A NEW CLASS OF VENTILATED DISC BRAKE

F.W. KIENHÖFER
University of the Witwatersrand, Johannesburg

Associate Professor at the University of the Witwatersrand. Researching brake systems, PBS and developing lightweight automotive components.

M.A. ATKINS
University of the Witwatersrand, Johannesburg

Lecturer at the University of the Witwatersrand. Researching brake disc cooling, flow visualisation using PIV and thermofluids.

T. KIM
University of the Witwatersrand, Johannesburg

Professor at the University of the Witwatersrand. Researching porous media, including thermo-physical property characterisation, thermal management during their fabrication process, and thermo-fluidic characterisation in applications.

Abstract

Most road vehicles are equipped with ventilated disc brakes to prevent overheating that causes increased disc wear and potential failure. Heavy vehicle disc brakes operate under severe conditions, due to their heavy loading and can, therefore, generate significant heat even at low vehicle speeds. We introduce a new class of ventilated disc brake - the highly porous ventilated brake disc - that significantly improves the cooling performance of the disc brake beyond currently commercially available disc brake designs. To demonstrate the superior performance of this new disc brake concept, field tests were conducted on a heavy vehicle at the Gerotek oval test track facility. Under controlled conditions, the new brake concept achieves a dramatic 30% reduction in operating surface temperature in comparison to a conventional OEM disc brake. In addition, this new disc brake concept is substantially lighter than current brake discs, with a 10% reduction in disc mass, which has significant benefits for vehicle emissions. In this presentation, a brief review on the evolution of the design development and field test results are discussed.

Keywords: Ventilated brake disc, porous media, thermal performance and characterisation, heavy vehicle safety.

1. Introduction

The braking system converts the kinetic energy of the vehicle into heat [1-2], which raises the temperature of the brake disc (or rotor) and pads (Fig. 1). Heat build-up occurs at the friction interface during braking. While a certain amount of the heat generated is absorbed by brake components such as the caliper by conduction, the majority of heat is absorbed by the disc [3-6]. This heat generation causes elevated operating surface temperatures on the brake disc and pads.

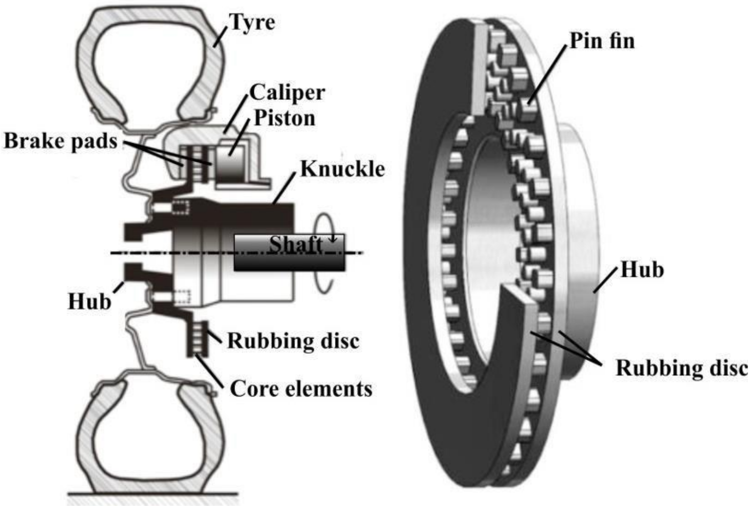


Figure 1: Conventional brake system showing brake disc with the pin finned ventilated disc configuration, pads and caliper

Brake maintenance and safety concerns are associated with heat generation and increased braking system operating temperatures. Some of these issues are (a) elevated surface temperatures (e.g., 550 °C) that have a detrimental effect on disc and pad wear [7-10], (b) brake fade (reduction of brake torque due to a temperature increase) [11-12], and (c) thermal distortion and cracking [13-15]. Mew et al. [1] demonstrated that the brake disc structure significantly affects the operating disc surface temperature, which in turn affects the wear rate of the brake components (i.e., disc and pads) [7-10]. In addition, brake fade poses a significant safety concern as it can potentially reduce brake torque by up to 25% [12]. The factors leading to brake fade, thermal distortion of the brake geometry, and boiling of the brake fluid, are directly caused by excessive disc operating temperatures. Thermal distortion and cracking are typically due to circumferential and radial thermal gradients developing within the disc during a braking event [13]. Thermal cracking is associated with a low cycle thermo-mechanical fatigue, which can be mitigated with decreased brake temperature [14].

The brake temperature is dependent on the individual brake design and the braking mode (continuous, repeated, or single stop) [15-17]. For a short single brake application, the temperature rise at the friction interface is dominated by the thermal capacity of the disc, because the rate of heat application exceeds the rate of heat dissipation. For this reason, a solid disc is expected to operate at a lower temperature during a short brake application in comparison to a ventilated disc (Fig. 1) as a typical solid disc has approximately 30% more mass than a ventilated disc. For longer brake applications, as the temperature of the disc increases, the gradient between the disc surfaces and the cooling airflow is increased, resulting in a higher rate of heat dissipation via forced convection. For continuous braking (or extended braking), the rate of heat dissipation from the disc will ultimately determine the disc temperature. As a ventilated disc has larger surface area and increased convective cooling in the ventilated channel compared to a solid disc, more heat is dissipated during continuous braking, and thus the operating temperature is lower.

Mew et al. [1] introduced a new class of lightweight ventilated brake discs, utilising a highly porous metallic open cellular core to further improve the cooling performance of ventilated disc brake systems (Fig. 2). The new ventilated brake disc is constructed by integrating a wire-woven bulk diamond (WBD) core into the ventilated channel of the brake disc. The prototype disc is 5% lighter than its OEM counterpart (enhancing lightweighting to reduce emissions) and operated at a 15% lower surface temperature when tested on a laboratory rig. The laboratory results systematically compared the two brake disc configurations under idealised conditions where (1) the discs operated in quiescent air and (2) with no obstructions from the wheel or wheel house. In this study a field test comparison of the WBD disc and OEM counterpart were conducted, which aims to confirm the improved performance of the WBD disc under more realistic operating conditions, with cross-flow and the obstructions from the wheel and wheel house are present.

Figure 2: Custom made brake disc with Wire-woven bulk diamond (WBD) core used in the ventilated channel

2. Research approach

2.1 A highly porous ventilated brake disc

The construction of the new ventilated brake disc is made possible by integrating a wire-woven bulk diamond (WBD) core into the ventilated channel of the brake disc. Various periodic cellular materials with tetrahedral, pyramidal, and Kagome unit cells have been recently developed [18-20]. Studies have shown that such materials have excellent specific strength and stiffness as well as heat dissipation capability [21-23], making them a good candidate material for lightweight ventilated brake discs where simultaneous thermal and mechanical load bearing capabilities are required. Among these cellular materials, the WBD core has shown the most potential for this ventilated brake disc application as it has the highest strength.

The WBD disc brake was manufactured by first fabricating the annular WBD core using cold-rolled mild steel helical wires (SAE1006B) with the wire diameter of 1.5 mm and the helical pitch of 19.0 mm. Afterwards, the assembly is sprayed with copper paste (CubondTM grade 17LR, from SCM Metal Products, Inc.) and brazed at 1120 °C in a de-oxidation atmosphere of H2-N2 mixture. The bonding significantly improves the thermo-mechanical performance of the WBD compared with un-brazed WBD cores [23]. The single-layered WBD block is subsequently cut into an annular shape. After which, the WBD is sandwiched by and brazed onto two mild steel rubbing discs. The porosity and surface area density of the WBD core were respectively estimated to be ~0.9 and ~255 m^2/m^3. The equivalent yield strength, maximum strength, and Young's modulus of the core were measured to be 3.2 MPa, 4.8 MPa, and 1.08 GPa, respectively. The porosity and area density of the conventional pin- finned ventilated brake disc is approximately 0.7 and 81 m^2/m^3. Other dimensions of the WBD brake discs are identical to those of the pin-finned brake disc to facilitate a direct comparison of the respective cooling performances.

2.2 Field testing details

A test vehicle (Iveco Eurocargo 120e21 truck) weighing approximately 4310 kg was pulled continuously with a towing vehicle (Toyota Corolla 1.8) around the Gerotek's high speed oval track (Pretoria, South Africa), as shown in Fig. 3. The towing vehicle maintained a constant speed of approximately 40 km/h using the cruise control function and front brake pressure was applied to the test vehicle, for duration of approximately 2 hours, so that the front brake disc temperatures can reach steady state condition. The test conditions were representative of a constant speed descent of a 5.6% gradient in the extended braking mode.

Figure 3: A test vehicle (Iveco Eurocargo 120e21 truck) is towed at constant velocity, while the front brake pressure is applied to the test vehicle

Purpose built instrumentation was installed on the test vehicle as shown in Fig. 4. The instrumentation controlled the pneumatic front brake line pressure and recorded (1) towing force, (2) brake line pressure (front wheels), (3) front wheel speed, and (4) front disc surface temperatures.

(a) (b) (c)

Figure 4: Instrumentation is installed on the test vehicle, (a) Data acquisition and brake control unit, (b) Non- contact IR high temperature sensors and proximity sensor fitted to the right wheel, (c) 10 kN load cell with a tow-bar

The braking power can be determined from the product of the towing force and vehicle velocity which was held constant by varying the braking pressure using the brake control unit inside the cab of the test vehicle. This test was carried out on the pin-finned brake discs provided by the conventional original equipment manufacturer (OEM) (Fig. 5(a)) that were fitted to the test vehicle. Subsequently, the WBD ventilated brake discs (Fig. 5(b)) were fitted onto the test vehicle and the disc temperatures were recorded over an extended period of braking as described previously.

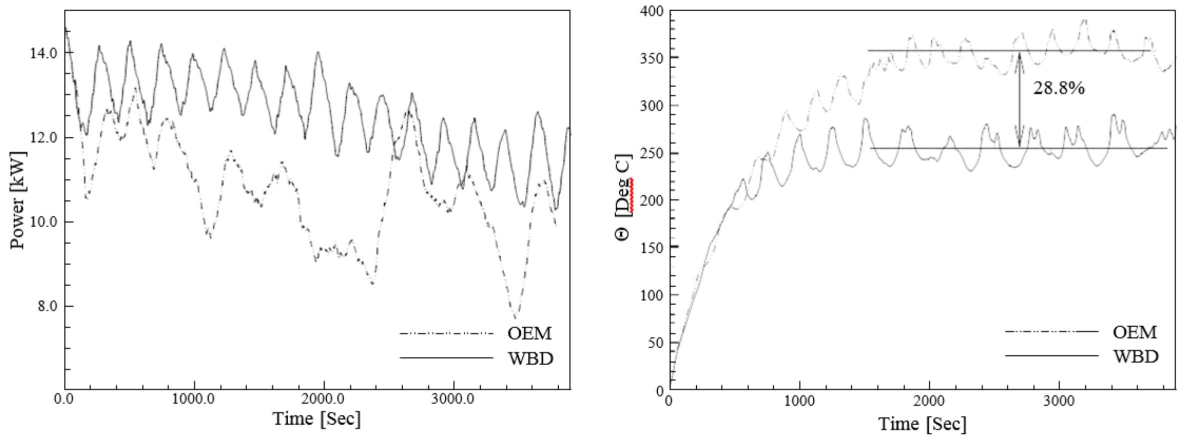
(a) (b) (c)

Figure 5: Front brake disc and caliper assembly, (a) OEM ventilated brake disc with pin fins, (b) highly porous WBD brake disc, (c) Right front wheel hub assembly with a WBD brake disc fitted

3. Field testing results and discussion

Figure 6(a) shows the variation the braking power over the duration of the field test for the two test cases (i.e., the OEM brake disc and the WBD brake discs). To determine the braking force (F_b) contribution that is measured from the total towing force (F_T) using the load cell, the contributions of the mean aerodynamic (F_a) and rolling resistance (F_r) of the test vehicle were measured at the test velocity (i.e., 40 km/h) without brake pressure. (i.e., $F_a + F_r = 800$ N). This value was then subtracted from the total measured towing force (i.e., $F_b = F_T - (F_a + F_r)$). During the tests, there was a prevailing northerly crosswind blowing across the track with a velocity of approximately 3-4 m/s. This cross wind resulted in a periodic fluctuation of the total towing force relating to a certain location on the test track. When the OEM disc was tested, the applied brake pressure was varied continuously to keep the mean braking power at approximately 10.8 kW. However, in testing the WBD disc the brake pressure was constant and the braking power was maintained at approximately 12.4 kW.

Figure 6(b) shows the temporal variation of the left front disc surface temperature that was obtained using the non-contact infrared temperature sensor. The results of the field test indicate that the steady-state temperature of the WBD disc was approximately 29% lower than the OEM ventilated pin-finned disc steady state temperature. Similarly to Fig. 6(a), there was a periodic fluctuation of the disc surface temperature, due to the prevailing cross wind. During extended braking, as experimentally demonstrated through field testing, the porous core improves the internal cooling in the ventilated channel, resulting in reduced operating disc temperature compared to the OEM pin-finned brake disc (~29%). The improved cooling is from the increased surface area of the WBD core as well as the promoted flow mixing by the three-dimensional WBD ligaments, which increases heat transfer from the disc to the cooling flow. Ultimately the reduced temperatures during extended braking are important because they reduce the likelihood of brake fade which can cause a catastrophic accident when a heavy vehicle descends a hill.



(a) (b)

Figure 6: Temporal variation of (a) braking power and (b) disc surface temperature using IR temperature sensor

4. Conclusions

The conducted field test results demonstrated that:

- The WBD core achieves approximately 29% reduction of surface temperature in the extended braking mode in comparison to the conventional OEM pin-finned ventilated brake disc for a similar braking power (approximately 10-12 kW).
- Cooling down tests further confirmed that the WBD core achieves a higher rate of cooling with a reduced time constant, indicating that there is enhanced heat transfer in comparison to the conventional OEM pin- finned ventilated brake disc.

5. Future work

Future work will implement:

- Closed loop control of the applied brake pressure should be implemented to maintain constant brake force, and deliver a more stable input brake power.
- More tests should be conducted under the present test conditions to confirm these results.
- The effect of velocity and brake power on the cooling performance of the ventilated brake disc concepts should also be investigated.
- Laboratory tests using the brake discs used in current field tests should be conducted to confirm the findings of present testing activities.

6. Acknowledgements

The authors would like to thank the Gauteng Innovation Hub (South Africa) for financially supporting this study and Iveco South Africa for supplying the Iveco vehicle for testing.

References

[1]. Mew TD, Kang K-J, Kienhöfer FW, Kim T, "Transient thermal response of a highly porous ventilated brake disc," Proc IMechE Part D: J Automobile Engineering, 229(6), 674–683, 2015

[2]. Limpert R, "Brake design and safety," 3rd edition, Warrendale, Pennsylvsnia: SAE International, 2011

[3]. Adamowicz A, Grzes P, "Influence of convective cooling on a disc brake temperature distribution during repetitive braking," Appl Thermal Engng, 31(14–15), 2177–2185, 2011
[4]. Day AJ, Newcomb TP, "The dissipation of frictional energy from the interface of an annular brake disc," Proc IMechE Part D: J Automobile Engineering, 198(11), 201–209, 1984
[5]. Loizou A, Qi HS, Day AJ, "A fundamental study on the heat partition ratio of vehicle disk brakes," Trans ASME, J Heat Transfer, 135(12), 121302-1–21302-8, 2013
[6]. Parker R and Newcomb T, "The performance and characteristics of the disc brake," SAE paper 640140, 1964
[7]. Jacko MG, "Physical and chemical changes of organic disc pads in service," Wear, 46(1): 163–175, 1978
[8]. Olshevskiy A, Olshevskiy A, Berdnikov O, Kim C-W, "Finite element analysis of railway disc brake considering structural, thermal, and wear phenomena," Proc IMechE Part C: J Mechanical Engineering Science, 226(7): 1845– 1860, 2012
[9]. Ostermeyer GP, Muller M, Abendroth H, Wernitz B, "Surface topography and wear dynamics of brake pads," SAE paper 2006-01-3202, 2006
[10]. Rhee SK, Jacko MG, Tsang PHS, "The role of friction film in friction, wear and noise of automotive brakes," Wear, 146(1), 89–97, 1991
[11]. Mortimer RG, Segel L, Dugoff H, Campbell JD, Jorgeson CM, Murphy RW, "Brake force requirement study: driver–vehicle braking performance as a function of brake system design variables, summary final report (contract FH-11–6952)," HSRI Report HuF- 6a, Highway Safety Research Institute, Ann Arbor, Michigan, USA, 1970
[12]. Rhee SK, "Friction properties of a phenolic resin filled with iron and graphite-sensitivity to load, speed and temperature," Wear, 28(2), 277–281, 1974
[13]. Dufrenoy P, "Two-/three-dimensional hybrid model of the thermomechanical behaviour of disc brakes," Proc IMechE Part F: J Rail and Rapid Transit, 218(1), 17–30, 2004
[14]. Mackin TJ, Noe SC, Ball KJ et al., "Thermal cracking in disc brakes," Engng Failure Analysis, 9(1): 63–76, 2002
[15]. Abbas SA, Cubitt NJ, Hooke CJ, " Temperature distributions in disc brakes," Proc IMechE, Automobile Div, 184(1): 185–194, 1969
[16]. Hwang P, Wu X, Jeon Y, "Repeated brake temperature analysis of ventilated brake disc on the downhill road," SAE paper 2008-01-2571, 2008
[17]. Grieve DG, Barton DC, Crolla DA, Buckingham JT, "Design of a lightweight automotive brake disc using finite element and Taguchi techniques," Proc IMechE Part D: J Automobile Engng, 212(4): 245–254, 1998
[18]. Wadley HNG, "Multifunctional periodic cellular metals," Phil Trans R Soc A, 364(1838): 31–68, 2006
[19]. Lee Y-H, Lee B-K, Jeon I, Kang K-J, "Wire-woven bulk Kagome truss cores," Acta Mater, 55(18): 6084–6094, 2007
[20]. Lee M-G, Ko G-D, Song J, Kang K-J, "Compressive characteristics of a wire-woven cellular metal," Mater Sci Engng A 539: 185–193, 2012
[21]. Kim T, Zhao CY, Lu TJ, Hodson HP, "Convective heat dissipation with lattice-frame materials," Mech Mater, 36(8): 767–780, 2004
[22]. Joo J-H, Kang K-J, Kim T, Lu, TJ, "Forced convective heat transfer in all metallic wire- woven bulk Kagome sandwich panels," Int J Heat Mass Transfer Int, 54(25), 5658–5662, 2011
[23]. Feng SS, Li MZ, Joo JH, Kang K-J, Kim T, Lu TJ, "Thermomechanical properties of brazed wire-woven bulk Kagome cellular metals for multifunctional applications," J

Thermophys Heat Transfer, 26(1): 66–74, 2012