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THERMAL PERFORMANCE OF PEO COATED LIGHTWEIGHT BRAKE ROTORS COMPARED WITH GREY CAST IRON

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ABSTRACT – Brake rotors play a significant role in converting the vehicle kinetic energy into heat energy that is dissipated through conduction and convection. The automotive industry has been looking for many years to develop lightweight brake rotors to reduce vehicle weight and subsequently improve fuel efficiency and vehicle emissions targets. Uncoated wrought aluminium alloys and metal matrix composite (Al-MMC) rotors have been reported to have insufficient safety margin for most passenger car applications. In this study, the thermal performance of coated and uncoated lightweight aluminium disc brake rotors was investigated numerically and experimentally, using both small scale and full size brake dynamometers. Five small scale solid brake rotors were investigated: grey cast iron, forged aluminium alloy (6082), the same 6082 alloy but with an alumina surface layer applied by plasma electrolytic oxidation (PEO), cast aluminium MMC (AMC640XA), and the same MMC again with PEO alumina surface layer. The disc and pad temperatures, brake pressure, coefficient of friction and brake torque were monitored during the tests for each disc brake material. In addition, a two dimensional axisymmetric finite element model was developed using Abaqus software in order to investigate the temperature distribution through the disc. The 2D FE model demonstrated good overall agreement with the experimental results and showed the same general trends. It was found that the PEO coated aluminium alloy has the best overall performance of the lightweight rotors tested in terms of friction and structural integrity at elevated temperature.

INTRODUCTION

Legislation due to be introduced in 2014 will require vehicle emissions to be reduced by around 50 percent of current levels (Euro 6 [1]). This has fuelled automotive industry research into the reduction of vehicle mass by the use of lightweight material. In order to meet the legislation limits, reduce fuel consumption and improve the vehicle performance, efforts are needed to reduce the unspring mass of the vehicle and one effective way to do this is by replacing the heavy cast iron brake disc with a lightweight alternative.

Many researchers have investigated the possibility of using lightweight disc brake rotors instead of the conventional grey cast iron or steel disc brake rotor [2-6]. Most research considers the use of aluminium alloy and metal or ceramic matrix composites as the material for the brake rotor. The reason for considering aluminium based materials is that they have tremendously encouraging properties such as relatively high specific heat capacity, low density and high thermal conductivity, which make them favourable candidates for many engineering applications. On the other hand, aluminium alloys have disadvantages, namely low maximum operating temperatures and low wear resistance, which can limit their application. To overcome this problem, surface modification of the alloy, using processes like thermal spraying [7] and anodizing [8] can be applied. More recently a relatively new coating process known as plasma electrolytic oxidation (PEO) has been developed by a UK

Company, Keronite International Ltd [9]. This ceramic coating prepared by PEO has several advantages such as significantly enhancing wear and corrosion resistance of lighter aluminium alloys. The coating also provides a low thermal conductivity layer which works like a thermal barrier over the substrate or base material [4, 10-12].

Full understanding of the thermal behaviour of a coated disc brake system needs further experimental investigation and also corresponding numerical models need to be developed and validated using the experimental results. However, using a full-scale brake dynamometer test is a time consuming process and relatively high in cost. Sanders et al. [13] designed and developed a reduced scale brake dynamometer which has the advantages of low cost and a shorter time to operate. The main aim of their research was to generate accurate experimental data which could be used in brake system design [2, 13, 14]. Likewise in preparation for the present work, a scaling methodology was used to develop a representative small scale dynamometer [15].

In the present study, small scale solid brake rotors were machined from blocks of cast iron, wrought aluminium alloy and a 30% SiC reinforced aluminium metal matrix composite (Al-MMC). Several of the wrought alloy and Al-MMC rotors were then subjected to a PEO process that formed c.50 and 30 micron thick layers of alumina on their rubbing surfaces respectively. Both coated and uncoated rotors were subjected to a demanding series of brake applications using both small scale and full size brake dynamometers during which the maximum temperature on the surface of each rotor was measured with a rubbing thermocouple. Alongside these experimental studies, numerical simulations were also conducted to predict the sub-surface temperature distributions within the rotors.

EXPERIMENTAL PROCEDURE

(A) MATERIALS AND COATING TECHNIQUE

In this study, representative small scale disc brake rotors were designed based on the constant energy scaling methodology [2, 15]. The selection of the disc brake rotor materials was based on the literature review [3, 5, 15] and the materials available. The small scale brake rotors were machined from two different aluminium-based materials, namely: wrought aluminium alloy (6082-T6) and aluminium MMC (AMC640XA). To provide benchmarks, a standard grey cast iron (EN-GJL-250) brake rotor was machined and tested under the same braking conditions. The disc geometry used for all rotors is shown in Figure 1.

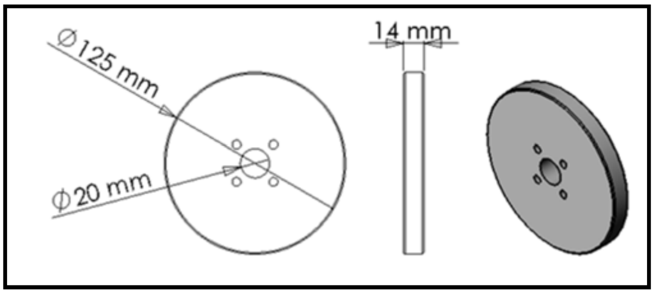


Figure 1: Disc geometry

Plasma electrolytic oxidation (PEO) was used to coat the rubbing surfaces of several aluminium alloy and aluminium metal matrix composite rotors. PEO coating is a cost effective technique for obtaining a hard aluminium oxide (alumina) coating on aluminium alloy substrates [4]. The thickness of the PEO coating for the treated Al-alloy and Al-MMC rotor was approximately 50 and 30 μm respectively.

All rotors were tested against a proprietary pad material manufactured by TMD Friction. This pad material was developed specifically to rub against an alumina coating but was also found to produce acceptable levels of friction performance against the standard cast iron and uncoated aluminium rotors brake.

The approximate physical and thermal properties for the different small scale brake rotors and the property of pad material are shown in Table 1.

Table 1: Physical and thermal properties for different materials used in study

Materials	Density ρ [kg/m^3]	Specific heat c_p [J/kg.K]	Conductivity k [W/m.K]
Aluminium Alloy (6082-T6)	2700	895	180
Grey Cast Iron (GCI)	7200	649	53
Al-MMC (AMC640XA)	2900	800	130
Alumina Coating	3030	828	1.6
Pad Material	3200	800	2.8

(B) BRAKE DYNAMOMETERS

In the current study, two test rigs were used to investigate the thermal performance of the different disc brake rotors. The first rig was a small scale dynamometer which was developed at Leeds based on the constant energy scaling methodology [2, 15], and the second was a full size brake dynamometer with high torque motor used to assess the thermal performance of the small scale rotors under extreme braking conditions. Figure 2 shows the main components of the two test rigs used in the current project.

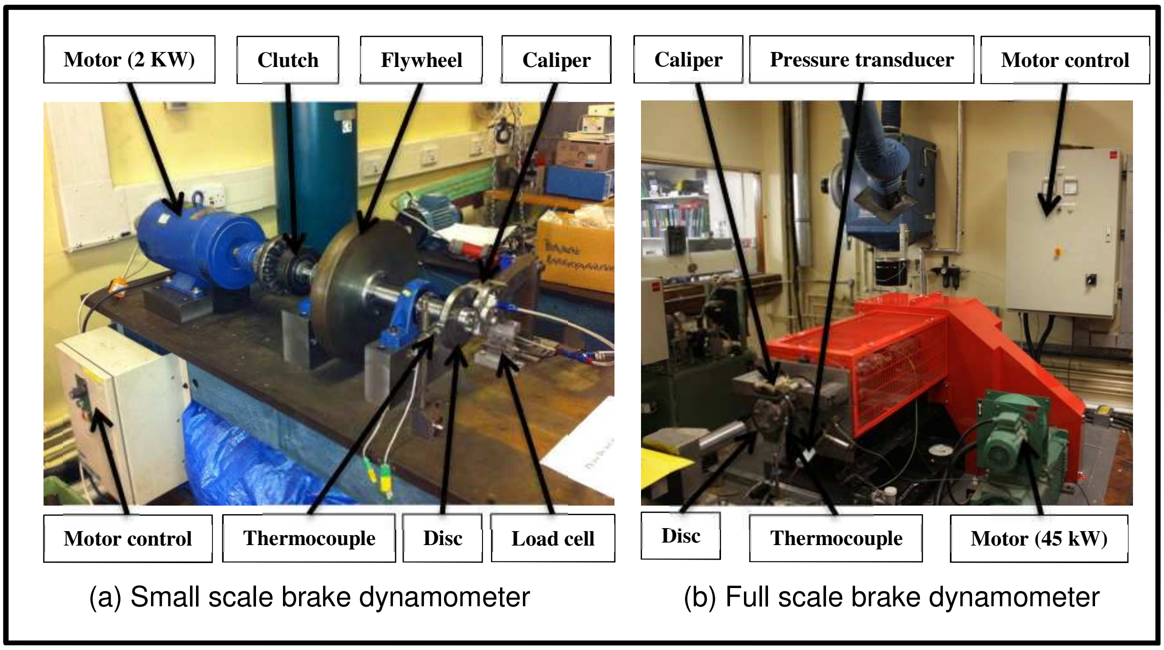
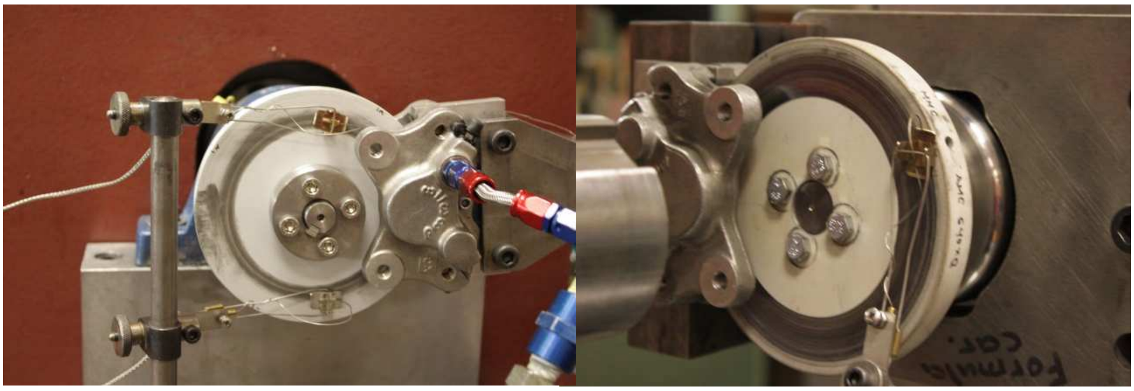


Figure 2: Main components of the small and full scale brake dynamometers

Both the small and full scale brake dynamometers were controlled by LabView software which can be modified to simulate any braking scenario and imposed thermal conditions. The small scale brake dynamometer was used to conduct burnishing and constant G stopping whereas the full scale brake dynamometer was used for drag braking only (constant rotational speed) as there is no large inertia available on this rig.

The braking pressure on both dynamometers was applied using linear actuator acting on the master cylinder and controlled via the LabView software. Sliding thermocouples were used to monitor the surface temperature of the disc on both dynamometers as shown in Figure 3. Also, the brake pad temperature was monitored using embedded thermocouples. Furthermore, the pressure and brake torque were monitored using a pressure transducer and load cell. A speed encoder was used to record the speed of the disc.



(a) Small scale brake dynamometer (b) Full scale brake dynamometer

Figure 3: Thermocouple position on the full and small scale dynamometers

(C) TEST MATRIX

The test matrix shown in Table 2 was developed to investigate the thermal performance of the different brake rotor materials. It is based on SAE J212 [16] although there is a big difference in the number of stops between this test matrix and the SAE standard for the following reasons:

1. The main aim of this research is to assess the brake rotor material not the friction pair.
2. The initial temperature for most of the tests was 100 ^{o}C and this was achieved by applying hundreds of braking pulses in order to reach the desired temperature.
3. The coefficient of friction was monitored for all the tests and showed good consistency which gave the researchers confidence that this text matrix was appropriate even though the number of stops was far lower than in SAE J212.

Table 2: Test matrix for all brake rotors

No.	Test Name	No. Stops	Simulation time for each stop	Speed (kph)	Brake pressure (bar)	Initial Temp. ^oC	Rig used
1	No - pressure	--	--	50	--	Room temp	Small Scale rig
2	Pre-burnish check	10	Braking time	50	2.5	Room temp	Small Scale rig
3	First (pre-burnish) effectiveness check	5	Braking time	50 and 80	1.2	100	Small Scale rig
		5	Braking time	50 and 80	2.5	100	Small Scale rig
		5	Braking time	50 and 80	3.8	100	Small Scale rig
		5	Braking time	50 and 80	5	100	Small Scale rig
		5	Braking time	50 and 80	6.1	100	Small Scale rig
		5	Braking time	50 and 80	7.3	100	Small Scale rig
4	Burnish	25	Braking time	70	3	100	Small Scale rig
5	High speed stop test	10	Braking time	100	6.4	100	Small Scale rig
6	Drag brake (low)	--	1 hour	50	Variable less than one	Room temp	Small Scale rig
7	Drag brake (moderate)	--	1 hour	80	Variable less than one	Room temp	Small Scale rig
8	Drag brake (high)	--	1 hour	100	Variable less than one	Room temp	Small Scale rig
9	Drag brake (high)	--	Variable	35	constant up to 3	Room temp	Full scale rig

EXPERIMENTAL RESULTS AND DISCUSSION

The small and full scale brake dynamometers were used to perform the test matrix shown in Table 2 for the five small scale brake rotors. The results showed that the aluminium alloy (6082 –T6) disc could not withstand the braking conditions specified in Table 2 and scratches started to appear on the rubbing surface at relatively low temperatures as shown in Figure 4. This is because during a friction process there are many small asperities that create localizes areas of high pressure and at these microscopically small locations the temperature becomes very high. This temperature can exceed the melting point of the Al-alloy, which means that the disc will melt at these spots thereby creating a rough disc surface. These peaks on the rough disc surface can then lead to further localized melting of the disc material which eventually results in complete disruption of the disc surface.

The uncoated aluminium MMC disc showed more resilience than the uncoated aluminum wrought alloy although scratches started to appear on the rubbing surface albeit at a higher temperature (around 250 ^{0}C) than for the aluminium alloy. The coated Al-alloy and the coated Al-MMC showed better thermal performance than the uncoated discs and lasted throughout the test matrix without any signs of surface disruption. As an example of a completed test matrix, the detailed temperature responses for the coated Al-MMC disc are shown in Figure 5 together with images of the rotor before and after test where no damage can be seen.

Figure 4: Uncoated aluminium alloy rotor after test showing badly degraded rubbing surface

The disc and pad temperatures for the different lightweight small scale brake rotors are compared against the conventional grey cast iron disc in Figure 6, for test 9 as shown in Table 2. The results show that the grey cast iron disc has the lowest surface temperature, whilst the coated Al-alloy has the highest surface temperature for the same braking conditions. In fact it was found that the coated discs always had a higher surface temperature than the corresponding uncoated discs which was as expected due to the thermal barrier effect of the coating. Although the coated Al-alloy always had a higher surface temperature than the coated Al-MMC, the friction performance of the coated Al-alloy was much better. The temperature responses in the brake pads were in the same order as the disc surface temperatures. In addition, the coating thickness was monitored and it showed that the variation in coating thickness for the Al-alloy was of the order of 2 µm, whilst the variation in coating thickness of the Al-MMC was of the order of 10 µm as shown in the SEM micrographs of Figure 7.

According to the material characterisation analysis and SEM images of the cross section shown in Figure 7, the wrought Al 6082 has extremely dense and uniform coating with alpha / gamma alumina as major constituents. This gives an extremely hard and durable tribo surface with stable CoF in addition to some thermal barrier effect. On the other hand, in the Al-MMC, only 60% is 6082 and the remaining 40 vol% is SiC particles. This high proportion of SiC presents considerable challenges to the PEO process and in fact to any surface modification process. The resulting coating is not very uniform with high levels of porosity and thus a resulting significantly lower bulk coating hardness. While the coating gives a considerable improvement of corrosion resistance compared to the MMC substrate, the tribological performance is poorer compared to the coated wrought alloy due to: a) poorer, low density and softer coating; b) crumbling and subsequent detachment of the oxidised ceramic particles (alumina) + some SiC which results in three-body abrasion wear between the disc and the brake pad, similar to the effect of feeding sand into the rubbing interface.

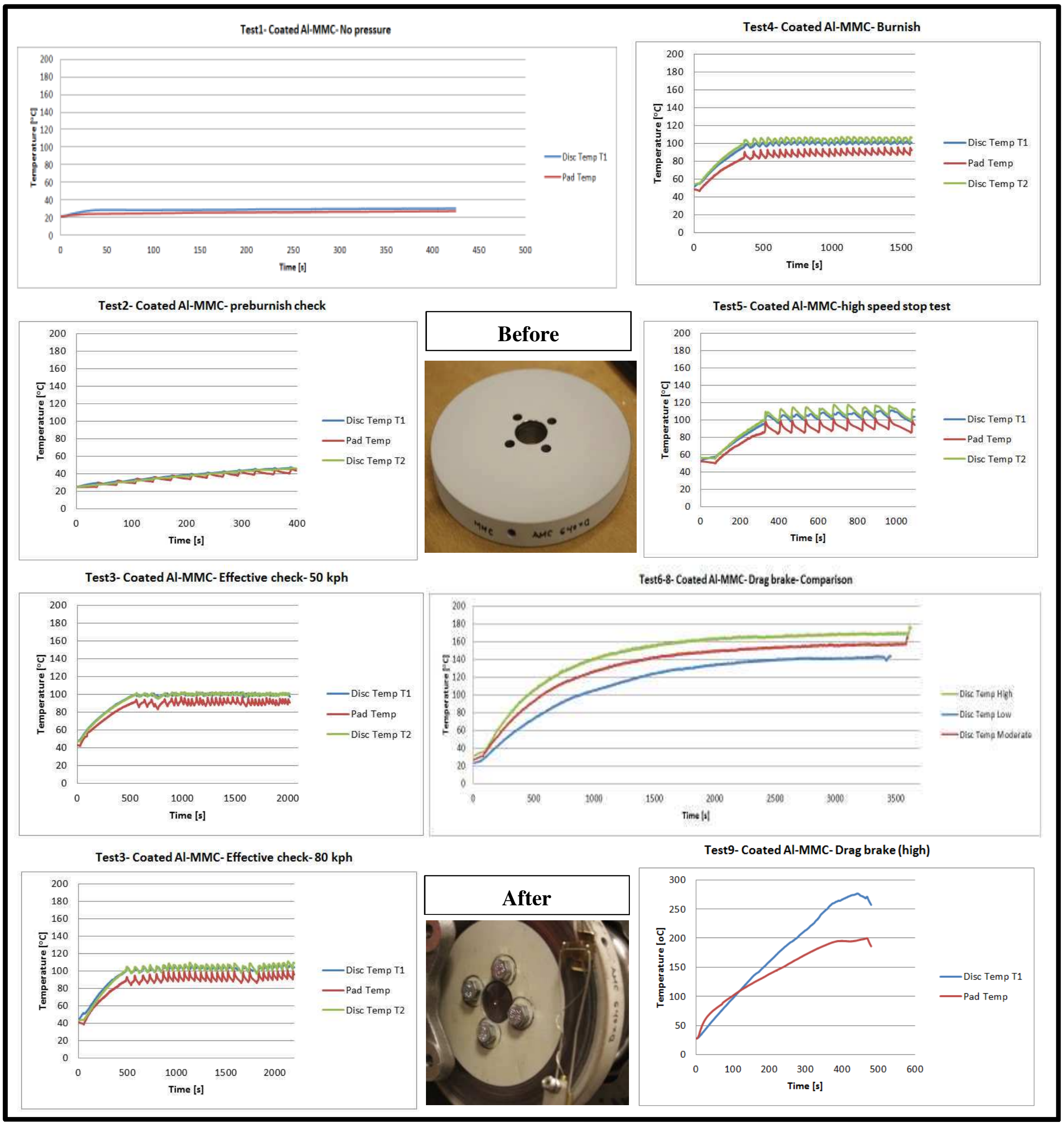


Figure 5: Temperature responses of the coated aluminium MMC disc

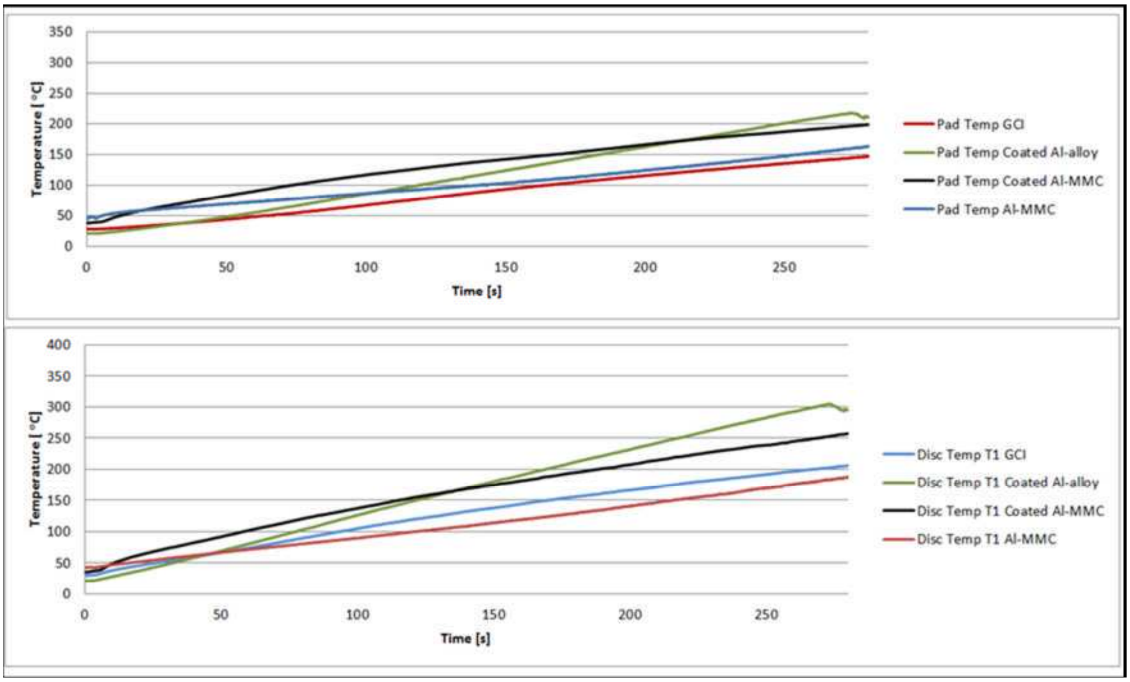


Figure 6: Temperature response of different disc brake materials

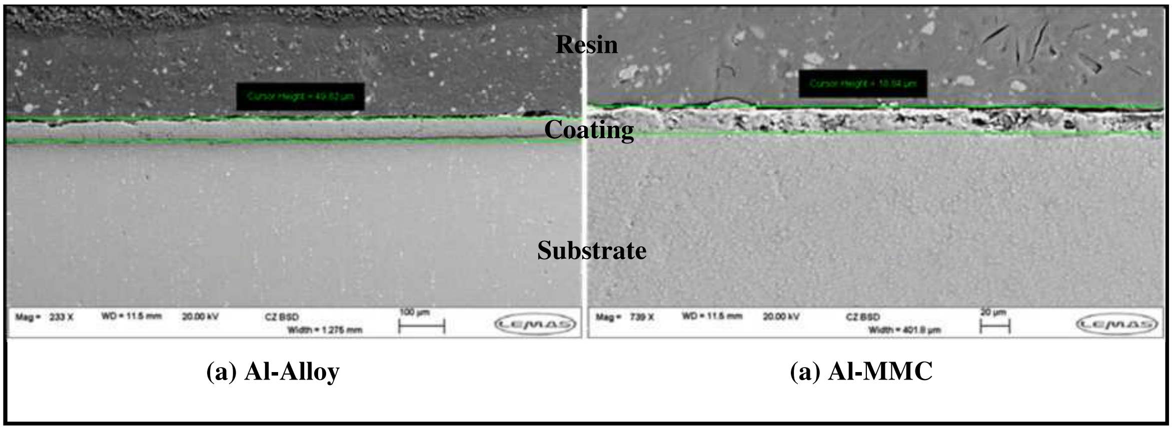


Figure 7: SEM image of the coated aluminium alloy and aluminium MMC cross section after the testing

FINITE ELEMENT MODEL

The thermal performance of the small scale disc brake rotors manufactured from different materials and both with and without a thin alumina coating was investigated using an axisymmetric transient heat transfer model developed in Abaqus\standard. The boundary condition and model setup are shown in Figure 8. The rotors were meshed using 4-node linear axisymmetric heat transfer quadrilateral elements (DC2D4). A mesh sensitivity anlaysis was carried out in order to choose the optimum element size. The heat flux was applied on the rubbing surface using a Matlab Mscript.

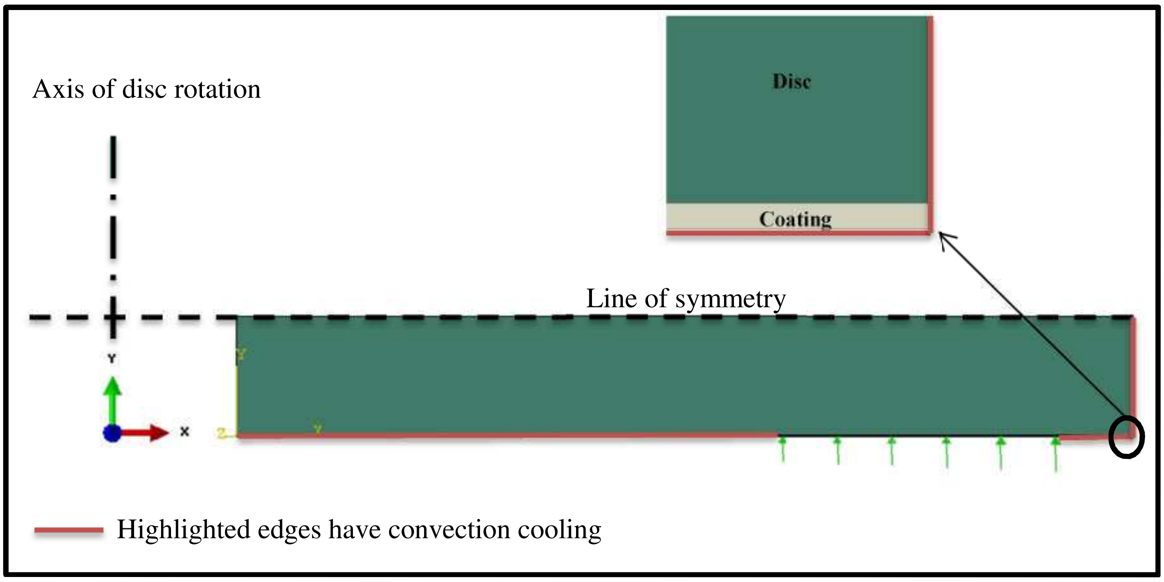


Figure 8: Two dimensional axisymmetric model of the small scale brake rotor

The experimentally obtained data was used to validate the 2D axisymmetric FE model. The heat flux was calculated based on the most extreme braking conditions (drag braking at a vehicle speed of 35 km/h for a vehicle with an average brake torque of 35 Nm, test 9) and applied in the Abaqus model. Two FE models were used; the first without coating and the second with a 30 µm alumina coating. Figure 9a shows that the numerical and experimental disc surface temperatures for grey cast iron are in very good agreement. The numerical and experimental surface temperatures for the coated Al-MMC small scale disc are shown in Figure 9b, and again the numerical results show good agreement with the experimental data.

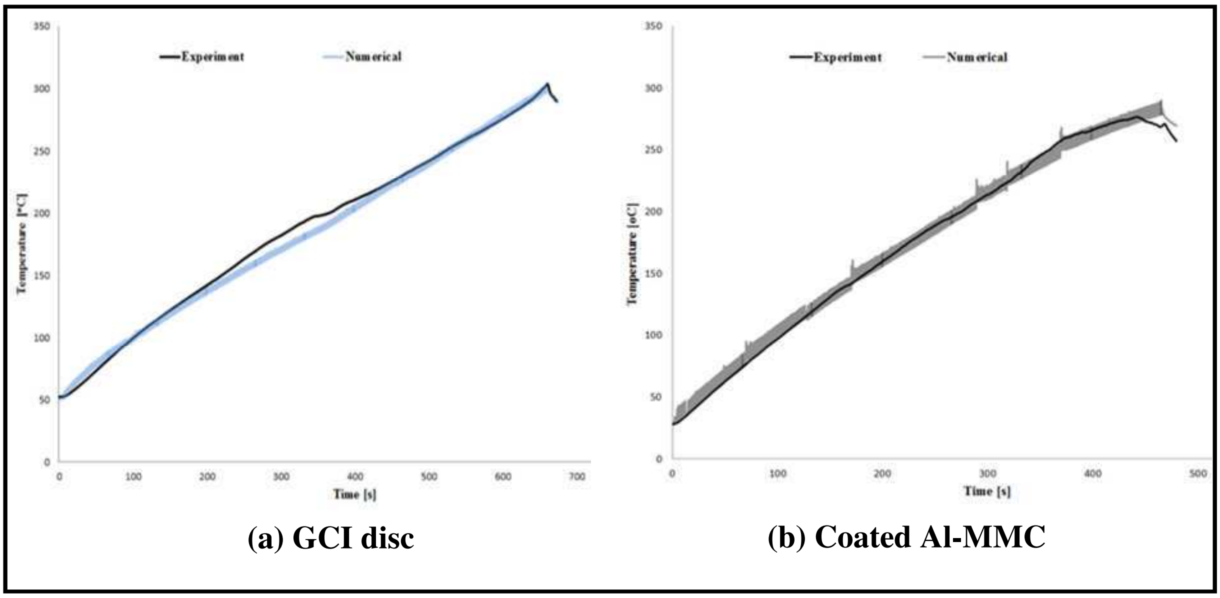


Figure 9: Numerical and experimental temperature response for GCI and coated Al-MMC disc

CONCLUSION AND FUTURE WORK

The five selected small scale disc brake rotors were tested using a representative brake test matrix. The results show that, after CGI, the coated aluminium alloy had the best thermal performance of the lightweight rotors tested in terms of structured integrity at elevated temperature. The friction coefficient for the coated aluminium alloy was also more stable than for the plain Al-alloy, Al-MMC or coated Al-MMC rotors. The uncoated aluminium alloy and aluminium metal matrix composite rotors did not withstand the higher temperature on the rubbing surface where scratches began to appear at a relatively low temperature due to softening of the aluminium Furthermore, the variation in coating thickness for aluminium alloy is much less than for the coated Al-MMC which makes it more resistant to wear.

A two dimensional axisymmetric transient heat transfer model was developed in Abaqus/standard. The model was validated using the experimental results obtained from the brake dynamometer and will be used to investigate the sub-surface temperature distributions in the different rotors.

In the current study the thermal performance of different lightweight brake rotors was investigated in detail. The discs were tested to their limits to assess the thermal performance of each material both with and without a coating. Material characterisation studies have been carried out to investigate the surface texture, transfer layer and coating performance. In the future, wear, corrosion and erosion resistance will be investigated to make sure that the selected aluminium alloy disc with the proposed PEO coating is capable of surviving real world conditions. The validated FE model will be used in the future to investigate different braking conditions and to investigate the optimum lightweight disc brake rotor design prior to full scale dynamometer and on-vehicle testing.

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