shown in **Fig. 1**.
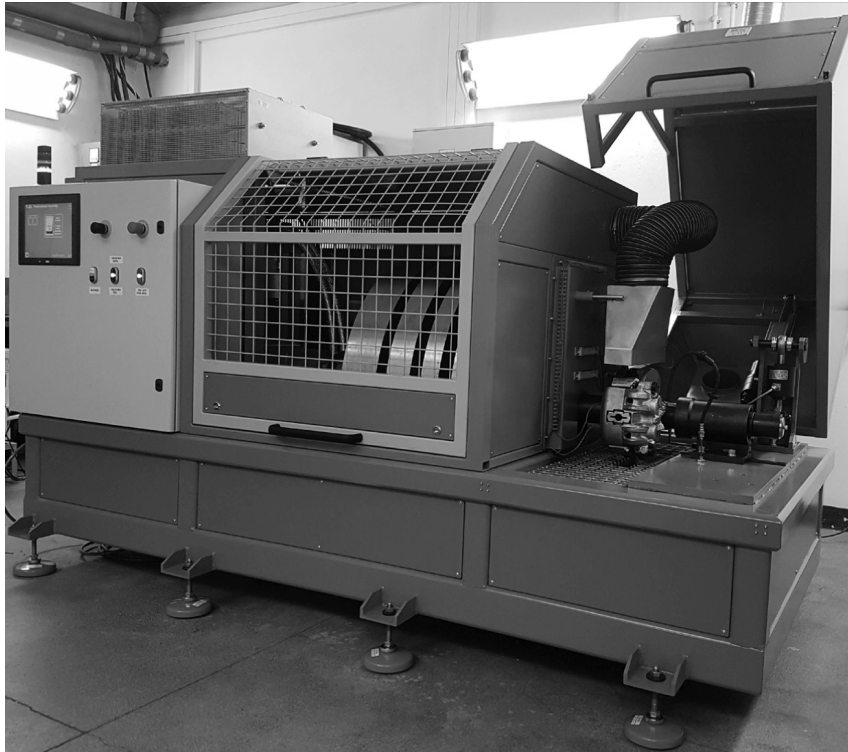
Fig. 2 shows the brake setup of the Iveco Daily III Van, fully assembled in the T-33 stand.

The device is equipped with a constant speed and temperature air supply system. The air is fed from the nozzle shown in **Fig. 2**, cooling the brake components during the tests.

The test method is in accordance with the "Cold application section" procedure of the SAE J2522:2003 standard widely used in the world.

During the tests, an inertia mass corresponding to the GVW of a given vehicle is put into rotation, along with a brake disc, up to a specific speed – corresponding to the vehicle speed at the time of brake application and the dynamic tire effective rolling radius – and then the brake calliper is activated with simultaneous automatic disconnection of the dynamometer motor.

The dynamic system of the T-33 dynamometer is presented in **Fig. 3** (3D model).

Fig. 1.   T-33 dynamometer with the raised bonnet of the test chamber
Rys. 1.   Stanowisko T-33 z uniesioną osłoną komory montażu elementów hamulca

Fig. 2.   Brake setup of the Iveco Daily III Van
Rys. 2.   Układ hamulca samochodu Iveco Daily III Van

The dynamic system consists of a motoreducer, an automatically engaged / disengaged electromagnetic clutch – for decoupling the motor before braking, the main shaft with inertia masses, and a brake disc assembly.
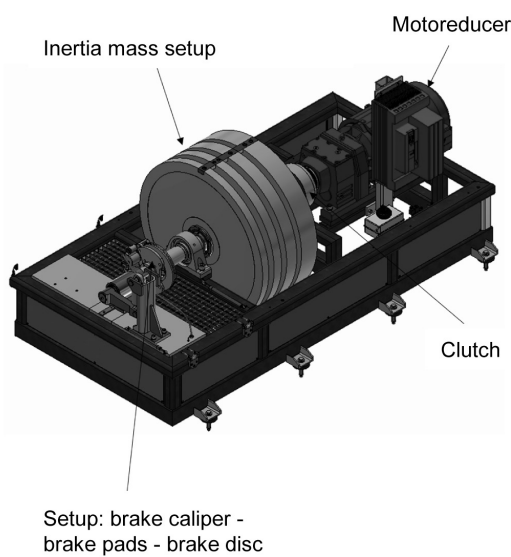
Fig. 3.   Dynamic system of the T-33 dynamometer
Rys. 3.   Układ dynamiczny stanowiska T-33

A photograph of the control cabinet integrated with the T-33 dynamometer is shown in **Fig. 4**.

Fig. 4.   Control   cabinet   integrated   with   the   T-33 dynamometer
Rys. 4.   Szafa sterownicza stanowiska T-33

A graphical control panel (touch screen) is located on the front wall of the control cabinet. From the touch screen, the operating parameters are set, the venting of the brake system is performed, and the analysis of emergency situations and errors is possible. Measured values are also displayed on the touch screen, including the following: brake pad and disc temperatures, rotational speed, braking force and torque, pressure in the master cylinder, as well as temperature, relative humidity, and dew point in the test chamber. The calculated values, i.e. braking deceleration and friction coefficient during the brake application, are also displayed.

The newest class PLC controller is used in the measurement and control system of the dynamometer.

The applied electronic systems allow the analysis of data with high sampling frequency – up to 500 Hz.

TEST BRAKE SETUP

Brake pads and brake discs from the Cinquecento vehicle were tested. The tested brake components are shown in **Fig. 5**.

Fig. 5.   The   tested   brake   components   of   Cinquecento vehicle
Rys. 5.   Zestaw hamulca od samochodu Cinquecento

TEST METHOD

The test was divided into three phases:
    Phase I. Initial burnish.
    Phase II. Control burnish.
    Phase III. Friction tests.

The test variables were identical in all the phases. They were consistent with the parameters in the "Cold application section" procedure, included in the SAE J2522:2003 standard. The number of initial burnish stops (500) was adopted on the basis of arrangements with the BOSMAL Institute from Bielsko-Biała for brake pads of the Cinquecento vehicle. In turn, the number of control burnish stops (18) was in accordance with the "Characteristic value 3 section" procedure of the SAE J2522:2003 standard and with the "Recovery 1,2,3 section" procedures of the said standard, but at different speeds.

Table 1 gives test variables of the T-33 dynamometer during all the phases of the test.

Maximum and average values of the friction coefficient were determined. They were determined in Phase III – friction tests.

The maximum values of the friction coefficient were determined automatically from the moment of reaching 90% of the pressure in the master cylinder (27 bar) until the rotational speed of the brake disc dropped to 1/8 of its initial value (which corresponds to a simulated vehicle speed of 5 km/h).

The average values of the friction coefficient were determined for a given brake application on the basis of continuously recorded values.

Table 1.   Test variables

Tabela 1.   Parametry badań

Parameter	Phase I Initial urnish	Phase II Control burnish	Phase III Friction test
Pressure	30 bar		
Inertia	50 kg m²		
Simulated vehicle speed at the start of brake application	40 km/h		
Rotational speed of the brake disc at the start of brake application	389 rpm		
Average sliding velocity between the brake pad and brake disc at the start of brake application	3.95 m/s		
Cooling air speed	3.7 m/s		
Cooling air temperature	10°C		
Initial brake disc temperature (IBT)	≤100°C	≤100°C	≤40°C
Initial brake pad temperature	≤200°C	≤200°C	≤200°C
Number of stops	500	18	15
Cleaning procedure (before burnish)	Brake disc: washing with extraction gasoline Brake pad: blowing with compressed air		

The momentary friction coefficient was calculated from the following formula (1):

$$f = 5000 * \frac{F}{p \ \pi \ d^2 \ R \ k} \tag{1}$$

where

f – friction coefficient,

F – braking force measured by the strain gauge [N],

p – pressure at the outlet of the master cylinder [bar],

d – brake piston diameter [mm],

R – average friction radius of the brake pad [mm],

k – number of brake pistons in the calliper,

5000 – coefficient resulting from the conversion of units of particular quantities, also taking into account the arm, with a fixed length (250 mm) on which the force F is measured.

For the Cinquecento vehicle, it was adopted that d = 48 mm, R = 97 mm, and k = 1.

In order to confirm the correctness of the results generated using the T-33 inertia dynamometer, an inter-laboratory comparison test was carried out with the BOSMAL Institute from Bielsko-Biała.

In both institutes, the burnish and friction tests were carried out under identical conditions described earlier. In order to ensure the identity of the test object, brake pads from the same packaging were separated – 2 pieces for both institutes. The same was done with brake discs – both institutes received one disc from the same packaging.

The BOSMAL Institute carried out tests using the commercial LINK Engineering M3000 inertia dynamometer.

When comparing the average coefficient of friction obtained in the friction tests, the last 8 values were taken into account, i.e. values from brake applications from 8 to 15.

When comparing the maximum coefficient of friction, all 15 values were taken into account, resulting from the number of brake applications in the friction tests.

All friction coefficient values were analyzed by Dixon statistical tests to reject possible outliers.

TEST RESULTS

The change of the maximum friction coefficient (f_{max}) during 500 stops (burnish) is shown in **Fig. 6**.
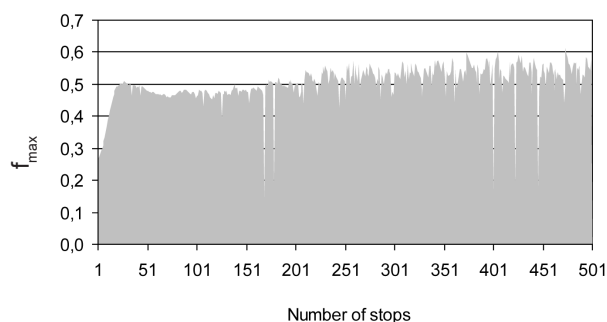
Fig. 6. The change of the maximum friction coefficient (f_{max}) obtained using the T-33 inertia dynamometer

Rys. 6. Przebieg maksymalnego współczynnika tarcia (f_{max}) uzyskany na stanowisku T-33

It can be seen from **Fig. 6** that the change of the friction coefficient is correct; at first the coefficient of friction increases as a result of burnish, then falls, and

then stabilizes. This indicates that the brake pads and brake disc were fully burnished before starting the friction tests.

Table 2 summarizes the values of the maximum (f_{max}) and average (f) coefficient of friction obtained at both institutes during friction testing.

Table 2. **Comparison of maximum (f_{max}) and average (f) friction coefficient; mean values are given with a confidence interval for a 95% probability**

Tabela 2. Porównanie wartości maksymalnego (f_{max}) i średniego (f) współczynnika tarcia; wartości średnie podano wraz z przedziałem ufności dla prawdopodobieństwa 95%

Number of stops	ITeE, Radom		BOSMAL, Bielsko-Biała	
	f_{max}	f	f_{max}	f
1	0.57	–	0.63	–
2	0.64	–	0.63	–
3	0.57	–	0.63	–
4	0.66	–	0.63	–
5	0.65	–	0.62	–
6	0.64	–	0.62	–
7	0.64	–	0.63	–
8	0.63	0.53	0.63	0.57
9	0.57	0.54	0.63	0.57
10	0.63	0.51	0.63	0.57
11	0.59	0.53	0.64	0.58
12	0.53	0.53	0.64	0.58
13	0.53	0.53	0.64	0.58
14	0.62	0.52	0.64	0.58
15	0.63	0.54	0.64	0.57
Mean value	0.61 ±0.02	0.53 ±0.01	0.63 ±0.00	0.58 ±0.00

All values in **Table 2** passed the Dixon test.

Comparing the mean values of the average friction coefficient (f), it can be seen that the results generated using the T-33 dynamometer are about 8.6% lower than those obtained at the BOSMAL Institute. The probable reason is that they were calculated on the basis of data sampled at 20 Hz (T-33 dynamometer). At BOSMAL, this is up to 50x faster; therefore, these include momentary friction coefficient peaks. Nevertheless, the difference can be considered acceptable. Such a conclusion can be drawn on the basis of information provided in UNECE Regulation No. 90, Appendix 3. This appendix sets out the requirements for brake pad friction material substitutes, including for vehicles of Category M_1 (including Cinquecento). In Section 2.2.3.3 regarding tests on an inertia dynamometer, 15% is given as the allowable difference in the average braking deceleration (the friction coefficient is directly proportional to it).

Comparing the mean values of the maximum friction coefficient (f_{max}), it should be stated that the results generated using the T-33 dynamometer and obtained at the BOSMAL Institute are statistically identical; f_{max} values are determined using the T-33 stand automatically – with a sampling frequency of 500 Hz, thus covering the momentary peaks of the friction coefficient, hence very good comparability of results.

SUMMARY

The values of the maximum friction coefficient obtained with the developed T-33 inertia dynamometer are statistically identical to the results obtained with the LINK Engineering M3000 test stand, which belongs to the devices with the highest technical level on an international scale. Moreover, the average coefficient of friction values are similar and the difference between them is acceptable. This proves the proper operation of the T-33 dynamometer. This machine, due to the many times lower cost than the cost of commercial stands, can be more available for laboratories dealing with testing friction and wear of brake pads and discs, including the modelling of tribological processes in such setups.

ACKNOWLEDGEMENT

REFERENCES

1. Orłowski T.: Wpływ wybranych napełniaczy na właściwości użytkowe bezazbestowych hamulcowych materiałów ciernych (in Polish). PhD Thesis. Poznan University of Technology. Poznan 2012.
2. Act of June 19, 1997, prohibiting the use of asbestos-containing products (in Polish).
3. Nagesh S.N. et al.: Characterization of brake pads by variation in composition of friction materials. Procedia Materials Science, vol. 5, 2014, pp. 295–302
4. Barros L.Y. et al.: Influence of copper on automotive brake performance. Wear, vol. 426–427, 2019, pp. 741––749.
5. Polajnar M. et al.: Friction and wear performance of functionally graded ductile iron for brake pads. Wear, vol. 382–383, 2017, pp. 85–94
6. EL-Tayeb N.S.M., Liew K.W.: On the dry and wet sliding performance of potentially new frictional brake pad materials for automotive industry. Wear, vol. 266, 1–2, 2009, pp. 275–287.
7. Shi L.B. et al.: Study of the friction and vibration characteristics of the braking disc/pad interface under dry and wet conditions. Tribology International, vol. 127, 2018, pp. 533–544.
8. Wahlström J. et al.: A pin-on-disc investigation of novel nanoporous composite-based and conventional brake pad materials focussing on airborne wear particles. Tribology International, vol. 44, 12, 2011, pp. 1838–1843.
9. Abdul Hamid M.K. et al.: Effect of brake pad design on friction and wear with hard particle present. Jurnal Teknologi, vol. 71, 2, 2014, pp. 135–138.
10. Dąbrowski T. et al.: The influence of the brake pad surface machining and finishing on its friction performance – examined by inertia brake dynamometer testing. Eksploatacja i testy – Autobusy, vol. 6, 2018, pp. 399–404.
11. Mahale V., Bijwe J., Sinha S.: A step towards replacing copper in brake-pads by using stainless steel swarf. Wear, vol. 424–425, 2019, pp. 133–142.
12. Martinez A., Echeberria J.: Towards a better understanding of the reaction between metal powders and the solid lubricant Sb_2S_3 in a low-metallic brake pad at high temperature. Wear, vol. 348–349, 2016, pp. 27–42.
13. Matějka V. et al.: On the running-in of brake pads and discs for dyno bench tests. Tribology International, vol. 115, 2017, pp. 424–431.
14. Collignon M. et al.: Failure of truck brake discs: A coupled numerical–experimental approach to identifying critical thermomechanical loadings. Tribology International, vol. 59, 2013, pp. 114–120.
15. Oleksowicz S.: Modelowanie procesu tarcia w hamulcach tarczowych pojazdów (in Polish). PhD Thesis. Cracow University of Technology. Cracow 2009.
16. Habig K.H.: Verschleiß und Harte von Werkstoffen. Hansen Verlag München. Wien 1980.
17. Alliston-Greiner A.F.: Test methods in tribology. Proc I. World Tribology Congress in London. 1997, pp. 85–93.