Wear 384–385 (2017) 124–130

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

A pin-on-disc tribometer study of disc brake contact pairs with respect to wear and airborne particle emissions

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ARTICLE INFO

Keywords:
Disc brake
Emissions
Materials
Pin-on-disc
Friction
Wear
Coating

ABSTRACT

In the EU, PM_{10} from the wear of disc brakes can contribute up to 50% of the total non-exhaust emissions from road transport. The wear originates from the contact surfaces of the friction material and the disc. One possible way to decrease PM_{10} emissions is to change the materials of the contact pair in terms of composition and coatings. The wear and particle emissions of three novel friction material formulations, one novel disc formulation, one disc WC/CoCr coating realized with the HVOF technique, and one disc surface treatment realized by a nitriding process, were investigated. Pin-on-disc tests were run to rank the novel materials in terms of specific wear rate and particle number and mass rate. The results show that it is possible to achieve a reduction in particle emissions of up to 50% by changing the materials of the contact pair.

1. Introduction

Cars, trucks, airplanes and trains use disc brakes to slow down or to maintain a constant speed by transforming kinetic energy into frictional heat. Car disc brakes basically consist of a calliper with one or more pistons, a rotor, and two pads. The rotor is firmly fitted to the wheel. The brake pads are mounted inside the calliper, which is mounted on the knuckle, which is attached on the chassis. When the driver applies the brakes, the brake cylinder pressure increases and the piston pushes the pads into contact with the rotor. The friction force between the brake pads and the rotor produces a braking torque on the rotor, which is connected to the wheel, and the subsequent friction between the tire and the road makes the car slow down. During this process both the pads and rotor are worn and some of the wear will become airborne as particle emissions. Particulate matter with an aerodynamic diameter less than 10 µm (PM_{10}) from disc brakes may contribute up to 50% of the total non-exhaust emissions from road transport in the EU [1,2].

In simplified form, a typical brake pad consists of a stiff backplate to which a friction material has been bonded. The friction material consists basically of four components [3]: a binder, reinforcing fibres, fillers, and frictional additives. The binder keeps the components of the friction material together and is usually made of a polymer-based resin. The reinforcing fibres are used to give mechanical strength to the brake pad. Fillers are used to reduce cost and to control the friction material properties. Friction additives are used to control the friction and wear. Friction additives based on nanoparticles have been shown to contribute to improved wear resistance because of their positive effect on the smoothness of the friction layer and their ability to decrease the overall porosity of the final friction composite [4,5]. Geopolymers, also called synthetic stones, are products achieved by alkali activation of fired clays [6], metallurgical slags or fly ashes [7]. The resulting products usually reach the hardness of the light abrasives used in the formulation of friction materials. Geopolymers used as a partial substitute for phenolic resin have already been tested by Lee et al. [8].

Today most discs are made of cast iron. Airborne wear from these discs constitutes up to 50% of the total disc brake emissions [9], and thus decreasing their contribution to particle emissions is important. Carbon ceramic discs offer high temperature resistance and relatively low wear, but they are costly. It has already been shown that the wear rate of discs can be decreased by tuning the chemical composition of cast iron [10]. Another approach to decreasing the wear rate of cast-iron discs is to deposit a wear resistant hard layer on the friction surface of the discs [11]. Such coatings are expected to reduce wear and improve high temperature wear resistance as well as the thermal fatigue resistance of the braking system, while maintaining stable frictional properties.

The friction and wear performance of disc brakes are usually evaluated by testing. Although the full brake system could be tested under real conditions in field tests, the environment cannot be controlled, which makes it hard to make reliable particle measurements [12]. In inertia brake dynamometers the full contact pair (pad to rotor) is studied under more controlled conditions [13]. In tribometers the

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http://dx.doi.org/10.1016/j.wear.2017.05.011
Received 28 February 2017; Received in revised form 22 May 2017; Accepted 22 May 2017

contact pair is replaced by simplified geometries, which makes it possible to study novel materials early in the design process.

Pin-on-disc tribometers (POD) are frequently used in academia [14–19] to study the friction and wear behaviour of disc brake materials in a controlled environment. In these set-ups, the pad to rotor contact pair is replaced by pin and disc-shaped geometries. The pins are usually cut out of the pad, while the discs are cut from the rotor. The pin is pressed against the rotating disc with a normal load that can be applied using dead weights or hydraulics. The disc can be mounted either horizontally or vertically. The usual outputs from PODs are the coefficient of friction (COF) and the specific wear rate during steady state conditions. If the cleanness of the air surrounding the POD is controlled, it is also possible to measure the airborne wear particles generated by the contact pair [17–19].

The purpose of this paper is to investigate whether novel friction and disc materials can affect particle emissions from disc brakes. Three novel friction material formulations with friction additives based on nanostructured particles, one novel disc formulation, one disc WC/CoCr coating, and one disc treated by a nitridation process, were investigated. POD tests were run to rank the novel materials with respect to reference materials in terms of wear, and particle number and mass rate.

2. Materials

The left front disc brake of a typical medium-sized car used in the European Union is used as a reference in this study. Table 1 shows the data of the reference car and brake system. This disc brake consists of a sliding calliper, two low-met pads (F1), and a ventilated cast-iron rotor (D1).

Three novel pad friction materials (F2, F3, and F4) were developed to decrease the wear of the pads and rotor. Titanium dioxide (F2) and zinc oxide (F3) nanoparticles were embedded in the surfaces of kaolinite clay; the conceptual basis for this approach can be found in [20]. The resulting nanostructured composites were mixed into the friction formulations. The geopolymers based on alkali-activated blast furnace slag [21] were used as a light abrasive in friction material F4. The elemental composition (measured using X-ray fluorescence spectrometry) and the density (determined knowing the weight of the sample in air and in liquid of known density) for each friction material is presented in Table 2.

Three novel rotors (D2, D3, and D4) were developed in addition to the friction materials. The reference rotor (D1) and the chemically tuned rotor (D3) are made from lamellar cast iron with a density of 7100 kg/m^3. The chemical composition of D1 and D3 is shown in Table 3. Rotor D2 is high-velocity oxygen fuel (HVOF) coated with a WC-Co-Cr material [11] to reach a final thickness of approximately 70 µm and is then polished to a surface roughness R_a below 1.5 µm. The density of the D2 coating is about 15.6 g/cm^3. The bulk material of rotor D2 is the same as D1. The nitrided rotor (D4) is made by a gas nitridation process applied to a disc similar to D1. The nitridation was performed by heating at 540 °C for 4 h in a controlled gas atmosphere.

Table 1
Data of the reference car and brake system.

Front wheel load	690 kg
Wheel radius	314 mm
Rotor outer radius	139 mm
Rotor inner radius	80 mm
Rotor effective radius	113 mm
Pad surface area	5080 mm^2
Cylinder diameter	57 mm

Table 2
Elemental compositions and densities of the pad friction materials.

Element	wt. %			
	F1	F2	F3	F4
C	39.8	42.7	44.1	43.0
F	0.43	0.30	0.28	0.34
Mg	6.50	4.39	4.10	5.22
Al	7.11	6.69	6.29	6.17
Si	3.13	4.32	4.29	4.73
S	2.37	2.15	1.89	2.10
K	1.03	1.07	1.02	1.14
Ca	0.52	0.53	0.52	2.94
Ti	0.20	3.66	0.23	0.24
Cr	2.53	2.28	1.99	2.19
Fe	16.7	15.1	13.7	14.6
Cu	9.12	7.27	7.07	7.21
Zn	5.57	5.03	9.96	5.36
Mo	0.21	0.31	0.30	0.32
Sn	4.08	3.87	3.82	4.05
Density (g/cm^3)	2.75	2.82	2.88	2.73

Table 3
Elemental compositions of cast-iron discs D1 and D3.

Disc	wt. %			
	C	Si	Mn	S
D1	3.80	1.80	0.65	0.06
D3	3.75	1.45	0.65	0.08

3. Pin-on-disc tribometer

The tests were performed in a pin-on-disc tribometer with a horizontal rotating disc, using a dead weight to provide a desired nominal contact pressure on the pin. The tribometer is a conventional tribometer that was redesigned for particulate emission testing [17]. It can run with constant applied normal forces of up to 100 N and rotational speeds of up to 3000 rpm. In the tribometer the coefficient of friction was indirectly measured using an HBM® Z6FC3/20 kg load cell that gives the tangential force. The disc bulk temperature was registered using a K-type thermocouple 3 mm below the contact surface.

The mass loss of the test specimens was measured by weighing the test samples before and after the test to the nearest 0.1 mg using a Sartorius® ME614S balance. The specific wear rate for each specimen could then be determined as

$$k = \frac{\Delta m}{\rho \cdot \Delta s \cdot F_N} \tag{1}$$

where Δm is the mass loss of the specimen, ρ is the density of the specimen, Δs is the sliding distance during the test, and F_N is the normal load applied to the pin. This method enables calculation of the specific wear rate of both pin and disc.

The tribometer was placed inside a closed box to enable airborne particle measurements. The test equipment is schematically presented in Fig. 1. A fan pumps ambient air through a HEPA filter to the air inlet. The HEPA filter is of class H13 EN 1822 with a collection efficiency of 99.95% at the maximum penetrating particle size, which ensures particle-free inlet air. The inlet air velocity was measured with a TSI® air velocity transducer model 8455. The air is assumed to be well mixed inside the box due to the complex volume of the pin-on-disc tribometer and the high air exchange rate. The air inside the box transports the generated particles to the air outlet where the sampling point for the particle instruments is located. The temperature and humidity inside the box are measured but they are not controlled.

Three instruments were used to measure particle emissions. The first