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T–01M TESTER ADAPTATION FOR WEAR DEBRIS COLLECTION AND ANALYSIS

PRZYSTOSOWANIE TESTERA T–01M DO GROMADZENIA I ANALIZY PRODUKTÓW ZUŻYCIA

Key words: tribological tester, modernization, separating chamber, wear debris collection, particle analysis, dust control.

Abstract: The article describes the need to collect and analyse data on stereological features of car tire and brake system friction material wear products, as required under new European Union regulations and by the project to expand the existing T–01M tester with a separation chamber and equipment enabling their capture. The structure of the chamber is described and the conditions for measuring the average diameter of particles emitted by the tested contacts are presented. The basic task of the additional chamber is to separate the surroundings of the tested friction node from environmental influences and to enable the capture of wear products to measure stereological features and analyse their chemical composition. A unidirectional filtered air flow towards the friction node is provided in the separation chamber in order to limit the deposition of wear products on the tester components. Mounting the separation chamber does not require any interference in the structure of the T–01M tester, because it is mounted on a sealed base frame screwed to the station plate. The chamber is equipped with holders for mounting a replaceable filter at the air inlet and a removable cyclone particles separator with a container for wear debris collected.

Słowa kluczowe: tester tribologiczny, modernizacja, komora separacyjna, produkty zużycia, gromadzenie, analiza cząstek, ograniczenie pylenia.

Streszczenie: W artykule opisano potrzebę gromadzenia i analizy cech stereologicznych produktów zużycia opon samochodowych oraz materiałów ciernych układów hamulcowych, czego wymagają nowe uregulowania Unii Europejskiej oraz projekt rozbudowy istniejącego testera T–01M o komorę separacyjną i aparaturę umożliwiającą to wychwytywanie. Opisano budowę komory i przedstawiono warunki pomiarów średniej średnicy cząstek emitowanych przez badane skojarzenia. Podstawowym zadaniem dodatkowej komory jest oddzielenie otoczenia badanego węzła tarcia od wpływów środowiska oraz umożliwienie wyłapywania produktów zużycia w celu dokonania pomiaru cech stereologicznych i analizy składu chemicznego. W komorze separacyjnej przewidziano jednokierunkowy przepływ strumienia filtrowanego powietrza w kierunku węzła tarcia w celu ograniczenia osadzania produktów zużycia na elementach stanowiska. Umocowanie komory separacyjnej nie wymaga ingerencji w budowę testera T–01M, ponieważ jest ona osadzona na uszczelnionej ramce podstawy przykręconej do płyty stanowiska. Komora jest wyposażona w uchwyty do mocowania wymiennego filtra na wlocie powietrza i demontowalnego cyklonowego separatora cząstek z zasobnikiem na zebrane produkty zużycia.

INTRODUCTION

During braking, a kinetic energy is dissipated by a conversion into a frictional heat and by overcoming the cohesive forces of materials (wear). The results of braking are heating of braking systems and wear products of friction elements (dust) **[L. 1]**. Among them, there are PM2.5 and PM10 (graphite, steel wool, glass fibres, iron oxides) products, which are harmful to humans because they penetrate the

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lungs and indirectly into the blood. Some of these particles are soluble in water and can enter living organisms that are at the bottom of the food chain.

In the EU, air pollution (PM2.5 particles) was the cause of approximately 477,000 premature deaths in 41 countries in 2009, and 417,000 in 2018. **[L. 2]**. On average, 39% of NOx emissions and 11% of PM10 emissions are attributed to road transport **[L. 3]**. The reduction in death rates was the result of tighter emission regulations. To further cut down the environmentally harmful emissions of particulate matter, the European Parliament issued the Euro 7 regulation, which is scheduled to come into force on July 1, 2025 for light-duty vehicles, and on July 1, 2027 for heavy-duty vehicles.

This standard provides for the development and presentation in 2023 of uniform principles and conditions for measuring particles emitted by braking systems and tires of newly registered vehicles. It was also assumed that the development of a standardized, repeatable and reliable method for controlling particulate matter emitted by braking systems and tires, and the production of a sufficient number of control and measurement devices will take approximately 2 years.

After protests from representatives of the automotive industry, that requirement was suspended for passenger cars and vans **[L. 5]**. The advisory group of the European Commission – AGVES (Advisory Group on Vehicle Emission Standards) admitted that the original assumptions of Euro 7 were technically impossible to meet.

Among the emissions of particulate matter, wear products of braking systems and car tires (microplastics) were distinguished. The wear of one summer car tire 25/40 R18 after driving 15,000 km is 130 grams per 1,000 kilometres, and the wear of a winter tire is 139 g/1,000 km (average ADAC test results **[L. 6]**). From installation to replacement, the average tire wear is up to 2 kilograms. 80% of tire wear products have dimensions between 100 and 500 µm, 18% 50–100 µm and up to 2% particles 20–50 µm.

As a part of the European Green Deal, it is planned to achieve climate neutrality by 2050. The possible costs that will have to be incurred when adapting vehicles to these requirements are also indicated, i.e. passenger cars and vans: EUR 357–929 for a vehicle with a diesel engine and EUR 80–181 for a vehicle with a petrol engine; heavy-duty vehicles: EUR 3,717–4,326 **[L. 2]**.

To effectively reduce particulate emissions, quantitative and qualitative testing of brake system wear products is important at the stage of developing friction contact materials, i.e. under laboratory conditions. Research for large manufacturers of braking systems is conducted in many scientific and research centres **[L. 7, 8]**. The Faculty of Transport and Aviation Engineering at the Silesian University of Technology, in cooperation with the Faculty of Materials Engineering and industry representatives, conducts research on the wear resistance of friction elements of braking systems, the aim of which is to reduce environmental pollution caused by wear products **[L. 9, 10]**.

So far, during the basic research, the wear of friction elements and friction (braking) forces have been determined. The authors' experience shows that the wear of a 45 mm diameter disc made of GJL-150 cast iron used for brake discs when working with a 5 mm diameter pin ($S = 20\ mm^2$) made of the brake pad material (F701) is 1.92–4.4 mg/1,000 m, and for the brake pad 0.8–2.52 mg/1,000 m at $v = 0.5$ m/s and $p = 1$ MPa. In total, the contact emits 2.72–6.92 mg/1,000 m of a friction distance under braking conditions in a city traffic at a speed of 30 km/h with a slight pressure on the brake pedal.

a)

b)

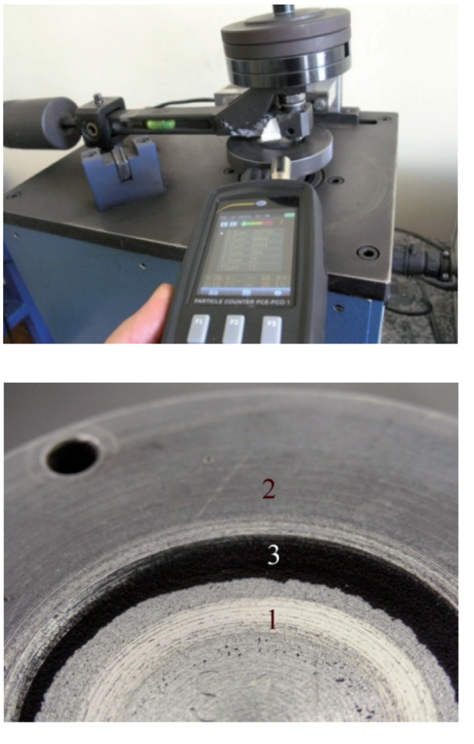

Fig. 1. Localization of the measuring device during the analysis of wear debris (a) and wear debris collected at the edge of nut (b): 1 – disc (countersample), 2 – nut fastening disc, 3 – wear debris

Rys. 1. Położenie miernika podczas pomiaru produktów zużycia (a) i produkty zużycia zgromadzone przy krawędzi nakrętki (b): 1 – tarcza (przeciwpróbka), 2 – nakrętka mocująca tarczę, 3 – produkty zużycia

Based on the measurements of the stereological features of wear products from 18 contacts employing an optical meter, it was estimated that PM10 particles constitute 0.03% ($\sigma = 0.00004$) of all particles emitted by the tested contacts in the diameter range of 0.3; 0.5; 1.0; 2.5; 5.0; and 10.0 µm. Particle measurements were made directly at the open friction node, i.e. without the housing, for 20 seconds (friction distance S = 10 m). The disadvantage of these measurements is that the particle meter pump captures only a part of the wear products emitted into the environment at the meter location (**Fig. 1a**). The designed separation chamber with an air filter at the inlet eliminates this disadvantage.

So far, prototypes of devices for sucking out brake and tire wear products, called car vacuum cleaners, designed by car manufacturers, capture up to 60% of dust **[L. 10]**.

After converting to the conditions of a real braking system (the pad surface area Sk = 4,000 mm^2, the pin area Sp = 20 mm^2), the total wear of one brake with a single pad is approximately 200 times higher than the wear of the contact in laboratory tests and it may amount to 544–1,384 mg/1,000 m. In today's passenger cars equipped with disc brakes with a floating calliper, there are eight contacts emitting wear products. Taking this into account, we get that one vehicle emits from 4,352 to 11,072 mg/1,000 m particles. Assuming that PM10 particles constitute 0.03% of all wear products, it can be estimated that an actual braking system equipped with GJL150 cast iron brake discs and F701 pads will emit from 1.31 mg to 3.32 mg of these particles per 1,000 m. Comparing this to the EU requirements planned for 2025, stating that particle emissions from braking systems cannot exceed 7 mg/1,000 m (3 mg/1,000 m after 2034), it can be assumed that when driving in the city at a speed of up to 30 km/h, the limit determined for 2025 is achievable, and for 2034 it has already been exceeded with cast iron discs.

Taking into account the tendency to almost double the total wear of the contact (**Table 1**) with an increase in the unit pressure from p = 1 MPa to p = 2 MPa, it can be expected that the total emission of PM10 particles under braking conditions from higher speeds will be higher than that estimated on the basis of laboratory tests (2.72–6.92 mg/1,000 m). Therefore, the AGVES concluded that the original assumptions of Euro 7 are technically impossible to meet using currently produced materials and given their price. Such high requirements can be met by braking systems with composite discs, the price of which is much higher than that of cast iron discs **[L. 4, 8]**.

Currently, European Union regulations require, regardless of the final permissible limits and the entry into force, testing wear particles emitted by braking systems. Therefore, in order to expand the scope of research carried out at the Silesian University of Technology, to include the analysis of stereological features of friction-generated particles, it was decided, with the participation of the PBL students, to equip the previously used T–01M tester with a system for catching and analysing wear products separated from the surroundings.

Table 1. Wear of the elements of P50 094/GJL-150 contact [L. 4]

Tabela 1. Zużycie elementów skojarzenia P50 094/GJL-150 **[L. 4]**

Pressure Δm, mg/1000 m	p = 1 MPa	p = 1.5 MPa	p = 2 MPa
Pin	1.2; 0.8; 0.66 $\Delta m_{av.} = 0.89$	5.7; 8.4; 2.4 $\Delta m_{av.} = 5.5$	6; 10.4; 11.4 $\Delta m_{av.} = 9.26$
Disc	3.46; 2.24; 1.82 $\Delta m_{av.} = 2.51$	10.5; 22; 3.4 $\Delta m_{av.} = 11.96$	16.3; 22.6; 30 $\Delta m_{av.} = 22.96$
Contact summarized mg/1000 m	3.39	3.49	6.44
µ	0.1–0.40 [1)]	0.26–0.32	0.18–0.44

[1)] minimal and maximal values from 3 measurements.

The available literature contains information on tribological testers with the ability to capture particles and analyse their stereological features. Generally, two groups of testers can be distinguished, i.e. laboratory ones **[L. 9–12]** for sample testing and industrial (dyno bench tester) **[L. 13–14]** for testing entire braking systems. Their common feature is the separation of the friction node from the surroundings, the filtration of the air (high-efficiency HEPA filters) entering the chamber, and the suction of wear products. In the working chambers of the testers, the air flow speed varies from 2.2 l/s **[L. 10]** to 11.5 l/s **[L. 9]**. Air exchange in the chamber occurs up to 99 times per hour **[L. 9]**. Dynamometric stations for testing real brakes were obligatorily equipped with systems capturing wear products, and laboratory testers were sporadically equipped.

The article presents the assumptions of the project and the initial method of capturing and analysing the stereological features of wear products. The modernization of the tester will contribute to improved safety of using the tester during tests of contacts made of harmful materials and help select brake materials with reduced particle emissions during laboratory tests and during usage.

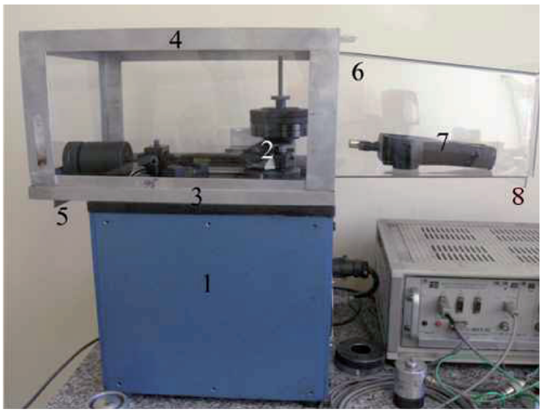

Fig. 2. T–01M tester with a designed separation chamber for collecting and analysing stereological features of solid wear products of the tested contacts

Rys. 2. Tester T–01M z zaprojektowaną komorą separacyjną do gromadzenia i analizy cech stereologicznych stałych produktów zużycia badanych skojarzeń

1 – tester base with drive unit;
2 – pin-on-disc friction node from which wear products are caught;
3 – frame attaching the chamber to the tester base;
4 – separation chamber to isolate the tester from the surroundings;
5 – hook for the replaceable air intake filter into the chamber;
6 – air outlet from the separation chamber;
7 – PCE-PCO 1 particle meter;
8 – hook for the cyclone particle separator and the fan extracting air from the chamber.

BRIEF FOR DESIGN

The conditions for testing selected contacts on the T–01M tester are imposed by its construction. The heart of the tester is the pin-on-disc contact (2 in **Fig. 2** and **Fig. 3a**). The pin is pressed by the loading system against the rotating disc. The disc (1) is attached to the sample holder using a nut (2) with a 3 mm thick collar (**Fig. 1b**). Pressure, relative speed, and friction radius can be adjusted during testing. Wear products (3) first settle on the disc at the edge of the nut flange (**Fig. 1b**). Depending on the amount of products and the rotation speed of the disc, after covering the edges of the cap, the particles are released the friction zone into the surroundings. The amount of the wear products emitted depends on the materials tested (**Fig. 2**). The range of particle emission depends on their mass and the rotational speed of the disc, i.e. larger particles are thrown farther as the speed increases.

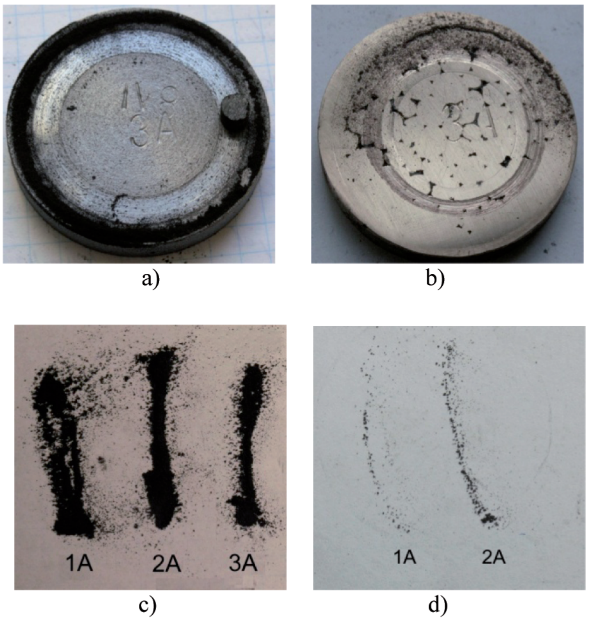

Fig. 3. Samples made of cast-iron (a) and of composite with cast-iron matrix (b) with wear debris collected in the nut as well as wear debris removed from the nut during rubbing of cast-iron (c) and composite with cast-iron matrix (d)

Rys. 3. Próbki wykonane z żeliwa (a) i z kompozytu z osnową żeliwną (b) z produktami zużycia zatrzymanymi w nakrętce oraz produkty zdjęte z nakrętki podczas tarcia żeliwa (c) i kompozytu z osnową żeliwną (d)

The collection of wear products and analysis of particle dimensions requires isolation of the tested contact from the environment and directional emission of products. For this purpose, a separation chamber (4, **Fig. 2**) is provided, placed on the base frame (3) screwed to the upper base plate of the tester (1). The chamber can be removed without fear of particles entering from the surrounding air, because there is a flexible micro-rubber gasket in the base frame. When designing the separation chamber, the possibility of particle sedimentation on the tester's structural elements was taken into account. To avoid this, there is a one possible direction of an air flow that minimizes a particle sedimentation, because the friction contact is located at the right edge of the housing.

A filter is installed at the air inlet channel to the chamber (the left edge of the housing) to eliminate particles from the environment (**Fig. 3**). The chamber is equipped with a hook (5) for attaching the air filter housing to enable its quick replacement.

At the outlet of the chamber, an optical meter of the stereological features of particles (7) was mounted in a hole located in the channel axis. This meter is equipped with a pump sucking in the air containing wear products and an optical counting system with a coincidence error (particle sticking together) of less than 5%. It allows you to measure the number of particles with dimensions of 0.3; 0.5; 1.0; 2.5; 5.0; and 10.0 μm. Before the actual measurement, the pump sucks in the air and cleans the measuring system. Measurement results are automatically saved on a memory card, which facilitates their subsequent statistical analysis.

On the outlet side of the separation chamber there is a flange (8) for mounting a cyclone particle separator equipped with a particle container. The separator is placed between the chamber outlet and the fan sucking air into the chamber. The collected particles are subjected to dimensional and, if necessary, chemical composition control analysis using a specialized station with a laser meter. The container can be filled with water, which increases safety when disposing of the used products, or it creates a suspension if further analyses are performed using a laser analyser.

SUMMARY

Retrofitting the T–01M tester with a separation chamber enabling the capture of wear products and an analyser for PM2.5 and PM10 particles enabling their dimensional analysis will contribute to improving the safety of tester operators and allow determination of the dimensions and number of particles in the established diameter ranges (0.3; 0.5; 1.0; 2.5; 5.0; and 10.0 μm) generated by the materials of the tested contacts, including those intended for friction materials of braking systems identified in Euro 7 already at the laboratory testing stage.

The ability to control the dimensions of wear products emitted during laboratory tests will allow the selection of pairings that generate fewer pollutants with the most dangerous dimensions, including PM2.5 and PM10, already at the stage of basic research. So far, such tests were usually performed on cast prototypes of brake discs or drums using a dynamometric test stand (approval requirements).

The T-01M tester with a designed chamber differs from the testers known from the cited literature in that it can be retrofitted with a cyclone particle separator. This separator allows you to catch wear products without having to separate them from the air filter inserts. The wear products collected in the separator, after previously measuring stereological features, can be re-examined on another particle analyser in terms of stereological features and chemical composition.

The participation of students from the Faculties of Transport and Aviation Engineering and Materials Engineering in the modernization of the T–01M tester, as part of Project Based Learning (PBL), allowed them to gain design experience and become familiar with the current problems of environmental pollution by frictional contacts of technical means of transport and the requirements for climate neutrality under the European Green Deal.

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