On Airborne Wear Particles Emissions of Commercial Disc Brake Materials – A Pin on Disc Simulation

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Abstract

A novel test method was used to study the concentration and size distribution of airborne wear particles from disc brake materials. A pin-on-disc tribometer equipped with particle counting instruments was used as test equipment. Four different non-asbestos-organic (NAO) linings for the U.S. market and four different low metallic linings for the EU market were tested against material from gray cast iron rotors. The result indicates that the low metallic linings are more aggressive to the rotor material than the NAO linings, resulting in higher amount of wear and concentrations of airborne wear particles. But, although there are variations in the measured particle concentrations, similar size distributions were obtained regardless of lining material.
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A: Result from test with front brake materials
B: Result from test with rear brake materials
1 Introduction

Most modern passenger cars are equipped with disc brakes which are not sealed off from the ambient air. During braking both the brake pads and rotors are worn. This wear process generates wear particles. Some of these particles will be deposited on the brake hardware, and others may become airborne. A problem with measuring airborne brake particles in field test is to distinguish them from other sources such as road dust and exhaust fumes. To gain increased knowledge about airborne brake particles, it may therefore be preferable to use laboratory test stands where the cleanliness of the surrounding air can be controlled. Recently, Olofsson and Olander [1] used a pin-on-disc tribometer with a clean air supply to measure the airborne wear particles generated at the sliding contact between a steel pin and steel disc. The objective of the work presented here is to investigate the possibilities to use the experimental set up proposed by Olofsson and Olander to compare different disc brake materials. This report describes the experimental set up and presents the result from a test series where non asbestos organic (NAO) linings for the U.S. market and low metallic linings for the EU market have been tested against gray cast iron.
2 Experimental Set Up

The tests were performed on a pin-on-disc machine with a horizontal rotating disc and a dead weight loaded pin, see Figure 1. The machine is a conventional tribometer and is used for tribological testing of various material combinations in terms of friction and wear. The machine runs under stationary conditions with constant applied normal forces of up to 100 N and constant rotational speeds of up to 440 rpm. A load cell was used to measure the tangential force acting on the pin. The coefficient of friction was calculated as the measured tangential force divided by the applied normal force. The wear of the test samples was measured by two different methods. The mass loss was measured by weighting of the test samples prior and after the test using a Sartorius 2604 balance. To have a continuous measure of the wear throughout the test, an inductive displacement gauge of type WA/10 mm from Hottinger Baldwin Measurement GMbH was used to measure normal displacement of the level arm. The displacement gauge gives an on-line measure of the total wear both pin and disc sample, making it possible to observe changes in the wear rate due to running-in effects or changes in wear mechanisms.

![Figure 1 Schematic figure of the test equipment. A: Room air, B: Fan, C: Flow rate measurement, D: Filter, E: Flexible tube, F: Inlet for clean air, measurement point, G: Closed box (Chamber); H: Pin-on-disc machine, I: Air inside box, well mixed, J: Air outlet, measurement points, K: Displacement gauge, L: Dead weight, M: Rotating disc sample, N: Pin Sample.](image)

The pin-on-disc machine is placed in a climate chamber, which allows testing at different temperatures and levels of air-humidity. In these tests the climate chamber was used as a closed box with control of the cleanliness of the incoming air, see Figure 1. In this figure the fan (B) takes the air from the room (A) and presses it into the box (G) via a flow measurement system (C) and a filter (D) and through the air inlet opening (F). The connections between fan and measurement system and between measurement system and filter and between filter and chamber were flexible tubes (E). All connections from
the measurement system to the chamber were sealed to prevent leakages. A leakage could not disturb the tests, since the air pressure inside the tubes were higher than outside, but a leakage would change the measured airflow rate, which would influence the particle measurements.

In the box the air was well mixed (I), due to the complicated volume of the pin-on-disc machine (H) and the high air change rate. This was also verified by the smooth concentrations measured during the tests. The air in the box transported the generated particles to the air outlet (J), where sample points for the particle measurement were placed.

The fan had a variable speed and was set at a flow rate of 7.2 m³/h (2 l/s), which gives an air change rate in the empty box of 53/h. (Box volume 0.135 m³) The volume of the pin-on-disc machine was approximately 0.035 m³, which gives an approximate air change rate during the tests of 72/h (1.2/min). The flow rate measurement system consisted of a straight, calibrated tube, with separate connections for total and static pressure. These were measured using an ordinary U-tube manometer. The calibration was for the flow interval from 2 to 50 m³/h. The filter was used to ascertain a particle-free inlet air and was of class H 13 (according to standard EN 1822) with a certified collection efficiency of 99.95 % at MPPS (Maximum Penetrating Particle Size). The particle-free inlet air was verified by measuring the particle concentrations both in the inlet and the outlet of the box, before the tests started and after the tests were finished. In both cases the measured particle concentrations were zero. During the measurements one particle counter (PTrak) continuously measured the inlet concentration which, except when some problems did occur, was zero.

Inside the box a small pneumatic tube, with a filter that cleaned the pressurized air totally, was attached to the pin-on-disc and the air was directed with high velocity (>10 m/s) at the contact point through two small nozzles to minimize the number of particles stuck to the test materials. The air flow in these nozzles were 0.07-0.08 l/s, which increases the calculated air change rates to 54/h and 74/h, for empty box and box with equipment, respectively.

The air and the particles in the box were transported through the box to the outlet opening (diameter 80 mm, same as the inlet diameter) where the sample point for particle measurements was situated.

The main particle instrument was an optical particle counter (light scattering), in this case called Aerosol Spectrometer, of type Grimm 1.109 [2], which measures airborne particles from 0.25 µm to 32 µm in 31 size intervals and concentrations from 1 particle/litre to 2*10⁶ particles/litre with a sample flow rate of 72 l/h (0.02 l/s). Minimum measurable concentrations depend on sensitivity of the particle counter, sampling time, sample flow rate and airflow rate through the box. With the used flow rates, minimum concentrations are approximately one decade below presented results for particles up to one micrometer and more than two decades lower for larger particles. An optical particle counter is sensitive to the form and refractive index of the particles, which means that the measured
particle sizes and number distributions tentatively can be seen as approximately correct [3].

In the outlet from the box was also the sampling point for the other particle instruments. The first was the counter for particles between 0.02 and 1 µm. This was identical with the instrument that measured the concentration in the inlet air and was of type PTrak [4]. This is a condensation nuclei counter that measures the number concentration of airborne particles between 0.02 and 1 µm. For both limits the 50 % cut-off in counting is given. There is no size resolution between upper and lower limits and the particle concentration is stored every second.

The second instrument in the outlet was of type DustTrak [5], which measured the mass concentration in mg/m³. This instrument is also of type light scattering and can measure particle concentrations corresponding to respirable size, PM10, PM2.5 or PM1.0 size fraction. Without any pre-precipitator it was used in these experiments and then measures particles between 0.1 and 10 µm. The instrument is calibrated with a standardized test dust, which has different size distribution, density and refractive index than here measured particles. Thus the output from this instrument can only be used as a relative measure, but is useful to see the changes in time of generated particle mass.

The third instrument sampling in the outlet was a Scanning Mobility Particle Sizer (SMPS) [6]. The SMPS combines an electrostatic classifier (TSI 3071) with a particle counter (TSI CPC 3010). The particles are charged in a controlled manner and then sequentially classified according to their electrical mobility. With the controlled charging, particle electrical mobility corresponds to particle size. The counter subsequently registers the particles in the sequential size classes. The counter is a condensation nuclei counter which by means of condensation optically may count particles down to 10 nm.

The SMPS gave a particle number concentration size distribution every 5½ minutes. The size distribution reached from 10 nm to 520 nm in 110 size classes. Total number concentrations down to a few particles per cm³ could be registered, but for some runs the concentrations where at a lower limit for meaningful individual cycle size distribution data.

The whole system, including pin-on-disc machine, was tested by starting all parts, except that there was no contact between the pin and the disc. The measured particle concentration in the outlet became zero after 5 to 10 minutes, depending on earlier activity in the room and the box. Thereafter the wear tests started.
3 Material

The tests were conducted on disc shaped rotor samples with diameter 43 mm and thickness 6 mm, and pin-shaped pad samples with diameter 10 mm and height 15-17 mm. The test samples were manufactured from brake pads and rotors of passenger cars, see Figure 2. The material combinations used in the tests are given in Table 1 and consists of four lining materials used in front brakes and four lining materials used in rear brakes. Two low metallic lining materials from the EU market and two NAO linings from the U.S. market were included for front brakes and rear brakes respectively. All front brake lining materials were test against the gray cast iron (GME 05002 Type D) that is used together with the T4139 material in front brakes, whereas the rear brake pad material were combined with an alternative gray cast iron (GME 05002 Type A) used in rear brakes together with the G4656 pad material.

The disc samples were cut out of the rotors using waterjet cutting. The porosity and chemical composition of the friction material in the brakes pads complicated the manufacturing process of pin samples. So instead of using waterjet cutting the pin samples had to be sawed out mechanically and additionally grinded to the specified cylindrical shape. The contact surfaces of the test samples were not re-machined, i.e. the original contact surfaces of both pads and rotors were kept unaltered.

The disc samples were cleaned ultrasonically with propane and methanol prior to testing. Due to porosity of the lining material and the risk of dissolving the binder, the pin samples were not clean with solvents only dusted off by a blast of dry air.

4 Test Conditions

The test conditions were set up to simulate urban traffic as close as possible. The disc rotated at constant rotational speed of 440 rpm (maximal speed of the pin-on-disc machine) and the obtained wear track on the disc had diameter (midpoint of track to midpoint of disc) 30 mm, giving a resulting mean sliding speed of 0.7 m/s. If scaled to typical passenger car conditions the motion corresponds to a vehicle speed of 7 km/h. The nominal contact pressure was 1.2 MPa, which is considered typical for light braking sequences that serve to reduce the speed of the vehicle but not bring it to a full stop. The samples were in contact for 60 minutes and the corresponding sliding distance was 2 520 m. The temperature and the relative humidity in climate chamber were not actively controlled and the ambient air temperature varied between 23 to 25°C and the relative air humidity varied between 35 to 55%. Three individual tests were run for each material combination.
Table 1 Material combinations

<table>
<thead>
<tr>
<th>ID</th>
<th>Disc sample material</th>
<th>Pin sample material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gray Cast Iron (Front)</td>
<td>Textar T4139 (Low Metal lining material for the European market)</td>
</tr>
<tr>
<td>2</td>
<td>Gray Cast Iron (Front)</td>
<td>Ferodo FE4432 (Low Metal lining material for the European market)</td>
</tr>
<tr>
<td>3</td>
<td>Gray Cast Iron (Front)</td>
<td>Akebono NS308H (NAO lining material for the U.S. market)</td>
</tr>
<tr>
<td>4</td>
<td>Gray Cast Iron (Front)</td>
<td>Akebono NS309H (NAO lining material for the U.S. market)</td>
</tr>
<tr>
<td>1</td>
<td>Gray Cast Iron (Rear)</td>
<td>Galfer G4656 (Low Metal lining material for the European market)</td>
</tr>
<tr>
<td>2</td>
<td>Gray Cast Iron (Rear)</td>
<td>Textar T4140 (Low Metal lining material for the European market)</td>
</tr>
<tr>
<td>3</td>
<td>Gray Cast Iron (Rear)</td>
<td>Akebono NS530H (NAO lining material for the U.S. market)</td>
</tr>
<tr>
<td>4</td>
<td>Gray Cast Iron (Rear)</td>
<td>Akebono NS308H (NAO lining material for the U.S. market)</td>
</tr>
</tbody>
</table>

Figure 2 Test samples manufactured from brake pad and rotor
5 Result

Typical time history curves showing the measure coefficient of friction and normal displacement of the level arm are shown in the two upper graphs in Figure 3 and Figure 5. The corresponding particle concentration curves are presented in the two lower graphs in Figure 3 and Figure 5, and in the two upper graphs in Figure 4 and Figure 6. The concentrations measured with GRIMM instrument have been divided into two curves. The first curve shows the concentration of particles smaller than 1 μm, i.e. the same measurement range that is registered by the P-Trak instrument. The second curve shows particles larger than 1 μm, and can be compared with the DustTrak concentrations.

Figure 4 and Figure 6 shows typical size distributions on the size interval 0.1 μm to 32 μm measured with the GRIMM instrument. The corresponding size distributions measured with the SMPS instrument on the size interval 10 nm to 1 μm are shown in Figure 7 and Figure 8. For both instrument the volume distributions is presented in addition to the measured number distribution. The volume distribution has been computed under the assumption that all particles are spherical. The distribution curves have been normalized with the mean particle concentration during the test.

The mean value of the coefficient of friction in the different tests is presented in Figure 9 and Figure 12.

The measured wear during the individual tests is compared Figure 10 and Figure 13 in terms of displacement of the level arm at the end of the test and mass losses of the test samples. No result was obtained from the displacement measurement during the third test with the NS309H material.

The particle concentrations measured with the different instruments during the individual tests are compared in Figure 11 and Figure 14. Note that the DustTrak instrument was not connected during the first test with the T4139 material and SMPS instrument was not connected during the second test with the Galfer 4656 and NS308H materials.
Figure 3 Typical curves presenting the measured coefficient of friction, normal displacement of level arm and particle concentrations in tests with front brake materials.
Figure 4 Typical curves presenting the particle concentrations and size distributions, measured with the GRIMM instrument during tests with front brake materials.
Figure 5 Typical curves presenting the measured coefficient of friction, normal displacement of level arm and particle concentrations in tests with rear brake materials
Figure 6 Typical curves presenting the particle concentrations and size distributions, measured with the GRIMM instrument during tests with rear brake materials.
Figure 7 Typical number distributions for front brake linings measured with the SMPS instrument

Figure 8 Typical number distributions for rear brake linings measured with the SMPS instrument
Figure 9 Mean values of coefficient of friction in tests with front brake material

Figure 10 Wear measured in terms of total displacement of level arm (top) and mass loss of test samples (middle and bottom) at end of tests with front brake materials
Figure 11 Mean values of particle concentrations measured with PTrak, DustTrak, GRIMM and SMPS during tests with front brake materials
Figure 12 Mean values of coefficient of friction in tests with rear brake linings

Figure 13 Wear measured in terms of total displacement of level arm (top) and mass loss of test samples (middle and bottom) at end of tests with rear brake materials
Figure 14 Mean values of particle concentrations measured with PTrak, DustTrak, GRIMM and SMPS during tests with rear brake materials
6 Discussion

Overall the tests with low metallic lining materials distinguished themselves with higher coefficient of friction, amount of wear and particle concentrations. The only exception was the T4140 material, which behaved similar to the NAO materials.

The NAO linings showed a stable coefficient of friction reaching a steady state level after just a few minutes, where as the low metal linings showed an increasing coefficient of friction throughout the major part of the test. Regarding the wear characteristic, the low metal linings were more aggressive to the discs, resulting in higher mass losses of both pin and disc samples than the NAO linings. Furthermore the low metal linings showed a higher variation in wear characteristics between individual tests. The same variations could be seen in particle concentrations. In most cases a high amount of wear corresponds to high concentrations of airborne particles. The FE4432 material showed the highest amount of wear and particles concentrations among the tested front brake material, whereas the Galfer 4656 material had the highest values of the rear brake materials. The FE4432 material seemed to generate much higher concentrations of particles smaller than 520 nm than the other materials.

Although there were variations in the measured particle concentrations, similar size distributions were obtained regardless of lining material. The number distributions measured with the SMPS instrument showed a dominating peak at a particle size of about 100 nm, whereas the corresponding GRIMM distributions showed a dominating peak at a particle size of about 0.3 μm and two lower peaks at 0.2 μm and 0.6 μm, respectively. If we look at the volume distributions measured with the SMPS instrument we find that they have a peak at the higher limit of the measured size range. The distributions measured with the GRIMM instrument show a dominating peak at a particle size of 3 μm. One possible explanation to why the size distributions are similar could be that the major part of the airborne particles originates from the disc material. One way of investigate this would be to collect particles on filter and analyze their chemical composition to determine if there are originated from the rotor or the lining material.

In this work the tests conditions were set up to simulate urban traffic conditions. Limitations in the pin on disc machine did not make it possible to increase the sliding velocity above 0.7 m/s, which corresponds to a vehicle speed of only 7 km/h. The nominal contact pressure was 1.2 MPa, which is considered typical for light braking sequences that serve to reduce the speed of the vehicle but not bring it to a full stop. Since the experimental set up has proven to be useful, it would be of interest to conduct tests at higher load levels to investigate the effects on the airborne wear particle emissions. Temperature measurement could also be included in the experimental set up by preparing all pin samples with a thermocouple.
7 Conclusions

The following conclusions can be drawn from this work:

- The experimental setup that can be used to gain information about airborne wear particles of different combinations of lining and rotor materials.

- The low metallic linings showed to be more aggressive than the NAO linings, distinguish themselves by higher amount of wear and concentrations of airborne wear particles. They also show a higher variation between individual test runs with the same material combinations.

- Although there are variations in the measured particle concentrations, similar size distributions are obtained regardless of lining material.
8 References


Result from tests with front brake material
T4139: Friction, Displacement, PTrak and DustTrak

![Coefficient of friction graph](image)

![Normal Displacement graph](image)

![PTrak graph](image)

![DustTrak graph](image)
T4139: GRIMM

GRIMM: 0.25 \mu m < D < 1 \mu m

GRIMM: 1 \mu m < D < 32 \mu m

GRIMM: Number distribution

GRIMM: Volume distribution
T4139: SMPS

**SMPS: Number distribution**

- Test 1
- Test 2
- Test 3

**SMPS: Volume distribution**

- Test 1
- Test 2
- Test 3
FE4432: Friction, Displacement, PTrak and DustTrak
FE4432: GRIMM

GRIMM: 0.25 μm < D ≤ 1 μm

GRIMM: 1 μm < D ≤ 32 μm

GRIMM: Number distribution

GRIMM: Volume distribution
FE4432: SMPS

SMPS: Number distribution

SMPS: Volume distribution
NS308H: Friction, Displacement, PTrak and DustTrak
NS308H: SMPS

SMPS: Number distribution

SMPS: Volume distribution
NS309H: Friction, Displacement, PTrak and DustTrak
NS309H: GRIMM

GRIMM: 0.25 \( \mu m \) < \( D \) < 1 \( \mu m \)

GRIMM: 1 \( \mu m \) < \( D \) < 32 \( \mu m \)

GRIMM: Number distribution

GRIMM: Volume distribution
NS309H: SMPS
Result from tests with rear brake material
G4665: Friction, Displacement, PTrak and DustTrak

![Graphs showing Coefficient of friction, Normal Displacement, PTrak, and DustTrak over time for different tests.](image-url)
G4665: GRIMM

GRIMM: 0.25 μm <D≤ 1 μm

GRIMM: 1 μm <D≤ 32 μm

GRIMM: Number distribution

GRIMM: Volume distribution
G4665: SMPS

SMPS: Number distribution

SMPS: Volume distribution
T4140: Friction, Displacement, PTrak and DustTrak
T4140: GRIMM

GRIMM: 0.25 μm < D < 1 μm

GRIMM: 1 μm < D < 32 μm

GRIMM: Number distribution

GRIMM: Volume distribution
T4140: SMPS

**SMPS: Number distribution**

**SMPS: Volume distribution**
NS530H: Friction, Displacement, PTrak and DustTrak
NS530H: SMPS

SMPS: Number distribution

SMPS: Volume distribution
NS308H: Friction, Displacement, PTrak and DustTrak

Coefficient of friction

Normal Displacement

PT-Trak

DustTrak
NS308H: GRIMM

GRIMM: $0.25 \mu m < D \leq 1 \mu m$

GRIMM: $1 \mu m < D \leq 32 \mu m$

GRIMM: Number distribution

GRIMM: Volume distribution
NS308H: SMPS

**SMPS: Number distribution**

**SMPS: Volume distribution**