DEVELOPMENT OF ENVIRONMENTAL FRIENDLY NOVEL COUNTERPART FOR AUTOMOTIVE BRAKE-PAD DISC SYSTEM

Dissertation-II

Submitted in partial fulfillment of the requirement for the award of degree

Of

Master of Technology

IN

MECHANICAL ENGINEERING

By

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CERTIFICATE

I hereby certify that the work being presented in the dissertation entitled "**DEVELOPMENT OF ENVIRONMENT FRIENDLY NOVEL COUNTERPART FOR AUTOMOTIVE BRAKE-PAD DISC SYSTEM"** submitted in partial fulfillment of the requirement of the award of the Degree of master of technology and submitted to the Department of Mechanical Engineering of Lovely Professional University, Phagwara, is an authentic record of my own work carried out under the supervision of Mr. Kamlesh Kumar Mishra (Assistant Professor) Department of Mechanical Engineering, Lovely Professional University. The matter embodied in this dissertation has not been submitted in part or full to any other University or Institute for the award of any degree.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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1. INTRODUCTION

The braking system is an indispensible part of any automobile. The term braking implies use of external force for force reduction of the vehicle which is achieved by the rubbing action of two surfaces in contact. Friction is the resistance to the motion of two bodies in contact.

The pads and linings suffer from wear when they come in contact with the brake rotor to bring vehicle to a halt. The researchers have always been interested in improving the braking efficiency throughout the history of automobile evolution. The present day automobiles are bigger, heavier and faster which further emphasizes the need to design brake rotors and pads to improve braking efficiency and thus automobile safety.

The drum brakes were widely used as the automotive braking system until the 1960's. However, drum brakes suffered from a serious limitation. Under the condition of downhill braking, drum brakes overheated as a result of which their braking efficiency reduced. Moreover, the wear rate of the brakes was also accelerated. To check this limitation, disc brakes were introduced in the automobiles in the 1960's. Due to its unique design, disc brakes were able to dissipate heat faster which resulted in reduced wear rates.

Present day automobiles, be it cars, long haul trucks or motorbikes, they all employ disc brakes at the front end of the vehicle and drum brakes at the rear end (in general).

The principle of operation of the braking system is converting the kinetic energy of moving vehicle into heat (frictional) while retarding the motion of the automobile.

The disc rotor is fitted and revolves with the front wheels of the vehicle. The brake fluid is crucial in the operation of the disc brakes. The brake pads, which directly come in contact with the revolving brake rotor when the driver pushes the brake pedal, is required to have high coefficient of friction in order to have high braking efficiency. Two brake pads are fitted in a housing further mounted on the chassis of the vehicle.

When the pedal is pressed, the brake fluid is compressed which leads to increase in pressure of the brake fluid inside the brake cylinder. The resultant action is the brake pads coming in contact with the revolving brake rotor. The frictional resistance of the pads coming in contact with the brake rotor results in braking torque acting on the rotor. As the rotor is firmly mounted on the front wheels of the vehicle, this leads to retardation of the motion of the vehicle.

The pads are essential components of all the automotive braking systems using disc brakes. The pads consist of a steel plate upon which friction material is bound on the side coming in contact with the revolving brake rotor.

The braking efficiency is significantly impacted by the friction material which constitutes the brake pads alongside microstructure of the friction material. Some of the constituents frequently found in brake pads are ceramics, fibers, elastomers, metallic chips and solid lubricants.

One of the prime requirements of any brake rotor material is reliable, stable coefficient of friction over the entire range of operating conditions such as manner of application of brakes, humidity and temperature.

Automobiles have been identified as the major source of particulate emissions, especially in metropolitan cities. The vehicular emissions can be broadly classified into exhaust and non exhaust, both contributing equally to particulate emission [1]. Brake wear is identified as major source of non exhaust vehicular emission with minor contributions from tyres, road surface and clutch in regions of high automobile traffic density. As automobile brake wear is the primary contributor of non exhaust vehicular pollution, it needs to be regulated.

However, the braking system is an indispensible part of any automobile. Braking is primarily achieved by rubbing action of two surfaces in contact which produce friction. Brake pads are the consumables which are placed in contact with the automotive brake rotor to bring the vehicle to a halt, when external force is applied. The researchers have always been interested in improving the braking efficiency throughout the history of automobile evolution. The present day automobiles are bigger, heavier and faster which further emphasizes the need to design the braking system in such a way that improves the braking efficiency and is environment friendly. The drum brakes were widely used in the automobile braking system till the 1960's. However, under the condition of downhill braking, drum brakes overheated, as a result of which the braking efficiency reduced. Wear rate of the brakes was also increased. The disc brakes were introduced in the front wheels of the automobiles and due to its unique design disc brakes were able to dissipate heat faster resulting in reduced wear rates [2]. Present day automobiles, be it cars, long haul trucks or motorbikes, employ disc brakes in front wheels and drum brakes in the rear wheels (in general). The kinetic energy of the moving vehicle is converted into heat (frictional) which is further dissipated quickly, as the disc brakes are well ventilated. The brake pads which come in contact with revolving brake rotor, when the driver presses the brake pedal, are required to have high coefficient of friction in order to have high braking efficiency. Coming in contact with the brake rotor leads to a resultant braking torque acting on the rotor which is firmly attached to front wheels of the vehicle leading to retardation of motion of vehicle [3].

Friction materials (fibers, ceramics, elastomers, metallic chips and solid lubricants) are applied to brake pads to improve braking efficiency by stabilizing coefficient of friction over operating conditions such as manner of application of brakes, humidity and temperature [4].

Due to low cost of production, ease of fabrication, grey cast iron is the most widely used material for manufacture of automotive brake rotors. The composition of grey cast iron is as under:

S.no	Name of constituent element	% (by weight)
1	Carbon	3.4
2	Silicon	1.8
3	Manganese	0.5
4	Iron	Balance

Table – 1 Chemical composition of Grey Cast Iron

However research in the field of novel materials for automotive brake rotors is still ongoing. The disc rotors manufactured from grey cast iron undergo a change in their microstructure while in operation due to exposure exposure to fluctuating temperature and coefficient of friction. The microstructural changes in brake rotor material have a significant impact on the braking efficiency and wear emissions [5].

The problem of suspended fine debris suspended in the atmosphere needs to be tackled in order to negate their harmful effects on human health along with environmental degradation. It is because of this reason that novel environmental friendly techniques must be developed to reduce wear debris suspended in the atmosphere. In the present study it is proposed to analyse the effect of surface modification techniques on automotive brake rotors especially on particulate emissions and microstructure of the disc surface after wear. As the brake disc is counterpart of brake pad, its surface modification is expected to alter the wear emissions from automotive brake pad- disc assembly.

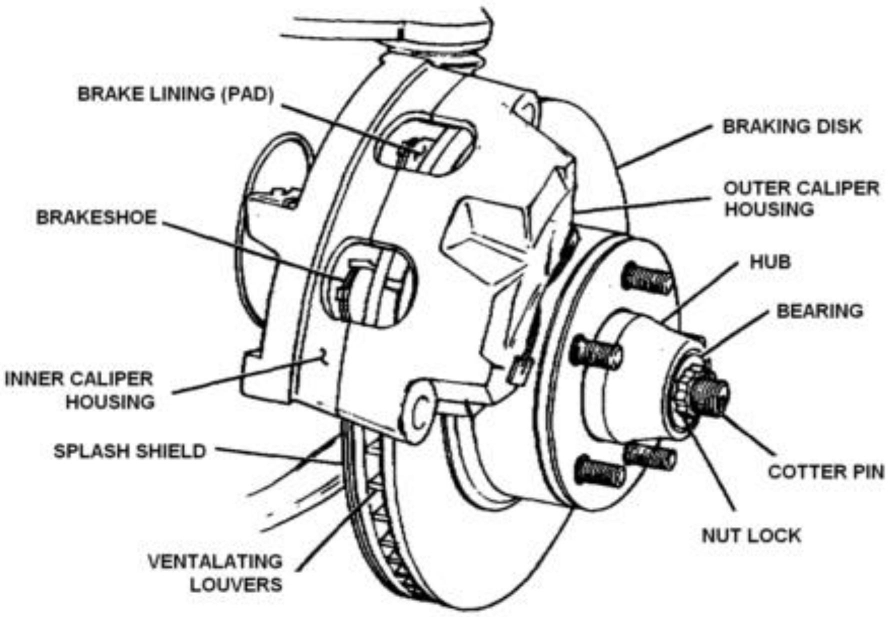

Figure 1- Automotive brake pad-disc assembly

2. REVIEW OF LITERATURE:

Particulate matter emissions from automotive brake wear adversely affect the atmosphere especially in regions of high traffic density. Contribution from exhaust and non-exhaust sources of vehicular emissions is reported to be approximately equal. Technological advancement has resulted in significant reduction in exhaust emissions [6]. However non exhaust vehicular emission has not been investigated in depth [7]. The major source of automobile non exhaust particulate emission consists of brake wear, tyre wear, clutch and road surface wear [8]. Analysis of the wear mechanism for automobile brakes the wear particles generated as a result of frictional automotive brake wear and its adverse effects on the atmosphere was done [9],[10]. It was concluded that the wear debris was a potential source of atmospheric pollution. Further advancements in testing were required in order to serve the customers as well as the manufacturers better. Further it was analysed that the emission of wear debris suspended in the atmosphere as a result of frictional wear of automotive braking system [11]. The equipment used in the experiment was a brake dynamometer. It was concluded that the resuspended wear debris contributed significantly towards the total non-exhaust emission and must be included in the total emission measurement. Researchers had reviewed the emission of wear debris due to frictional wear of automotive brake rotor. Various factors affecting the amount of particulate matter generated as a result of automotive non exhaust wear emissions, particularly from frictional wear of automotive brake rotors on human health and environment. Various aspects of non exhaust vehicular emission particularly from frictional wear of automobile brake wear were presented.

Investigations regarding development of technology for improvement of braking efficiency have been carried out and it was reported thermal analysis of Si-Al alloy during emergency braking [12].

It was reported temperature stresses of grey cast iron brake disc [13]. It was further reported that cracking of brake system due to thermo mechanical factors [14]. The investigations regarding thermal analysis of full disc and ventilated disc brake rotors with frictional heat generation were carried out [15]. The modelling of disc brake system in frictional contact tribology was analysed in depth [16].The fatigue phenomenon of grey cast iron brake rotor at high temperature encountered during application of brakes of automobiles was analysed [17]. It was reported that mechanical properties remained constant up to a particular temperature range and declined suddenly after exceeding a certain temperature (700^{o}C). The tests on a pin on disc tribotester for impact of frictional material sliding against grey cast iron automotive brake rotor were conducted [18]. Heat treatment was reported to reduce the wear of both brake disc and brake pads.

The analysis the surface of automobile brake rotors was done [19]. The chemical composition and microstructure of the disc surface was compared for contact and non contact region of the brake rotor. It was observed that high temperatures encountered during operation of automotive brakes can cause changes in the microstructure of surface of the brake rotor.

As present day automobiles are bigger, heavier and faster, improvement in design of brake pad disc assembly and application of friction material to improve braking efficiency and reducing wear emissions have been reported. The characterization of the wear debris produced as a result of frictional wear of automotive brakes for conventional and unconventional brake pad friction materials was done [20]. The tests were carried out on a subscale disc brake testing apparatus. It was concluded that characteristics of wear debris produced were significantly different for different friction materials and are also related to different wear modes and changes in the surface of the disc brake counterparts. Study of the wear debris produced as a result of frictional wear of automotive brakes was carried out [21]. Study included dynamometer testing, vehicular field tests, size and chemical composition. It was reported that the wear debris suspended in the atmosphere and the debris sticking to the automotive braking assembly are similar. [22] Analysed the automotive brake rotor with reference to residual stresses. It was reported that due to strain gradient (tensile), which was present throughout the disc thickness, brake rotor is bent away from the hub of the wheel. [23] Studied the interface of the brake pad – disc contact region. The designed model provided data on the crack propagation at the surface of the cast iron brake rotor and the plastic region at the contact region of the brake pad-disc contact region. [24] Studied the third body behaviour while in operation and compared the results of experiments with modelling. It was concluded that compact layer of worn out powder due to frictional wear of automotive braking system and the powder particles trapped between brake rotors and brake pads have almost same coefficient of friction and sliding characteristics. [25] Studied effect of low metallic friction material on wear while sliding against a cast iron disc. Tests were conducted on pin on disc tribotester. It was reported that a limited third body was formed on the friction layer and an oxide layer was observed on the wear track of cast iron.

Brake wear particles (particulate matter) comprises of solid and semisolid suspended particles of varying sizes. [26] Reported scanning electron microscopy (SEM) image of the brake wear particles of varying sizes generated as a result of tribological tests performed in the laboratory. The prime debris is suspended directly into the environment and the secondary wear debris formed by chemical reactions while being suspended in the atmosphere.

The research results are well established for the relation between adverse human health effects and the particulate matter (PM) concentration in the atmosphere. Researchers have found that particle size of the automotive brake wear debris is a crucial factor which directly impacts the respiratory tract, affecting human health adversely [27], [28]. While most coarse particles have are deposited in the nose and throat, smaller wear debris (micro and nano sized) can penetrate deep into lungs. This can lead to inflammation, formation of free radicals in human body cells which can damage the DNA due to oxidative stress [29]. Metal contact (especially heavy metals) can have significant toxic effect on human health. Different coatings and solid lubricants on the brake pads have been reported to improve wear resistance of brake pads. Generally brake pads have complex composition containing more than 30 different components out of which, some are more hazardous than others. [30] Reported effect of antimony trisulphide and zirconium silicate friction on brake pads. Friction characteristics were studied [31]. [32] Studied the tribological properties of solid lubricants for brake pads friction lining. The properties were determined using a brake dynamometer. It was concluded from results obtained that brake pads containing tin and graphite improved fade resistance and stability of coefficient of friction with use solid lubricants. The phenomenon of fade was also subdivided.

The test equipment used was scale dynamometer for friction tests. [33] Studied the wear behaviour of ceramic coating which were sprayed thermally onto automotive brake counterparts. The results indicated that at low rpm,the toughest coating (alumina) exhibited the greatest wear resistance while other coatings such as titanium oxide alloys showed higher wear rates and instability of coefficient of friction. [34] Designed a new testing method to study the concentration and size of wear debris suspended into atmosphere as a result of friction of automobile brakes. The test equipment was a pin on disc tribotester. It was reported that non asbestos organic (NAO) brake pads caused less wear to brake discs as compared to low metallic brake pads.

[35] Studied the braking efficiency of environment friendly brake pad friction material without antimony, copper, tin and lead. The thermal analysis and coefficient of novel brake pad material was performed using energy dispersive microanalysis and SEM. It was suggested that new environment friendly brake pad material are best replacements for the present brake pad friction material. Researchers investigated the braking efficiency of coated light weight brake discs and compared results with performance of grey cast iron brake disc coating method for braking rotor was plasma electrolytic oxidation (PEO). It was reported that out of all materials available, PEO coated aluminium alloys when used for the manufacture of automobile brake rotors offered the best braking efficiency in terms of stable coefficient of friction and microstructural stability. It was further analysed that the braking efficiency and non exhaust wear emissions from automotive braking system for semi-metallic brake pad friction material. The wear debris was tested using brake dynamometer. It was reported that the wear debris generated as a result of frictional wear of automotive brakes showed resembling chemistry as observed for the friction layer developed while under operation. It was also reviewed that the use of copper as friction material in automotive brake pad and related environmental impact. It was observed that absence of copper in brake pad friction material makes the formation of friction layer more difficult which in turn leads to increased wear rates and increased non exhaust vehicular emissions particularly from frictional wear of automobile braking system.

3. RESEARCH OBJECTIVES:

- The development of novel experimental technique to affect size and concentration of wear debris generated due to frictional wear.
- To characterise the surface microstructure after wear of disc.
- To record the effect of the coating on the test disc for coefficient of friction (fading) and the amount of wear debris generated.

4. SCOPE OF STUDY:

The present work attempts to control the non exhaust vehicular emission due to frictional wear by novel approach of coating the wear disc surface.

As the disc- brake pad assembly wear contributes to particulate matter suspended in air, the coating of counterpart of brake pads is expected to reduce wear and hence improve the quality of air especially in metropolitan cities.

5. MATERIAL AND RESEARCH METHODOLOGY:

With an objective of reducing non exhaust wear emissions from automotive brake assembly, particularly of epoxy/polyester hybrid powder coating was tested on pin-on-disc in a rotatory tribological tester. The powder contained a standard type 3 Bisphenol A epoxy resin and a high reactivity carboxyl terminated polyester resin with an acid number range of 35-45. The powder coating is prepared by shaking together the ingredients under specific conditions. After mixing, the resin blends are passed through a lab scale of 80 mm extruder. The formulations are given in phr (parts per hundred resin where mass of resin (epoxy+ polyester) totals 100. The epoxy polyester hybrid powder coating usually contains catalysts that speed up the curing process or lower the curing temperature.

Figure 2 – Uncoated and Coated disc after Tribological testing.

The epoxy/polyester hybrid powder was procured from Varna Coats Pvt Ltd Bangaluru. The standard EN31 wear disc was procured from DUCOM Instruments Pvt Ltd Bangaluru. EN31 is an excellent high carbon alloy steel (C – 0.9-1.20%, Si – 0.10-0.35%, Mn – 0.3-0.75%, S – 0.050% max,P – 0.050 % max and Cr – 1.00- 1.60%). It has high measure of toughness with compressive strength and abrasion resistance. Its well balanced alloy composition renders it suitable for testing resistance

The standard test disc for wear and friction monitor had the following specifications:

I. Diameter – 165 mm
II. Thickness – 8 mm
III. Hardness – 62 HRC

After chemical cleaning of the test disc, 10 mg coating powder was sprayed over the disc using GEMA powder spray gun which is operated at 100 kV. The gun imparts a positive electric charge to the powder, which is then sprayed towards the object by mechanical or compressed spraying and accelerated towards the object by electrostatic charge. The object is then heated and powder is then thermoset that becomes hard on cooling. Powder coating is a type of coating that is applied as a free flowing dry powder electrostatically and is then cured at 180^{o}C for 1 hour. When a thermoset powder is exposed to elevated to, it begins to melt, flows out and then chemically reacts to form a higher molecular weight polymer in a network like structure. This cure process is called cross linking which requires a certain temperature for a certain period of time.

During the curing process, the coating flows and forms a skin after coat which is further oven dried. The disc is then further cooled through a fan dryer for 30 minutes.

The advantages of powder coating are as under:

1. As no solvent carrier is involved, no volatile organic compounds are released into the atmosphere.
2. Powder coating produces thicker coatings then conventional liquid coatings without sagging or running.
3. Powder coated items generally have fewer appearance differences between horizontally coated and vertically coated surfaces than liquid coated items.

For measuring the friction and wear characteristics of coated and uncoated test disc, following test specifications were set on Wear and Friction Monitor of the tribological tester.

Sno.	Description	Details
1	Speed (rpm)	500
2	Load (N)	100
3	Wear Track Diameter (mm)	50
4	Sliding speed (m/sec)	1.39
5	Preset timer (min)	20
6	Pin size (mm)	8
7	Wear disc	EN31
8	Chamber Temperature	Ambient Temperature

Table 2 – Test rig specifications for friction and wear tests.

Main instrument was connected to lubrication module and environment chamber. The general operating procedure is as under:

1. Power input cable was connected to 230 V, 50 Hz and 16 amp power supply. Controller was switched on and 5 minutes time was allowed to normalize the electronic devices.
2. Specimen pins were thoroughly cleaned, and burs were removed from the circumference, using the paper.
3. After clamping the wear disc on holder after thorough cleaning with solvent. With thorough cleaning with solvent. With the help of the dial indicator and magnetic base clamp disc within 10 micron runout, 4 opposite Allen screws were tightened sequentially, while observing the wobble with a dial gauge. Wobble was within ±5 micrometer.
4. Specimen pin was inserted inside hardened Jaws and tightened to specific holder. Height of specimen pin was adjusted above the wear disc using height adjustment block that ensured the loading arm was always parallel. Then height adjustment block was swivelled away from loading arm.

5. LVDT (Linear Variable Differential Transformer) lock screw was loosened; thumb screw was rotated to bring the LVDT plunger visually to mid position. The wear reading display on the controller was set at 0 by pressing zero push button on controller.
6. Frictional force display was set at 0
7. 10 minutes time was set on controller. Test start button was pressed and rotated. RPM knob was set on controller in clockwise direction till required test speed was displayed. Run was controlled for specific time.
8. Data acquisition cable was connected from controller to PC. Software used was winducom 2010 and the required test parameters are displayed both on controller and on PC screen.

The amount of wear generated depends on the applied load, sliding speed, sliding distance and material properties. For getting reliable and repeatable wear data, contact between wear disc and specimen pin has to be 100% and virgin material of specimen pin is to be exposed to the wear disc. Due to the surface roughness foreign material present in the specimen pin surface initially wear rate is not uniform. This initially period is known as break-in period during which surface roughness and foreign material is done away with. Once the surface is smoothened out and foreign material is removed, complete contact between the wear disc and the specimen pin is established. Wear rate at this stage is the true wear rate of the specimen under operating conditions. Due to friction between specimen pin and wear disc, heat is generated at the tip of the specimen pin. With heavy load, specimen tip may become soft and seizure may occur.

Wear characteristics are also affected by interference from thermal expansion and contraction and wear debris transfer film in the gap.

The reproducibility of repeated tests on the same material depends on the material homogeneity, material interaction and adherence to experimental conditions. Top and bottom plate should be placed between the collet holder depending on specimen diameter, position and the respective hole of fixture below the collet. Two screws should be tightened manually to retain the fixture. M4 screws should be tightened from top of collet, to push the specimen pin down.

The wear of specimen is not always taken as actual wear. To calculate actual wear, mass loss method is used. Specimen is weighed before and after test on highly accurate weight balance having least count of 0.0001 mg.

Sliding distance in meters = $\pi DNT/60000$

Here,

$\Pi = 3.142$

D = diameter of wear track

N = Disc speed in rpm

T = Test duration in seconds

To determine the microstructure, stability of coated wear disc, Scanning Electron Microscope images of coated wear disc before and after wear test on pin on disc setup along with XRD analysis was conducted at IIT Roorkee. The investigations helped in study of the surface characterisation of the test samples.

6. RESULTS AND DISCUSSION:

The uncoated test disc was clamped on wear disc holder of the rotatory Pin on Disc tribological tester. The specimen pin (8mm diameter) was adjusted above the wear disc ensuring that the loading arm was always parallel. Friction and wear displays were set at 0. Load selected was100 N, speed of the rotating disc was 500 rpm. The wear track diameter was 50 mm and testing duration was 20minutes. Total wear after completion of test was 543 microns, force of friction was 22 N and coefficient of friction was 0.220 as shown in Table 3. The table shows the wear and friction test results for uncoated wear disc tested on pin on disc rotator tribotester.

Sno	Property	Reading
1	Wear (microns)	543
2	Frictional Force (N)	22
3	Coefficient of friction	0.220
4	Initial weight of test sample (gm)	4.36187
5	Final weight of test sample (gm)	4.13924
6	Weight loss (gm)	0.22263

Table 3- Wear and friction test results for uncoated standard disc specimen.

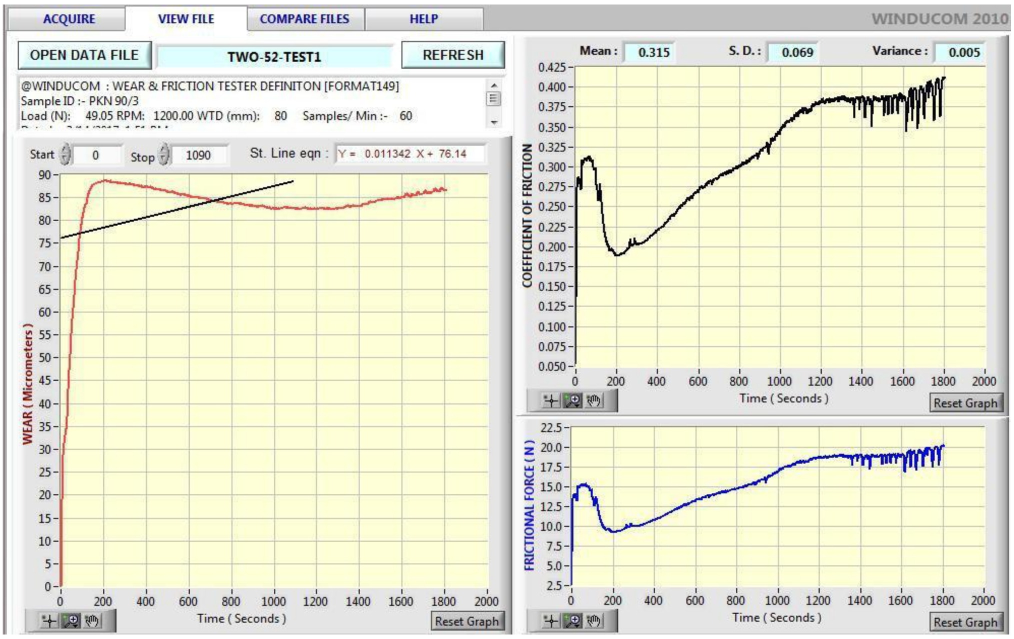

Figure 3- Wear emissions, force of friction and coefficient of friction over the test duration of 1200 seconds for uncoated standard disc specimen.

As the total wear data includes the surface wear from pin that are released during initial break in period during which the surface roughness of the pin is smoothened out and 100% contact between the test disc and the virgin material of the pin is achieved. Wear rate at this stage is the true wear rate of the test sample under operating conditions. Heat is generated at the top of the pin due to friction. Thermal expansion and the wear debris transfer film in the gap also affect the wear characteristics. Thus actual wear of the disc is calculated from the weight loss during test duration using a highly accurate weighing balance having a least count of 0.0001 mg. The weight loss of uncoated test disc was 0.22263 gm. Figure 5 describes relationship between wear emissions and time. With time wear emissions increase steadily from 5µm to 550µm.

The figure also describes force of friction and coefficient of friction during test duration of 1200 seconds. Both parameters show decline in initial 400 seconds and later both parameters remain stable during remaining test duration.

After coating the disc specimen with epoxy/polyester hybrid coating powder as described in the earlier chapter, the wear (microns) was 89, Frictional force was 14.7 N and coefficient of friction was 0.147

Sno	Property	Reading
1	Wear (microns)	89
2	Frictional force (N)	14.7
3	Coefficient of friction	0.147
4	Initial weight of the disc specimen (gm)	4.21160
5	Final weight of the disc specimen (gm)	4.21148
6	Weight loss (gm)	0.00012

Table 4- Wear and friction test results for coated standard disc specimen.

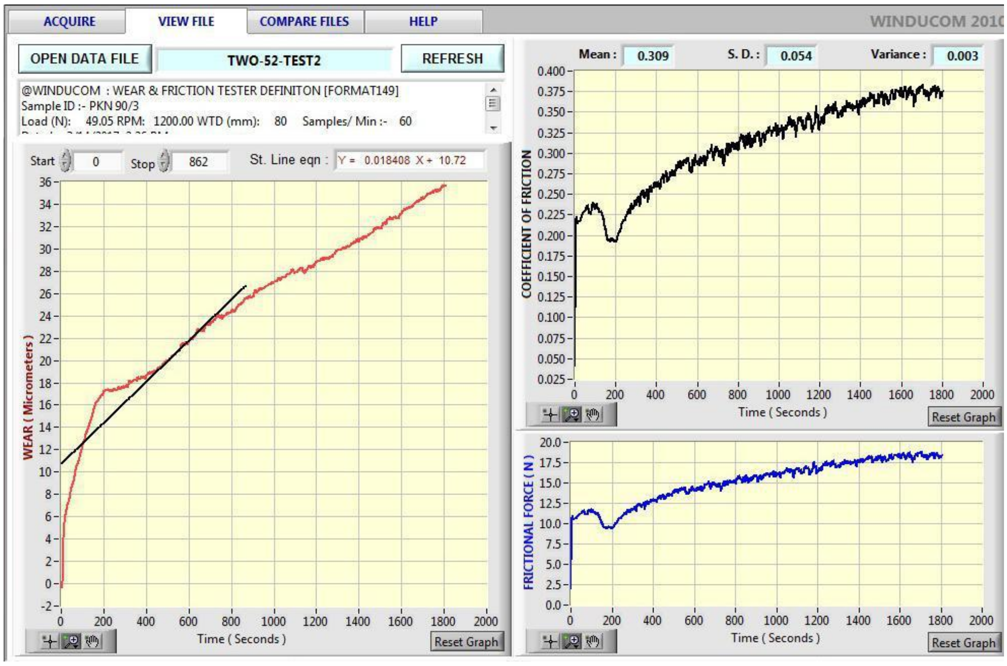

Figure 4- Wear emissions, force of friction and coefficient of friction over the test duration of 1200 seconds for coated standard disc specimen.

Wear of coated standard disc specimen was less by almost 99%than uncoated wear disc when calculated on the basis of weight loss of the wear disc under similar operating conditions. Force of friction and coefficient of friction were also decreased after coating of the wear disc (Table 4). From figure 6, it can be observed that there is an initial decline in wear which is followed by a steady increase with time. However there is a fluctuating trend of wear of coated disc specimen but the overall wear of coated disc specimen is less than the uncoated disc specimen by 83.6%. Figure 6 also describes the relationship between force of friction and coefficient of friction over the entire test duration of the coated wear disc. Both parameters show sharp increase after start of experiment for a very brief period (20 seconds). The increase is slow and steady over the next 300 seconds and thereafter both force of friction and coefficient of friction remain stabilized. Towards the end of the test duration there is an increase observed in both the parameters.

The SEM and XRD analysis of the coated and uncoated disc specimen was done in order to investigate the microstructural changes that occur while the standard disc specimen was exposed to operating conditions. The SEM images and XRD pattern for the coated and uncoated standard disc specimen are as under:

(A)

(B)

Figure 5- A- Standard disc specimen used for SEM analysis.

B- Standard disc specimen used for XRD analysis.

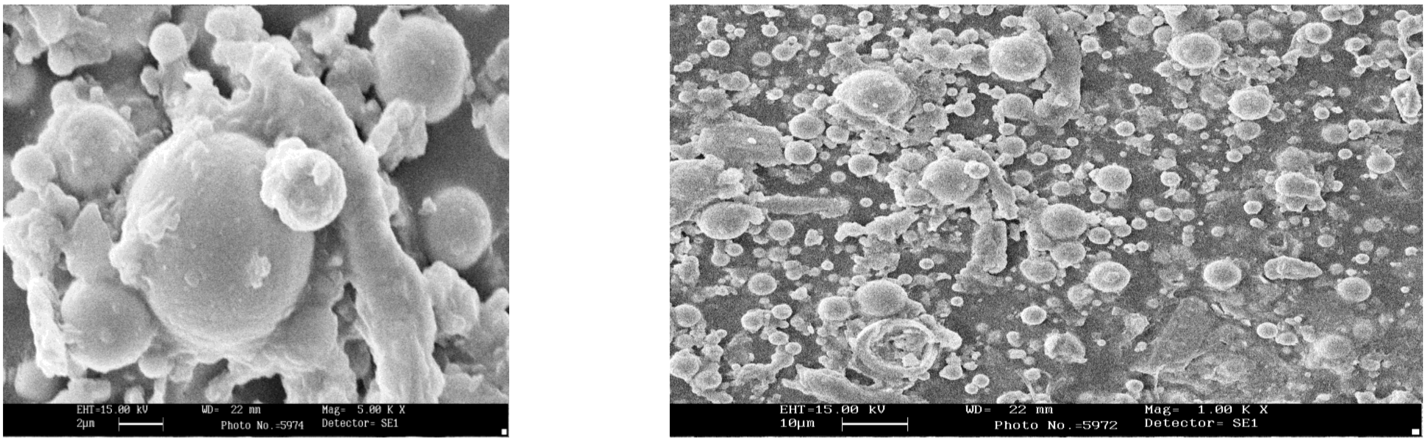

Figure 6- SEM images of the coated standard disc specimen

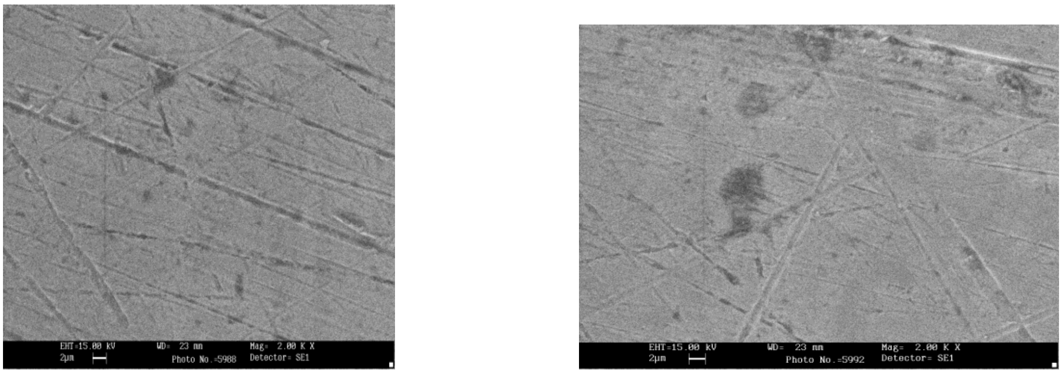

Figure 7- SEM images of the uncoated standard disc specimen

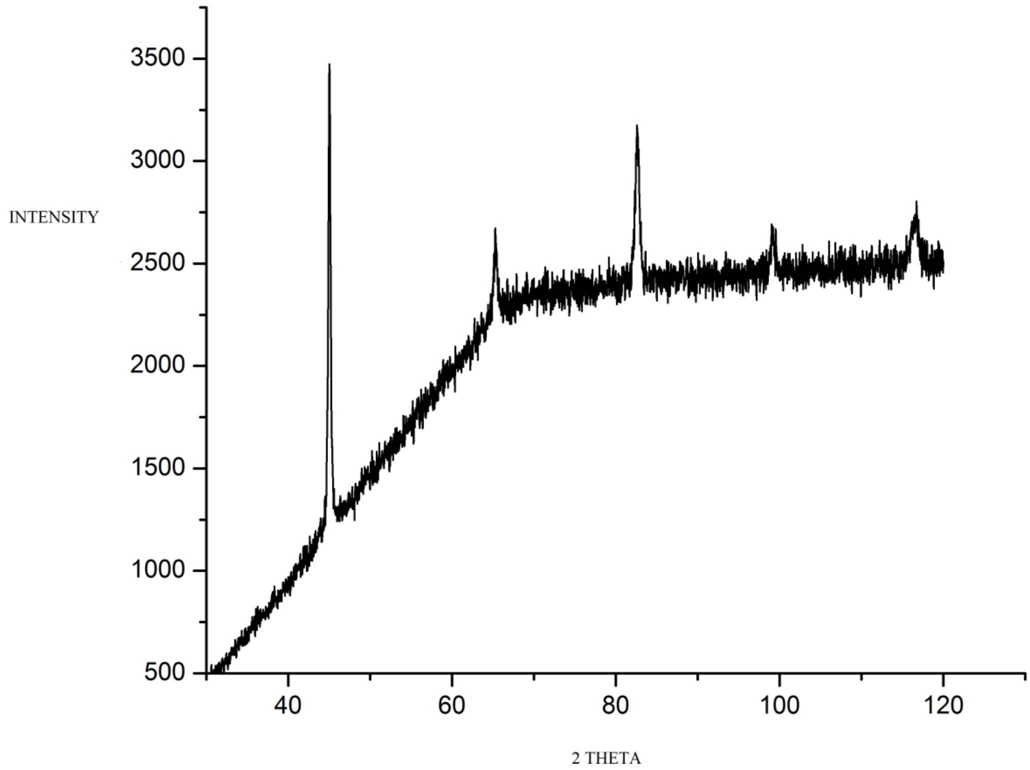

Figure 8 – XRD analysis of uncoated standard disc specimen.

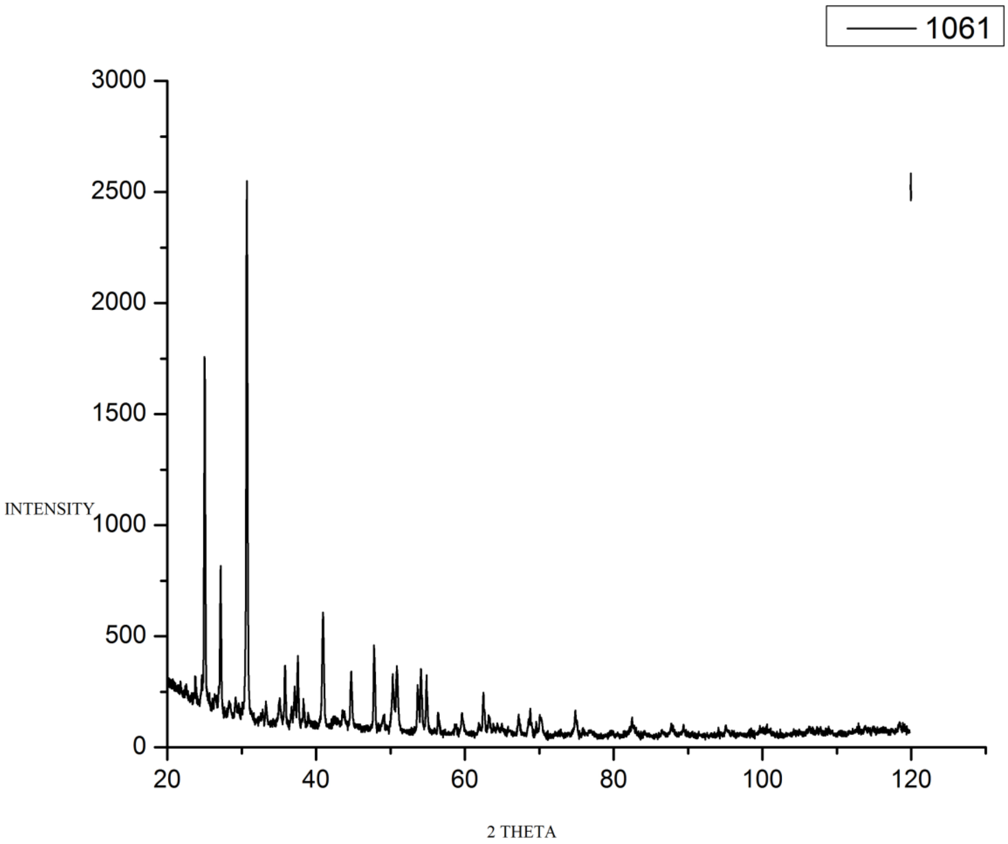

Figure 9- XRD analysis of the coated disc specimen.

The images indicate that the coating of epoxy/ polyester hybrid powder has stabilized the microstructure of the wear disc as well as little wear is visible after completion of test duration of coated wear disc. The SEM images and XRD pattern of coated disc before and after tribological testing showed stability with epoxy/ polyester hybrid powder coating.

From environmental and human health point of view, the non-metallic epoxy/polyester hybrid powder coating used in present study has reduced wear and decreased coefficient of friction when tested on pin on disc setup and can be used as an alternate coating material for automotive brake pad-disc assembly.

7. CONCLUSIONS AND FUTURE SCOPE:

1. Non metallic epoxy/polyester hybrid powder coated standard disc specimen when tested on a pin on disc rotatory tribotester reduced brake wear by 99% on the basis of weight loss of the wear disc. The coating further resulted in lowering of coefficient of friction by 33%.
2. The coating selected did not have metal constituents. Thus, chances of environmental pollution and adverse effects on human health due to non exhaust automotive brake wear debris containing metal (especially heavy metal), is removed.

Thus, when brake disc is also coated along with brake pad, with environmental friendly friction material, it may significantly reduce non exhaust wear emissions and help both customers as well as the manufacturers in reducing particulate matter specifically in the metros, provided that the braking efficiency is not affected by the selected coating.

8. REFERENCES:

1. T. Grigoratos and G. Martini, “Brake wear particle emissions: a review,” *Environ. Sci. Pollut. Res.*, vol. 22, no. 4, pp. 2491–2504, 2015.

2. D. J. Paustenbach, B. L. Finley, E. T. Lu, G. P. Brorby, and P. J. Sheehan, “Environmental And Occupational Health Hazards Associated With The Presence Of Asbestos In Brake Linings and Pads (1900 To Present): A ‘State-of-the-Art’ Review,” *J. Toxicol. Environ. Heal. Part B*, vol. 7, no. 1, pp. 25–80, 2004.

3. J. Wahlström, *A study of airborne wear particles from automotive disc brakes*. 2011.

4. P. C. Verma, R. Ciudin, A. Bonfanti, P. Aswath, G. Straffelini, and S. Gialanella, “Role of the friction layer in the high-temperature pin-on-disc study of a brake material,” *Wear*, vol. 346–347, pp. 56–65, 2016.

5. W. Österle and I. Urban, “Third body formation on brake pads and rotors,” *Tribol. Int.*, vol. 39, no. 5, pp. 401–408, 2006.

6. Y. J. Liu and R. M. Harrison, “Properties of coarse particles in the atmosphere of the United Kingdom,” *Atmos. Environ.*, vol. 45, no. 19, pp. 3267–3276, 2011.

7. Denier Van der Gon H, Gerlofs-Nijland M, Gehrig R, Gustafsson M,Janssen N, Harrison R, Hulskotte J, Johansson C, Jozwicka M,Keuken M, Krijgsheld K, Ntziachristos L, Riediker M, Cassee F(2013) The policy relevance of wear emissions from road transport,now and in the future—an international workshop report and consensusstatement. J Air Waste Manag Assoc 63:136–149

8. Abu-Allaban M, Gillies JA, Gertler AW, Clayton R, Proffitt D (2003)Tailpipe, resuspended road dust, and brake-wear emission factorsfrom on-road vehicles. Atmos Environ 37:5283–5293

9. Amato F, Pandolfi M, Escrig A, Querol X, Alastuey A, Pay J, Perez N,Hopke PK (2009) Quantifying road dust resuspension in urbanenvironment by multilinear engine: a comparison with PMF2.Atmos Environ 43:2770–2780

10. J. Kukutschová *et al.*, “Wear performance and wear debris of semimetallic automotive brake materials,” *Wear*, vol. 268, no. 1, pp. 86–93, 2010.

11. H. Hagino, M. Oyama, and S. Sasaki, “Airborne brake wear particle emission due to braking and accelerating,” *Wear*, vol. 334–335, pp. 44–48, 2015.

12. Harper, G. A. 1997. *Brakes and friction materials: The history and development of the technologies*. Bury St. Edmunds: Mechanical Engineering.

13. M. Bouchetara, A. Belhocine, M. Nouby, D. C. Barton, and A. Bakar, “Thermal analysis of ventilated and full disc brake rotors with frictional heat generation,” *Appl. Comput. Mech.*, vol. Volume 8, p. pp 5–24, 2014.

14. S. W. Kim, D. Z. Segu, and S. S. Kim, “The thermo-mechanical cracking analysis of break system,” *Procedia Eng.*, vol. 68, pp. 586–592, 2013.

15. M. Bouchetara, A. Belhocine, M. Nouby, D. C. Barton, and A. Bakar, “Thermal analysis of ventilated and full disc brake rotors with frictional heat generation,” Appl. Comput. Mech. pp 5–24, 2014.Vol 8, pp 5-24,2014.

16. A. Belhocine and M. B. A.R. Abu Bakar b, “Numerical Modeling of Disc Brake System in Frictional Contact Tribology in Industry,” vol. 36, no. 1, pp. 49–66, 2014.

17. M. Pevec, G. Oder, I. Potrč, and M. Šraml, “Elevated temperature low cycle fatigue of grey cast iron used for automotive brake discs,” *Eng. Fail. Anal.*, vol. 42, pp. 221–230, 2014.

18. G. Straffelini, S. Verlinski, P. C. Verma, G. Valota, and S. Gialanella, “Wear and Contact Temperature Evolution in Pin-on-Disc Tribotesting of Low-Metallic Friction Material Sliding Against Pearlitic Cast Iron,” *Tribol. Lett.*, vol. 62, no. 3, 2016.

19. Š. Eva, R. Pavla, P. Ivana, P. Martin, F. Jan, and S. Oldřich, “ANALYSIS OF THE SURFACE LAYER OF THE BRAKE DISK,” pp. 2–7, 2015.

20. P. J. Blau and H. M. Meyer, “Characteristics of wear particles produced during friction tests of conventional and unconventional disc brake materials,” *Wear*, vol. 255, no. 7–12, pp. 1261–1269, 2003.

21. P. G. Sanders, N. Xu, T. M. Dalka, and M. M. Maricq, “Airborne brake wear debris: Size distributions, composition, and a comparison of dynamometer and vehicle tests,” *Environ. Sci. Technol.*, vol. 37, no. 18, pp. 4060–4069, 2003.

22. M. I. Ripley and O. Kirstein, “Residual stresses in a cast iron automotive brake disc rotor,” *Phys. B Condens. Matter*, vol. 385–386 I, pp. 604–606, 2006.

23. A. I. Dmitriev and W. Österle, “Modeling of brake pad-disc interface with emphasis to dynamics and deformation of structures,” *Tribol. Int.*, vol. 43, no. 4, pp. 719–727, 2010.

24. I. Dmitriev, W. Österle, H. Kloß, and G. Orts-Gil, “A study of third body behaviour under dry sliding conditions. Comparison of nanoscale modelling with experiment,” *Est. J. Eng.*, vol. 18, no. 3, p. 270, 2012.

25. G. Straffelini, P. C. Verma, I. Metinoz, R. Ciudin, G. Perricone, and S. Gialanella, “Wear behavior of a low metallic friction material dry sliding against a cast iron disc: Role of the heat-treatment of the disc,” *Wear*, vol. 348–349, pp. 10–16, 2016.

26. Samet JM, Dominici F, Curriero FC, Coursac I, Zeger SL (2000) Fine particulate air pollution and mortality in 20 U.S. cities, 1987–1994. N Engl J Med 343:1742–1749

27. Pope CA, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K, Thurston GD (2002) Lung cancer, cardiopulmonary mortality, and long-termexposure to fine particulate air pollution. J Am Med Assoc 287:1132–1141

28. Karlsson HL, Nilsson L, Moller L (2005) Subway particles are more genotoxic than street particles and induce oxidative stress in cultured human lung cells. Chem Res Toxicol 18:19–23

29. H. Jang and S. J. Kim, “The effects of antimony trisulphide (Sb2S3) and zirconium silicate (ZrSiO4) in the automotive brake friction material on friction characteristics,” *Wear*, vol. 239, no. 2, pp. 229–236, 2000.

30. M. K. Stanford and V. K. Jain, “Friction and wear characteristics of hard coatings,” *Wear*, vol. 250–251, no. PART 2, pp. 990–996, 2001.

31. M. H. Cho, J. Ju, S. J. Kim, and H. Jang, “Tribological properties of solid lubricants (graphite, Sb2S3, MoS2) for automotive brake friction materials,” *Wear*, vol. 260, no. 7–8, pp. 855–860, 2006.

32. G. Bolelli, V. Cannillo, L. Lusvarghi, and T. Manfredini, “Wear behaviour of thermally sprayed ceramic oxide coatings,” *Wear*, vol. 261, no. 11–12, pp. 1298–1315, 2006.

33. J. Wahlström, A. Söderberg, L. Olander, A. Jansson, and U. Olofsson, “A pin-on-disc simulation of airborne wear particles from disc brakes,” *Wear*, vol. 268, no. 5–6, pp. 763–769, 2010.

34. R. Yun, P. Filip, and Y. Lu, “Performance and evaluation of eco-friendly brake friction materials,” *Tribol. Int.*, vol. 43, no. 11, pp. 2010–2019, 2010.

35. G. Straffelini, R. Ciudin, A. Ciotti, and S. Gialanella, “Present knowledge and perspectives on the role of copper in brake materials and related environmental issues : A critical assessment,” *Environ. Pollut.*, vol. 207, pp. 211–219, 2015.